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Spatio-temporal analysis of rainfall variability across drought prone districts of Odisha under changing climate conditions

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ABSTRACT

Climate change has altered rainfall patterns globally, increasing the frequency of extremes and posing significant risks to agriculture, water resources, and disaster management. The agrarian economy of Odisha, eastern India, is highly dependent on monsoon rainfall, making it particularly vulnerable to rainfall variability. This study analyses long-term rainfall trends over five drought-prone western districts of Odisha Nuapada, Balangir, Bargarh, Kalahandi, and Kandhamal—using 32 years (1990–2021) of daily gridded rainfall data at a 0.25° × 0.25° spatial resolution. Rainfall trends were assessed at monthly, seasonal, and annual scales using the Mann–Kendall test and Sen's slope estimator. Results indicate non-significant declining annual rainfall trends in Balangir, Bargarh, Kalahandi, and Kandhamal, while Nuapada exhibited a non-significant increasing trend. Monsoon rainfall showed non-significant negative trends across most districts, with no substantial increase observed in Nuapada. During the post-monsoon season, non-significant decreasing trends were noted in Nuapada, Balangir, and Kandhamal, whereas Bargarh and Kalahandi showed increasing tendencies. Winter rainfall exhibited non-significant increasing trends in all districts except Kandhamal, which recorded a declining trend. Summer rainfall showed non-significant decreasing trends in Nuapada, Balangir, and Kandhamal; however, Kalahandi experienced a statistically significant decline (Z = −2.06, p = 0.04) with a Sen's slope of −1.40 mm yr^{-1}. Monthly rainfall trends displayed considerable spatial variability across the study area. Nevertheless, strong natural climatic variability, particularly monsoon dynamics, poses challenges in clearly distinguishing long-term climate change signals from natural fluctuations. The findings highlight pronounced spatial and temporal rainfall variability in western Odisha, emphasizing the need for climate-resilient agricultural planning and adaptive water resource management.

Keywords: *Rainfall trends, Climate change, Drought-prone districts, Mann–Kendall test Sen's slope test, Western Odisha.*

Introduction

Agriculture forms the backbone of India's economy, supporting livelihoods, employment, and national food security. Monsoon rainfall is the most critical determinant of agricultural productivity, as its onset, progression, and spatial distribution govern all stages of crop growth, ranging from sowing and crop establishment to growth and harvesting. Although the South-West monsoon often delivers near-normal rainfall at the national scale, many regions continue to experience agricultural droughts and fluctuations in surface and groundwater levels due to pronounced spatial and temporal variability in rainfall. Numerous studies have documented global and regional rainfall trends and variability, highlighting the increasing complexity of monsoon behaviour under changing climatic conditions. Several researchers conducted studies on global rainfall trends and variability. The multi-decadal persistence of anomalies over Northern Africa is one of the most significant rainfall disparities as indicated by [14].

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The changing trends in rainfall and temperature have been reported across all thirteen districts of Uttarakhand [27]. The historical rainfall data of the Sindh River basin in India was analysed for the years 1901–2002 and 1942–2002 to study the monthly, seasonal and yearly changes [4]. Since the turn of the century, efforts have been undertaken to study patterns in seasonal and annual rainfall across India. The long-term patterns of Indian monsoon rainfall for the nation as well as for smaller sub-divisions has also been examined [16-19, 21]. Post monsoon rainfall from 1871 to 1980 was analysed across several regions, including North-West India, 1844-1996; North-Central India, 1842-1996; North-East India, 1829-1996; West Peninsular India, 1841-1996; East Peninsular India, 1848-1996; and South Peninsular India, 1813-1996 [25]. They found that these regions lacked a significant long-term trend and had weak correlations. The rainfall patterns in Delhi and Mumbai, between 1951 and 2004 was analysed and it was found that precipitation at both the locations varied significantly [22]. The long-term South-West monsoon rainfall over Delhi decreased insignificantly, while the long-term South-West monsoon of Mumbai showed slightly significant declining patterns. The temporal variation in monthly, seasonal and annual rainfall was observed over Kerala from 1871 to 2005 [7]. Their findings revealed a significant decrease in South-West monsoon rainfall and an increase in post monsoon season rainfall, while rainfall during the winter and summer season showed an insignificant increasing trend. Using daily rainfall data spanning 1971–2010, the analysis revealed shifting rainfall trends across the river basin in the coastal region of Odisha, indicating notable changes in the spatial and temporal distribution of precipitation over the study period [12]. The present study employed the Mann–Kendall trend test, originally proposed by Mann [10] and subsequently refined by Kendall [6]. This widely used non-parametric statistical method is particularly effective for detecting monotonic increasing or decreasing trends in time-series data [1,15]. Since the Mann–Kendall test is based on the ranking of observations rather than their absolute values, it is less sensitive to outliers and is independent or remains unaffected by the underlying data distribution.

The primary objective of this study was to analyze the variability and long-term trends in precipitation across five drought-prone districts of Odisha over a 30-year period (1990-2021). The analysis focused on assessing inter-annual rainfall variability and evaluating the potential implications of observed rainfall patterns for drought occurrence, water availability, and agricultural sustainability in the region.

Materials and Methods

Study area

Odisha, a state located on the eastern coast of India, lies between 17.49°N and 22.34°N latitude and 81.27°E and 87.29°E longitude, and has a coastline extending approximately 480 km along the Bay of Bengal. It has a geographical area of 1,55,707 sq. km (4.8% of total area of India). The five drought prone districts of western Odisha (Fig.1) include Nuapada (20.80˚N latitude and 82.53˚E longitude), Balangir (20.70˚N latitude and 83.48˚E longitude), Bargarh (21.25˚N latitude and 83.60˚E longitude), Kalahandi (19.91˚N latitude and 83.16˚E longitude) and Kandhamal (erstwhile Phulbani) (20.13˚ N latitude and 84.02˚ E longitude). Odisha experiences a tropical monsoon climate, similar to much of India. Owing to its proximity to the Bay of Bengal, the state's weather is strongly influenced by maritime conditions. The western districts of Odisha receive an average annual rainfall ranging from approximately 1100 mm to 1500 mm. Summer maximum temperature varies between 35˚C and 40˚C, while minimum temperatures fluctuate between 12˚C to 14˚C. Winters are generally mild across the state, except in some locations of Koraput and Kandhamal, where temperatures can drop as low as 3-4°C [3].

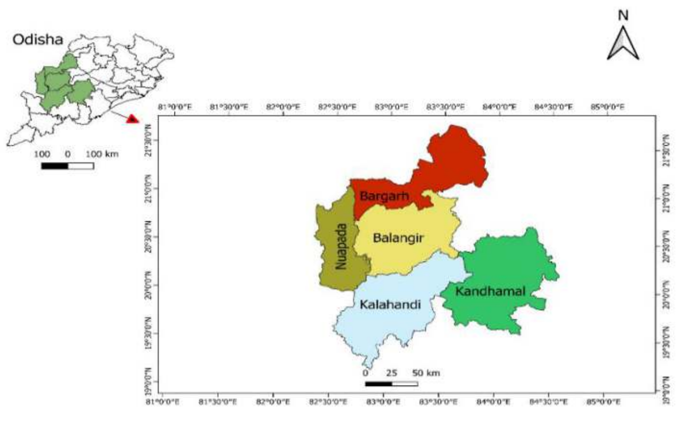


Fig. 1: Map depicting drought prone districts of Odisha

Data collection

Daily gridded rainfall data of India at a spatial resolution of 0.25° × 0.25° were obtained from the India Meteorological Department (IMD) for a 32-year period (1990–2021). The binary/.nc rainfall files were converted into a CSV (comma separated values) format using Python. The required daily rainfall data for the drought-prone districts of Odisha—Nuapada, Balangir, Bargarh, Kalahandi, and Kandhamal—were extracted from the national gridded dataset using QGIS. Subsequent data processing and analysis were performed using QGIS, the MAKESENS template, and R software.

Trend analysis

Following data collection, trend analysis was conducted to identify patterns or trends within the dataset. Time-series analysis, which evaluates data arranged in chronological order, is essential for understanding relationships among variables and for predicting future tendencies. This approach enables the comparison of a specific parameter over an extended period, thereby facilitating the identification of long-term patterns and trends. Long-term gridded rainfall data at a spatial resolution of 0.25° × 0.25° for a 32-year period (1990–2021) were used to assess monthly, seasonal, and annual rainfall trends in the drought-prone districts of Odisha. The non-parametric Mann–Kendall test was employed to detect the presence and statistical significance of monotonic trends, while Sen's slope estimator was applied to quantify the magnitude of change in rainfall over time. In the present study, monthly, seasonal, and annual rainfall trends were evaluated using the MAKESENS template and R software. Following the India Meteorological Department (IMD) seasonal classification, the year was categorized into four seasons relevant to Odisha's climatic conditions: southwest monsoon (June–September), post-monsoon or northeast monsoon (October–November), winter (December–February), and summer or pre-monsoon (March–May).

Mann-Kendall method

The Mann–Kendall (MK) test is a widely used and robust non-parametric method for detecting trends in time-series data, particularly in climatological studies. The test is designed to identify monotonic increasing or decreasing trends over time without requiring any assumption about the underlying data distribution. It operates by pairwise comparison of each observation with all subsequent observations in the series, assigning a positive sign when a later value exceeds an earlier one and a negative sign when it is lower. The resulting Mann–Kendall statistic *S* reflects the direction and magnitude of the trend. Accordingly, the MK statistic *S*, as defined in the following equation, is used to determine whether a statistically significant upward or downward trend exists in the time series under investigation.

MAKESENS performs two types of statistics depending upon the number of data values *viz*. *S*-statistic and *Z*-statistic.

S-Statistic

It is used if number of data values are less than 10, the statistic *S* is calculated as shown in equation (I):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad \text{(i)}$$

where, x_i and x_j are annual values in years i and j, j > i respectively, n is the number of data points and *sign* $(x_j - x_i)$ is calculated using equation (ii):

$$\text{Sign (xj - xi)} = \begin{Bmatrix} +1, > (x_j - x_i) \\ 0, = (x_j - x_i) \\ -1, < (x_j - x_i) \end{Bmatrix} \quad \text{(ii)}$$

A positive or negative value of the Mann–Kendall statistic S indicates an upward (increasing) or downward (decreasing) trend, respectively. When the number of data points (n) is 10 or greater, the statistic S approximately follows a normal distribution, and the significance of the trend is evaluated using the standard normal distribution, with the mean and variance defined as follows [equations (iii) & (iv)].

$$E(S) = 0 \quad \text{(iii)}$$

$$Var(S) = \frac{n(n-1)(2n+5)-\sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \quad \text{(iv)}$$

where, n is the length of the time series, m is the number of tied groups, and ti denotes the number of data points in the i^{th} tied group.

Z-statistic

Z-statistic (normal approximation/distribution) is used for data values greater than or equal to 10. The standard normal distribution (Z-statistic) is computed using equation (v)

$$Z = \frac{S+1}{\sqrt{Variance(S)}} \; IF \; S > 0$$

$$Z = 0 \; IF \; S = 0 \quad \text{(v)}$$

$$Z = \frac{S-1}{\sqrt{Variance(S)}} \; IF \; S < 0$$

where, S= p - q, p = number of (+1) values and q = number of (-1) values. The presence of a statistically significant trend is assessed using the standardized Mann–Kendall test statistic (Z) The positive value of the standardized test statistic (Z) indicates an upward (increasing) trend, while a negative value denotes a downward (decreasing) trend. The statistic Z follows a standard normal distribution. In the present study, trend significance was evaluated at the 90% and 95% confidence levels.

When the calculated Z value exceeds the corresponding critical value of the normal distribution, the trend is considered statistically significant. Conversely, if the Z value is negative, but the associated p-value exceeds the chosen significance level, the series exhibits a downward trend that is not statistically significant. Similarly, when the Z-value is positive and the associated p-value exceeds the chosen significance level, the series exhibits an increasing trend that is not statistically significant. Overall, the test employs a non-parametric monotonic trend approach to determine whether the y-values show a tendency to increase or decrease over time.

Sen's slope method

Sen's slope estimator was employed to quantify the magnitude of the detected trend. This non-parametric method provides a robust estimate of the rate of change and is insensitive to outliers, making it well suited for hydro-climatological time-series analysis. Algebraically, Sen's slope is expressed as follows [equation (vi)]:

$$Q_t = \frac{x_j - x_k}{j-k} \; j = 1, 2, 3, \; j > k \quad \text{(vi)}$$

For a time series containing n observations, a total of

$$N = \frac{n(n-1)}{2}$$

Individual slope estimates Q_t are computed. These slope values are ranked in ascending order, and the median of all Q_t values is taken as Sen's slope estimate, representing the magnitude of the trend [equations (vii) & (viii)].

A positive Sen's slope ($Q_t > 0$) indicates an increasing trend, while a negative value ($Q_t < 0$) signifies a decreasing trend.

$$Q_t = Q_{\frac{N+1}{2}} \text{ if N is odd (vii)}$$

$$Q_t = \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+1}{2}}\right) \text{ if N is even (viii)}$$

Tau value (τ)

The Kendall's tau (τ) value is used to quantify the strength and direction of a monotonic trend in a time series. It is based on the rank correlation between pairs of observations and forms the foundation of the Mann–Kendall test. The method assumes that all observations are independent.

The test statistic S is calculated as follows [equation (ix)]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\,(y_j - y_i) \quad \text{(ix)}$$

where, $sign(y_j - y_i)$ is equal to 1 when $y_j > y_i$,0 when $y_j = y_i$ and -1 when $y_j < y_i$

The Kendall's tau (τ) ranges from -1 to 1. A value of τ=0 indicates no trend, while τ =1 or τ = -1 represents a perfect positive or negative trend, respectively. The closer the magnitude of τ is to 1, the stronger the monotonic relationship equation (x). The tau value is calculated as:

$$\tau = \frac{S}{\frac{1}{2}n(n-1)} \quad \text{(x)}$$

where, S is the Mann–Kendall test statistic and n is the number of observations in the time series.

p-value

The p-value is used to determine whether an observed trend is statistically significant. In this study, a p-value less than 0.05 indicates significance at the 5% level. When the p-value falls below this threshold (0.05), the detected trend is considered statistically significant and reliable.

Results and Discussion

Descriptive statistics of rainfall data

The rainfall data were statistically analyzed to examine the spatial variability in rainfall distribution across the study area. The mean, standard deviation (σ), and coefficient of variation (CV) for the respective rainfall normals has been presented in Table 1. The CV represents the degree of dispersion in a probability distribution and helps assess how much variability exists relative to the mean. The descriptive statistics indicate that Kalahandi district exhibits substantial rainfall variability, with a standard deviation of 371 mm during the period 1990–2021, reflecting considerable inter-annual fluctuations in annual rainfall. Among all districts, Nuapada shows the highest relative dispersion, with a CV of 25.6%, suggesting that rainfall in this district is highly inconsistent from year to year compared to its long-term normal.

Table 1. Descriptive statistics rainfall data for drought prone districts of Odisha

District	Rainfall (1990-2021)		
	Mean (mm)	S.D (mm)	CV (%)
Nuapada	1260	322	25.6
Balangir	1402	338	24.1
Bargarh	1455	290	19.9
Kalahandi	1531	371	24.2
Kandhamal	1414	295	20.8

Annual rainfall analysis

The annual rainfall trend analysis for the 32-year period (1990–2021) across the four drought-prone districts of Odisha revealed non-significant decreasing trends in annual rainfall (Fig. 2b-e).

Particularly, Balangir (Z=-0.762, Q=-4.57 mm/year), Bargarh (Z=-0.503, Q=-2.776 mm/year), Kalahandi (Z =-1.48, Q= -12.25 mm/year) and Kandhamal (Z=-1.05, Q=-7.95 mm/year) exhibited declining rainfall tendencies. In contrast, Nuapada district showed a non-significant increasing trend, with a Z value of 0.15 and a Q value of 0.50 mm/year (Table 2, Fig. 2a). Similar regional-scale findings were reported while assessing long-term gridded rainfall variability at the regional level over Odisha [20]. Likewise, the spatial and temporal annual rainfall trends across 30 districts of Odisha was examined and a significant decreasing trend in Balangir district was reported, with a Sen's slope (Q) of -1.425 mm/year [24]. At the national scale, the long-term rainfall trend (1871–2011) was studied and predominantly decreasing annual rainfall was reported across India, except in the core monsoon region and northeastern India [8]. Furthermore, the analysed annual and seasonal rainfall of different districts of Odisha and observed that most of the districts experienced decreasing rainfall [23].

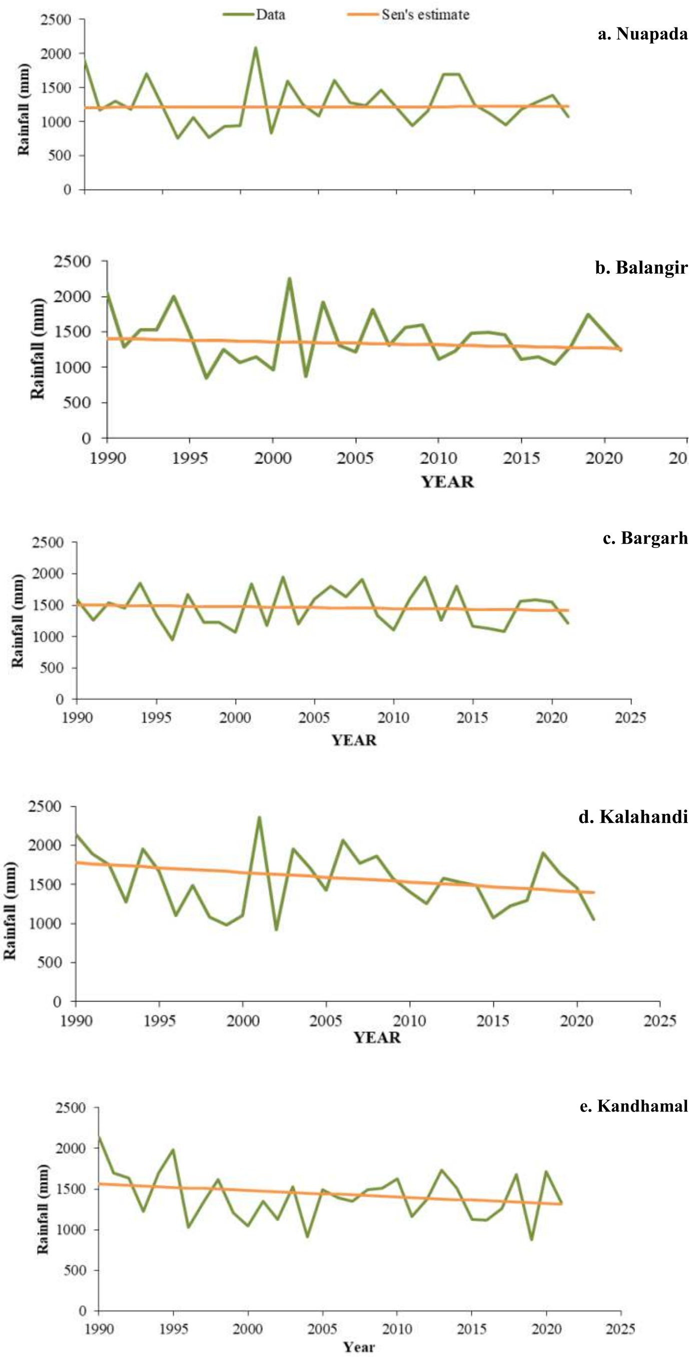


Fig. 2: Annual rainfall trend of drought prone districts of Odisha

Table 2. Annual, monthly and seasonal rainfall trend across drought prone districts of Odisha

Variable	Nuapada			Balangir			Bargarh			Kalahandi			Kandhamal		
Month	Z- Test	P value	Sen's slope(Q)	Z- Test	P value	Sen's slope(Q)	Z- Test	P value	Sen's slope(Q)	Z- Test	P value	Sen's slope(Q)	Z- Test	P value	Sen's slope(Q)
January	-0.454	0.650	0.000	0.462	0.644	0.000	0.065	0.948	0.000	-0.250	0.802	0.000	-0.245	0.806	0.000
February	0.196	0.845	0.000	-0.114	0.909	0.000	0.536	0.592	0.056	-0.666	0.506	-0.022	-1.530	0.126	-0.283
March	-1.103	0.270	-0.060	-0.632	0.527	-0.077	-0.130	0.897	-0.007	-0.405	0.685	-0.071	-0.503	0.615	-0.194
April	-0.114	0.910	-0.058	-0.146	0.884	-0.076	-0.341	0.733	-0.080	-1.41	0.158	-0.653	-1.12	0.263	-0.486
May	-0.276	0.783	-0.148	-0.308	0.758	-0.150	0.049	0.961	0.050	-1.31	0.189	-0.700	-1.800	0.072	-1.126+
June	0.243	0.808	0.542	-0.665	0.506	-0.962	0.178	0.858	0.237	-0.470	0.638	-0.874	-1.09	0.277	-1.594
July	-0.568	0.570	-1.613	-0.795	0.427	-2.88	-0.892	0.372	-1.866	-1.25	0.212	-4.063	-0.081	0.935	-0.127
August	-0.341	0.733	-0.771	-0.827	0.408	-2.96	-0.568	0.570	-1.848	-0.762	0.446	-2.804	-1.77	0.077	-4.216+
September	1.541	0.123	3.097	1.48	0.140	3.39	0.535	0.593	0.952	0.957	0.339	1.736	1.12	0.263	2.029
October	-0.081	0.935	-0.030	0.892	0.372	0.738	1.087	0.277	0.834	0.178	0.858	0.103	-0.049	0.961	-0.205
November	-1.991	0.046	-0.077*	-1.85	0.065	-0.179+	-1.658	0.097	-0.267+	-1.59	0.112	-0.133	-1.672	0.094	-0.548+
December	0.699	0.485	0.000	0.917	0.359	0.000	1.471	0.141	0.000	0.655	0.512	0.000	0.586	0.558	0.000
Annual	0.15	0.881	0.5	-0.762	0.446	-4.570	-0.503	0.615	-2.776	-1.48	0.140	-12.25	-1.05	0.292	-7.949
Monsoon	0.114	0.910	0.441	-0.470	0.638	-2.67	-0.308	0.758	-2.011	-0.924	0.355	-6.984	-0.697	0.486	-2.832
Post monsoon	-0.600	0.549	-0.431	-0.114	0.910	-0.100	0.568	0.570	0.522	0.243	0.808	0.335	-0.438	0.661	-1.217
Winter	0.406	0.685	0.069	0.324	0.746	0.076	0.989	0.323	0.569	0.032	0.974	0.002	-0.292	0.770	-0.110
Summer	-0.438	0.661	-0.352	-0.276	0.783	-0.217	0.438	0.661	0.170	-2.05	0.039	-1.399*	-1.573	0.116	-1.495

*(*Significance at 95 percent confidence level and + Significance at 90 percent confidence level)*

Monthly rainfall analysis

Based on the monthly trend analysis, both positive and negative non-significant trends have been observed (Table 2). In Nuapada district, a statistically significant decreasing trend in rainfall has been observed in November (Z=-1.99, P=0.046) having magnitude of slope -0.077 mm/year at 95% confidence level. Decreasing but non-significant rainfall trends have been observed in January (Z=-0.454), March (Z=-1.10), April (Z=-0.114), May (Z= -0.276), July (Z=-0.568), August (Z=-0.341) and October (Z=-0.081) [Table 2]. Conversely the months of February (Z=0.196), June (Z=0.243), September (Z=1.54) and December (Z=0.70) exhibited non-significant increasing rainfall trends.

In Balangir district, a significant decreasing trend was noticed in November (Z=-1.85, P=0.065) having magnitude of slope -0.179 mm/year at 90% confidence level. Non-significant decreasing rainfall trends have been observed in February (Z =-0.114), March (Z=-0.632), April (Z =-0.146), May (Z =-0.308), June (Z=-0.665), July (Z=-0.795) and August (Z= -0.827). Increasing non-significant rainfall trends were found in January (Z=0.462), September (Z=1.48), October (Z=0.892) and December (Z=0.917).

For Bargarh district, November again exhibited a significant decreasing trend (Z=-1.66, P=0.097) having magnitude of slope -0.276 at 90% confidence level. Decreasing but non-significant rainfall trends have been noticed in March (Z= -0.130), April (Z= -0.341), July (Z= -0.892) and August (Z= -0.568). The rainfall pattern during January (Z= 0.065), February (Z= 0.536), May (Z= 0.049), June (Z= 0.178), September (Z= 0.535), October (Z= 1.087) and December (Z= 1.47) showed an increasing non-significant trend.

In Kalahandi district, non-significant decreasing rainfall trends have been observed in January (Z= -0.250), February (Z= -0.666), March (Z= -0.405), April (Z= -1.41), May (-1.31), June (-0.470), July (Z= -1.25), August (Z= -0.762) and November (Z= -1.59). Non-significant increasing rainfall trends has been noticed in September (Z= 0.957), October (Z= 0.178) and December (Z= 0.655).

In Kandhamal district, a significant decreasing trend was observed in May (Z= -1.80, P=0.072) having magnitude of slope -1.13 mm/hr, August (Z=-1.77, P=0.077) having magnitude of slope -4.22 mm/yr and November (Z=-1.67, P=0.094) having magnitude of slope -0.548 mm/yr at 90% confidence level. January (Z= -0.245), February (Z= -1.530), March (Z= -0.503), April (Z= -1.12), June (-1.09), July (-0.081) and October (-0.049) showed non-significant decreasing trends. A non-significant increasing trend has been observed in September (Z=1.12) and December (Z=0.586). These findings are consistent with earlier studies. For instance, alternating positive and negative monthly trends was reported across six months each, reflecting largely non-significant conditions [12], while mixed positive and negative monthly rainfall trends was documented in the Vamanapuram River Basin, Kerala using the Mann–Kendall test [2].

Seasonal rainfall analysis

Seasonal trend analysis of rainfall data over the 32-year period (1990-2021) across the study districts indicates predominantly non-significant trends, with notable seasonal contrasts. During the southwest monsoon season, Balangir (Z= -0.47), Bargarh (Z= -0.31), Kalahandi (Z= -0.92), Kandhamal (Z= -0.70) followed non-significant negative trends (Fig. 4a-7a). Although the monsoon-season trends were statistically insignificant, seasonal contrasts became more evident during the post-monsoon, winter, and summer seasons. Similar results have been found by while evaluating district level rainfall characteristics over Odisha (1901–2013) using high resolution gridded dataset [13]. In contrast, Nuapada district showed a non-significant increasing monsoon trend (Z= 0.114) was found with magnitude of slope 0.441mm/year (Fig. 3a). Similar findings reported an increase in Odisha's monsoon rainfall at a rate of 0.92 mm/year (p-value=0.44) by [11]. Additionally, spatial heterogeneity in monsoon rainfall trends across Odisha was reported, with significant increases in 29 blocks and decreases in 21 blocks, and contrasting monthly signals within the monsoon season [9]. Monsoon rainfall showed a statistically significant downward trend in June and August, whereas a statistically significant upward trend in July and September (Table 2).

During the post monsoon period, Nuapada, Balangir and Kandhamal showed non-significant negative trends (Fig. 3b, 4b, 7b) while remaining two districts, Bargarh and Kalahandi (Fig. 5b, 6b) confirmed non-significant positive trends. Similar post-monsoon rainfall decline has been reported for neighbouring eastern India, including West Bengal, which attributed to reduced moisture availability in severe cyclonic storms during the post-landfall stage [5].

During winter season, Nuapada, Balangir, Bargarh and Kalahandi showed non-significant increasing rainfall trends (Fig. 3c-6c) while Kandhamal showed non-significant decreasing trend (Z= -0.29, Q= -0.11) [Fig. 7c]. These findings are consistent with Sahu and Khare [24], who observed increasing winter rainfall trends for 30 districts of Odisha, and with Patra *et. al.* [19], who reported a long-term increase in winter rainfall over the state during the twentieth century (1871–2006). However, at the national scale, decreasing winter rainfall trends was reported across most subdivisions of India (1901–2019) [26].

During summer season, decreasing non-significant rainfall trends were reported in Nuapada, Balangir and Kandhamal with respective magnitude -0.35 mm/year, -0.217 mm/year and -1.49 mm/year (Fig. 3d, 4d and 7d). In contrast, Kalahandi reported statistically significant decreasing trends (Z= -2.06; P=0.04) with magnitude of slope -1.40 mm/year (Fig. 6d, corroborating findings reported by [24]. Inversely, Bargarh reported non-significant increasing trend analysis with magnitude of 0.170 mm/year (Fig. 5d). At the regional scale, the long term gridded rainfall variability was assessed over Odisha and the coexistence of both increasing and decreasing seasonal rainfall trends was documented [20].

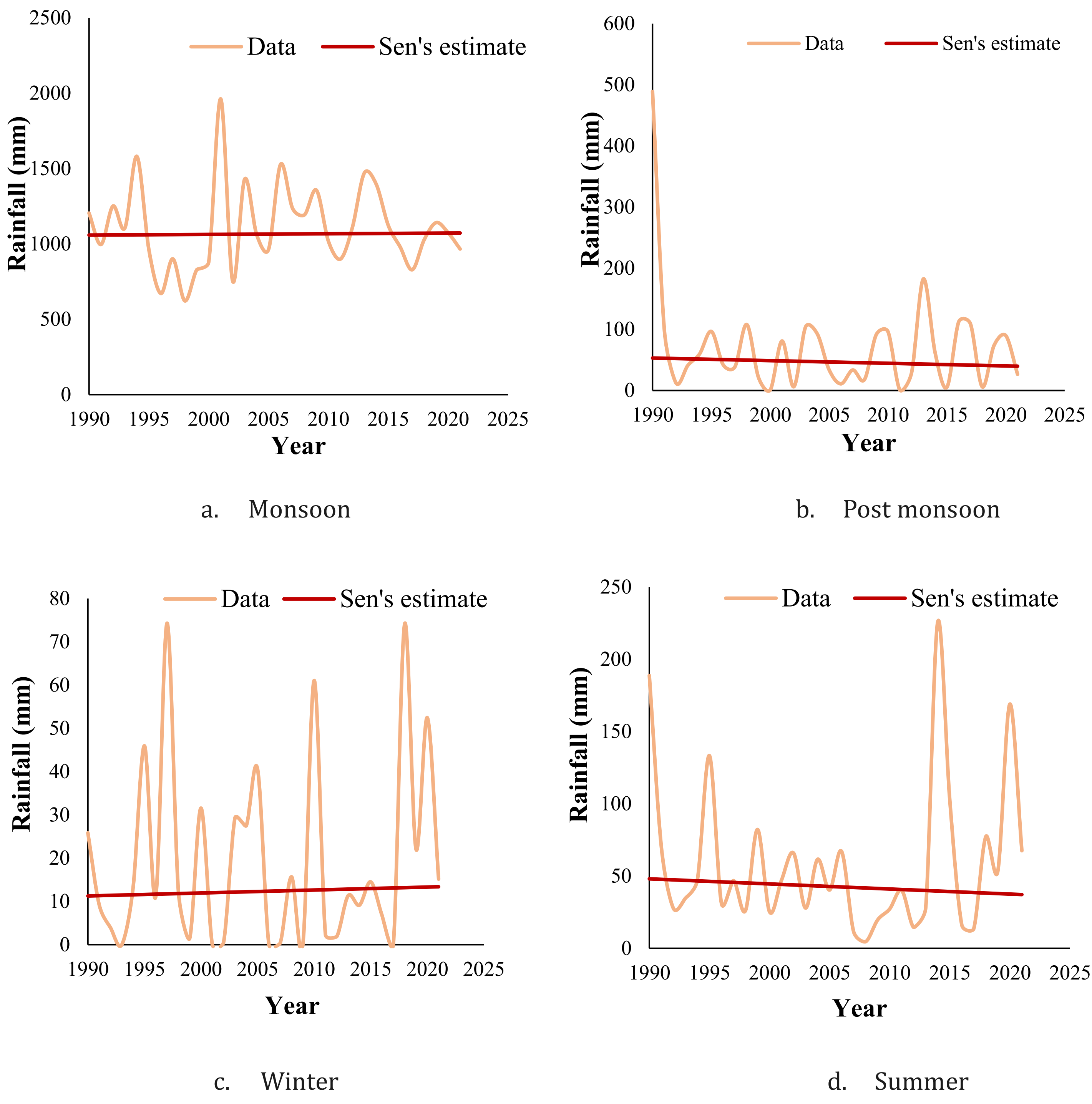
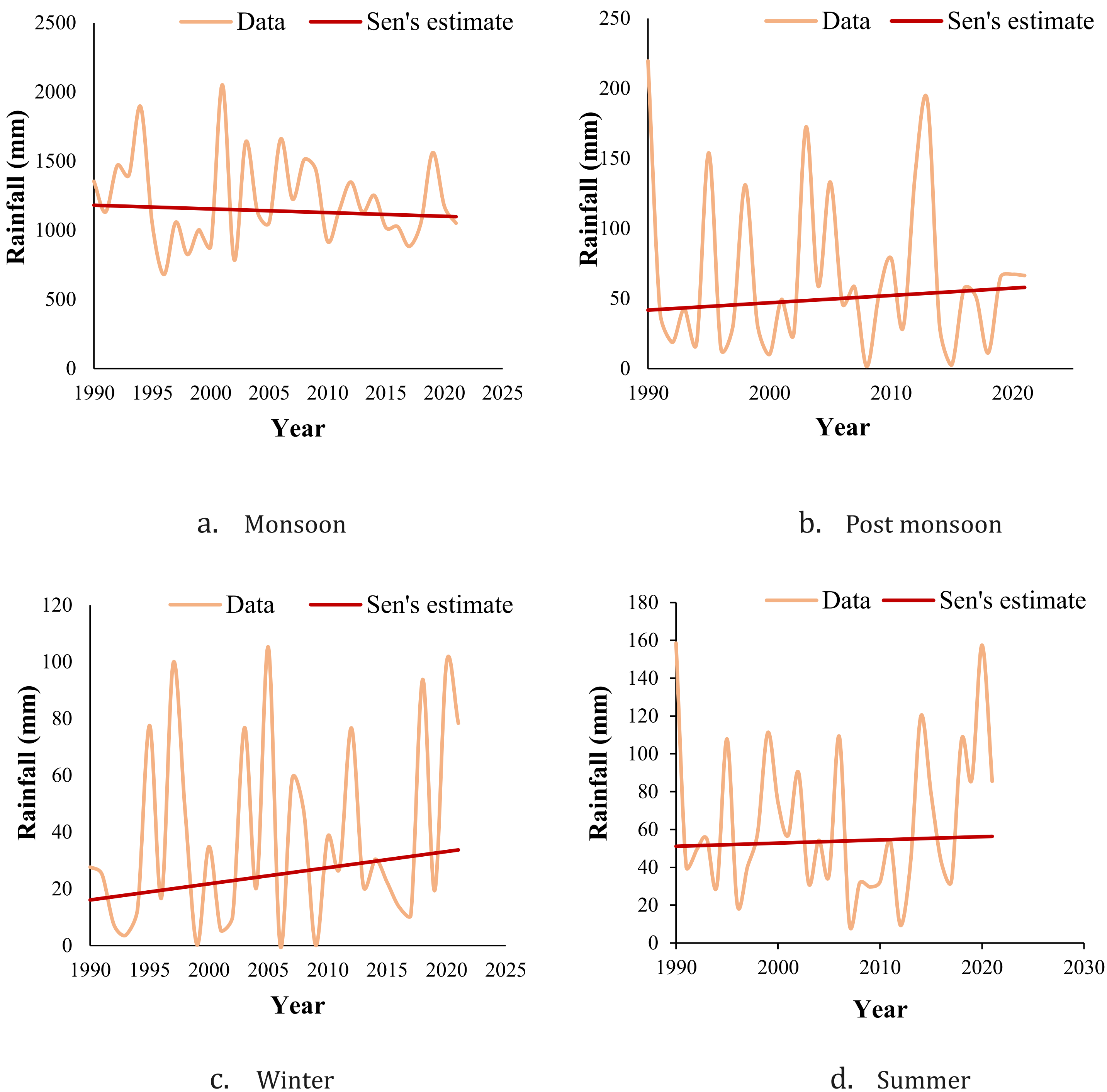


Fig. 3: Seasonal rainfall trend graph for Nuapada



a. Monsoon

b. Post monsoon

c. Winter

d. Summer

Fig. 4: Seasonal rainfall trend graph for Balangir

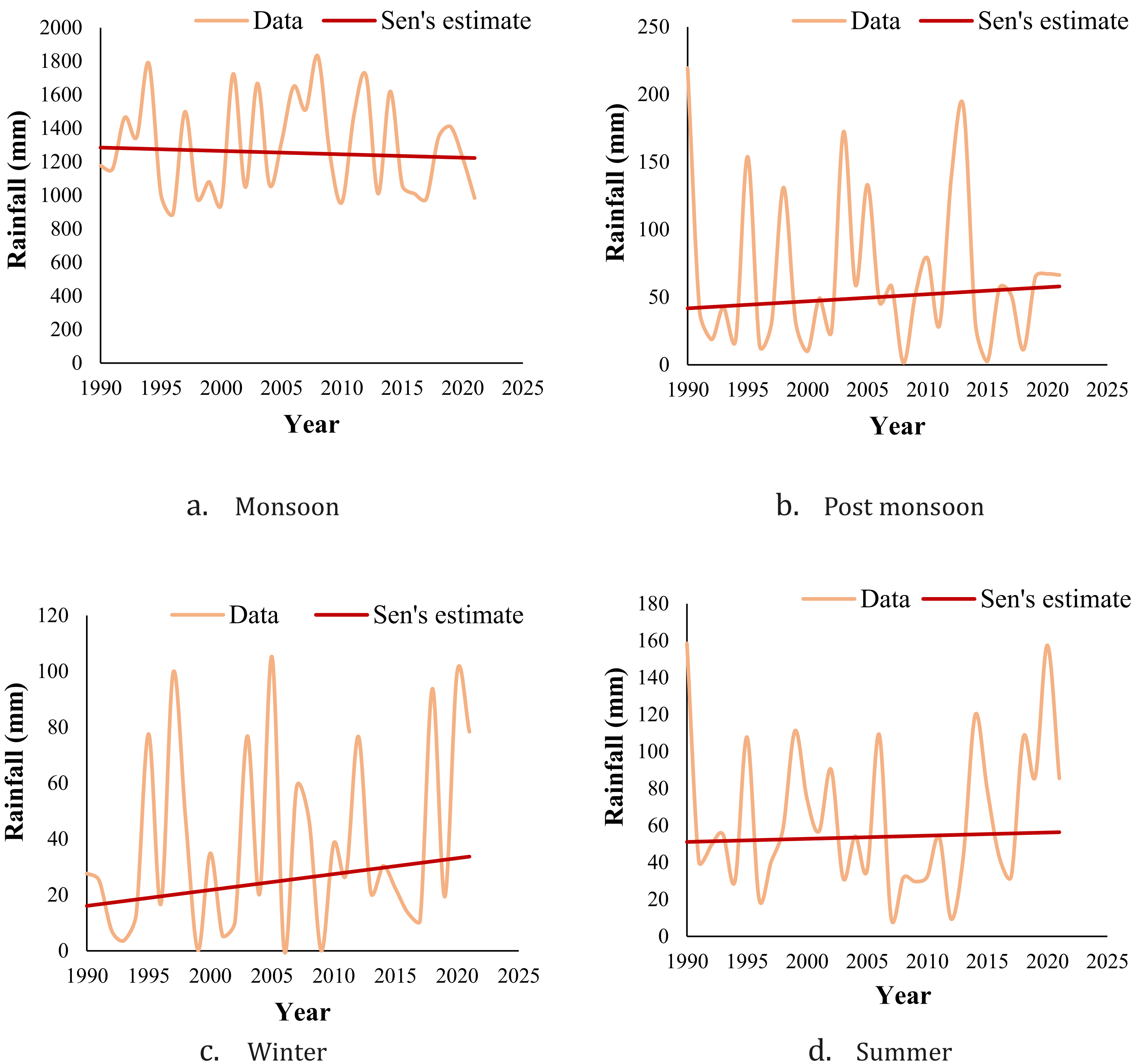
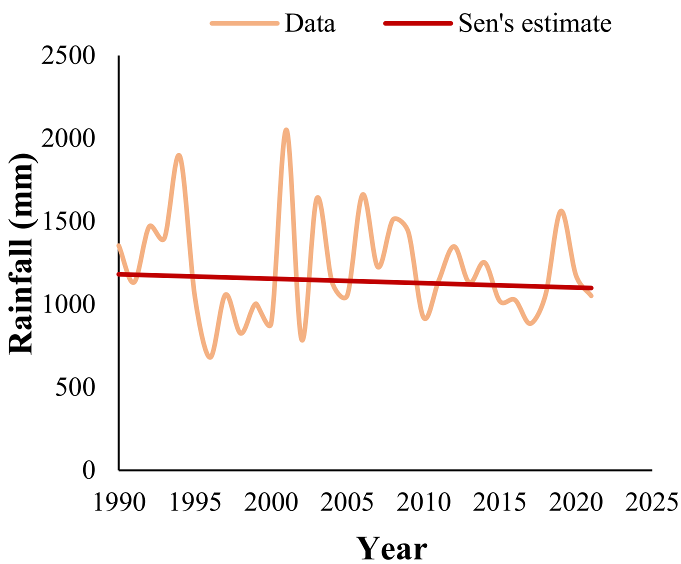
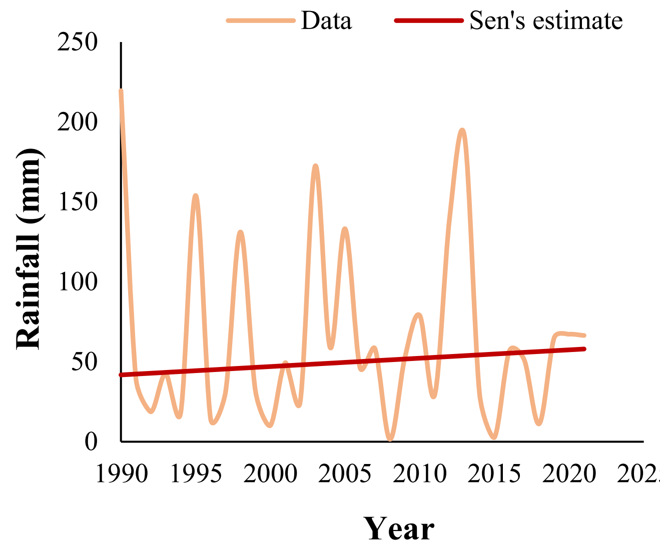


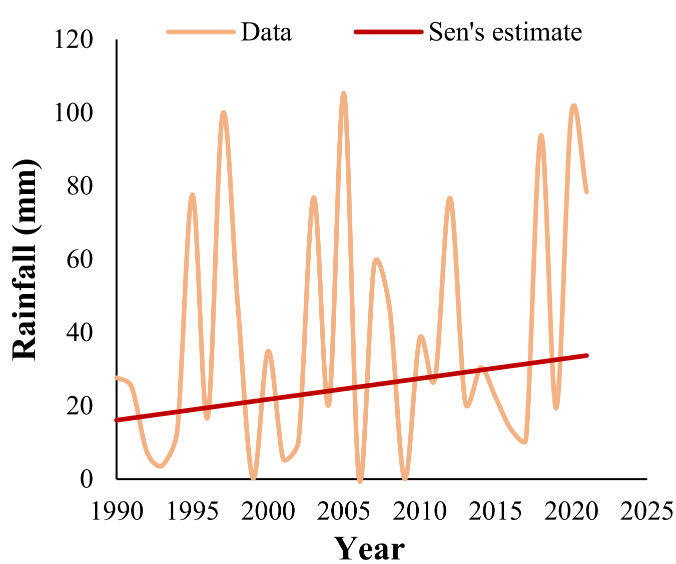
Fig. 5: Seasonal rainfall trend graph for Bargarh



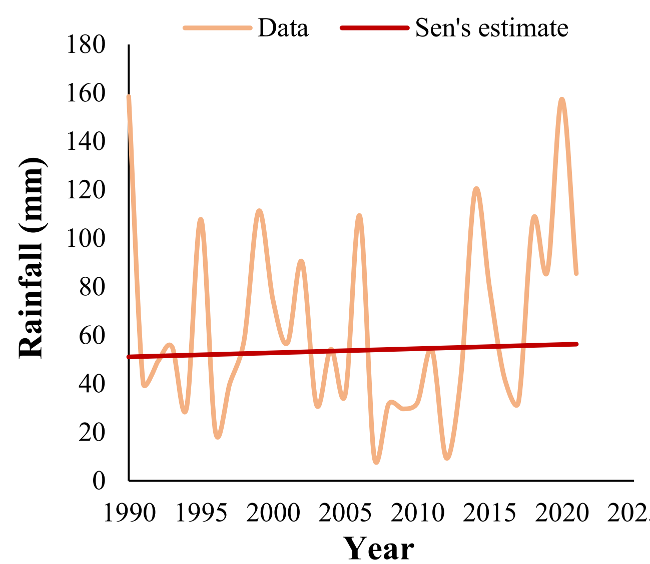
a. Monsoon



b. Post monsoon

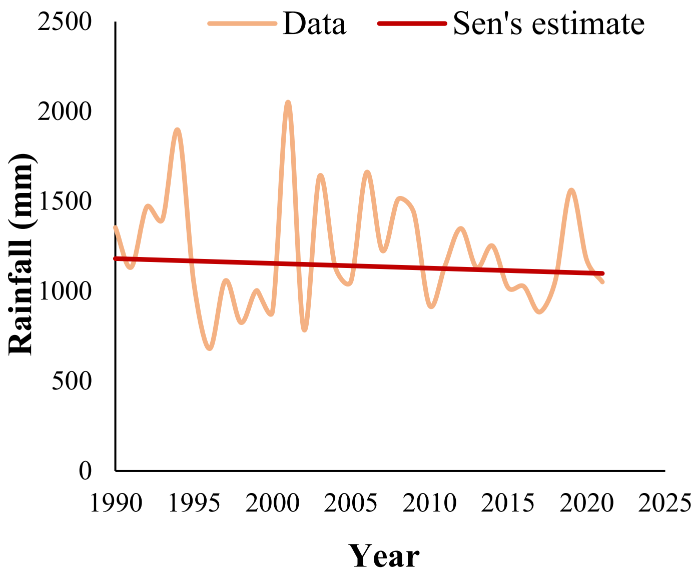


c. Winter

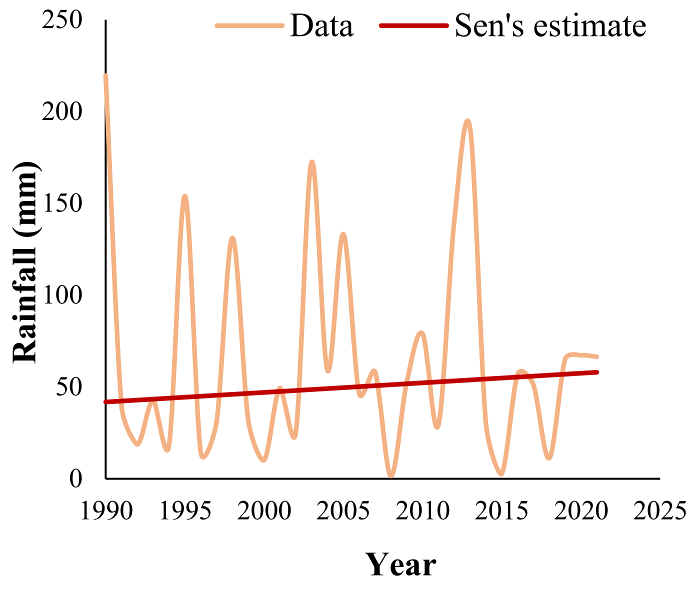


d. Summer

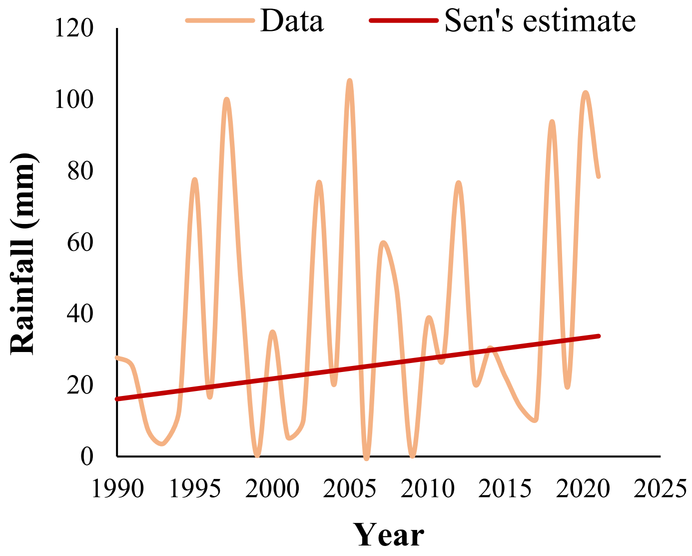
Fig. 6: Seasonal rainfall trend graph for Kalahandi



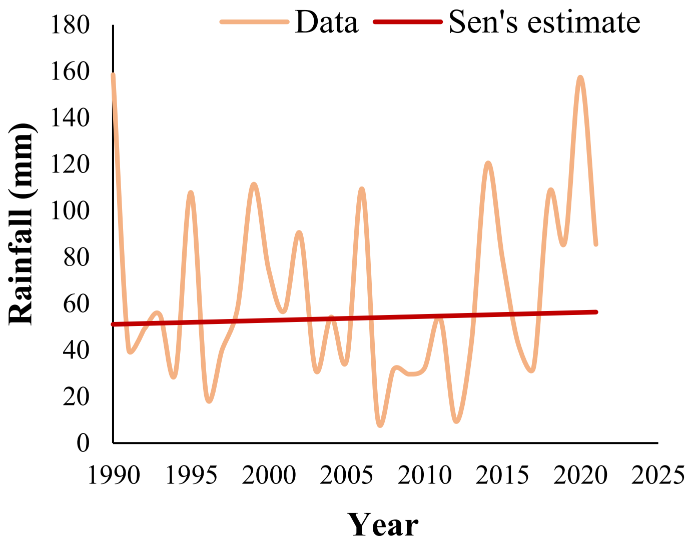
a. Monsoon



b. Post monsoon



c. Winter



d. Summer

Fig. 7: Seasonal rainfall trend graph for Kandhamal

Conclusion

The analysis of long-term rainfall data (1990–2021) across five drought-prone districts of Odisha reveals notable variability in rainfall patterns at annual, seasonal and monthly basis. Although the annual analysis of rainfall revealed non-significant decreasing trends in four drought prone districts; Balangir, Bargarh, Kalahandi and Kandhamal, and a non-significant increasing trend in Nuapada, the results highlight pronounced inter-annual variability across the region. Seasonal trend analysis further shows non-significant declining tendencies during the monsoon season, suggesting a gradual but statistically inconclusive reduction in monsoon precipitation across these regions.

During the post-monsoon period, Nuapada, Balangir, and Kandhamal exhibited non-significant decreasing trends, while Bargarh and Kalahandi showed non-significant increasing trends. In the winter season, Nuapada, Balangir, Bargarh, and Kalahandi experienced non-significant increasing rainfall trends, whereas mixed signals were observed in other districts. During the pre-monsoon (summer) season, Nuapada, Balangir, and Kandhamal reported non-significant decreasing trends, while Kalahandi showed a statistically significant decline. At the monthly scale, November emerged as a critical month, with significant decreasing trends observed in Nuapada, Balangir, and Bargarh, while Kandhamal exhibited significant declines during May, August, and November at the 90% confidence level. Such shifts can adversely impact crop planning, water availability, and groundwater recharge.

Although statistically significant changes in annual rainfall remain limited, the observed declining tendencies in monsoon and monthly rainfall across most districts are a matter of concern. Such subtle but persistent shifts have important implications for crop planning, water availability, and groundwater recharge. Overall, these findings underscore the need for adaptive water resource management, climate-resilient agricultural practices, and strengthened drought preparedness strategies to enhance resilience and safeguard livelihoods in Odisha's drought-prone regions.

Future Scope

Future research should integrate high-resolution regional climate models to project rainfall variability under multiple climate change scenarios, enabling more reliable assessments of future drought risk in Odisha. Such projections can support state-level water resource planning, including reservoir operation, groundwater management, and drought preparedness. Further studies should evaluate the implications of changing rainfall regimes on crop productivity and irrigation scheduling, thereby informing climate-smart agricultural planning, crop diversification strategies, and adaptive interventions under state and national initiatives such as the National Mission for Sustainable Agriculture (NMSA) and Odisha State Action Plan on Climate Change (OSAPCC).

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Conflict of Interests

The authors declare that there is no conflict of interest in this article.

Author Contributions

Ravita: Methodology, Data collection, analysis, and writing the original draft. Ankita Jha: Conceptualization, Methodology, Analysis support, validation, Supervision and project administration; Asha Latwal: Data collection; Dibakar Ghosh & A.K. Gupta: Manuscript drafting and review; A.K.B. Mohaptatra: Supervision, project administration.

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