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SPATIO TEMPORAL ANALYSIS OF HISTORICAL PRECIPITATION VARIABILITY AND RAINFALL EXTREMES IN BADAMALEHRA, CHHATARPUR DISTRICT, CENTRAL INDIA

Imran Siddique[1*], P.K. Jain[2]

Author's Affiliations:
[1]Research Scholars, Maharaja Chhatrasal Bundelkhand University, Chhatarpur, Madhya Pradesh, India
[2]HOD Department of Geology, Maharaja Chhatrasal Bundelkhand University, Chhatarpur, Madhya Pradesh, India

***Corresponding Author: Imran Siddique,** Research Scholars, Maharaja Chhatrasal Bundelkhand University, Chhatarpur, Madhya Pradesh, India
E- mail: imransiddique2017@gmail.com

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Abstract:
Erratic and extreme rainfall strongly governs rain-fed farming and water availability in drought-prone Bundelkhand, a semi-arid tract of central India. In this study, 33 years (1990–2022) of daily observations from the Badamalehra rain gauge, Chhatarpur district, Madhya Pradesh, were examined to describe how rainfall behaves, shifts and peaks at month, season and year scales. After screening for errors, the daily values were aggregated into month, season and year totals. Dispersion was quantified through the CV (coefficient of variation), the PCI (precipitation concentration index) and IMD departure categories. Monotonic tendencies were examined with the Mann–Kendall statistic and their size with Sen's estimator, step changes were located with Pettitt's procedure, and extremes were described using thirteen ETCCDI and IMD indices. Mean yearly rainfall amounted to 1200.3 mm (CV 26.7%); the June–September monsoon supplied 94.3% of this total, and July and August alone contributed 62.8%. The non-monsoon seasons exhibited very high CV (196 to 224%) and the mean PCI was very high (32.8%) suggesting a strongly seasonal rainfall regime. For the 33 years 16 years were the normal years, 9 years were the excess years and 8 years were the deficient years, the deepest being 2007 (−54.7%). The annual rainfall (−3.09 mm yr−1) and monsoon rainfall (−5.66 mm yr−1) exhibited non-significant downward trends, respectively, and did not contain any significant change point. Rainfall in the month of September experienced a significant ($p < 0.01$) decreasing trend between 1990-1999 and 2010-2022, with more years of deficiency after the year 2000, while the rainfall during winter and pre-monsoon showed strong increasing trends ($p < 0.01$). No significant changes in extreme intensity or extreme frequency for the precipitation occurred, but very wet days still supply roughly a quarter of yearly rainfall, while the longest dry spell shortened significantly (−1.88 days yr^{-1}). These outcomes point to the value of capturing rainwater, conserving soil moisture on the field and preparing alternate crop plans to cope with late-season monsoon failure at Badamalehra.

Keywords: *Rainfall variability, Mann–Kendall test, Rainfall extremes, Bundelkhand, Trend analysis*

1. INTRODUCTION

The 50% of the net sown area is rainfed in India, rainfall is the key climatic variable shaping farm output, water supply and rural livelihoods. The hydrological cycle is becoming stronger and rainfall in many parts of the world is increasing in intensity, quantity and time in a warming

climate (IPCC, 2013). In India such changes are represented by the seasonal distribution of the south-west monsoon, inter-annual fluctuations of the monsoon, the count and severity of heavy downpours, and the water accessible to crops, all of which have an impact on the availability of crops for production.

Central India is emerging as a hotspot of such changes. The analysis of long term gridded daily data has revealed a rise of heavy and very heavy rain events over Central India since mid-20th century and a threefold increase of widespread extreme rain events in the period 1950-2015. Meanwhile, a few studies have shown a reduction in the mean monsoon and annual rainfall over Madhya Pradesh. Duhan and Pandey (2013) noted decreasing precipitation trends in most districts of the states for 1901–2002 period, and Kumar et al. (2023) observed that the annual and monsoon trends were not significant but the pre-monsoon trend was positive with a change point around 1998 for the period 1951–2021.

Bundelkhand region (Chhatarpur district) ranks among the most drought-exposed and agriculturally fragile parts of central India. The monsoon rains are critical for agriculture here; irrigation is scarce; and the area has had repeated periods of droughts followed by periods of heavy rainfall. Som and Dey (2022) reported growing rainfall variability and declining annual totals across five Bundelkhand districts of Madhya Pradesh for 1951–2018, while Fanai et al. (2022) found that south-west monsoon rainfall fell in every Bundelkhand district of the state over 1981–2020. But most of these studies use district-averaged/gridded information and few have combined rainfall extremes with monthly, seasonal and annual information at the level of the tehsil.

Farmers and local agencies respond to the rainfall that occurs at their location which is why station-level information is important for local crop planning, design of water-harvesting structures, drought and flood preparedness. The long-term rainfall record of Badamalehra tehsil has not yet been analysed. The present study was therefore undertaken following objectives:

- To convert the daily rainfall record of Badamalehra for 1990–2022 into monthly, seasonal and annual series and describe their statistical characteristics;
- To assess rainfall variability, seasonal concentration and the frequency of excess and deficient years;
- To detect trends and change points with non-parametric tools, namely the Mann–Kendall statistic, Sen's slope and the Pettitt change-point method;
- To examine shifts in extreme rainfall through ETCCDI and IMD indices. The outcomes are intended to guide climate-resilient farming and water planning in the tehsil.

2. MATERIALS AND METHODS

This work presents a long-term (1990–2022) single-station analysis of rainfall data of Badamalehra station in Chhatarpur district of Madhya Pradesh. The daily rainfall data provided for the station have been assessed for central tendency, variability, concentration, inter-annual anomalies, monotonic trends, change points and rainfall extremes after being quality checked and aggregated to month, season and annual totals. The study area, data and each analytical procedure are described below.

2.1. Study area

Badamalehra (Bada Malhera; approx. 24.57° N latitude and 79.33° E longitude) is a town in the tehsil (sub-district) headquarters of Chhatarpur district in the Union of the Union Territory of Madhya Pradesh, Central India, and lies within Bundelkhand in the north-east of the state. The tehsil experiences a tropical monsoon regime ranging from sub-humid to semi-arid, with a hot season (March-June), south-west monsoon season (June-Sep) accounting for the majority of the annual rainfall and a cold dry winter. The area is mainly rainfed where the amount, timing and reliability of rainfall is a major factor determining kharif and rabi crop production, surface-water storage and recharge of groundwater. Fig. 1 maps the position of the tehsil.

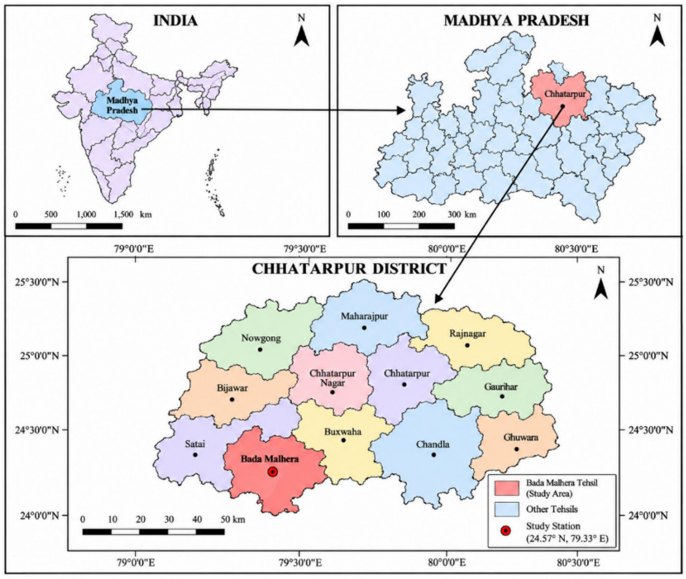


Figure 1: Map showing the position of Badamalehra (Bada Malhera) tehsil, Chhatarpur district, Madhya Pradesh, India

2.2. Data source and quality control

The data observed from 1st Jan 1990 to 31st Dec 2022, which consists of 33 years of data, was used for daily rainfall at the Badamalehra rain-gauge station at 08:30 IST. There were 12,023 daily observations in the file and 12,053 calendar days, with 30 missing days representing all in November 2015. There were no negative dates or duplicate dates. November is a month with less than 1% of the annual rainfall and as such the missing month was not included in all the monthly statistics and trend tests for November and was only substituted with the long-term November mean (10.1 mm) when calculating the 2015 seasonal and annual totals. The days available were used for extreme indices in 2015.

2.3. Conversion of daily data into monthly, seasonal and annual series

The daily values were added together for each calendar month, thus creating a continuous monthly rainfall series of 396 months (33 years × 12 months). Following the seasonal scheme of the IMD (India Meteorological Department), monthly sums were then grouped into four seasons: January–February (winter), March–May (pre-monsoon), June–September (south-west monsoon) and October–December (post-monsoon). The annual total was calculated by adding up the totals from the 12 months. For descriptive analysis, variability and trend analysis, the monthly series was used and for computation of rainfall extreme indices the daily series was kept.

2.4. Descriptive statistics and variability indices

For each month, season and year, the mean, standard deviation (SD), median, maximum, minimum, skewness and percentage contribution to annual rainfall were computed. Relative variability was expressed by the coefficient of variation,

$$\text{CV}\ (\%) = \left(\frac{\text{SD}}{\text{mean}}\right) \times 100,$$

and, after Asfaw et al. (2018), grouped into four classes: below 20 % (low), 20–30 % (moderate), 30–40 % (high) and above 40 % (very high).

Within-year unevenness of rainfall was gauged with the Precipitation Concentration Index proposed by Oliver (1980),

$$\text{PCI} = 100 \times \frac{\sum p_i^2}{(\sum p_i)^2},$$

where $p_i$is the rainfall of month i. A PCI under 10 denotes evenly spread rainfall, 11–15 a moderate degree of concentration, 16–20 an

irregular spread and values over 20 a markedly irregular pattern (strong seasonality).

Annual departures from the 1990–2022 mean were grouped under the IMD categories of excess (≥ +20 %), normal (+19 % to −19 %), deficient (−20 % to −59 %) and scanty (≤ −60 %). A rainy day was defined, in accordance with IMD practice, as a day with rainfall ≥ 2.5 mm.

2.5. Trend and change-point detection

Whether monthly, seasonal and yearly rainfall followed a consistent upward or downward course was checked with the rank-based Mann–Kendall (MK) test (Mann, 1945; Kendall, 1948), whose statistic is computed as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right),$$

where $x_i$and $x_j$denote the observations in years $i$and $j(j > i)$ and $n$is the record length. The variance of $S$was corrected for tied values, and the standardised statistic $Z$was used to assess significance at the 1 %, 5 % and 10 % levels. Kendall's $\tau$was reported as a measure of trend strength. Trend size was quantified through Sen's (1968) slope,

$$Q = \operatorname{median}\left[\frac{x_j - x_i}{j - i}\right],$$

expressed in mm yr.

Since autocorrelated data may exaggerate MK significance (Hamed & Rao, 1998), every series was first screened for lag-1 serial correlation. The lag-1 coefficient of annual rainfall ($r_1 = -0.25$) and of the monsoon months (-0.29 to 0.06) was not significant at the 5 % level (critical value $\approx \pm 0.34$for $n = 33$); consequently, the original MK test was applied. Possible step changes (change points) in yearly rainfall were sought with the method of Pettitt (1979).

2.6. Rainfall extreme indices

For every calendar year, thirteen indices were derived from the daily record, drawing on the ETCCDI list (Expert Team on Climate Change Detection and Indices; Zhang et al., 2011) together with IMD thresholds: total rain on wet days (PRCPTOT, days ≥ 1 mm), rainy-day count (≥ 2.5 mm), mean wet-day intensity (SDII = PRCPTOT / wet-day count), highest 1-day (Rx1day) and 5-day (Rx5day) totals, counts of days reaching ≥ 10 mm (R10mm), ≥ 20 mm (R20mm) and ≥ 64.5 mm (IMD heavy rainfall), annual total on days above the 95th (R95p) and 99th (R99p) percentiles of wet-day rainfall, the percentage contribution of R95p to PRCPTOT, and the longest unbroken spells of dry days (CDD, < 1 mm) and wet days (CWD, ≥ 1 mm). The 95th and 99th percentile thresholds, derived from all wet days of 1990–2022, were 95.4 mm and 163.1 mm, respectively. Trends in every index were then evaluated through the same MK and Sen's slope as described above.

2.7. Software

Data entry, screening, aggregation of daily values into month, season and year totals, and table preparation were done in Microsoft Excel. The monthly and annual totals were cross-checked and the statistical computations performed in Python 3 using the pandas, NumPy and SciPy libraries, through which the trend, slope, change-point and extreme-index statistics were obtained.

3. RESULTS AND DISCUSSION

Results are reported in the order of analysis above: daily record to monthly series, monthly, seasonal and annual rainfall characteristics, inter-annual anomalies, trends and change points, decadal behaviour and finally, rainfall extremes. The results are discussed, taking the recent studies conducted in Bundelkhand, Madhya Pradesh and Central India into consideration.

3.1. Monthly rainfall series derived from daily records

Aggregation of the 12,023 daily observations produced a 33-year monthly rainfall matrix for Badamalehra (Table 1).

Table 1: Month-wise and yearly rainfall (mm) at Badamalehra computed from daily observations, 1990–2022

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	0.0	0.0	0.0	0.0	0.0	157.2	497.0	193.6	546.2	0.0	0.0	20.0	1414.0
1991	0.0	0.0	0.0	0.0	0.0	87.0	431.2	450.2	113.5	0.0	0.0	1.2	1083.1
1992	0.0	0.0	0.0	0.0	0.0	10.0	245.7	621.3	502.8	0.0	0.0	0.0	1379.8
1993	0.0	0.0	0.0	0.0	0.0	49.0	231.8	172.6	1032.8	0.0	0.0	0.0	1486.2
1994	0.0	14.6	0.0	0.0	0.0	358.8	638.0	545.0	73.2	0.0	0.0	0.0	1629.6
1995	0.0	0.0	0.0	0.0	0.0	136.2	157.8	398.8	66.2	0.0	0.0	0.0	759.0
1996	0.0	0.0	0.0	0.0	0.0	61.4	273.2	659.4	134.4	0.0	0.0	0.0	1128.4
1997	0.0	0.0	0.0	0.0	0.0	108.6	359.3	257.8	303.4	36.8	117.0	137.0	1319.9
1998	0.0	0.0	6.0	0.0	0.0	35.4	565.4	319.3	84.2	0.0	22.0	0.0	1032.3
1999	0.0	25.5	0.0	0.0	0.0	26.6	243.9	643.1	741.1	70.3	0.0	0.0	1750.5
2000	0.0	0.0	0.0	0.0	0.0	144.8	396.4	153.4	140.0	0.0	0.0	0.0	834.6
2001	20.8	0.0	0.0	0.0	0.0	356.0	415.6	173.0	48.0	41.4	0.0	0.0	1054.8
2002	0.0	36.2	0.0	0.0	30.2	54.6	26.0	664.0	348.0	0.0	0.0	0.0	1159.0
2003	0.0	0.0	0.0	0.0	0.0	96.2	311.8	396.8	716.1	3.0	0.0	10.0	1533.9
2004	5.0	0.0	0.0	0.0	6.2	336.6	155.4	370.2	133.0	0.0	0.0	0.0	1006.4
2005	5.2	0.0	36.2	0.0	0.0	134.9	655.4	267.6	203.6	0.0	0.0	0.0	1302.9
2006	0.0	0.0	0.0	0.0	0.0	52.0	475.8	283.8	62.0	0.0	0.0	0.0	873.6
2007	0.0	77.0	0.0	0.0	0.0	26.5	144.7	140.0	155.0	0.0	0.0	0.0	543.2
2008	0.0	0.0	0.0	0.0	4.0	740.2	252.8	350.4	120.0	0.0	0.0	0.0	1467.4
2009	15.0	0.0	0.0	0.0	0.0	38.7	264.2	241.6	142.4	142.6	124.0	13.0	981.5
2010	0.0	0.0	0.0	0.0	0.0	0.0	329.2	285.8	245.4	3.8	60.0	0.0	924.2
2011	0.0	0.0	0.0	0.0	35.0	418.4	444.0	519.8	210.9	0.0	0.0	0.0	1628.1
2012	11.0	0.0	0.0	0.0	0.0	0.0	625.4	539.0	119.9	0.0	0.0	0.0	1295.3
2013	0.0	15.0	0.0	0.0	0.0	368.0	639.8	691.3	5.2	44.0	0.0	5.0	1768.3
2014	77.4	110.4	15.8	0.0	0.0	0.0	190.8	276.6	137.0	21.4	0.0	36.0	865.4
2015	62.4	1.0	57.6	57.0	1.2	59.2	306.8	446.4	6.6	14.4	—	0.0	1022.7*
2016	16.8	1.8	12.8	0.0	6.4	152.2	798.0	597.2	40.6	6.2	0.0	0.0	1632.0
2017	0.0	0.0	0.0	0.0	0.0	175.8	446.4	150.8	40.6	6.2	0.0	0.0	819.8
2018	0.0	11.8	0.0	0.0	0.0	88.7	327.0	215.4	359.4	0.0	0.0	0.0	1002.3
2019	0.0	2.0	0.0	8.0	0.0	12.0	294.2	382.5	566.7	51.0	0.0	12.2	1328.6
2020	41.8	0.0	2.0	1.0	10.0	114.6	73.0	536.2	93.8	0.0	0.0	8.2	880.6

2021	0.0	1.4	0.0	0.0	102.0	194.8	240.6	445.6	104.8	0.0	0.0	0.0	1089.2
2022	76.0	0.0	0.0	0.0	7.2	179.6	460.6	545.6	148.4	196.0	0.0	0.0	1613.4
Mean	10.0	9.0	4.0	2.0	6.1	144.7	361.1	391.9	234.7	19.3	10.1	7.4	1200.3

* November 2015 was missing (—); the 2015 annual total includes the long-term November mean (10.1 mm).

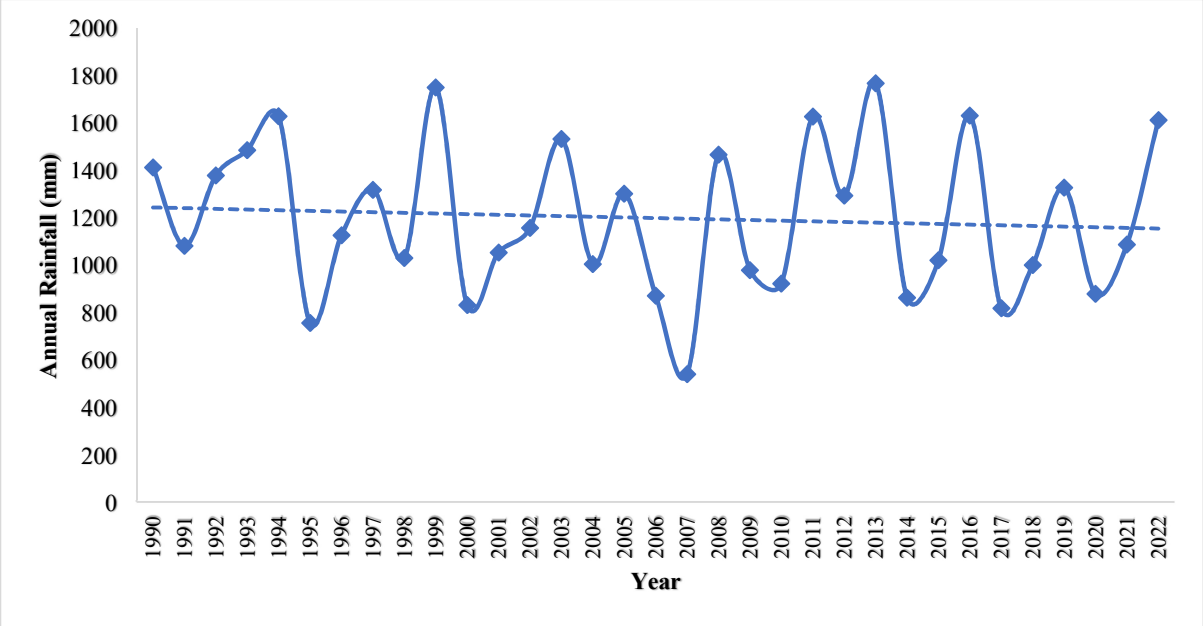


Figure 2: Annual rainfall at Badamalehra with linear trend line (1990–2022)

The mean annual rainfall for 1990–2022 was 1200.3 mm, ranging from 543.2 mm in 2007 to 1768.3 mm in 2013 (Fig. 2). Rainfall was overwhelmingly confined to June–September; in most years, January–May and October–December were nearly or completely dry. The matrix also reveals the extreme year-to-year irregularity of individual monsoon months—for example, September rainfall varied from 5.2 mm (2013) to 1032.8 mm (1993), and June from nil (2010, 2012 and 2014) to 740.2 mm (2008).

3.2. Monthly rainfall characteristics

Table 2 lists the summary statistics for each month.

Table 2: Month-wise rainfall statistics for Badamalehra (1990–2022)

Month	Mean (mm)	SD (mm)	CV (%)	Median (mm)	Maximum (mm) / Year	Minimum (mm)	Dry years (n)	Contribution (%)
Jan	10.0	21.8	217.0	0.0	77.4 (2014)	0.0	23	0.8
Feb	9.0	23.7	263.8	0.0	110.4 (2014)	0.0	22	0.7
Mar	4.0	11.9	302.3	0.0	57.6 (2015)	0.0	27	0.3
Apr	2.0	10.0	498.6	0.0	57.0 (2015)	0.0	30	0.2
May	6.1	19.0	310.1	0.0	102.0 (2021)	0.0	24	0.5
Jun	144.7	159.4	110.2	96.2	740.2 (2008)	0.0	3	12.1

Jul	361.1	182.2	50.5	327.0	798.0 (2016)	26.0	0	30.1
Aug	391.9	172.6	44.0	382.5	691.3 (2013)	140.0	0	32.7
Sep	234.7	243.7	103.8	137.0	1032.8 (1993)	5.2	0	19.6
Oct	19.3	43.2	223.8	0.0	196.0 (2022)	0.0	20	1.6
Nov	10.1	31.1	307.6	0.0	124.0 (2009)	0.0	28	0.8
Dec	7.4	24.5	333.1	0.0	137.0 (1997)	0.0	24	0.6

SD = standard deviation; CV = coefficient of variation. Dry years (n) = number of years with no rainfall in the month (November: n = 32).

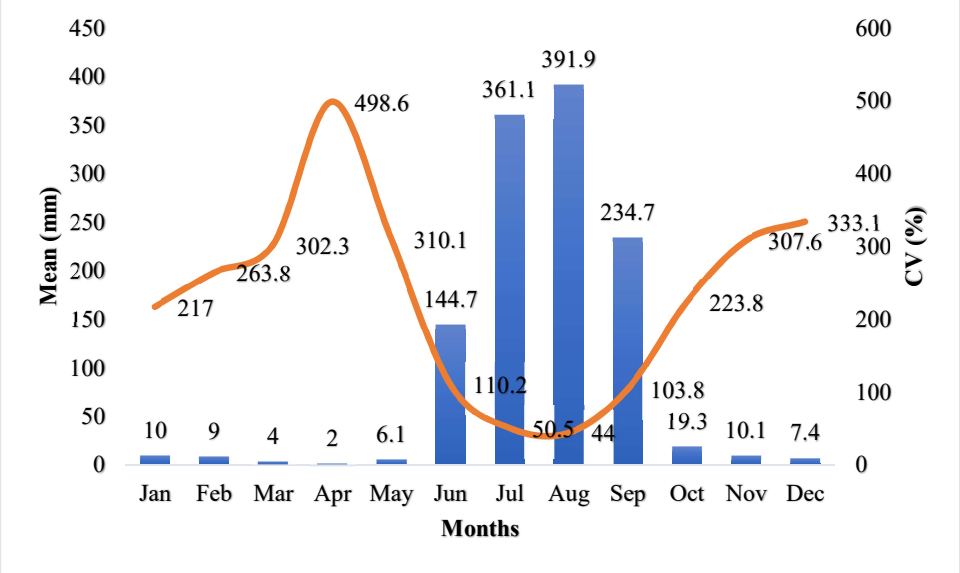


Figure 3: Average rainfall and CV for each month at Badamalehra (1990–2022)

August was the wettest month (mean 391.9 mm; 32.7% of annual rainfall; Fig. 3), followed by July (361.1 mm; 30.1%), September (234.7 mm; 19.6%) and June (144.7 mm; 12.1%). July and August together supplied 62.8% of the annual total and were the only months that received rain in every year of record. These two months also showed the lowest relative variability (CV of 50.5% and 44.0%), whereas June (110.2%) and September (103.8%) were far less dependable, reflecting year-to-year differences in the onset and withdrawal of the monsoon. All non-monsoon months had a median of 0.0 mm, recorded no rain in 20–30 of the 33 years and exhibited CV values between 217% and 499%, indicating that rainfall in these months is sporadic and associated with occasional western disturbances or convective storms.

The dominance of August and the concentration of rainfall in the south-west monsoon agree with the findings of Fanai et al. (2022), who analysed 40 years (1981–2020) of rainfall for the districts of Bundelkhand and reported that August receives the highest amount of rainfall and that the region receives about 90% of its annual rainfall during June–September. Kumar et al. (2023), using 1951–2021 IMD gridded data for the whole of Madhya Pradesh, similarly found very high variability in the non-monsoon seasons compared with the monsoon. The very high CV of the non-monsoon months at Badamalehra implies that rabi-season crops in the tehsil cannot rely on in-season rainfall and depend instead on residual soil moisture and supplemental irrigation.

3.3. Variability of season-wise and yearly rainfall

Table 3: Season-wise and yearly rainfall statistics for Badamalehra (1990–2022)

Season	Mean (mm)	SD (mm)	CV (%)	Maximum (mm) / Year	Minimum (mm) / Year	Skewness	Contribution (%)
Winter (Jan–Feb)	19.0	37.3	195.9	187.8 (2014)	0.0 (15 years)	3.16	1.6
Pre-monsoon (Mar–May)	12.1	27.1	224.1	115.8 (2015)	0.0 (20 years)	2.94	1.0
Monsoon (Jun–Sep)	1132.4	333.7	29.5	1704.3 (2013)	466.2 (2007)	0.06	94.3
Post-monsoon (Oct–Dec)	36.8	74.7	203.4	290.8 (1997)	0.0 (16 years)	2.58	3.1
Annual	1200.3	320.3	26.7	1768.3 (2013)	543.2 (2007)	0.11	100.0

Minimum '0.0 (n years)' gives the count of years with zero seasonal rainfall.

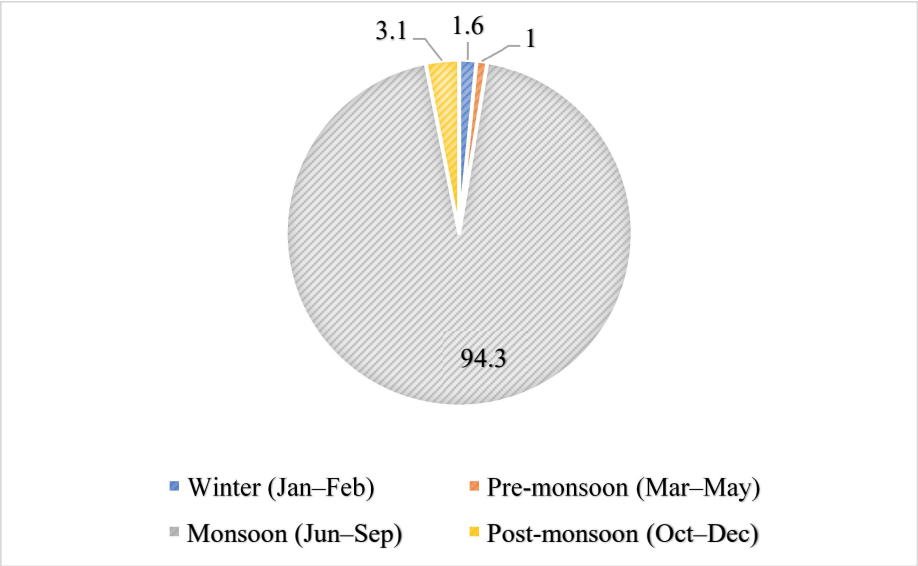


Figure 4: Seasonal contribution to annual rainfall at Badamalehra (1990–2022)

Seasonal statistics (Table 3; Fig. 4) show that the south-west monsoon contributed 1132.4 mm, or 94.3% of the mean annual rainfall, while the post-monsoon (36.8 mm; 3.1%), winter (19.0 mm; 1.6%) and pre-monsoon (12.1 mm; 1.0%) seasons together contributed less than 6%. Annual (CV = 26.7%) and monsoon (CV = 29.5%) rainfall fell in the moderate-variability class of Asfaw et al. (2018), whereas all three non-monsoon seasons had very high variability (CV = 196–224%) and were strongly right-skewed (skewness 2.6–3.2), with 15–20 years recording no seasonal rainfall at all. Eighteen of the 33 years received less than the mean annual rainfall, and the difference between the wettest (2013) and driest (2007) years was 1225.1 mm, more than the long-term mean itself.

The seasonal share of monsoon rainfall at Badamalehra (94.3%) is slightly higher than the 91.1% reported for Madhya Pradesh as a whole by Kumar et al. (2023) and the approximately 90% reported for Bundelkhand by Fanai et al. (2022), confirming the strongly monsoon-dependent character of the north-eastern part of the state. The station-level CV of annual rainfall (26.7%) is, however, considerably higher than

the state-average value of 17.21% obtained from gridded data by Kumar et al. (2023). This difference is expected, because point observations retain local convective variability that is smoothed out when rainfall is averaged over grid cells or large areas. The Precipitation Concentration Index averaged 32.8 (range 19.1–52.2) and exceeded 20 in 31 of the 33 years, indicating a strongly irregular (highly seasonal) rainfall regime in almost every year. Such a regime concentrates runoff into a few weeks, increasing the risk of soil erosion and flash floods during the monsoon and of water scarcity for the remaining eight months.

3.4. Inter-annual rainfall anomalies

Table 4: Classification of annual rainfall departures at Badamalehra (1990–2022)

Category (departure from mean)	Number of years	Frequency (%)	Years
Excess (≥ +20%)	9	27.3	1993, 1994, 1999, 2003, 2008, 2011, 2013, 2016, 2022
Normal (−19% to +19%)	16	48.5	1990, 1991, 1992, 1996, 1997, 1998, 2001, 2002, 2004, 2005, 2009, 2012, 2015, 2018, 2019, 2021
Deficient (−20% to −59%)	8	24.2	1995, 2000, 2006, 2007, 2010, 2014, 2017, 2020
Scanty (≤ −60%)	0	0.0	—

Categories follow the India Meteorological Department classification of departure from the long-term mean (1200.3 mm).

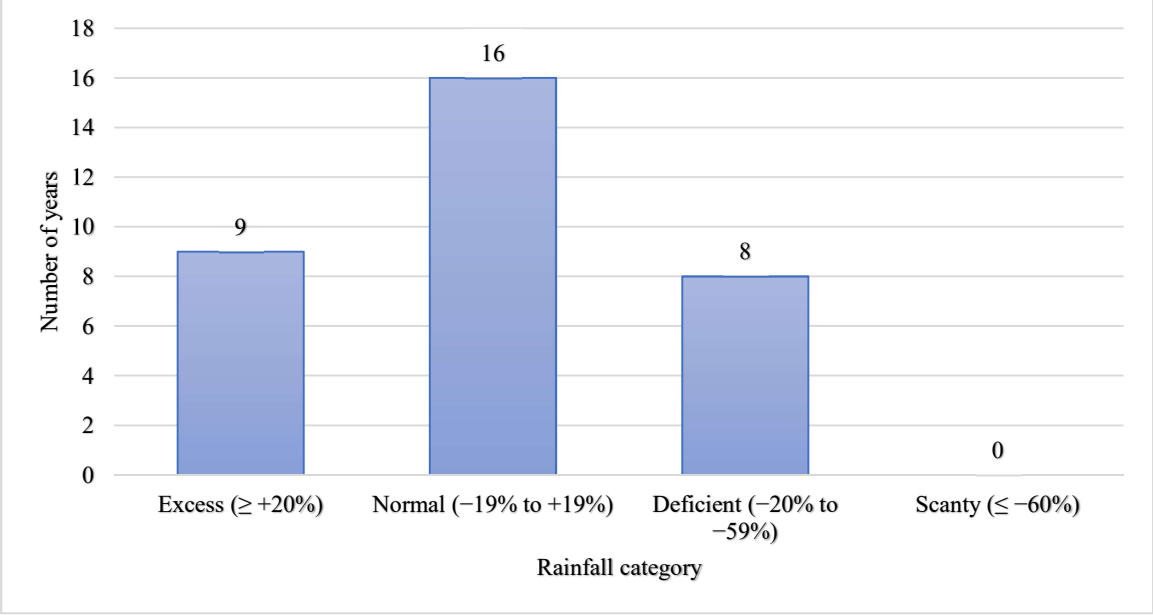


Figure 5: Frequency of annual rainfall departure categories at Badamalehra (1990–2022)

Classification of annual departures from the 1990–2022 mean (Table 4) shows that 16 years (48.5%) were normal, 9 years (27.3%) were excess and 8 years (24.2%) were deficient; no year was scanty. The most severe deficit occurred in 2007 (−54.7%), followed by 1995 (−36.8%), 2017 (−31.7%) and 2000 (−30.5%), whereas the largest surpluses were observed in 2013 (+47.3%), 1999 (+45.8%) and 2016 (+36.0%). Deficient years occurred on average once in four years and were distributed across the whole record, but they became more frequent after 2000: only one deficient year occurred in 1990–

1999, compared with three in 2000–2009 and four in 2010–2022.

The recurrence of deficient years, and in particular the 2007 drought, is consistent with the documented susceptibility of Bundelkhand to meteorological drought. Som and Dey (2022), who examined Chhatarpur, Damoh, Panna, Sagar and Tikamgarh districts for 1951–2018, reported high rainfall variability and used the CDD, R95p and Rx1day indices to show the region's exposure to both dry spells and intense rainfall. The alternation of excess and deficient years at Badamalehra—for example 2013 (+47.3%) followed by 2014 (−27.9%), and 2016 (+36.0%) followed by 2017 (−31.7%)—highlights the need for water-harvesting structures that can carry surplus monsoon runoff over into dry years.

3.5. Trends and change points in rainfall

Table 5 reports the outcomes of the trend (Mann–Kendall) and slope (Sen) analyses.

Table 5: Trend statistics (Mann–Kendall Z and Sen's slope) of month-wise, season-wise and yearly rainfall at Badamalehra (1990–2022)

Time scale	Z (MK)	p-value	Sen's slope (mm yr^{-1})	Trend
January	2.602	0.009	0.000	Increasing ($p < 0.01$)
February	1.558	0.119	0.000	Increasing (NS)
March	1.390	0.165	0.000	Increasing (NS)
April	2.125	0.034	0.000	Increasing ($p < 0.05$)
May	2.679	0.007	0.000	Increasing ($p < 0.01$)
June	0.248	0.804	0.463	Increasing (NS)
July	0.108	0.914	0.514	Increasing (NS)
August	0.418	0.676	1.849	Increasing (NS)
September	−1.364	0.173	−3.249	Decreasing (NS)
October	2.046	0.041	0.000	Increasing ($p < 0.05$)
November	−0.426	0.670	0.000	Decreasing (NS)
December	0.000	1.000	0.000	No trend
Winter (Jan–Feb)	2.692	0.007	0.191	Increasing ($p < 0.01$)
Pre-monsoon (Mar–May)	2.839	0.005	0.000	Increasing ($p < 0.01$)
Monsoon (Jun–Sep)	−1.224	0.221	−5.663	Decreasing (NS)
Post-monsoon (Oct–Dec)	0.990	0.322	0.000	Increasing (NS)
Annual	−0.604	0.546	−3.094	Decreasing (NS)

Z = standardised Mann–Kendall statistic; NS = not significant at the 10% level. A Sen's slope of zero arises where rainfall was nil in more than half of the years.

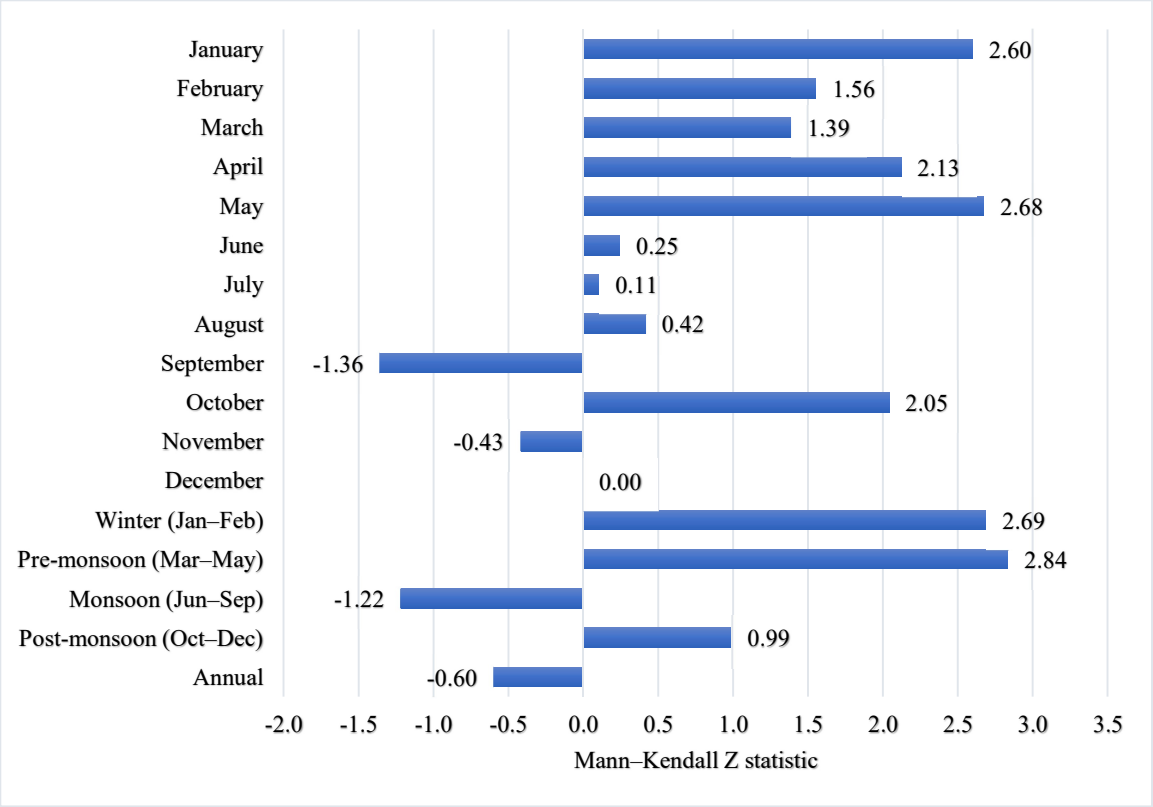


Figure 6: Mann–Kendall Z statistic for monthly, seasonal and annual rainfall at Badamalehra (1990–2022)

The annual rainfall decreased but the change was not statistically significant (Z = −0.604, p = 0.546) at a rate of −3.09 mm yr−1 according to Sen's slope. Monsoon rainfall likewise fell, though not significantly (Z = −1.224; −5.66 mm yr−1) with September being the dominant contributor, whereas June, July and August showed weak, non-significant increase. The positive trends were significant in dry-season months for January (Z = 2.602, p < 0.01), May (Z = 2.679, p < 0.01), April (Z = 2.125, p < 0.05) and October (Z = 2.046, p < 0.05) and in the whole season for winter (Z = 2.692, p < 0.01) and pre-monsoon (Z = 2.839, p < 0.01) rainfall. Since there has been no rainfall in most years for these months, their Sen's slopes are zero or very small, so the large value of Z is more likely to mean that the number of rainy months is increasing, but not the amount of rain. There was no change point in annual rainfall identified based on the Pettitt test (K = 66, p > 0.10).

The non-significant negative trends of annual rainfall and monsoon rainfall are in agreement with the study of Kumar et al. (2023) who reported non-significant annual rainfall (Sen's slope = −0.99 mm yr^{-1}) and monsoon rainfall (Sen's slope = −1.21 mm yr^{-1}) for the Madhya Pradesh region during 1951–2021 and Bundelkhand districts of Madhya Pradesh with a non-significant negative trend in annual rainfall during 1951–2021, as reported by Som and Dey (2022). Similarly, Fanai et al. (2022) noted a south-west monsoon (SWM) decreasing trend in 11 districts of Bundelkhand and in all districts except Sagar while assessing the annual decadal trend. The rate of loss at Badamalehra (−3.09 mm yr^{-1} annually) is larger than these regional estimates, but not significantly different, due to high inter-annual variability and relatively short record (33 years). In contrast to Kumar et al. (2023) who found a change point in state-averaged rainfall in the late 1990s, a change point was not found at Badamalehra, indicating that changes at this station are far from step-like. The rise in dry season rainfall should be treated with caution since negligible amounts of non-monsoon rainfall were registered in the 1990s, and this increased rainfall may be due partly to changes in the practice of recording light and isolated showers

from the stations and thus needs verification from the neighbouring stations.

3.6. Decadal behaviour of rainfall

Table 6: Decadal comparison of rainfall characteristics at Badamalehra

Parameter	1990–1999	2000–2009	2010–2022
Mean annual rainfall (mm)	1298.3	1075.7	1220.8
CV of annual rainfall (%)	23.1	28.0	28.0
June rainfall (mm)	103.0	198.1	135.6
July rainfall (mm)	364.3	309.8	398.1
August rainfall (mm)	426.1	304.1	433.2
September rainfall (mm)	359.8	206.8	159.9
Monsoon (Jun–Sep) rainfall (mm)	1253.2	1018.8	1127.0
Non-monsoon rainfall (mm)	45.0	57.0	93.8
Monsoon share of annual rainfall (%)	96.5	94.7	92.3
Rainy days (≥ 2.5 mm)	39.3	41.8	44.4
Rx1day (mm)	180.3	133.3	143.4
Heavy rainfall days (≥ 64.5 mm)	4.9	3.3	4.8
Deficient years (≤ −20%)	1	3	4
Excess years (≥ +20%)	3	2	4

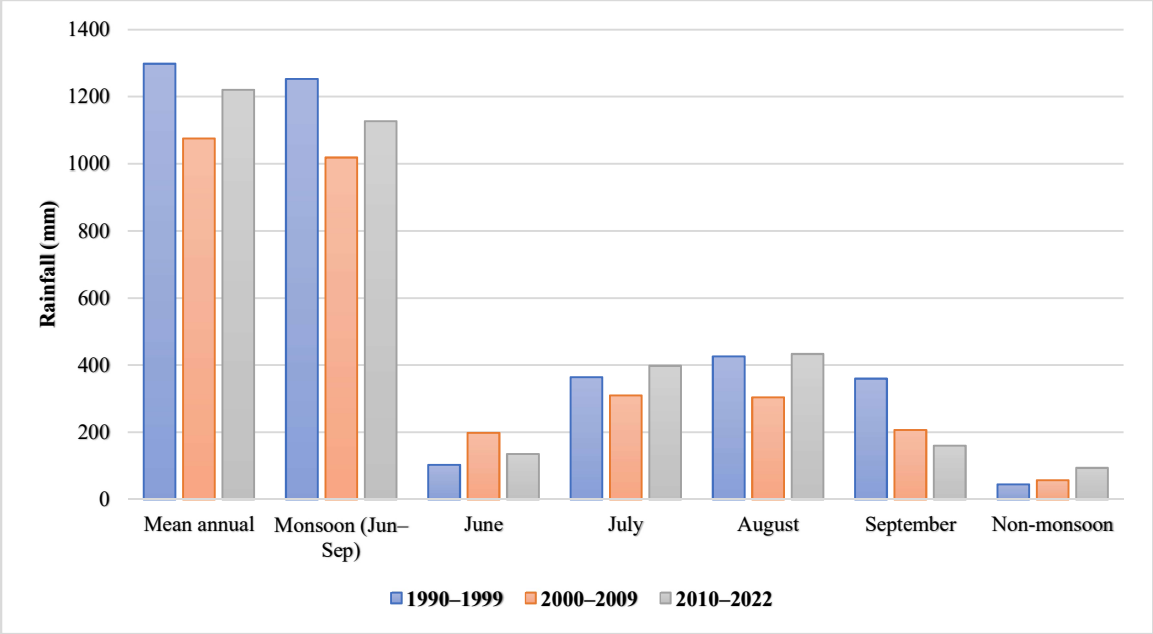


Figure 7: Decadal comparison of rainfall amounts at Badamalehra

A comparison of three sub-periods (Table 6) reveals that average yearly rainfall fell from 1298.3 mm in 1990–1999 to 1075.7 mm in 2000–2009 and partially recovered to 1220.8 mm in 2010–2022, while the CV rose from 23.1% to 28.0%. The most uniform decadal decrease was in September rainfall which declined from 359.8 mm to 206.8 mm and then to 159.9 mm (a loss of 55.6% between the first and last decade), suggesting an earlier withdrawal or weakening of September rainfall. Rainfall in June and July recovered well since 2010, however. The mean number of rainy days also increased slightly (39.3 to 44.4) and the monsoon share of annual rainfall decreased from 96.5% to 92.3% as non-monsoon rainfall increased from 45.0 mm to 93.8 mm (Table 6). Deficient years rose in number, from a single case in the 1990s to four during 2010–2022.

The reduction in late monsoon (September) rainfall and higher frequency of deficient years are in accordance with Century scale weakening of monsoon rainfall over Central India (Guhathakurta and Rajeevan 2008, Duhan & Pandey 2013) and all India analysis (Praveen et al. 2020) of recent years. A lower contribution in September decreases the length of the kharif season and the carry-over soil moisture for rabi sowing, which is directly affecting the rainfed farming in Badamalehra area.

3.7. Rainfall extremes

Table 7 summarises the extreme indices computed from the daily series.

Table 7: Rainfall extreme indices and their trends at Badamalehra (1990–2022)

Index	Unit	Mean ± SD	Range (year of max.)	Z (MK)	p	Sen's slope (yr^{-1})
Annual wet-day total (PRCPTOT)	mm	1199.6 ± 320.6	543.2–1768.3 (2013)	−0.604	0.546	−3.158
Rainy days (≥ 2.5 mm)	days	42.1 ± 8.8	27–59 (2003)	1.321	0.187	0.239
Simple daily intensity index (SDII)	mm day^{-1}	25.7 ± 7.0	13.6–47.9 (1993)	−1.937	0.053†	−0.237
Max 1-day rainfall (Rx1day)	mm	151.5 ± 43.8	68.0–240.4 (1993)	−1.116	0.265	−0.869
Max 5-day rainfall (Rx5day)	mm	285.0 ± 121.3	94.8–557.6 (2008)	−1.271	0.204	−2.700
Heavy precipitation days (R10mm)	days	28.3 ± 6.0	16–39 (1997)	−0.560	0.576	−0.074
Very heavy precipitation days (R20mm)	days	18.5 ± 4.8	8–30 (2013)	−0.467	0.640	−0.018
Heavy rainfall days, IMD (≥ 64.5 mm)	days	4.4 ± 2.0	1–9 (2011)	−0.568	0.570	0.000
Very wet-day total (R95p)	mm	325.5 ± 225.7	0.0–917.4 (1993)	−0.728	0.466	−3.339
Contribution of R95p to PRCPTOT	%	25.2 ± 13.8	0.0–61.7 (1993)	−0.837	0.403	−0.211
Extremely wet-day total (R99p)	mm	95.4 ± 157.1	0.0–435.6 (2008)	−0.842	0.400	0.000
Consecutive dry days	days	133.3 ± 37.7	33–185 (2012)	−2.062	0.039*	−1.877

Index	Unit	Mean ± SD	Range (year of max.)	Z (MK)	p	Sen's slope (yr^{-1})
(CDD)						
Consecutive wet days (CWD)	days	8.5 ± 4.0	4–22 (2013)	0.815	0.415	0.033

* significant at 5% level; † significant at 10% level; all other trends not significant. Percentile thresholds (95th = 95.4 mm; 99th = 163.1 mm) were derived from wet days (≥ 1 mm) of 1990–2022.

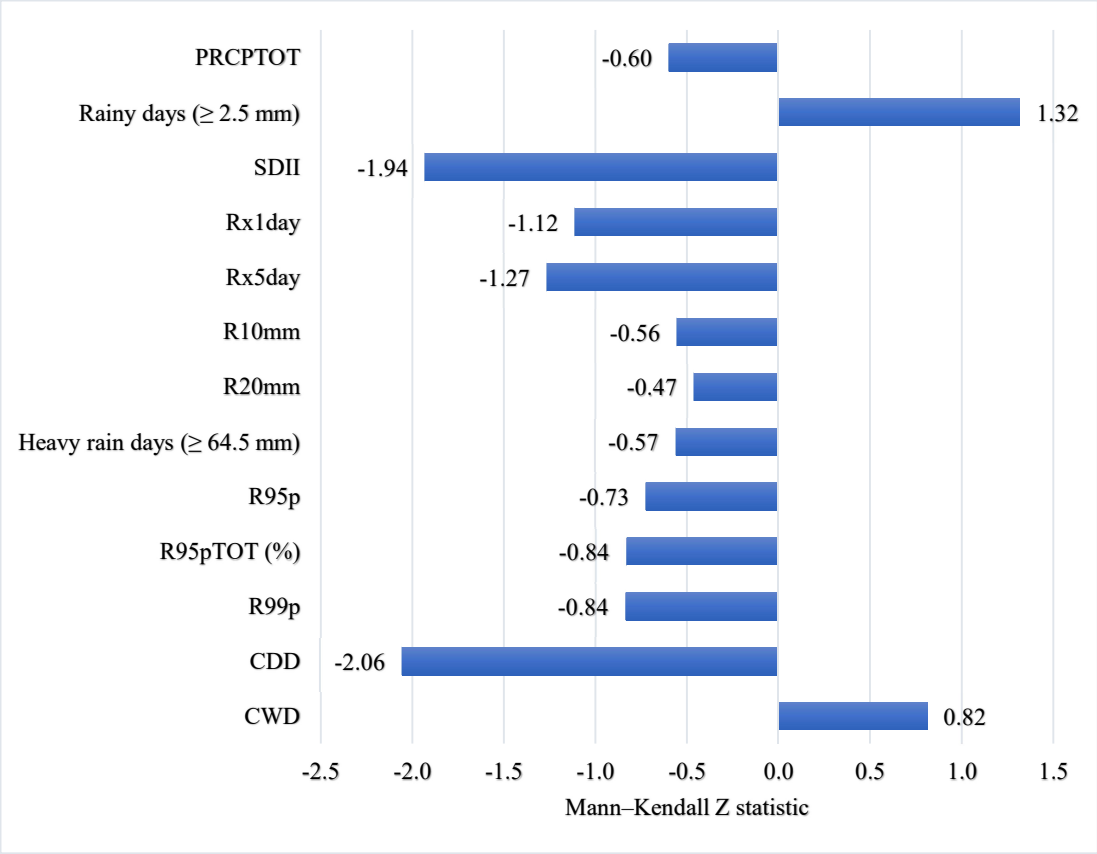


Figure 8: Mann–Kendall Z statistic for rainfall extreme indices at Badamalehra (1990–2022)

On average, the station recorded 42 rainy days per year, 28 days with ≥ 10 mm, 18.5 days with ≥ 20 mm and 4.4 days of IMD heavy rainfall (≥ 64.5 mm). The mean maximum 1-day rainfall was 151.5 mm, and the highest daily totals in the record were 240.4 mm (17 September 1993), 236.0 mm (2 August 1996) and 234.0 mm (19 June 2008). Very wet days above the 95th percentile (95.4 mm) contributed on average 25.2% of annual rainfall, and in 1993 this share reached 61.7%, showing that a handful of storms can determine whether a year is wet or dry. The longest dry spell averaged 133 days per year. At the 5% level, no intensity or frequency index exhibited a meaningful trend, except CDD, which fell ($Z = -2.062$, $p = 0.039$; −1.88 days yr^{-1}), while SDII declined weakly ($p = 0.053$), and rainy days and CWD showed non-significant increases.

Earlier work has shown that intense rainfall episodes over central India have become more common and stronger, with heavy and very-heavy rain days multiplying after the 1950s (Goswami et al., 2006; Rajeevan et al., 2008) and large-scale extreme episodes tripling between 1950 and 2015 (Roxy et al., 2017). The Badamalehra record does not show such an

increase for 1990–2022; Rx1day, Rx5day, R95p and heavy-rainfall days all displayed small, non-significant negative slopes, and the mean Rx1day of the 1990s (180.3 mm) was higher than that of the two subsequent periods (Table 6). This apparent contrast is not unusual, because the large-scale increase reported by Roxy et al. (2017) refers to widespread events over a large domain, which cannot always be detected at a single station over a 33-year period dominated by natural variability. The significant shortening of the longest dry spell, together with slightly more rainy days and lower SDII, suggests that rainfall at the station is becoming somewhat more evenly distributed across more days, a pattern that coincides with the increasing dry-season rainfall noted above. Nevertheless, the persistently large contribution of very wet days (≈ 25%) and the occurrence of daily totals exceeding 200 mm in six years confirm that flash floods and soil erosion remain important hazards at Badamalehra, in line with the vulnerability to both drought and intense rainfall reported for Bundelkhand by Som and Dey (2022).

4. CONCLUSION

Analysis of the daily rainfall data for the last 33 years (1990-2022) converted to monthly, seasonal and annual rainfall reveals a mean yearly total of 1200.3 mm at Badamalehra, of which the June–September monsoon delivers 94.3% and the July–August pair alone 62.8%, indicating a high degree of seasonality (mean PCI = 32.8), and moderate inter-annual variability (CV = 26.7%) with very high variability (CV >190%) during the non-monsoon seasons. Declines in both yearly and monsoon totals were statistically insignificant, and greater than a 50% drop in September precipitation occurred between 1990–1999 and 2010–2022, with fewer than the usual rainfall events occurring after 2000, but the precipitation trend significant in frequency was found for winter and pre-monsoon seasons; this result needs to be verified from nearby stations. There were no significant changes in extremes of rainfall, but very wet days still account for approximately 25% of annual rainfall and daily rainfall totals in excess of 200 mm are still being experienced, whilst the length of the dry spell has significantly reduced. Accordingly, water and crop management in the Badamalehra area must focus on conserving water in place and harvesting rainwater, to store excess monsoon water, contingency planning in the event of failure of monsoon rainfall, and the adoption of short-duration drought-tolerant crops adapted to a highly variable and monsoon dependent rainfall regime.

Conflict of Interest

There are no conflicts of interest.

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