**RESEARCH**

# Trend Analysis of Rainfall and Meteorological Drought Indices over India During 1958–2017

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## Abstract

Rainfall plays a very vital role and its deficit causes a huge impact on the environment. Understanding the pattern of rainfall and drought trends has become increasingly crucial in many regions due to climate change. In this study, using the rainfall data from 1958 to 2017 for thirty-four meteorological subdivisions of India, trend analysis is performed for annual and seasonal rainfall. Along with the rainfall trend analysis, the study is also performed for meteorological drought indices, i.e., Effective Drought Index (EDI), Standardized Precipitation Index-9 (SPI-9), and Standardized Precipitation Index-12 (SPI-12). The results obtained from the Mann–Kendall test show that the rainfall patterns in the area under investigation are changing over time. As evidenced by the decrease in rainfall, the study region has been experiencing a lack of water supply in numerous subdivisions. The drought frequency for the meteorological drought indices has also been investigated, and it has been observed that the region is experiencing drought from extremely dry conditions to normal dry conditions. The findings in this study will help us to better comprehend the changes in rainfall and drought severity over the study region. This study may also benefit effective disaster management and preparedness strategies for this catastrophe, which is wreaking havoc on the environment.

**Keywords** Drought · EDI · SPI · Mann–Kendall test · Rainfall

## Introduction

Rainfall, as one of the most crucial meteorological parameters [1], plays a pivotal role in shaping the natural environment, including how much water is available for agriculture, surface use, and ground use. Surface water refers to the water available in surface water bodies such as rivers, lakes, and reservoirs which can be utilized for various purposed such as irrigation and industrials needs. In contrast, ground use refers to the water available in underground aquifers, which can be accessed through wells and used for similar purposes [2]. The impact of rainfall scarcity leads to drought, causing severe water shortages that affect not only human life but also have far-reaching consequences for the environment. Understanding the trends in rainfall and drought conditions in a region is essential for effective planning, drought preparedness, early warning systems, and effective drought mitigation strategies [3, 4]. It is considered that the early or late beginning of the monsoon gives insight on the performance of monsoon activities; so, it is important to consider early or late onset for monsoon season planning and policymaking to reduce the projected impacts of the monsoon onset [5]. A delay in the onset and withdrawal of precipitation can significantly alter the rainfall patterns in a region and exacerbate drought conditions [6]. The increasing frequency of dry days indicates a declining trend in monsoon rainfall, making droughts more frequent in various areas. Spatiotemporal assessment of long-term climatology and trends at various timescales assists in understanding the impacts of rainfall variability and so enhances risk management techniques

### Highlights

- The vital role of rainfall and its significant impact on the environment.
- Emphasizing the importance of understanding rainfall patterns, the potential consequences of rainfall deficit.
- Investigation of drought indices: in addition to rainfall analysis, the study examines meteorological drought indices, such as EDI, SPI-9, and EDI-12, to understand the severity and frequency of droughts in the region.

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[7, 8]. Therefore, investigating rainfall and drought trends at different timescales becomes crucial for assessing water availability across the nation.

Various regions around the world have experienced significant changes in rainfall patterns and increasing incidences of drought. In monsoon-dominated areas like Kerala, India, there has been a rise in monsoon droughts due to changing rainfall patterns [9]. Coastal areas of West Bengal have witnessed considerable reductions in monsoon precipitation, rendering the region more vulnerable to drought and posing a threat to its agrarian economy [10]. Other regions in India, such as the Indo-Gangetic plains, parts of coastal South India, and central Maharashtra, have also been identified as vulnerable areas for recent droughts [11]. The Indian monsoon region, in particular, has experienced a steady increase in drought patterns in recent decades. India experiences the majority of its precipitation in the northeast, where rainfall volume and patterns are very variable [12]. Furthermore, regions like Zambia, with a tropical wet and dry climate, have witnessed increasing drought trends, posing significant challenges to agriculture and water resources management [13].

To investigate the distribution and trends of precipitation across regions, the Mann–Kendall test is widely used. Such studies aid in managing water supply projects, implementing soil erosion reduction measures, and designing strategies for drought mitigation [14]. In low-lying regions, trend analysis using the Mann–Kendall test provides crucial recommendations for sustainable water resource management and disaster risk reduction [15]. Similarly, analysis of temporal monotonic trends at various timescales of seasonal and annual drought using the SPI index and the Mann–Kendall method reveals that the arid and semi-arid climate region in Southern Iran is becoming drier, impacting agricultural activities, natural water resource management, and other water-related activities [16]. The longer timescale SPI is better able to capture the definite trends than shorter timescale, and also, the number of drought events reduces with increasing timescale [17]. Drought severity in the Bundelkhand-UP area is also increasing, making the region more susceptible to meteorological drought [18].

Understanding the rainfall trends and drought characteristics will further help in the development of water resource management, agricultural production, climate change projections, and predicting rainfall patterns [19–22]. Additionally, analyzing historical drought disasters helps in identifying and characterizing drought progression [23]. By utilizing standardized variability indices, spatial patterns of rainfall variability can be evaluated at various timescales [24]. For instance, significant decreasing trends in seasonal long rains following dry seasons have been observed in the Kibale National Park, threatening the environment [25]. Furthermore, trends and variability in rainfall can impact water resource management and sustainability in the future [26].

The analysis of rainfall and decadal trends is instrumental in identifying essential monotonic monthly and seasonal patterns, particularly in the context of changing rainfall patterns and global warming [27]. Historical rainfall trends are indispensable for studying changes in rainfall, mapping drought hotspots, and providing baseline data to mitigate climate change [21]. Using a longer period series of precipitation data is crucial to address water-related challenges, as global environmental factors significantly influence extreme rainfall distribution [28].

Climate change has led to changing precipitation patterns in India over the past few decades, impacting the country's economy and food security, which depend heavily on timely water availability [29, 30]. Accurate rainfall forecasting is crucial for determining the degree of meteorological drought indices, which span from extremely wet to extremely dry conditions [31]. Hence, our study focuses on the trend analysis of annual and seasonal rainfall (pre-monsoon, monsoon, post-monsoon, and winter), as well as the meteorological drought indices EDI, SPI-9, and SPI-12, for the period spanning 1958 to 2017. By shedding light on rainfall patterns and drought conditions across the study region, our research aims to establish crucial measures for drought preparedness and address water-related challenges effectively. Overall, India's climatic diversity, seasonal variations, and heavy reliance on the monsoon make it an intriguing and challenging region for studying rainfall patterns and drought trends. The IMD's comprehensive data provides a valuable foundation for understanding the intricate relationship between rainfall, drought, and their impacts on agriculture, water resources, and the economy in this region.

## Materials and Methods

### Study Area

India lies between 8° 4′ and 37° 6′ North latitude and 68° 7′ and 97° 25′ East longitude. India is renowned for its climatic diversity, being categorized into six major climate types according to the Koppen climate system. These climates encompass a wide range of environmental conditions, including arid deserts in the west, alpine tundra and glaciers in the north, humid tropical regions with rainforests in the southwest, and various islands. The India Meteorological Department (IMD) serves as the principal organization responsible for meteorological observations and weather forecasting across the nation. It plays a pivotal role in providing the necessary data for numerous hydrology and meteorology-related studies.

India experiences distinct climatic seasons, with some localized variations. These seasons are winter (December–February), summer (March–May), monsoon

(June–September), and post-monsoon (October–November). Any deficiency in monsoon rainfall can lead to drought conditions, which the IMD defines as occurring when a region receives less than 75% of its average rainfall. The monsoon's performance significantly impacts the Indian economy, with the lack of rain during this season affecting various sectors and livelihoods. For this study, thirty-four meteorological subdivisions within India were considered as the focus areas for analysis. Additionally, the study took into account the homogenous monsoon regions within the country. These regions play a crucial role in shaping the rainfall patterns and drought conditions observed in the study area. Figure 1 illustrates the geographical distribution of the thirty-four meteorological subdivisions and the identified homogenous monsoon regions, serving as essential reference points for the investigation. Table 1 shows the five homogenous monsoon regions and the thirty-four meteorological subdivisions of India.

## Data and Methods

India Meteorological Department has categorized India into five homogenous monsoon regions as Central Northeast India (CNE India), Northeast India (NE India), Northwest India (NW India), Peninsular India, and West Central India (WC India). IMD has also categorized India into thirty-six meteorological subdivisions, and in this study, thirty-four meteorological subdivisions were considered for the study. Rainfall data were obtained from the India Meteorological Department for thirty-four meteorological subdivisions for 60 years (1958–2017). The two subdivisions Andaman and Nicobar Island and Lakshadweep had been excluded due to the non-availability of proper rainfall datasets for the analysis. Figure 2 provide the simplified and visual explanation of the approach methodology that has been employed in this study.

**Fig. 1** Study area map of India with thirty-four meteorological subdivisions

**Table 1** Meteorological subdivisions of India used in the study

| Homogenous monsoon regions | Central Northeast | Northeast | Northwest | Peninsular | West Central |
|---|---|---|---|---|---|
| Meteorological subdivisions | Bihar (BI) | Arunachal Pradesh (AR) | East Rajasthan (ER) | Coastal Andhra Pradesh (CAP) | Chhattisgarh (CH) |
| | East Uttar Pradesh (EUP) | Assam-Meghalaya (AM) | Gujarat (GJ) | Coastal Karnataka (CK) | East Madhya Pradesh (EMP) |
| | Jharkhand (JH) | Gangetic West Bengal (GWB) | Haryana Chandigarh Delhi (HCD) | Kerala (KL) | Konkan-Goa (KG) |
| | Orissa (OR) | Nagaland Manipur Mizoram Tripura (NMMT) | Himachal Pradesh (HP) | Rayalaseema (RA) | Madhya Maharashtra (MM) |
| | Uttarakhand (UK) | Sub-Himalayan West Bengal Sikkim (SHWBS) | Jammu Kashmir (JK) | South Interior Karnataka (SIK) | Marathwada (MA) |
| | West Uttar Pradesh (WUP) | | Punjab (PN) | Tamil Nadu-Pondicherry (TN-P) | North Interior Karnataka (NIK) |
| | | | Saurashtra Kutch Diu (SKD) | | Telangana (TE) |
| | | | West Rajasthan (WR) | | Vidarbha (VI) |
| | | | | | West Madhya Pradesh (WMP) |

**Fig. 2** Schematic representation of the method adopted in the study
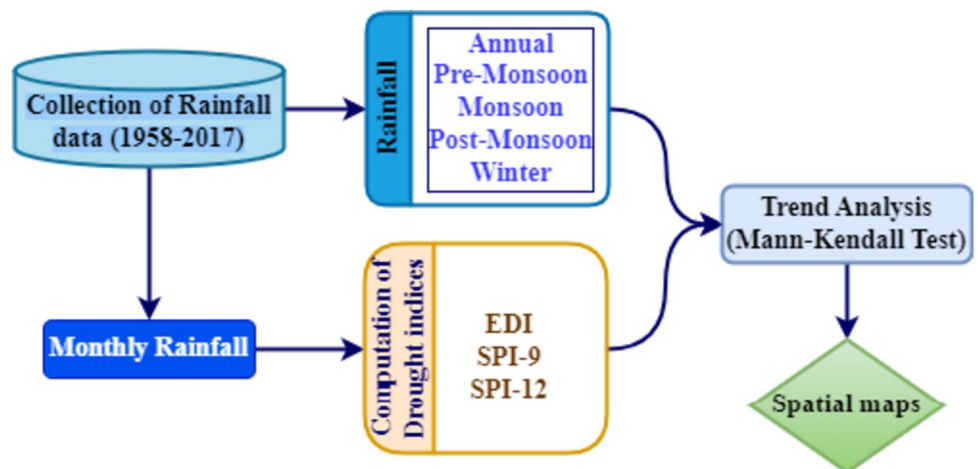


## Method for Trend Analysis

The Mann–Kendall test is a non-parametric statistical test which is used for identifying trends in time series. The method proposed by Mann (1945), Kendall (1975), and Gilbert (1987) are mainly used for detecting the trend in hydro-climatic data series. The Mann–Kendall test is evaluated as follows:

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

where $n$ is the number of data points and $x_i$ and $x_j$ are the data point in the time series $i$th and $j$th $(j > i)$.

The variance is evaluated as follows:

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

$t_i$ is the number of data values in $i$th and $m$th groups.

The standard test statistic $Z$ is computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}} & , \text{if } S > 0 \\ 0 & , \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}} & , \text{if } S < 0 \end{cases} \tag{3}$$

where the positive value of $Z$ signifies an increasing trend and the negative value of $Z$ signifies a decreasing trend. The $Z$-value is used to determine whether a statistically

significant trend exists. The significance level is used to test if a monotonic increasing or decreasing exists. At a significance threshold of $\alpha = 0.05$, the Mann–Kendall non-parametric test has been utilized in this study to assess the rainfall trend in the study area. If the $p$-value is lower than the significance level ($\alpha$), then there is statistically significant evidence that a trend is present in the time series data.

### Effective Drought Index (EDI)

EDI is a drought index that has been developed by [32]. Based on meteorological data such as precipitation, temperature, and soil moisture, it evaluates and monitors the severity of drought conditions. The EDI is a crucial tool for managing drought conditions, reducing their influence on water resource management, and assisting decision-makers with water allocation and conservation strategies. For computing EDI, various parameters like effective precipitation (EP), mean effective precipitation (MEP), and standardized value of monthly effective precipitation are required to be evaluated using the precipitation data.

### Standardized Precipitation Index (SPI)

SPI is one of the most widely used drought indices. It was developed by (McKee et al., 1993) and is based on the precipitation data for computation. The computation of SPI requires fitting a probability distribution to aggregated monthly precipitation series. The SPI is calculated to build a frequency distribution from the historical precipitation data for a specific period at a given location. Then, a theoretical probability density function of the gamma distribution is fitted to the empirical distribution of precipitation frequency for the selected timescale which develops the normal distribution function to have the mean values of SPI at zero. The values of SPI and EDI are shown in Table 2 with different categories of drought. The numerical representation with a negative sign indicates a dry condition and a positive sign indicates a wet condition.

## Results and Discussion

### Trend Analysis for Annual and Seasonal Rainfall

The study focuses on examining the trend analysis of rainfall and meteorological drought indices (EDI, SPI-9, and

**Table 2** Categorization of SPI and EDI values for drought severity

| Category | SPI values | EDI values |
|---|---|---|
| Extremely dry | $\leq -2.0$ | $\leq -2.0$ |
| Severely dry | $-1.5$ to $-1.99$ | $-1.5$ to $-1.99$ |
| Moderately dry | $-1.0$ to $-1.49$ | $-1.0$ to $-1.49$ |
| Normal | $-0.99$ to $0.99$ | $-0.99$ to $0.99$ |

SPI-12) across thirty-four meteorological subdivisions of India using a comprehensive dataset spanning 60 years, from 1958 to 2017. The Mann–Kendall test, a widely used statistical method for trend analysis, is employed to evaluate various parameters for annual and seasonal rainfall (pre-monsoon, monsoon, post-monsoon, and winter) as well as the meteorological drought indices (EDI, SPI-9, and SPI-12).

The analysis begins with the calculation of average annual rainfall for each meteorological subdivision. Coastal Karnataka stands out with the highest average annual rainfall, recording approximately 3500 mm (Fig. 3a). This region benefits from being on the windward side of the Western Ghats, receiving significant rainfall from the onset of the monsoon season and obtaining moisture from the adjacent sea. Similarly, meteorological subdivisions such as Konkan-Goa, Kerala, Arunachal Pradesh, Sub-Himalayan West Bengal Sikkim, and Assam-Meghalaya also experience average annual rainfall above 2500 mm during the study period, owing to their mountainous landscapes that encourage higher rainfall in some locations. On the contrary, West Rajasthan exhibits the lowest average annual rainfall, approximately 300 mm. The geographical distance from the Bay of Bengal, the primary source of rainfall in this region, contributes to the scarcity of rainfall. The area experiences a shadow effect due to its location and encounters arid climatic conditions with high temperatures and low humidity throughout the year.

Additional meteorological subdivisions such as Saurashtra-Kutch-Diu, Haryana-Chandigarh-Delhi, and Punjab also receive relatively low average annual rainfall, less than 600 mm. The presence of the Himalayan Mountains acts as a barrier, preventing moisture from the Arabian Sea and the Bay of Bengal from entering these regions. Moreover, these areas have arid or semi-arid climates characterized by high temperatures and low humidity, resulting in limited precipitation. The remaining meteorological subdivisions exhibit an average annual rainfall ranging from 600 to 2500 mm, influenced by their unique geographical features, orographic rainfall patterns, monsoon winds, and topography.

The spatial distribution maps, Fig. 3a–e illustrate the variations in average annual, pre-monsoon, monsoon, post-monsoon, and winter rainfall across India. The highest average rainfall is observed in Northeast India and some parts of Peninsular India, reflecting the influence of diverse geographical and climatic factors in shaping precipitation patterns.

This comprehensive analysis of rainfall and meteorological drought indices provides valuable insights into the spatial and temporal distribution of rainfall across the country. Understanding these patterns is crucial for effective water resource management, drought preparedness, and climate resilience planning in different regions of India. By identifying regions with varying rainfall patterns and drought conditions, policymakers can develop targeted strategies
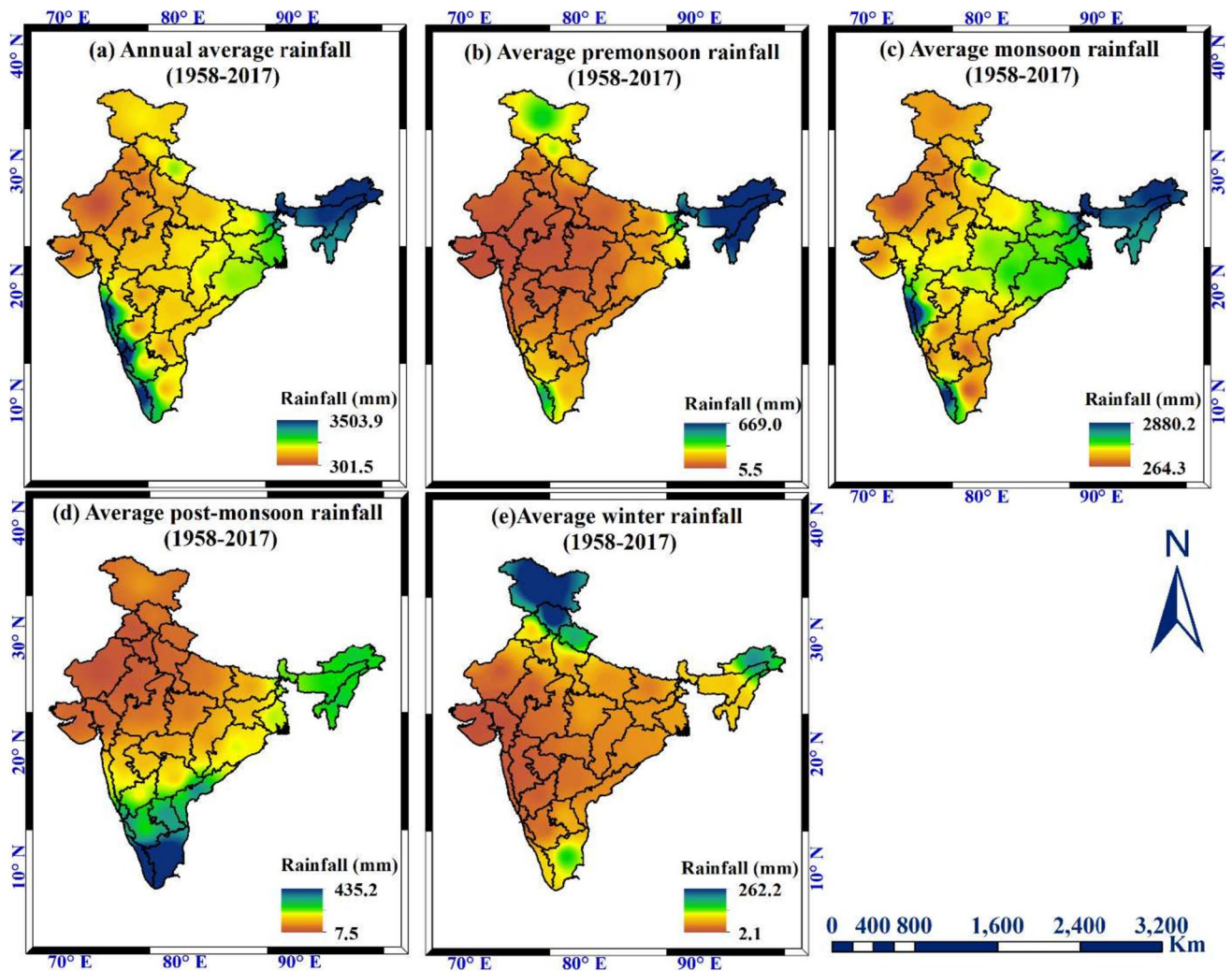
**Fig. 3  a–e** Spatial distribution map for average annual and seasonal rainfall (1958–2017)

to address water scarcity and its potential impacts on agriculture, environments, and communities. Studies have also revealed a notable decline in monsoon rainfall in almost every meteorological subdivision, with the exception of Peninsular India, where the declining monsoon rainfall trend has become an important issue [33].

The study incorporates the Mann–Kendall (M–K) test to analyze the trend of annual and seasonal rainfall across various meteorological subdivisions of India. The M–K test provides crucial parameters such as $p$-value and Kendall's tau as presented in Table 3 and Table 4, respectively, to assess the statistical significance of the observed trends.

For the annual rainfall trend analysis, specific meteorological subdivisions, including Gangetic West Bengal, West Rajasthan, Saurashtra-Kutch-Diu, Rayalaseema, and Tamil Nadu-Pondicherry, show an increasing trend. However, upon closer examination of the $p$-values, it is observed that the increase is not statistically significant ($p$-value > 0.05). On

the contrary, the majority of meteorological subdivisions exhibit a decreasing annual trend, which is also not statistically significant. However, certain subdivisions, such as Assam-Meghalaya, Nagaland-Manipur-Mizoram-Tripura, Sub-Himalayan West Bengal Sikkim, East and West Uttar Pradesh, Himachal Pradesh, Punjab, Haryana-Chandigarh-Delhi, and West Madhya Pradesh, display a statistically significant decreasing trend at a 95% confidence level. Figure 4 provides a visual representation of the trend analysis for annual rainfall. The observed variations in the trends of annual rainfall can be attributed to the unique topography, temperature, and other climate-related factors present in each region. These factors influence precipitation patterns and contribute to the changing trends in annual rainfall.

The study findings highlight the diverse trends in annual rainfall across the meteorological subdivisions of India. The statistical analysis provides insights into the significance of these trends, while factors such as topography, temperature, and
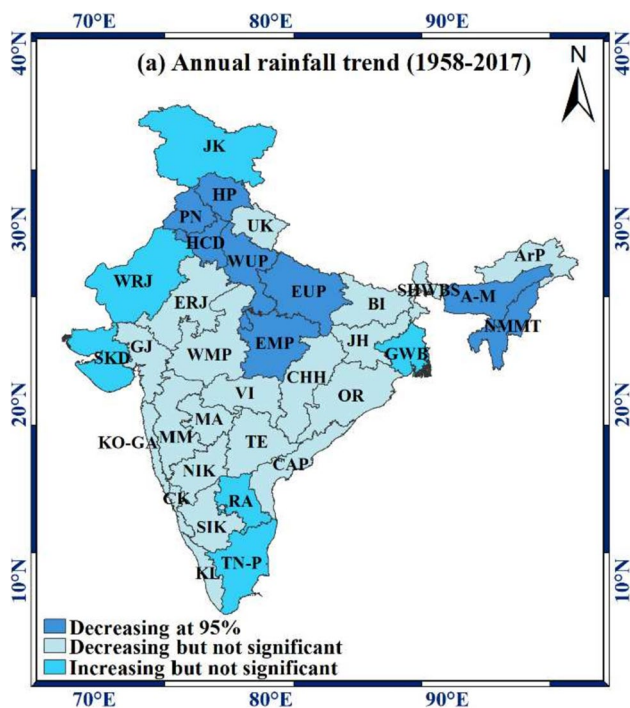
**Fig. 4** Meteorological subdivision-wise annual rainfall trend for the period 1958–2017

other climate-related elements contribute to the observed variations in rainfall patterns. Understanding these trends is essential for effective water resource management, climate adaptation strategies, and developing region-specific policies to cope with changing precipitation patterns and their potential impacts on agriculture, environment, and water availability.

The study examines the variability of rainfall patterns in the study region over both space and time. To assess the trends in annual and seasonal rainfall, the Mann–Kendall (M–K) test was employed, and the statistical significance was determined using $p$-values and Kendall's tau at a 95% confidence level ($p < 0.05$).

During the pre-monsoon period (March to May), the meteorological subdivisions of Arunachal Pradesh and Assam-Meghalaya in the Northeast region experienced the highest average pre-monsoon rainfall with 669.18 mm and 607.03 mm, respectively, as depicted in Fig. 3b. On the other hand, Saurashtra-Kutch-Diu and Gujarat received the least average pre-monsoon rainfall, with only 5.48 mm and 5.71 mm, respectively. The rest of the regions recorded pre-monsoon rainfall ranging from 10 to 500 mm. Significant trends were observed in some subdivisions, such as Bihar and Rayalaseema showing an increase and Vidarbha and Madhya Maharashtra displaying a statistically significant decrease in pre-monsoon rainfall. However, regions like Central Northeast, Gangetic West Bengal, Sub-Himalayan West Bengal Sikkim, East and West Rajasthan,

Haryana-Chandigarh-Delhi, Punjab, Coastal Andhra Pradesh, Telangana, South Interior Karnataka, and Uttarakhand showed increasing trends in pre-monsoon rainfall, though not statistically significant. The remaining regions showed decreasing trends in pre-monsoon rainfall, but they were not statistically significant (please refer to Fig. 5a).

During the monsoon period (June to September), the regions of Konkan-Goa, Sub-Himalayan West Bengal, Kerala, Arunachal Pradesh, and Assam-Meghalaya experienced the maximum average monsoon rainfall, with more than 2500 mm as illustrated in Fig. 3c. In contrast, the region of West Rajasthan recorded the least average monsoon rainfall, with less than 300 mm. The M–K test revealed statistically significant decreasing trends in some subdivisions, including Nagaland-Manipur-Mizoram-Tripura, East and West Uttar Pradesh, Haryana-Chandigarh-Delhi, and Punjab. On the other hand, regions like Assam-Meghalaya, Gangetic West Bengal, Jammu-Kashmir, East and West Rajasthan, Gujarat, Saurashtra-Kutch-Diu, Coastal Andhra Pradesh, Rayalaseema, and Konkan-Goa displayed increasing trends in monsoon rainfall, which were not statistically significant. The remaining regions exhibited decreasing trends in monsoon rainfall, though not statistically significant (please refer to Fig. 5b).

For the post-monsoon period (October and November), Kerala and Tamil Nadu-Pondicherry witnessed the maximum average post-monsoon rainfall, with more than 350 mm as shown in Fig. 3d. Meanwhile, West Rajasthan, Haryana-Chandigarh-Delhi, and Punjab experienced the least average post-monsoon rainfall, with less than 15 mm. The rainfall trend analysis for post-monsoon season is illustrated in Fig. 5c. The significant decreasing trends in post-monsoon rainfall were observed in East and West Uttar Pradesh, Uttarakhand, Haryana-Chandigarh-Delhi, and Himachal Pradesh. However, subdivisions like Coastal Karnataka, Kerala, Konkan-Goa, South Interior Karnataka, and Tamil Nadu-Pondicherry exhibited increasing trends in post-monsoon rainfall, though not statistically significant. The remaining regions showed decreasing trends in post-monsoon rainfall. The representation for the M–K test for post-monsoon rainfall trend has been shown in Fig. 5c, and the statistics are represented in Tables 3 and 4.

During the winter season (December–February), the maximum average winter rain was observed in Jammu-Kashmir and Himachal Pradesh with 262.35 mm and 218.64 mm, respectively. The least average winter rainfall was experienced in Saurashtra-Kutch-Diu, Gujarat, Konkan-Goa, Madhya Maharashtra, and West Rajasthan with less than 10 mm of rainfall which is depicted in Fig. 3e. From the M–K test, Jammu-Kashmir has been observed with an increasing trend, while Arunachal Pradesh, Nagaland-Manipur-Mizoram-Tripura, and Uttarakhand have been observed with a statistically significant decreasing trend. Trend analysis results for winter rainfall shows that the regions of Gangetic West Bengal, Coastal Andhra
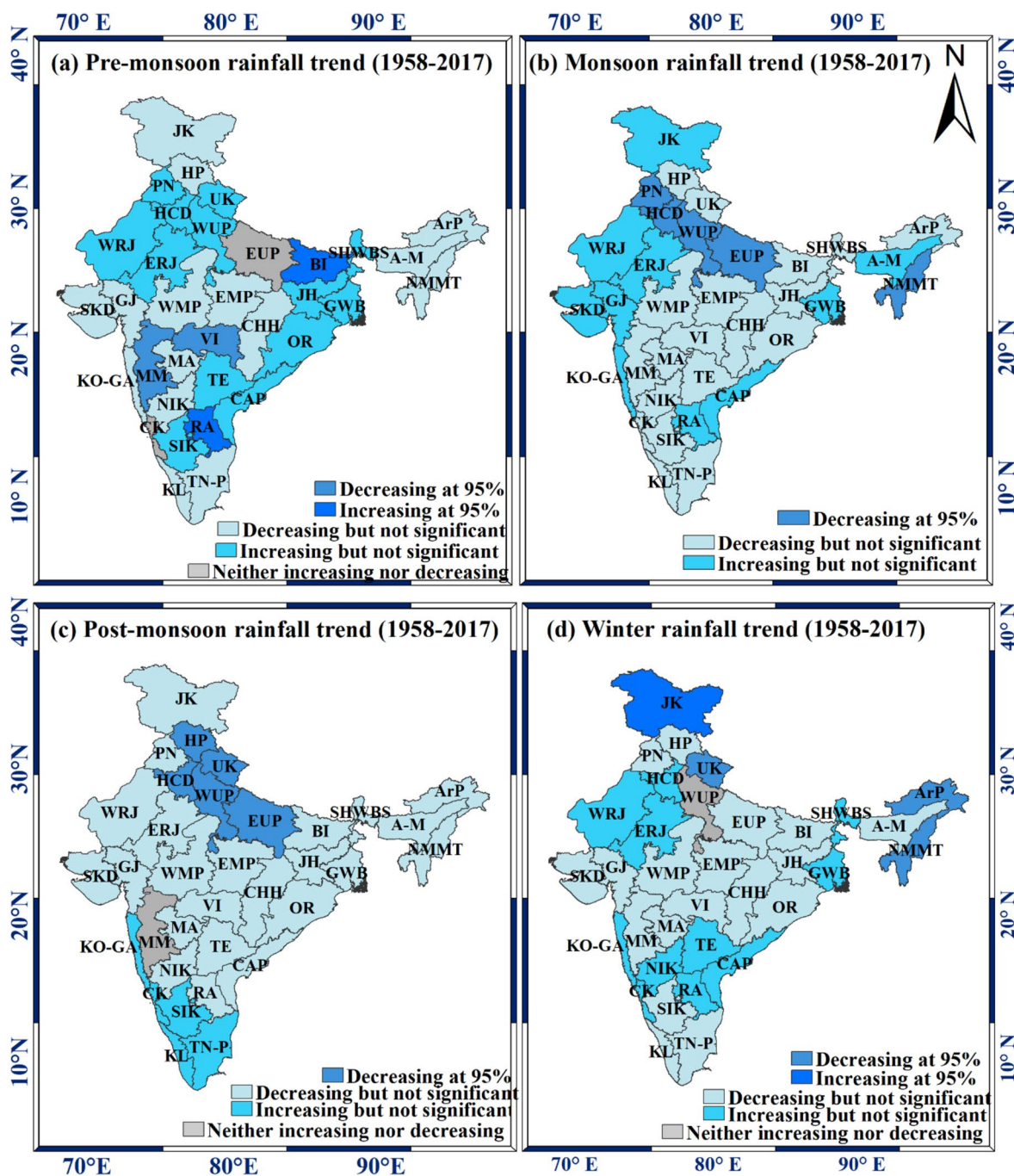
**Fig. 5  a–d** Meteorological subdivision-wise pre-monsoon, monsoon, post-monsoon, and winter rainfall trend for the period 1958–2017

Pradesh, Coastal Karnataka, Rayalaseema, South Interior Karnataka, Konkan-Goa, North Interior Karnataka, East and West Rajasthan, Haryana-Chandigarh-Delhi, and Jammu-Kashmir indicate an increasing winter rainfall trend whereas the remaining meteorological subdivisions show a decreasing winter rainfall trend which is not significant. West Uttar Pradesh observed that it has neither an increasing nor decreasing rainfall trend as shown in Fig. 5d.

## Trend Analysis of Meteorological Drought Indices

### Effective Drought Index (EDI)

In this study, the focus shifts to understanding the trend of drought by using the Mann–Kendall (M–K) test to assess the temporal trends of three meteorological drought indices: the Effective Drought Index (EDI), Standardized Precipitation

Index with 9-month timescale (SPI-9), and Standardized Precipitation Index with 12-month timescale (SPI-12). These indices were computed using precipitation data as input, providing valuable insights into drought conditions.

Table 5 provides the M–K test statistics, *p*-values, and Kendall's tau for EDI, allowing for a comprehensive analysis. The statistical significance was determined at a confidence level of 95%. From the obtained *p*-values, it was discovered that not all meteorological subdivisions displayed statistically significant trends for EDI. Among the subdivisions, Bihar, East Uttar Pradesh, Uttarakhand, West Uttar Pradesh, Arunachal Pradesh, Assam-Meghalaya, Nagaland-Manipur-Mizoram-Tripura, Haryana-Chandigarh-Delhi, Himachal Pradesh, and Punjab experienced a statistically significant decreasing trend for EDI. This implies that these regions have been facing a worsening trend in drought conditions over the study period.

On the other hand, Jammu-Kashmir and West Rajasthan exhibited an increasing trend in EDI, suggesting an improvement in drought conditions. However, for the remaining meteorological subdivisions, the trend in EDI was not statistically significant. This could imply that drought conditions in those regions remained relatively stable or experienced minor fluctuations during the study period. A spatial map for EDI trend has been illustrated with Fig. 6.

Shifting the focus to SPI-9 and SPI-12, the analysis reveals a more pronounced trend, with most regions showing statistically significant trends where *p*-values were less than 0.05. This indicates that these regions have experienced significant changes in drought conditions over the specified timescales. The SPI-9 and SPI-12 analyses offer a more detailed perspective on the drought conditions in these regions, capturing fluctuations in drought intensity over a 9-month and 12-month period, respectively.

## Standardized Precipitation Index (SPI-9 and SPI-12)

The analysis of Standardized Precipitation Index with a 9-month timescale (SPI-9) and Standardized Precipitation Index with a 12-month timescale (SPI-12) provides important insights into the drought conditions across the study region. Table 6 presents the various statistical parameters obtained from the Mann–Kendall test for both SPI-9 and SPI-12. The statistical significance was evaluated at a 95% confidence level, where *p*-values less than 0.05 indicate a statistically significant trend.

The results indicate that a significant portion of the region experienced a statistically significant trend in both SPI-9 and SPI-12, implying notable changes in drought conditions over the respective timescales. This suggests that there have been significant fluctuations in drought severity across many areas, highlighting the dynamic nature of drought patterns in
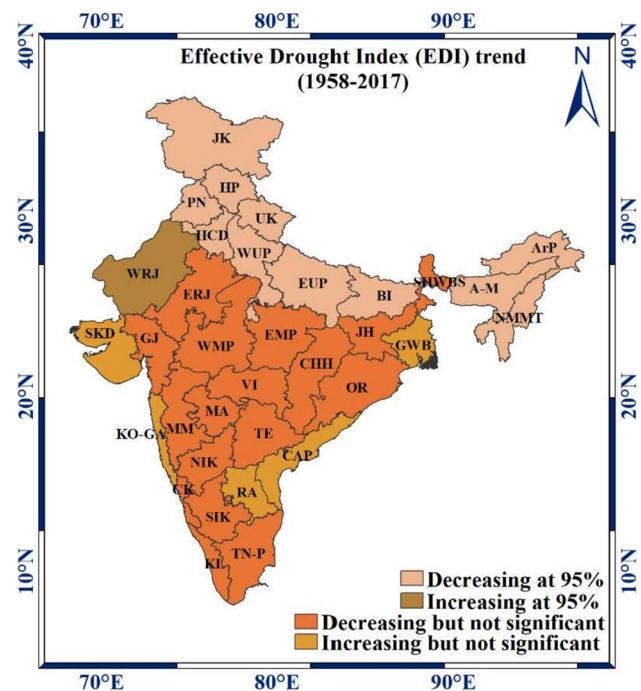


**Fig. 6** Meteorological subdivision-wise effective drought index trend for the period 1958–2017

the study region. Furthermore, the dominant drought condition observed for both SPI-9 and SPI-12 was extreme dry condition. This indicates that the region experienced severe drought episodes during the study period, which could have significant implications for various sectors, including agriculture, water resources, and environment. Extreme drought conditions can lead to water scarcity, crop failure, and environmental stress, posing serious challenges to societal well-being.

The study also identified specific time periods when the most intense droughts occurred for SPI-9 and SPI-12. For SPI-9, the most intense drought was observed in November 2002 in Tamil Nadu-Pondicherry, with a SPI-9 value of − 4.895. Similarly, SPI-12 recorded the most intense drought during September 2002 in Tamil Nadu-Pondicherry. These findings indicate that Tamil Nadu-Pondicherry experienced severe drought episodes during these specific months, which likely had adverse effects on water availability and agricultural activities in the region. Identifying such intense drought events and understanding their temporal patterns can help policymakers and stakeholders develop effective strategies for drought preparedness, mitigation, and adaptation.

Overall, the M–K test results for EDI, SPI-9, and SPI-12 provides valuable information on the severity and temporal patterns of drought conditions in different meteorological subdivisions. The statistically significant trends reveal regions experiencing increasing or decreasing drought severity over time. These findings are crucial for understanding

the vulnerability of various regions to drought and can aid in the development of targeted drought mitigation and adaptation strategies in the face of changing climate patterns.

Figure 7a and b presents the trend analysis results for the drought index SPI-9 and SPI-12, showing the spatial distribution of increasing and decreasing drought trends across the study region. These trends are evaluated using the Mann–Kendall test, with statistical significance calculated at a 95% confidence level.

From Fig. 7a, it is evident that certain regions in India are experiencing a statistically increasing trend in drought conditions based on SPI-9. These regions include Gangetic West Bengal, Uttarakhand, Jammu-Kashmir, West Rajasthan, Saurashtra-Kutch-Diu, and Rayalaseema. This indicates that these areas have been facing a gradual increase in drought severity over the study period. The implications of this trend could result in water scarcity, reduced agricultural productivity, and potential impacts on environment.

In the Konkan-Goa region, there is an increasing drought trend as well, but it is not statistically significant. This suggests that while drought conditions may be worsening in the area, the observed trend may not be substantial enough to establish statistical significance at the 95% confidence level. Conversely, several regions show a statistically significant decreasing drought trend based on SPI-9. These regions include Arunachal Pradesh, Assam-Meghalaya, Sub-Himalayan West Bengal Sikkim, Bihar, Jharkhand, East and West Uttar Pradesh, Uttarakhand, Haryana-Chandigarh-Delhi,

Himachal Pradesh, East and West Madhya Pradesh, Chhattisgarh, Marathwada, North Interior Karnataka, and Kerala. This indicates that drought conditions in these areas have been gradually improving or becoming less severe over the study period. In the remaining regions, the drought trend based on SPI-9 is decreasing as well, but it is not statistically significant. This suggests that some areas may be experiencing a decline in drought severity, but the observed changes are not significant enough to establish statistical confidence.

The results of SPI-9 and SPI-12 provide a valuable insight into the changing patterns of drought conditions across different regions in India. The regions with statistically significant increase or decrease provides close attention from policymakers and stakeholders. Understanding the drivers behind these trends can help develop effective drought mitigation and adaptation strategies to address the challenges posed by changing climate and hydrological patterns. Additionally, regions with non-significant trends also merit monitoring, as even subtle changes in drought conditions can have significant implications for water resources and agriculture.

Drought frequency is a crucial aspect of drought analysis, providing insights into the occurrence and patterns of drought events over a specific period in different regions. It quantifies how frequently droughts happen in each meteorological subdivision, offering valuable information for drought management and planning. To assess drought frequency, historical records of drought events are analyzed, and their occurrence and duration are determined. In this study, three drought indices,
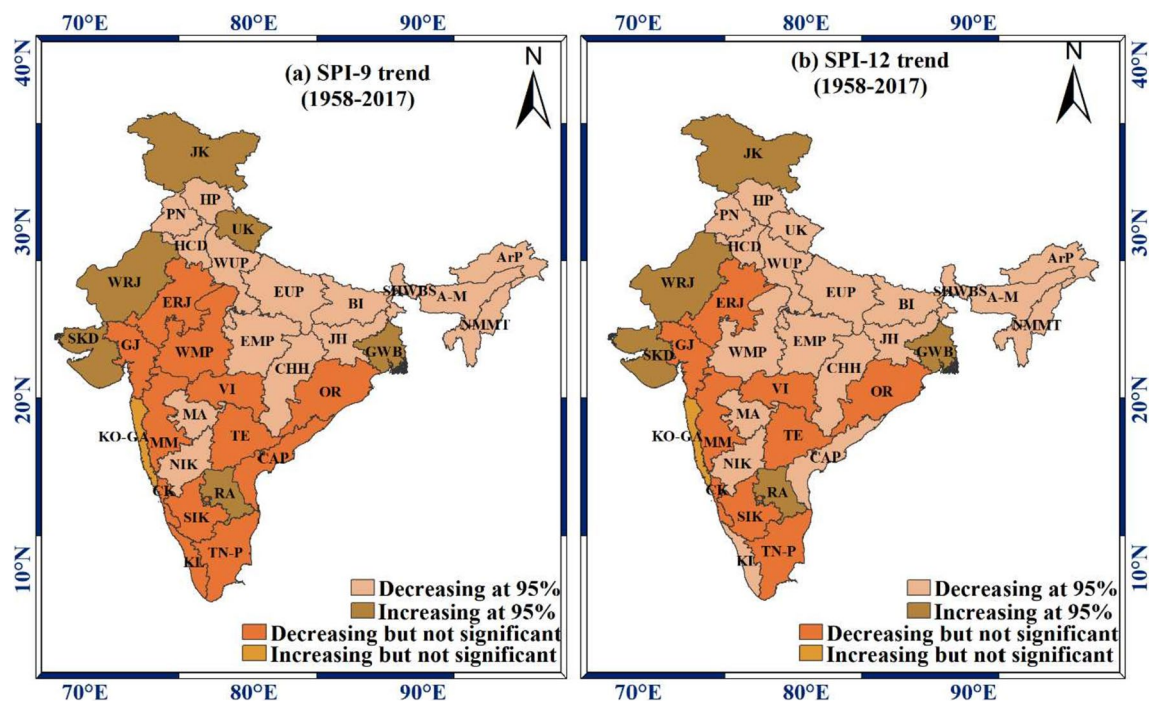


**Fig. 7** **a**, **b** Meteorological subdivision-wise SPI-9 and SPI-12 trend for the period 1958–2017

namely, EDI, SPI-9, and SPI-12, are utilized to quantify and characterize the frequency of droughts in each of the thirty-four meteorological subdivisions.

The results of the drought frequency analysis are visually depicted in Fig. 8a–e, Fig. 9a–e, and Fig. 10a–e for EDI, SPI-9, and SPI-12. The bar charts visually depict the occurrence and patterns of drought events for each region over the study period. The drought frequency analysis using these indices provides a comprehensive understanding of the variation in drought occurrence and duration across the study region. It enables the identification of regions that experience frequent and prolonged droughts, as well as areas that are relatively less affected by drought events. This information is essential for policy-makers, water resource managers, and other stakeholders to develop targeted drought mitigation strategies, improve water allocation, and implement effective drought preparedness measures. The use of multiple drought indices (EDI, SPI-9, and SPI-12) for the frequency analysis allows for a robust assessment of drought patterns, considering various timescales and drought severity levels. This comprehensive approach ensures a more accurate representation of the actual drought scenario in each meteorological subdivision.
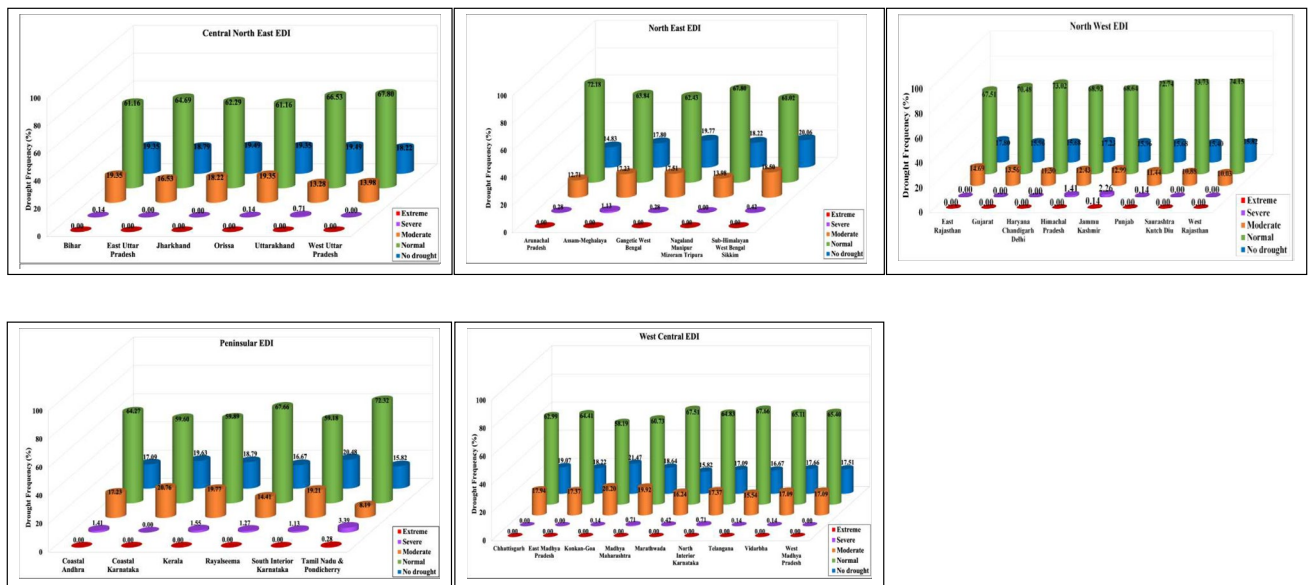


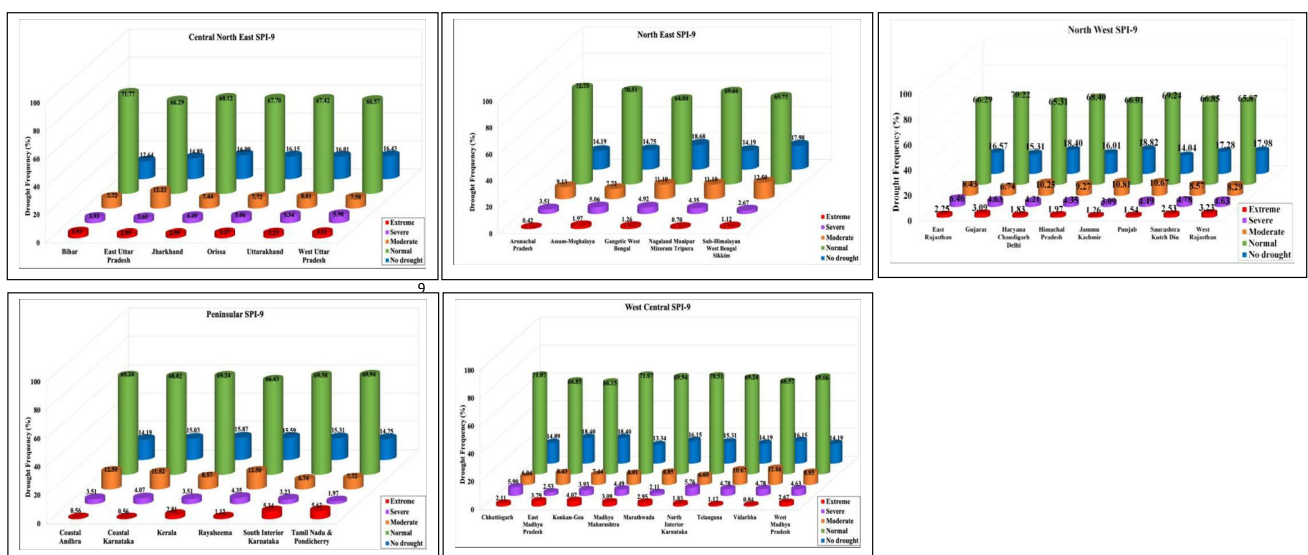**Fig. 8** (**a-e**). Bar charts of drought frequency alongwith numerical percentage for EDI



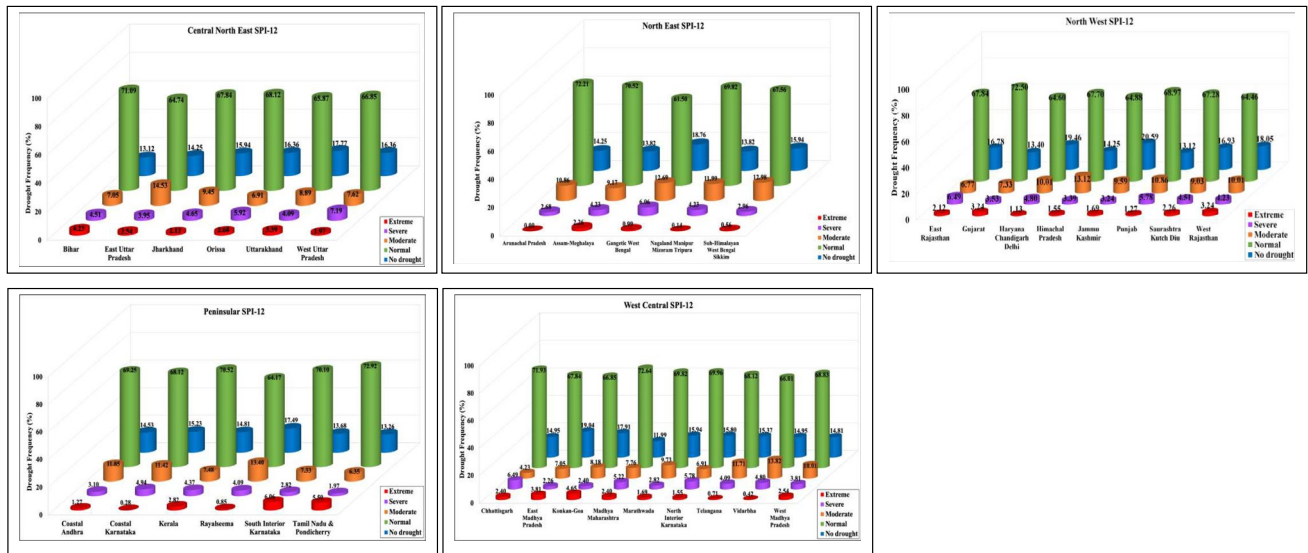**Fig. 9** (**a-e**). Bar charts of drought frequency alongwith numerical percentage for SPI-9

**Fig. 10** (**a-e**). Bar charts of drought frequency alongwith numerical percentage for SPI-12

Overall, the occurrence of extreme drought conditions was relatively infrequent compared to other categories of drought. The frequency of drought occurrences varied significantly from one location to another, influenced by the region's geography, climate, and other climatic factors. The frequency of normal drought occurrence was in the range of 60–75%, moderate drought has 6–20%, severe drought has 0–7%, and extreme drought has 0–6%. However, for EDI, extreme drought conditions were specifically observed in the Jammu and Kashmir subdivision of the Northwest region and the Tamil Nadu-Pondicherry subdivision of the Peninsular region during the study period.

The climate of Jammu and Kashmir, categorized as subtropical, experiences significant fluctuations in rainfall amounts and distribution over time. As a consequence, prolonged periods of little to no rain can lead to extreme drought conditions in this region. Similarly, Tamil Nadu-Pondicherry was also observed to experience severe drought conditions due to several weak or delayed monsoon events over the years.

From the drought frequency analysis, it has been observed that extreme drought conditions for SPI-9 and SPI-12 timescale occur in the study region except that for SPI-12 in the Arunachal Pradesh subdivisions of the Northeast region. Tables 5 and 6 provide further insights, indicating that in most subdivisions, severe drought was the dominant category for EDI, whereas for SPI-9 and SPI-12, extreme dry conditions were the most dominant. The study identified the most intense drought occurrences for each timescale. For EDI, the most severe drought was observed in Jammu and Kashmir, with an EDI value of − 2.05. For SPI-9, the most intense drought occurred in Tamil Nadu-Pondicherry, with

an SPI-9 value of − 4.895. SPI-12 showed the most intense drought in Tamil Nadu-Pondicherry as well.

The variations in the rainfall pattern played a crucial role in influencing drought conditions across the study region. Over the years, a decreasing trend in rainfall amounts has been observed, leading to water shortages in most regions. Understanding the frequency and intensity of drought occurrences is essential for developing effective strategies to mitigate and adapt to the impacts of droughts. By addressing the challenges posed by drought, the findings of this study can contribute to improved drought preparedness and water resource management in the affected regions.

The selection of the time period for rainfall trend analysis and drought trend analysis using EDI, SPI-9, and SPI-12 is a crucial aspect of the study. The choice of 1958–2017 for rainfall and drought trend depends on various factors, including data availability, historical context, and the research objectives. Analyzing data over a longer period helps identify the impact of climate variability and provide insights and recommendation that are more relevant for policymakers and stakeholders.

In results and discussion section, spatial variation in average annual rainfall and average seasonal rainfall have been analyzed. The Mann–Kendall test has been adopted to study the rainfall trend where the trend analysis for rainfall reveals that it indicates a decreasing trend in most region but not statistically significant. During the pre-monsoon, monsoon, post-monsoon, and winter seasons, rainfall patterns and trends vary across the regions based on their geographical features and climate conditions. The study also examines meteorological drought indices (EDI, SPI-9, and SPI-12) and reveals that certain regions experience statistically significant worsening trends in drought

conditions, while others show improving trends. SPI-9 and SPI-12 analyses provide detailed insights into drought severity over specific timescales. The frequency of drought occurrences varies across regions, with extreme drought being relatively infrequent, but most regions experiencing severe drought conditions. Overall, the study highlights the spatial and temporal variations in rainfall and drought conditions across India, offering valuable insights for effective water resource management and climate adaptation strategies. The findings can aid policymakers in developing targeted strategies to cope with changing precipitation patterns and their impacts on agriculture, water resources, and communities.

## Conclusions

Rainfall is one of the essential climatic parameters causing an impact on the environment. The occurrence which is a prolonged and challenging phenomenon to predict has a significant implication for water resources and environment. This study conducts trend analysis for annual, pre-monsoon, monsoon, post-monsoon, and winter rainfall using the Mann–Kendall test. Additionally, two meteorological drought indices, EDI and SPI (with SPI-9 and SPI-12 time-scales), are subjected to trend analysis. The research study for thirty-four meteorological subdivisions in India encompasses 60 years of monthly rainfall data (1958–2017).

India's diverse climatic conditions range from snow-capped mountains to arid lands. The spatial variability in rainfall distribution adds complexity to identifying trends, such as increasing or decreasing patterns over time. Analyzing rainfall and drought changes over the years aids in understanding potential causes and impacts.

From the Mann–Kendall test results, it reveals that the majority of regions experienced a decreasing trend in rainfall for annual, pre-monsoon, monsoon, and post-monsoon periods. During non-monsoon months, some regions face water shortages due to delayed or inadequate precipitation, inadequate water management, changes in rainfall patterns, and other factors impacting water resource availability. The numerical representations of drought indices underscore that rainfall plays a pivotal role in shaping wetness and dryness in the study area. Moreover, meteorological drought indices exhibit a dependency on rainfall, emphasizing that non-monsoon periods generally experience dry conditions.

The overall decline in rainfall across the study region is likely influenced by climate change, characterized by rising temperatures and reduced seasonal rainfall. Consequently, it becomes imperative to comprehend rainfall trends and drought conditions to develop effective mitigation strategies to address rainfall shortages and drought impacts. Analyzing trends in drought indices like EDI, SPI-9, and SPI-12 provides deeper insights into evolving drought conditions and their potential consequences on the environment, agriculture, and water resources.

Mann–Kendall trend analysis proves valuable in assessing and understanding rainfall and meteorological drought index patterns. The derived information guides policies and decision-making concerning drought management and planning. Notably, precipitation data served as the primary input parameter for drought analysis in this study. Future research could incorporate various input parameters, such as temperature data, to further enhance the analytical capacity. By grasping the evolving trends in rainfall and drought conditions, we can devise informed strategies to tackle the challenges arising from changing climate patterns and safeguard water resources for a sustainable future.

## Declarations

**Competing interests** The authors declare no competing interests.

**Conflict of Interest** The authors declare no competing interests.

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