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CASE REPORT

Long-term spatiotemporal trends and impacts of extreme rainfall and temperature in Telangana, India

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ABSTRACT

The growing unpredictability of the climate, particularly in maximum and minimum temperatures and extreme rainfall events, has drawn global attention. The variability and fluctuations of these climatic components vary significantly across regions. Therefore, it is crucial to analyze climate changes and develop workable adaptation solutions by evaluating the spatio-temporal variations of meteorological variables in the context of climate change, especially in nations like India where agriculture is prevalent. This study examines long-term trends and short-term variations in extreme rainfall and temperature across Telangana, India, from 1990 to 2020. The Mann-Kendall test and Sen's slope estimator were used to analyse gridded rainfall data (0.25° resolution) from the India Meteorological Department (IMD). The results showed that annual rainfall increased significantly in the north-western districts at a rate of approximately 2.1 mm/year, while it decreased by nearly 1.5 mm/year in the south-western districts. Temperature study indicated a warming trend, with maximum temperatures increasing by around 0.03°C year, particularly in urbanised areas such as Hyderabad and Rangareddy. Rainfall Anomaly Index and Precipitation Concentration Index show increasing irregularity, while Coefficient of Variation shows increased unpredictability in central and southern regions, making them more sensitive to climate extremes. These climatic shifts have intensified flood risks in high-rainfall areas while exacerbating droughts and heat stress in drier districts, impacting agriculture, water resources, and human health. To address these issues, policy interventions should prioritise sustainable water resource management, drought-tolerant crops, improved flood control infrastructure, and urban heat adaption measures. These findings highlight the need for focused adaptation efforts in Telangana to maintain climate resilience, agricultural sustainability, and socio-economic stability.

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INTRODUCTION

In climatic systems, calamitous events frequently occur within the confines of natural variability [1]. Nonetheless, human activities, especially the rising levels of atmospheric greenhouse gases (GHGs), substantially exacerbate global climate change. One of the most serious repercussions of this phenomenon is the increased variability of precipitation, which affects its temporal and spatial distribution, intensity, and frequency. Cho et al. [3] emphasised that anthropogenic factors have exacerbated extreme precipitation events, exemplified by the June 2013 flood in northern India, whereas Zamani et al. [4] illustrated the irregular distribution of seasonal and annual rainfall trends in Jharkhand, India, shaped by local climatic conditions. These findings highlight the vulnerability of climate-extreme locations, requiring localised studies to explain precipitation patterns.

India is classified as a medium-risk nation for climate change, possessing a World Risk Index (WRI) of 6.77% and ranked 85th globally [5]. Global precipitation patterns are increasingly influenced by climate variability and long-term changes. The recent IPCC report [6] states that global surface temperature has been increasing at an unprecedented rate, significantly disrupting the hydrological cycle and precipitation trends worldwide. Temperature and precipitation are the two most essential elements of the global climate system, with their fluctuations directly affecting ecosystems, water supplies, and agriculture [7, 8].

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Significant long-term trends in precipitation have been observed in multiple regions, with the IPCC forecasting a general rise in worldwide precipitation. However, regional-scale estimates show both rises and declines, depending on local climate circumstances. Precipitation fluctuations were more spatially variable than temporally variable, according to the AR4 synthesis report [9].

Regional causes including industrialisation, deforestation, and fast urbanisation have also led to changes in the Indian summer monsoon, even though global warming is a major contributor in changing precipitation patterns [10, 11]. These alterations have directly affected local precipitation patterns, impacting the frequency and severity of extreme weather phenomena, including intense rainfall and droughts, especially in urbanised regions. The climate of India is extremely susceptible to global warming as a result of its diverse climatic zones, which encompass the tropical monsoon belt and the Himalayan cold deserts. The nation exhibits considerable seasonal and regional variability in precipitation, predominantly affected by the Indian Summer Monsoon, which accounts for around 80% of yearly rainfall [12]. Studies have shown that monsoonal variability has grown due to rising sea surface temperatures and atmospheric disturbances [13]. Due to these changes, extreme weather events including flash floods, protracted droughts, and heavy rainfall have become more common, especially in areas that are environmentally sensitive and heavily urbanized [14].

Comprehending precipitation variability - both geographically and temporally - is essential, since it directly influences water resource management, disaster preparedness, and agricultural productivity [15, 16]. Hydrometeorological variability has clear trends in both space and time, which affects how often and how bad extreme events are [17-19]. Given its role in moderating disaster damage, precipitation fluctuation analysis is crucial for designing adaptation strategies and flood control models to mitigate impacts on vulnerable sectors such as agriculture, infrastructure, and tourism [20-24].

Numerous spatio-statistical methods have been extensively employed in previous literature to examine the trends and intensities of precipitation and temperature [25, 26]. To address possible flooding threats and heat waves across the country, a number of studies on extreme precipitation and temperature patterns have been carried out to determine which areas are most affected by the rising frequency of extreme climate events [26-29]. Urbanisation in India intensified after 1970, with the number of metropolitan cities rising from 9 in 1971 to 53 in 2011, influencing alterations in extreme weather patterns [30]. Observational and climatological studies indicate that precipitation increased during the twentieth century, and this pattern is anticipated to continue due to probable drastic atmospheric deviations [31, 32]. A study indicated a notable upward increase in both monsoon and annual precipitation in Mumbai, New Delhi, Chennai, and Kolkata [33].

Comprehensive research has been undertaken to assess and forecast precipitation patterns, their regional variability, and temporal trends [34-37]. Historical precipitation trend analysis offers valuable insights into local precipitation patterns, which are essential for the development of hydrological measures to mitigate potential disasters, including droughts and flooding. This thereby enhances water resource management by maximising the efficient utilisation of existing data. Certain studies have utilised gauge station data, whereas others have adopted high-resolution gridded datasets to examine notable trends in time-series through methodologies including the Mann-Kendall Test (MKT), Modified Mann-Kendall Test (MMKT), Theil-Sen Method (TSM), and sequential Mann-Kendall Test (SMKT) [38-42].

Trend analysis is extensively employed to assess fluctuations in precipitation, temperature, and other environmental variables across time. The nonparametric Mann-Kendall test (MKT) is often suggested as a way to find trends in hydrometeorological data because it works well with datasets that are not normally distributed and has been used a lot in climate studies [43, 44]. Sen's slope estimator (SSE) is frequently employed alongside the Mann-Kendall test (MKT) to assess the extent of identified trends [45]. Numerous research have utilised geostatistical methods, including Kriging interpolation, to improve the spatial analysis of climatic variables [46].

Variation in precipitation from observed climatic data and large-scale analysis cannot be directly implemented in small-scale sectors like water management and urban planning. This difficulty has been acknowledged by the scientific community [47, 49]. Research on the temporal and spatial variation of precipitation and temperature in Telangana is limited within the realm of Indian studies. While numerous studies have examined extreme rainfall and temperature trends in India, most have focused on larger regions or states, with limited attention to Telangana's unique climatic conditions [50, 51]. Furthermore, several studies depend on coarse-resolution data, overlooking localised fluctuations, and few incorporate both rainfall and temperature trends [25, 52, 54].

This study rectifies existing gaps by utilising high-resolution gridded data (0.25° × 0.25°) to examine spatiotemporal trends in Telangana, employing sophisticated methodologies such as the Mann-Kendall Test with Sen's slope estimator and Kriging interpolation, while considering autocorrelation [53, 54]. By focusing on Telangana and integrating both rainfall and temperature analysis, we provide region-specific insights for climate adaptation, filling a critical gap in the literature and offering actionable recommendations for water resource management and agriculture in this underrepresented region.

This study seeks to address this gap by analysing trends in precipitation and temperature in Telangana. The aims of this study are: To identify probable trends in the daily maximum precipitation time series. To ascertain monotonic trends in yearly, seasonal, and monthly maxima of precipitation and temperature utilising the Mann-Kendall Test at a 5% significant threshold. To forecast the extent of trends in maximum precipitation and temperature time-series utilising Sen's slope method. To enhance the assessment of extreme rainfall and temperature variability, this study incorporates additional statistical techniques such as the Anomaly Index, Coefficient of Variation, and Precipitation Concentration Index (PCI). These methods provide a more detailed understanding of the intensity, distribution, and spatial patterns of climatic extremes in Telangana.

STUDY AREA, DATA USED AND METHODOLOGY

Study Area

The present study focuses on Telangana (Figure 1), a state in southern India, bordered by Maharashtra to the north, Karnataka to the west, Andhra Pradesh to the east, and Chhattisgarh to the northeast. Telangana spans 112,077 square kilometers and lies predominantly on the Deccan Plateau, with elevations ranging from 300 to 600 meters above sea level. The state's capital, Hyderabad, is a major urban center known for its historical significance and rapid development. Telangana's topography is shaped by the Deccan Plateau and interspersed with hill ranges, forests, and rivers. The state is drained by the Godavari and Krishna Rivers, which serve as vital resources for irrigation, drinking water, and hydropower. The region experiences a tropical climate with hot, dry summers and warm, wet winters. The average temperature ranges from 27°C (81°F) in January to 39°C (102°F) in May. Telangana receives an annual average rainfall of approximately 800 mm (31 inches), with the majority concentrated during the monsoon season from June to September. The surrounding mountains trap moisture-laden monsoon winds, leading to relatively higher rainfall compared to some neighboring regions. The climate of Telangana is also influenced by its proximity to the Arabian Sea. The sea breeze helps to moderate the temperatures, making the summers cooler and the winters warmer.

The state has a well-developed network of reservoirs and irrigation systems, with notable projects like the Kaleshwaram Lift Irrigation Project, which is among the largest in the world. However, Telangana faces challenges such as groundwater depletion and increasing variability in rainfall patterns. These issues underscore the importance of understanding hydrometeorological trends for effective water resource management. Telangana is highly vulnerable to the effects of climate change, including erratic rainfall, prolonged droughts, and increasing heatwaves. These climatic shifts significantly impact agriculture, water resources, and overall livelihoods, making the region a critical focus for climate studies.

Data Used

In the current study, high-resolution datasets were utilized to represent the spatial distribution of precipitation with improved accuracy and practicality [51]. Daily gridded precipitation data with a resolution of 0.25° × 0.25° for the 30-year period from 1990 to 2020 was analyzed to examine trends in precipitation and temperature at annual, seasonal, and monthly time scales [55]. This gridded data set was obtained from India Meteorological Department (IMD), Pune website which was specially designed for Indian conditions and regions. It was developed using a network of measurement stations spread across India, ensuring uniform distribution over the selected study area.

The seasonal classification for the study follows the four predominant seasons of the region:

- Winter (December, January, February)
- Pre-Monsoon (March, April, May)
- Monsoon (June, July, August, September)
- Post-Monsoon (October, November)

These datasets provided a comprehensive foundation for analyzing precipitation and temperature trends, enabling detailed spatiotemporal assessments for the Telangana region.

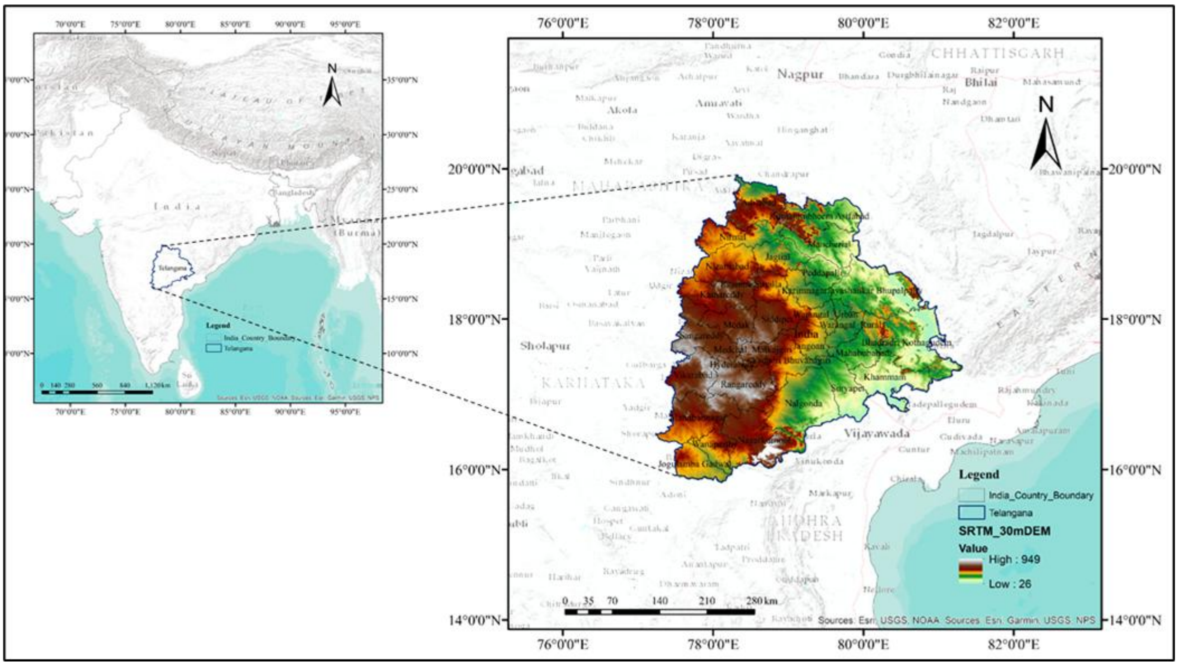

Figure 1. Location map of Telangana

Methodology

Trend analysis is a commonly used methodology to identify variations in precipitation, temperature, and other variables over recent periods. Several methods have been developed to analyze the patterns of hydrometeorological factors, each with its own advantages and limitations. These methods are generally classified into nonparametric and parametric techniques. Nonparametric methods commonly used among researchers for trend detection because of the fact that they are less affected by anomalies and can be applied to datasets that are not normally distributed [56]. The World Meteorological Organization (WMO) recommends the nonparametric Mann-Kendall test (MKT), developed by Mann (1945) and Kendall (1975), for analyzing precipitation time-series data [57]. However, MKT has a significant limitation: it assumes no significant autocorrelation in the data, which is often not the case in time-series datasets [58].

Generally, any time-series of hydro-climatological variables are auto correlated. Under the Effect of correlation in the time-series, the decreasing serial correlation leads to underestimating the significance of trends and vice-versa [55, 56]. Numerous studies have used MKT and related methods to analyze the trends in hydrometeorological variables [59-63].

To detect trends in precipitation time-series data, the Mann-Kendall Test (MKT) is commonly used, as it is well-suited for identifying monotonic trends in hydrometeorological data. The test is a nonparametric method that does not require the data to follow any specific distribution, making it ideal for time-series data that may not conform to normal distribution assumptions [43, 44]. In this study, the MKT was employed to examine trends in precipitation data over a 30-year period.

MKT statistics is defined as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \quad (1)$$

Where, the length of dataset is n and data points in time-series *i* and *j* are denoted as *Xi & Xj (i < j).*

$$sgn(X_j - X_i) = \{-1, if \quad X_j - X_i < 0 \;\; 0,\; if \quad X_j - X_i = 0 \;\; 1, if \quad X_j - X_i > 0 \quad (2)$$

S statistics value is normally distributed as follows for *n* ≥ 10

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} \; t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

$$E(S) = 0 \quad (4)$$

Where Variance of *S* is *V(S)*, Mean of *S* is *E(S),* size of ith tied group is to and no of tied groups is m. The statistics *Z* value is as follows

$$Z = \{\frac{S+1}{\sqrt{V(S)}},\; if\; S < 0 \;\; 0,\; if\; S = 0 \;\; \frac{S-1}{\sqrt{V(S)}}, if\; S > \quad (5)$$

The null hypothesis (H_0) assumes no significant trend, while the alternative hypothesis (H_1) suggests the presence of a trend. A *Z*-value is calculated to assess the significance of the trend, with a threshold of ±1.96 for a 95% confidence level. If the *Z*-value exceeds this threshold, H_0 is rejected, indicating a significant trend. A positive *Z*-value indicates an increasing trend, while a negative *Z*-value points to a decreasing trend. This methodology provides valuable insights into long-term trends in precipitation, helping to better understand climatic shifts and inform water resource management strategies.

This study utilizes the Anomaly Index (AI), Coefficient of Variation (CV), and Precipitation Concentration Index (PCI) to provide a comprehensive assessment of rainfall and temperature variability. The AI is used to identify deviations of rainfall and temperature from the long-term mean, helping to assess extreme climate conditions. Positive values indicate wetter or warmer conditions, while negative values signify drier or cooler periods. The CV measures the relative variability of rainfall and temperature over time, with higher values indicating greater climate fluctuations. The PCI is employed to analyze the seasonal distribution of rainfall, where higher PCI values suggest a more uneven rainfall distribution, potentially leading to water stress during dry periods.

Impact Assessment Approach

To assess the hydrological impacts of rainfall extremes, flood event data from the NRSC-ISRO (NRSC-ISRO, 2023) "Flood Affected Area Atlas" (2006–2020) were integrated with the statistical rainfall anomaly trends. A spatial overlay analysis and time-series comparison were carried out to correlate the Rainfall Anomaly Index (RAI) with flood occurrences at both temporal and district levels. District-wise flood extent data were used as a proxy for validating the significance of rainfall variability indices.

RESULTS AND DISCUSSION

The precipitation and temperature trends for monthly, seasonal (monsoon, post-monsoon, winter, and pre-monsoon), and annual variations across 10 selected southern metropolitan cities of India were analyzed. In trend analysis, the pre-whitening process is commonly employed to address errors related to serial correlation. However, this approach has a significant drawback: it may accept the null hypothesis (*H0*) even when a trend exists in the series. In this study, the pre-whitening process was not applied, as the dataset was sufficiently large to mitigate serial correlation issues [55, 56].

Figure 2(a) shows the annual average precipitation data in Telangana, which is classified into five different categories of rainfall intensities. Red colour indicate from 600-775 mm rainfall, brown colour from 775-895 mm, yellow colour from 895-1030 mm, light green colour from1030-1165 mm, dark green colour from 1165-1320 mm, and blue colour from 1320-1579 mm. The highest rainfall was recorded in north-east districts, and lowest rainfall was recorded in south districts. The rainfall was slowly decreasing from northeast to south districts. The highest rainfall was recorded in the districts of some parts of Komurambheem Asifabad, Mancherial, Bhadradri kothagudem, mulugu and jayashankar bhupalpally. The highest rainfall is more in north west districts because of forests. The lowest rainfall was recorded in the districts of Jogulamba gadwal, Wanaparthy, major part of Nagarkurnool, Narayanpet, Mahaboobnagar, Rangareddy and some parts of Nalgonda and some parts of siddipet. Due to the lowest rainfall recorded in south districts, the irrigation facilities are very low for agriculture purpose which leads to unemployment crisis. This factor leads to the migration of people to other parts of Telangana and India.

Annual rainfall trend data in Telangana is shown in Figure 2(b). Red colour indicates a significant negative trend i.e., -1.645, dark green colour indicates insignificant negative trend i.e., -1.645, yellow colour indicates insignificant positive trend i.e., +1.645, blue colour indicates significant positive trend i.e., +1.645. The highest positive significant rainfall was recorded in the districts of north-west side of Telangana and lowest negative significant trend of rainfall was recorded at the districts of small portion of south of Telangana. The lowest precipitation is leads to crop damage, water shortages, and famines. In the districts of Wanaparthy, Nagarkurnool, Nalgonda and some parts of Mahaboobnagar and Rangareddy recorded low rainfall due to highest temperature in that area. Most of the districts are under insignificant negative and positive trend of annual rainfall which is a good sign to irrigation and helps in improving employment opportunities mainly in agricultural sectors. The rainfall distribution in Telangana shows a north-east to south decreasing trend, with higher rainfall in forested northern regions and lower rainfall in southern districts, impacting agriculture and employment. The annual rainfall trend is mostly insignificant, which is favorable for irrigation, but southern districts with significant negative trends face water shortages, crop damage, and migration issues.

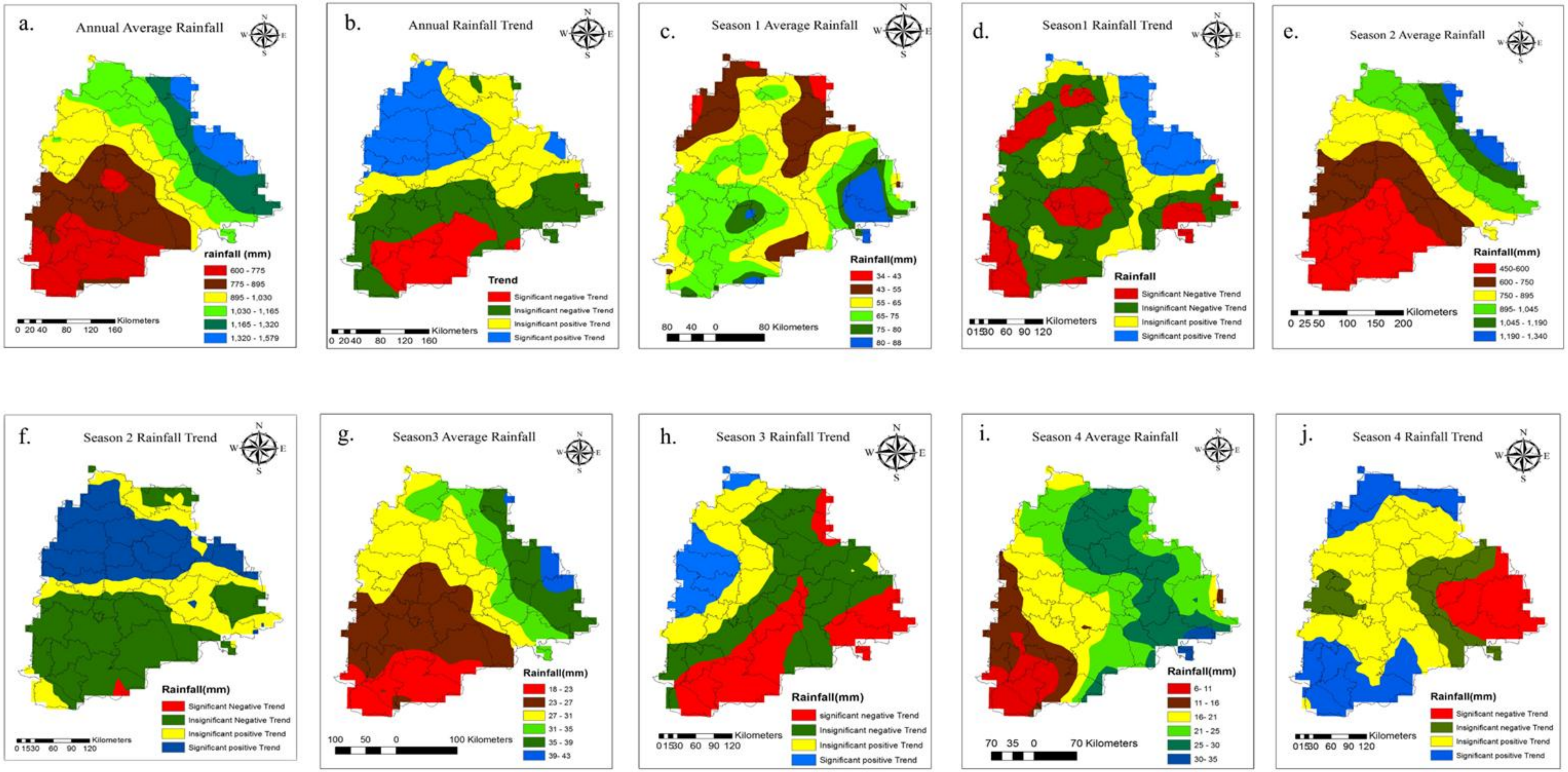

Figure 2. The spatial rainfall distribution maps of Telangana for the period of 1990-2020 for (a) Annual average rainfall (b) Annual rainfall trend (c) Season 1 average rainfall, (d) Season 1 rainfall trend, (e)Season 2 average rainfall, (f) Season 2 rainfall trend, (g) Season 3 average rainfall, (h) Season 3 rainfall trend, (i) Season 4 average rainfall, and (j) Season 4 rainfall trend.

Figure 2(c) demonstrates the season 1 average rainfall data in Telangana. They are red colour indicates 34 - 43mm rainfall, brown colour indicates 43-55mm rainfall, yellow colour indicates 55-65mm rainfall, light green colour indicates 65-75mm rainfall, dark green colour indicates 75-80mm rainfall and blue colour indicates 80-88mm rainfall. In season 1, the highest rainfall was recorded in small portion of Khammam, Mahabubabad, Bhadradri kothagudem nagar, Kurnool and Rangareddy districts and the lowest rainfall was recorded in the districts of Komurambheem, Asifabad, Adilabad and Nirmal. Compared to highest and lowest rainfall intensities, moderate rainfall intensities are more throughout the Telangana for season 1. This average rainfall does not follow any specific pattern. Most of the telangana average rainfall is about 55-65mm. The highest elevation areas in Telangana was recorded rainfall as 65-75mm and partly 43-55mm and the lowest elevation areas was recorded rainfall as 55-65mm.

The Figure 2 (d) indicates season 1 rainfall trend data in Telangana. The highest rainfall was recorded in small portion of north-east side of Telangana and lowest rainfall intensities was recorded in west side districts (Nirmal, Adilabad, Komurambheem, Asifabad, Mancherial, Nizamabad, Kamareddy, Narayanpet, Jogulamba gadwal, Wanaparthy, Mahabubnagar) and some central districts (Rangareddy, Medchal, Malkajgiri, Yadadri Bhuvanagiri) and some east side districts (Khammam, Bhadradri Kothagudem). Most of the Telangana falls under insignificant negative trend and insignificant positive trend which is acceptable and useful rainfall trend for irrigation, agriculture sectors. This insignificant negative trend was recorded in high elevated areas of Telangana and insignificant positive trend was recorded in low elevated areas. The districts having significant positive trend contains high percentage of forest area. Season 1 rainfall in Telangana shows moderate intensities (55-65mm) across most regions, with higher rainfall in elevated areas and lower rainfall in northern and western districts. The rainfall trend is largely insignificant, which is favorable for agriculture and irrigation, while significant positive trends are observed in forested regions.

Season 2 average rainfall data in Telangana is shown in Figure 2 (e). Seasonal 2 average rainfall is divided into six. Red colour indicates 450-600mm, brown colour indicates 600-750mm, yellow colour indicates 750-895mm, light green colour indicates 895-1045mm, dark green colour indicates 1045-1190mm and blue colour indicates 1190-1340mm.The highest rainfall was recorded in small portion of north-east side of Telangana and lowest rainfall intensities was recorded in sound side districts of Telangana. The rainfall was slowly decreasing from north-east to south districts. Most south districts are there in lowest rainfall zone. This map looks like following a specific pattern. The districts covering forest area has rainfall in Telangana having 895-1045 and 1045-1190mm rainfall. The highest rainfall recorded in the districts some parts of Mulugu, Jayashankar Bhupalpally and Kumurambheem Asifabad.40% of Telangana have recorded rainfall as 450-600mm. The highest elevated areas of Telangana recorded rainfall as 600-750mm and 750-895mm. The lowest elevated areas in Telangana were recorded rainfall as 895-1045 and 750-895mm.Hence the Telangana receives sufficient rainfall for irrigation purposes.

Figure 2 (f) shows the season 2 rainfall trend data in Telangana. The highest rainfall trend was recorded in major portion of north Telangana i.e., significant positive trend (>+1.645). The major south portion of Telangana districts are under insignificant negative trend i.e., -1.645. The most rainfall of Telangana was under significant positive and negative trend. And also it contains partly insignificant positive trend in the middle area districts. A few areas in the southern part of Telangana contain significant negative trend. Overall Telangana state receives enough rainfall in season 2 irrespective of land characteristics. The rainfall from south side to north side districts of Telangana. The areas covering forest area on north east side receives significant positive trend this is also a low elevated area. Season 2 rainfall in Telangana follows a north-east to south decreasing pattern, with higher rainfall in forested and low-elevation areas and lower rainfall in southern districts. The rainfall trend is mostly significant, with positive trends in northern Telangana and insignificant to negative trends in the south, indicating overall sufficient rainfall for irrigation.

Season 3 average rainfall data in Telangana shows in Figure 2 (g). Red colour indicates 18-23mm rainfall, brown colour indicates 23-27mm rainfall, yellow colour indicates 27-31mm rainfall, light green colour indicates 31-35mm rainfall, dark green colour indicates 35-39mm rainfall and blue colour indicates 39-43mmrainfall. The highest rainfall was recorded in small portion of Mulugu and Bhadradri Kothagudem districts in Telangana and lowest rainfall intensities was recorded in some portion of south side districts. The rainfall was slowly decreasing from north-east to south districts.

Figure 2 (h) shows season 3 rainfall trend data in Telangana. The highest rainfall was recorded in small portions of west districts in Telangana and lowest rainfall was recorded in south and west sides of Telangana districts. The rainfall was slowly decreasing from east to south and west districts. It shows an irregular pattern. The most area of Telangana covering insignificant negative trend and significant negative trend, by this it concluded that the Telangana has low rainfall mostly which creates an impact on irrigation and mainly in agriculture sector. A very few districts like Sangareddy, medak, kamareddy and some parts of Adilabad receives highest rainfall. Season 3 rainfall in Telangana shows a north-east to south decreasing trend, with highest rainfall in Mulugu and Bhadradri Kothagudem and lowest in southern districts. The rainfall trend is mostly negative, with significant declines in many regions, which may impact irrigation and agriculture, leading to water scarcity concerns.

The season 4 average rainfall data in Telangana is shown in Figure 2 (i). Rainfall intensities are classified into six categories. Red colour indicates 6-11mm rainfall, brown colour indicates 11-16mm rainfall, yellow colour indicates 16-21mm rainfall, light green colour indicates 21-25mm rainfall, dark green colour indicates 25-30mm rainfall and blue colour indicates 30-35mm rainfall. The highest rainfall was recorded in small portion of Khammam and lowest rainfall intensities were recorded in some portion of south side districts.

Figure 2 (j) shows the season 4 rainfall trend data in Telangana. The highest significant positive trend was recorded in small portion of north and south districts and lowest negative significant trend was recorded in some portion of east side districts. Most central districts show insignificant positive trend (+1.645). The highest rainfall recorded in the districts of narayanpet, mahaboobnagar, jogulamba gadwal, wanaparthy and some parts of nagarkurnool Nalgonda, nirmal, Adilabad, komurambheem, asifabad and the lowest rainfall recorded in the districts of bhadradri kothagudem, mahaboobabad and some parts of Khammam, Mulugu, Warangal rural since the most of the Telangana is under insignificant positive trend it receives sufficient rainfall. Season 4 rainfall in Telangana shows higher rainfall in Khammam and lower rainfall in southern districts, with an overall insignificant positive trend across most regions. While some north and south districts exhibit significant positive trends, the general pattern suggests sufficient rainfall for the season, supporting irrigation and agriculture.

Season 1 average temperature distribution is shown in Figure 3 (a). The highest temperature is noted in the districts are Adilabad, Kumuram bheem Asifabad and major parts of Nirmal district. This highest temperature is indicated by red colour. Due to high temperature these districts get low rainfall and hot winds. This highest temperature is noted between 39.56-41°c. The north Telangana districts have high temperature. The lowest temperature was recorded in the districts of some parts of Bhadradri kothagudem and Khammam. This low temperature was indicated by green colour. This lowest temperature is in the range of 36-37-22°c which is 3-5°c lower than the highest recorded temperature. This low temperature was recorded in east Telangana. Due to this low temperature rainfall in these districts are accurate without any delay. Most of the West Telangana districts such as Vanaparthy, Narayanapet, Mahabubnagar, Rangareddy, Hyderabad, Vikarabad, Sangareddy, Medchal Malkajgiri, Medak, Siddipet etc are in the range of 38.39-38.97°C.

Figure 3 (b) shows the season 2 average temperature distributions. An only 1-few part of Khamman, Suryapet and Nalgonda has recorded high temperature in the range of 33.6 - 34°c. Comparing to overall Telangana in season 2 average temperature, the highest temperature recorded only in three districts which lies in Southeast Telangana. Generally, this temperature does not affect more because this is a normal temperature only. This highest temperature was indicated by red colour. The lowest temperature was recorded in the districts of Vikarabad, Sangareddy, Medak and kamareddy and also in some parts of Nizamabad, Rajanna Sircilla and Rangareddy. This lowest temperature in the range of 32-32.34°c. Which is1.6 -2°c lower than the highest temperature. This low temperature districts are located at west Telangana. Major districts have temperature under the range of 32.34-32-7°c and 32.7-33°c which is indicated by light green colour and Yellow colour respectively.

Season 3 average temperature is shown in Figure 3 (c), In this season, the highest temperature which is in the range of 32.10-32.3°c was recorded only in the districts of Adilabad and some parts of Kumurambheem Asifabad. Generally, this temperature does not affect more. It can be considered also a normal temperature. The lowest temperature was recorded in some parts of districts of Mulugu and Bhadradri kothagudem. The lowest temperature was denoted by green colour which is in the of 30-31.19°c. The difference between range lowest and highest temperature is 2.1-2.3°C. Most of the districts are in the range of 31.41-31.63°c and 31.63-31-85°C which are indicated by yellow and Blue colour respectively. The temperature is normal towards south, east and west Telangana and the temperature was gradually increased when moving towards north Telangana.

Figure 3 (d) shows the season 4 average temperature distribution. The high temperature in the range of 31.60-32°c was recorded in only in few parts of three districts they are Nagarkurnool, wanaparthy, Gogulamba Gadwal. The south part of Telangana has high temperature which is indicated by red colour. In this season the high and low temperatures recorded as 32.10-32.3°C and 30-31.19°c respectively. The low temperature was recorded in some parts of Mulugu and Bhadradri kothagudem districts. These districts lie towards East Telangana. Most of the districts recorded the temperature in the range of 31-31.3°C which was indicated by blue colour. 60% of Telangana is recorded as 31-31.3°C. The low temperature was recorded at East Telangana and gradually increased when moving towards south west Telangana.

The seasonal temperature distribution in Telangana shows higher temperatures in northern and southern districts and lower temperatures in eastern regions. Adilabad, Kumuram Bheem Asifabad, and Nagarkurnool consistently record the highest temperatures, while Bhadradri Kothagudem and Mulugu experience the lowest. Temperature variations range from 30°C to 41°C, with a gradual increase from east to north and southwest. These temperature differences influence rainfall patterns, evaporation rates, and overall climatic conditions, impacting agriculture and water availability in the region.

Season 1 temperature trend is shown in Figure 3 (e), The significant positive trend in temperature was recorded in the districts of Gogulamba gadwal, Wanaparthy, Narayanpet, Mahabubnagar, Vikarabad, Hyderabad, Sangareedy and Medak and in some parts of kamareddy, Siddipet, Medchel malkajgiri. This red colour indicates the significant positive trend i.e.> +1.645 in the range. All the high temperature districts was located at the west Telangana. The significant negative trend in temperature was recorded in Mulugu, Bhadradri Kothagudem, some parts of Mahabubabad and Khammam. This green colour indicates the significant negative trend i.e < -1.645.The Trend is negative at the East of Telangana and gradually increases while moving towards west.

Season 2 temperature trend is shown in Figure 3 (f). The significant positive temperature trend was recorded in the districts of Sangareddy, Medchal Malkangiri, Medak, Kamareddy Rajanna sircilla, Nizamabad, Jagityal, Nirmal, Adilabad and some parts of kumurambheem Asifabad, Hyderabad. The highest significant positive trend in temperature was recorded at North West districts of Telangana which is indicated as red colour and called as significant positive Trend. i.e > +1.645.

The significant negative trend in temperature was recorded in Bhadradri kothagudem, Khammam and some parts of Mulugu which is indicated in Green colour and it is called as significant negative Trend i.e <-1.645. Most of the districts are under Insignificant positive trend (0-1.645) and Significant positive trend (> +1.645). The significant negative trend in temperature was observed on East Telangana and gradually increased towards the Northwest side of Telangana.

Season 3 temperature trend is shown in Figure 3 (g). The significant positive trend in temperature was recorded in the districts of Gogulamba Gadwal, Wanaparthy, Nagarkurnool and some parts of Nalgonda, Bhadradri kothagudem, and suryapet districts. These districts are located at the south of Telangana. The negative trend in temperature was recorded in the districts of Adilabad, Nirmal, and in some parts of Asifabad, Nizamabad. Most of the districts are Insignificant Positive Trend which is indicated by yellow colour. Most of central Telangana is under the Insignificant Positive trend i.e. 0- 1.645. The negative significant trend in temperature is shows at North side of Telangana and trend is increased gradually on south side.

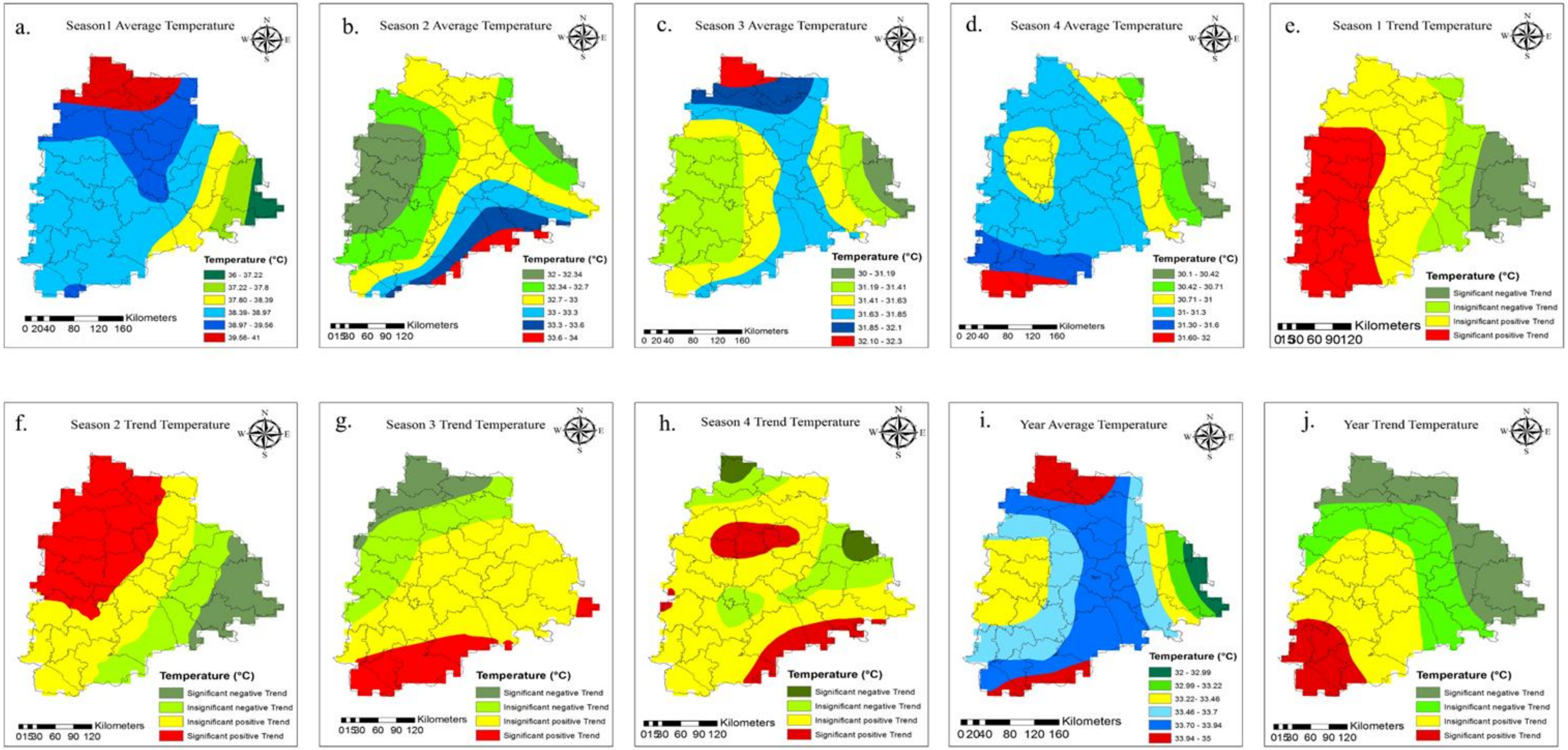

Figure 3. The spatial temperature distribution maps of Telangana for the period of 1990-2020 for (a) Season 1 average temperature (b) Season 2 average temperature (c) Season 3 average temperature, (d) Season 4 average temperature, (e) Season 1 temperature trend, (f) Season 2 temperature trend, (g) Season 3 temperature trend, (h) Season 4 temperature trend, (i) Annual average temperature, and (j) Annual temperature trend.

Season 4 temperature trend is shown in Figure 3 (h). The significant positive trend in temperature was recorded in central Telangana and south east Telangana, which represents in red colour. The central districts are Rajanna sircilla and some parts of Jagityal, karimnagar, Siddipet and kamareddy. The south east districts are Khamman, suryapet, Nalgonda. The negative trend in temperature was recorded in some parts of "Adilabad and Mulugu. This season 4 trend is in irregular pattern the trend in temperature is changing in irregular pattern. The maximum district of Telangana in this season is covered with insignificant positive Trend i.e. 0-1.645. Indicated by yellow colour.

The seasonal temperature trend in Telangana shows significant positive trends in western and central districts and negative trends in eastern regions. West Telangana (e.g., Gadwal, Wanaparthy, Hyderabad, and Sangareddy) consistently records rising temperatures, while Mulugu and Bhadradri Kothagudem in the east exhibit cooling trends. Most districts show insignificant positive trends, indicating a gradual warming pattern. The temperature trends follow an irregular spatial distribution, with a north-to-south increasing trend in some seasons and localized variations in others, influencing regional climate conditions and agricultural practices.

Figure 3 (i) shows the yearly temperature spatial distribution. It indicates that the highest temperature recorded in Adilabad, Asifabad and some parts in Nimal at North side of Telangana. At the south side also recorded high temperature in wanaparthy, Gadwal and Nagarkurnool in the range of 33.94-35°C. The low temperature was recorded in Bhadradri kothagudem and mulugu in the range of 32-32.99°C. The maximum area of Telangana is covered by 33.46 - 33.7°C and 33.70 - 33.94°c which is indicated by Blue and Dark violet colour. The East side experiences the less temperature comparing to other sides. Between 32.99- 33.22 °C the districts covered are very few.

Figure 3 (j) shows the spatial distribution of annual trend. The positive trend in temperature which indicates red colour has recorded only in few districts they are badwal. Narayanpet Nagarkurnool, wanaparthy Mahabubnagar. and also vikarabad. This highest temperature recorded at fourth west side of Telangana.The significant negative trend in temperature is recorded in mulugu, Bhadradr Kothagudem, Asifabad, Adilabad, Nirmal, Manchenal and etc. It was located at North and North east upto south side of Telangana. The significant positive trend indicates red colour has recorded only in few districts they are Gadwal, Narayanpet, Nagarkurnool, wanaparthy Mahabubnagar and also Vikarabad. This highest temperature trend was recorded at southwest side of Telangana. The negative trend in temperature was recorded in Mulugu, Bhadradri Kothagudem, Asifabad, Adilabad, Nirmal, Mancheriall and etc. It was located at North and North east upto south side of Telangana. The insignificant negative Trend, significant negative trend, insignificant positive trend covers the Telangana equally. The temperature trend increased while moving from north side to south side of Telangana.

The highest temperature was recorded at south side districts in season 2 Average temperatures and North side and south side in Year Average Temperature. Annual Average temperature has highest temperature in more districts comparing to season 2 Average temperatures. In annual Average temperature, the lowest temperature was recorded at East side of Telangana and west side and north east side in season2 average temperature map. In season 2 average temperature the maximum Telangana districts are between 32.34-33°c. But in annual average temperature map the maximum Telangana districts are in between 33.46-33.94°C.

The annual temperature distribution in Telangana shows higher temperatures in northern (Adilabad, Asifabad) and southern (Wanaparthy, Gadwal) districts, while eastern regions (Bhadradri Kothagudem, Mulugu) remain cooler. The temperature trend analysis indicates a warming trend in southwestern districts and a cooling trend in northeastern districts, with insignificant trends covering most of the state. Comparatively, annual average temperatures are higher than seasonal averages, with a north-to-south increasing temperature trend, impacting regional climate patterns and agricultural conditions.

Figure 4 illustrates the spatial distribution of the Coefficient of Variation (CV) of rainfall across Telangana, highlighting the variability in precipitation patterns. The CV values range from 22% to 38%, with lower values (22-27%) observed in the northern and northwestern regions, indicating relatively stable rainfall patterns. In contrast, higher CV values (34-38%) are concentrated in localized pockets, particularly in central and southern Telangana, suggesting greater variability and increased susceptibility to extreme rainfall events. Moderate variability (28-33%) is spread across the state, indicating transitional zones between stable and highly fluctuating rainfall regions. The observed spatial variation in CV suggests that certain areas may be more vulnerable to hydrological extremes, such as droughts and intense rainfall, which can significantly impact water resource management and agricultural productivity. Incorporating land use and topographical data in future analyses may provide deeper insights into the underlying factors influencing rainfall variability in Telangana.

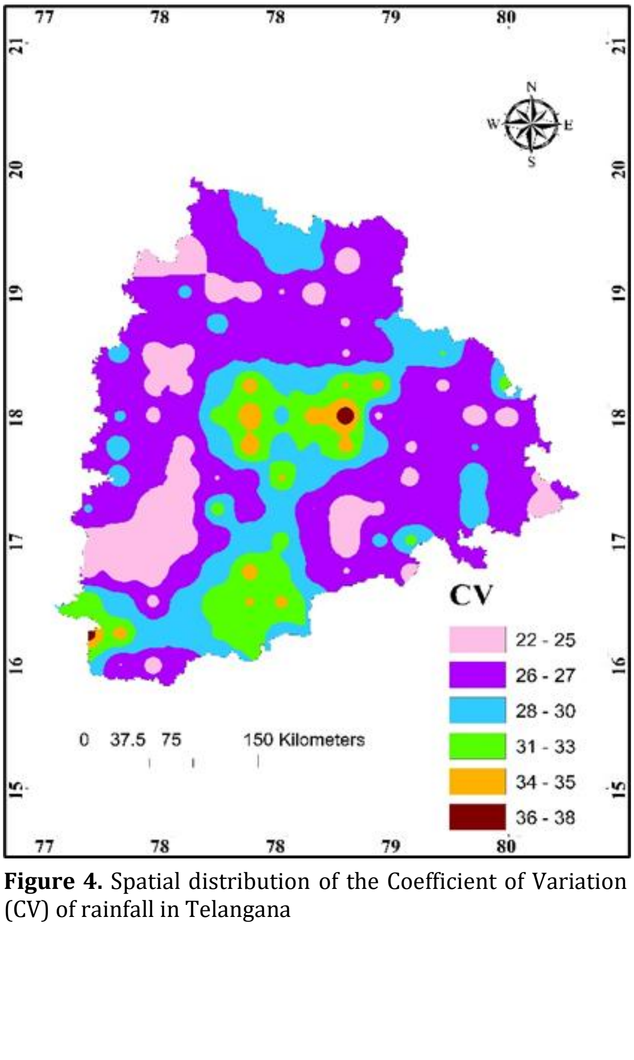

Figure 4. Spatial distribution of the Coefficient of Variation (CV) of rainfall in Telangana

Figure 5 illustrates the spatial variation of the Rainfall Anomaly Index (RAI) across Telangana, indicating regions experiencing deviations from the normal rainfall patterns. Higher RAI values, represented by dark brown and orange shades, suggest areas with relatively greater positive anomalies, primarily concentrated in the southern and southwestern parts of the state. Conversely, lower RAI values, depicted in pink and purple, indicate regions with negative anomalies, reflecting potential rainfall deficits. The spatial distribution highlights significant variability, emphasizing localized fluctuations in precipitation trends. Understanding these anomalies is crucial for assessing drought-prone areas and planning effective water resource management strategies.

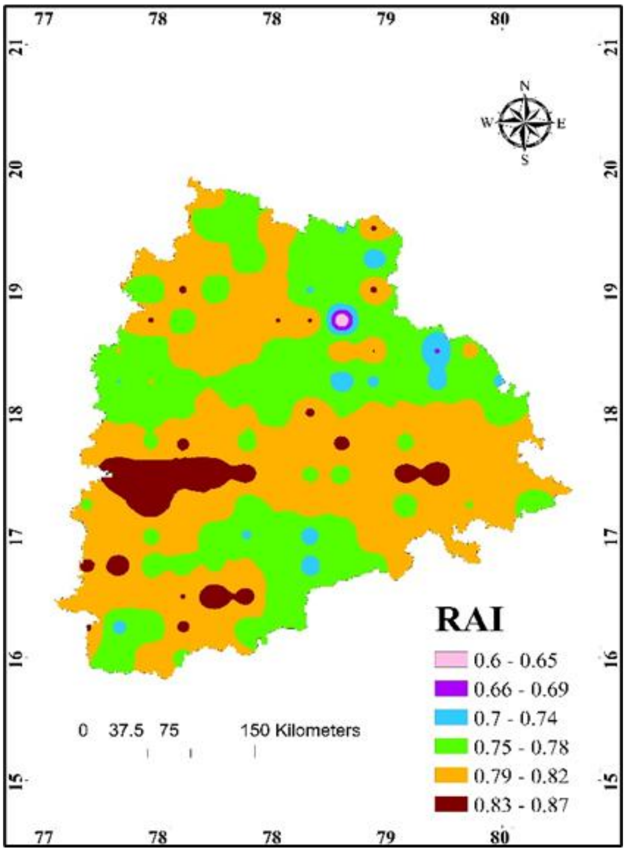

Figure 5. Spatial distribution of the Rainfall Anomaly Index (RAI) in Telangana

The spatial distribution of the Precipitation Concentration Index (PCI) across Telangana is depicted in Figure 6, illustrating the variability in rainfall concentration throughout the region. Higher PCI values, represented by dark brown and orange shades, indicate areas with a greater temporal concentration of rainfall, suggesting a higher likelihood of extreme precipitation events or strong seasonal dependency. In contrast, lower PCI values, shown in pink and purple, signify a more evenly distributed rainfall pattern over time. The central and southern regions of Telangana exhibit relatively lower PCI values, whereas the northern and northeastern parts display higher concentrations. Understanding PCI variations is crucial for assessing rainfall seasonality, optimizing water resource management, and mitigating risks associated with uneven precipitation distribution.

The observed variations in temperature and rainfall indices have significant implications for climate resilience, water resource management, and agricultural planning in Telangana. The warming trends in minimum and maximum temperature anomalies suggest increasing heat stress, higher evaporation rates, and changes in soil moisture retention, which can impact crop yields, forest health, and biodiversity. The spatial distribution of the Precipitation Concentration Index (PCI) highlights regions with highly concentrated rainfall, increasing flood risks in some areas while ensuring more stable precipitation in others, necessitating improved irrigation and urban drainage planning. The Rainfall Anomaly Index (RAI) reveals deviations from normal precipitation patterns, with positive anomalies indicating potential flood hazards and negative anomalies signaling drought risks, reinforcing the need for early warning systems and adaptive measures like rainwater harvesting and sustainable watershed management. The Coefficient of Variation (CV) in rainfall further underscores the vulnerability of certain regions to erratic precipitation, affecting agricultural stability and water resource planning. These findings emphasize the need for a comprehensive climate adaptation strategy that integrates meteorological monitoring, improved climate modeling, and sustainable resource management to mitigate risks and enhance environmental and economic resilience in Telangana.

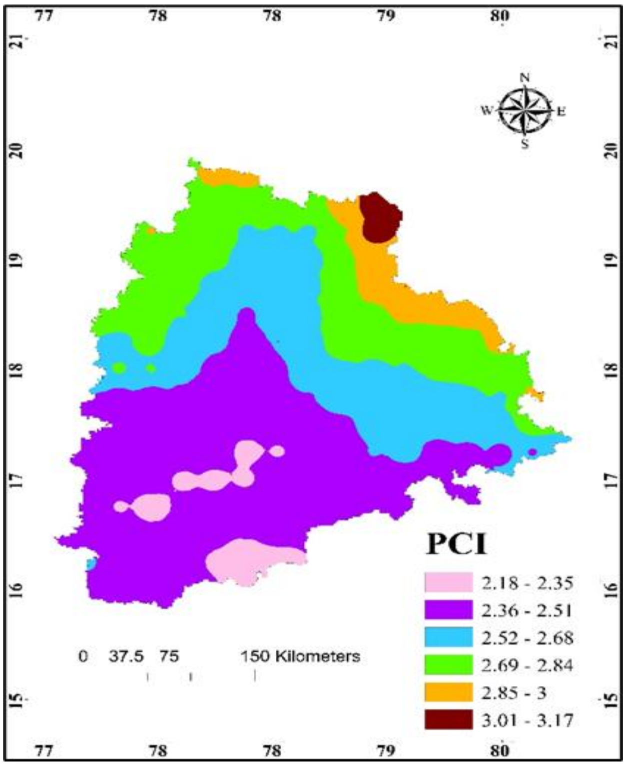

Figure 6. Spatial distribution of the Precipitation Concentration Index (PCI) in Telangana

Figure 7(a) represents the minimum temperature anomaly for the period 1991–2020. The observed trend indicates notable interannual variability, with alternating phases of positive and negative anomalies. During the early 1990s, negative anomalies were predominant, suggesting cooler-than-average minimum temperatures. This trend persisted until the late 1990s, with years such as 1992, 1995, and 1999 showing significant cooling. A shift toward positive anomalies is evident from the early 2000s onward, indicating a rise in nighttime temperatures. Notable warming years, such as 1998 and 2003, exhibit the highest positive anomalies, highlighting a potential influence of large-scale climate oscillations like El Niño. The period after 2015 is dominated by positive anomalies, reinforcing a gradual increase in nighttime temperatures, which is consistent with global warming trends. The implications of this trend are significant for agriculture and hydrology, as warmer nights can lead to increased evapotranspiration, altered crop growth cycles, and reduced soil moisture retention. Additionally, rising minimum temperatures contribute to increased energy demand for cooling, particularly in urban areas where the heat island effect may further amplify warming trends.

Figure 7(b) illustrates the maximum temperature anomaly over the same period. The anomaly pattern reveals substantial fluctuations, with alternating warm and cool periods. The 1990s exhibit a mix of positive and negative anomalies, reflecting variations in summer temperatures. The year 1998 stands out as an exceptionally warm year, likely influenced by the strong El Niño event, which is known to elevate temperatures across South Asia. Another peak in positive anomalies is observed in 2009, further supporting the notion of increased heatwave occurrences in the region. Between 2010 and 2013, a temporary cooling phase is evident, as indicated by negative anomalies. However, from 2015 onward, a sharp rise in maximum temperature anomalies is observed, marking a period of intensified warming. The increasing frequency of positive anomalies suggests a long-term trend toward higher daytime temperatures, which could have significant impacts on agriculture, human health, and infrastructure. Elevated maximum temperatures can exacerbate heat stress, increase irrigation demands, and contribute to prolonged drought conditions. Moreover, rising daytime temperatures may lead to greater energy consumption for air conditioning, posing challenges for sustainable energy use. The trend toward higher Tmax anomalies, particularly in recent years, underscores the urgent need for adaptation measures to mitigate the adverse effects of extreme heat.

Figure 7(c) depicts the variation of the Precipitation Concentration Index (PCI) averaged over all grids from 1991 to 2020. The PCI is a critical indicator of rainfall distribution patterns, with higher values signifying a more irregular and concentrated precipitation regime, while lower values indicate a more evenly distributed rainfall pattern throughout the year. The interannual variations in PCI exhibit fluctuations, with values generally ranging between 2.2 and 3.0. Notably, years such as 1998, 2005, and 2015 exhibit elevated PCI values, suggesting that rainfall during these years was more unevenly distributed, potentially leading to increased risks of flash floods and drought conditions within the same year. Conversely, years with lower PCI values indicate more uniformly distributed precipitation, which is favorable for agriculture and water resource management. The observed trends suggest an increasing tendency toward higher PCI values in recent years, which may indicate shifting rainfall patterns influenced by climate change. The increase in rainfall irregularity can have profound implications for hydrological cycles, as concentrated precipitation events may lead to enhanced runoff, reduced groundwater recharge, and heightened flood risks. Additionally, an erratic rainfall distribution can negatively affect crop yields, particularly for rain-fed agriculture, by creating water stress during critical growth periods. The long-term trend in PCI highlights the necessity for improved water management strategies, including rainwater harvesting and optimized irrigation scheduling, to mitigate the adverse effects of increasingly erratic precipitation patterns.

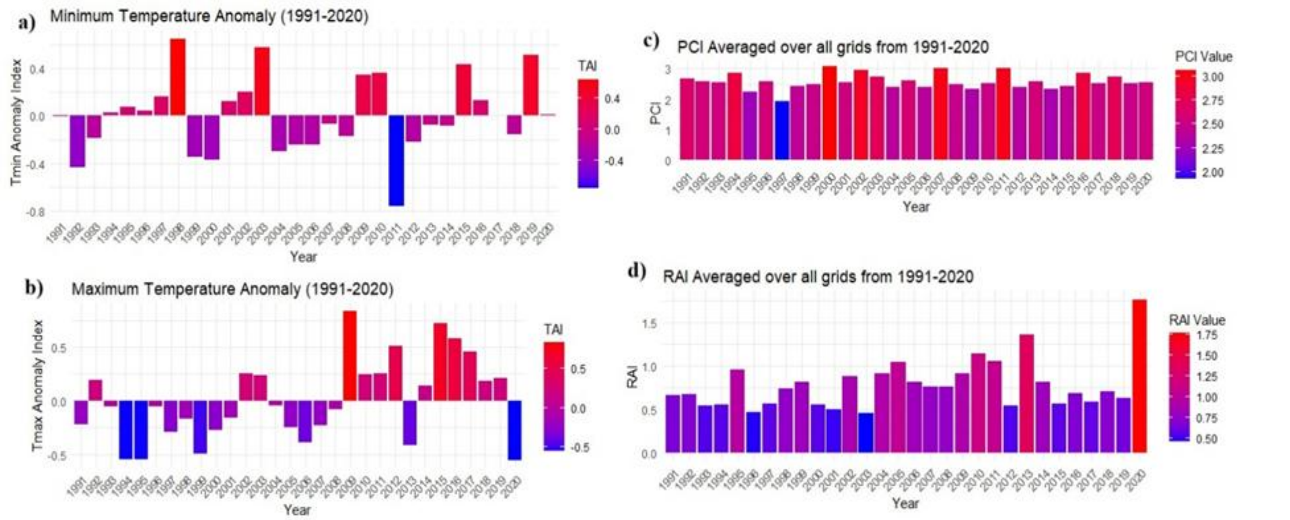

Figure 7. Temporal variations of (a) Minimum Temperature Anomaly (1991–2020), (b) Maximum Temperature Anomaly (1991–2020), (c) Precipitation Concentration Index (PCI) averaged over all grids (1991–2020), and (d) Rainfall Anomaly Index (RAI) averaged over all grids (1991–2020)

Figure 7(d) illustrates the Rainfall Anomaly Index (RAI) averaged over all grids from 1991 to 2020. The RAI serves as a measure of the departure of annual rainfall from the long-term mean, with positive values indicating wetter-than-average conditions and negative values representing drier-than-average conditions. The variability in RAI over the years suggests significant fluctuations between excess and deficient rainfall periods. Notable wet years, such as 1998, 2007, and 2020, exhibit pronounced positive RAI values, suggesting episodes of above-normal precipitation that could be associated with large-scale climate drivers such as La Niña events. In contrast, certain years, including 2002, 2009, and 2015, display negative RAI values, indicating significant drought conditions that may have severely impacted water availability and agricultural productivity. The sharp positive anomaly observed in 2020 suggests an exceptionally wet year, which may have resulted in excessive runoff, flooding, and soil erosion in several regions. The long-term fluctuations in RAI underscore the increasing unpredictability of monsoonal rainfall, emphasizing the necessity for adaptive measures to enhance resilience against both droughts and extreme rainfall events. The increasing frequency of alternating wet and dry periods poses challenges for water resource planning, necessitating the development of dynamic reservoir management strategies and climate-resilient agricultural practices. Moreover, the observed trends in RAI further reinforce the importance of integrating predictive modeling techniques for early warning systems to mitigate the socioeconomic impacts of climate extremes.

The results indicate a significant warming trend of approximately 0.03°C per year and spatial variability in rainfall trends across Telangana, with increasing rainfall in the northwestern districts (+2.1 mm/year) and decreasing trends in the southwestern districts (-1.5 mm/year). Comparable warming trends have been documented in several regions of India, as noted by Kothawale et al. (2010), who identified a substantial increase in mean surface temperatures nationwide, attributing this phenomenon to heightened greenhouse gas emissions and urban heat island effects [64]. Maharana et al. (2021) observed a decline in monsoon rainfall over central and western India, corroborating our findings for southwestern Telangana [65]. Additionally, Varikoden et al. (2020) reported that semi-arid regions of India, including Telangana, are experiencing erratic rainfall patterns due to weakening monsoonal circulation and increasing climate variability [66]. The rising precipitation in the northwestern districts may be associated with alterations in land use and heightened convective activity, as indicated by Niyogi et al. (2010) [67]. The comparisons demonstrate that the variations in rainfall and temperature in Telangana align with broader regional climate patterns, underscoring the impact of significant climate factors such monsoon fluctuations and El Niño phenomena. The observed trends in temperature and rainfall variability have significant implications for rural communities in Telangana. These climatic shifts can impact food security by influencing crop yields and water availability, which are crucial for agricultural livelihoods. Understanding these trends is essential for developing climate-resilient strategies to support farmers and ensure long-term agricultural sustainability in the region.

Telangana's warming rate must be analysed within a broader framework when juxtaposed with world temperature patterns. The IPCC Sixth Assessment Report (2021) reports that global temperatures have risen 0.18°C every decade since the 1980s [68]. In contrast, Telangana's warming trend seems to be marginally lower, potentially driven by factors such as regional land use patterns, urbanisation, and monsoonal influences. Recent studies [64, 69] show that local climatic conditions cause temperature changes in semi-arid locations like Telangana. Desai et al. (2018) found that Telangana's warming rate is slower than northern India's, which is increased by urban heat island effects, while some coastal locations have reduced warming due to oceanic causes [70].

The observed warming in Telangana, while slightly below the global average, has significant implications for agricultural and water resources. Successful adaptation approaches like improved water resource management and climate-resilient agricultural policies need understanding local and global temperature fluctuations. Climate model studies can improve projections and assess the long-term effects of these warming trends in Telangana and other semi-arid regions.

The findings of this study highlight the need for climate-resilient agricultural planning and adaptive policy measures to mitigate the impacts of rising temperatures and erratic rainfall in Telangana. Policymakers should prioritize sustainable water resource management, including improved irrigation infrastructure and groundwater conservation techniques, to address water scarcity. Additionally, promoting drought-resistant crop varieties and enhancing early warning systems for extreme weather events can help farmers adapt to changing climatic conditions. Strengthening climate monitoring and integrating climate data into agricultural decision-making will be crucial for ensuring long-term food security and sustainable livelihoods in the region.

Spatiotemporal Impact Analysis of Rainfall Anomalies and Flood Incidence

The impact of rainfall variability was evaluated by integrating statistical trend indicators with real-world flood data obtained from the Flood Affected Area Atlas of India by NRSC-ISRO (2023) [71]. This enabled both spatial and temporal assessment of how climatic anomalies are translating into hydrological impacts across Telangana.

A year-wise comparison between Rainfall Anomaly Index (RAI) values and recorded flood events reveals a strong temporal correlation. Notable flood years such as 2006, 2010, 2013, and particularly 2020, coincided with significant positive RAI values, indicating extreme rainfall conditions (Figure 8). For example, 2020 — which showed a sharp positive anomaly — corresponded to widespread flooding in Hyderabad and Bhadradri Kothagudem, caused by a deep depression in the Bay of Bengal. These correlations underscore the utility of RAI as a temporal indicator of hydrological risk.

Beyond temporal anomalies, spatial indicators such as the Coefficient of Variation (CV) and Precipitation Concentration Index (PCI) provide additional insight into flood vulnerability. High CV values observed in districts like Mulugu, Bhadradri Kothagudem, and Jayashankar Bhupalpally point to large year-to-year rainfall variability, which contributes to unpredictable flood events and infrastructure stress. Likewise, districts with elevated PCI values — indicating seasonal rainfall concentration in a few heavy events — were more prone to flash floods and surface inundation. These spatial indicators align with flood-affected districts, reinforcing the connection between climatic irregularity and hydrological extremes.

Moreover, trend analysis using the Mann-Kendall test and Sen’s slope estimator revealed increasing rainfall trends in certain districts, including Mancherial and Bhadradri Kothagudem, which also reported among the highest flood-affected areas in recent years. These upward rainfall trends — when combined with high CV and PCI — suggest an intensifying risk of flood events under changing climate patterns.

This spatial relationship is further illustrated in Figure 9, where flood-affected area mapping reveals that statistically rainfall-volatile districts are also among the most severely flooded. Districts such as Bhadradri Kothagudem, Mulugu, and Mancherial recorded over 10,000 hectares of inundation each, with Bhadradri Kothagudem alone exceeding 20,000 hectares (Figure 10). This strong spatial concurrence between climatic anomalies and observed hydrological impacts supports the use of statistical climate analysis not only as an early warning tool but also as a planning input for disaster risk reduction.

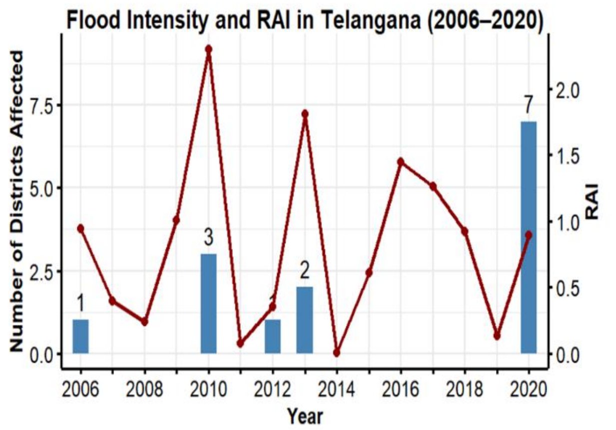

Figure 8. Temporal Distribution of Rainfall Anomaly Index (RAI) and Major Flood Events in Telangana (2000–2020)

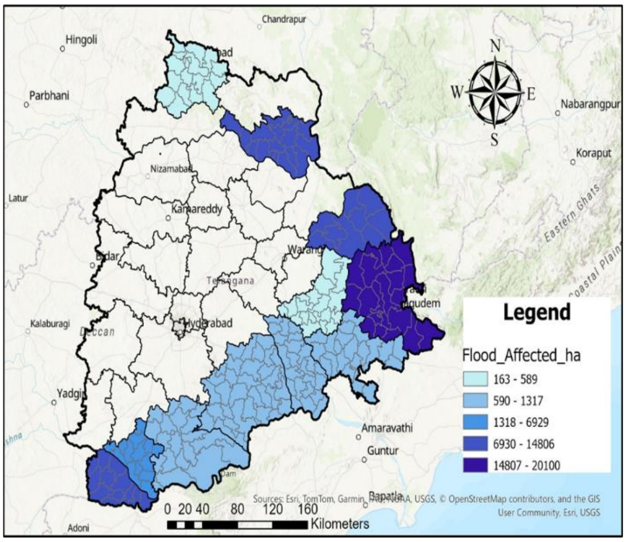

Figure 9. Spatial distribution of Flood-Affected Areas in Telangana Districts (2006–2020)

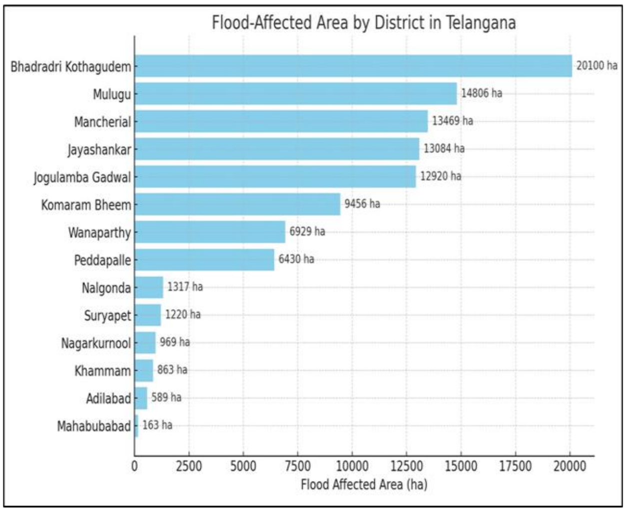

Figure 10. Flood-Affected Area (in Hectares) by District in Telangana

In summary, the combination of temporal anomalies (RAI), spatial variability (CV and PCI), and long-term trends (Sen's slope) offers a robust framework for flood impact assessment. The alignment of these indicators with real flood events and district-wise damage confirms that rainfall extremes are no longer isolated statistical patterns but are manifesting as tangible hydrological risks across Telangana. These findings underscore the importance of integrating multiple climatic indices to understand and manage regional vulnerability to extreme events.

LIMITATIONS OF THE STUDY

This study offers significant insights into the spatiotemporal patterns of high rainfall and temperature in Telangana, although important limitations must be recognised. First, the analysis is based on historical gridded datasets from IMD, which, although widely used, may contain inherent uncertainties due to interpolation techniques and station density variations. This study emphasises trend detection by non-parametric approaches, including the Mann-Kendall test and Sen's slope, while excluding future climate forecasts derived from General Circulation Models (GCMs) or Regional Climate Models (RCMs). Therefore, although observed trends indicate possible climate changes, this study does not specifically forecast future climate circumstances. Third, the study primarily examines hydrometeorological trends and does not incorporate the influence of land-use changes, urbanization, or socio-economic factors on climate variability. Incorporating these elements in next research may yield a more comprehensive knowledge of the effects of climate change. Ultimately, although the study delineates areas susceptible to extreme precipitation and temperature fluctuations, additional research utilising impact-based modelling (such as crop yield simulations and hydrological assessments for flood risks) would augment the relevance of the findings for disaster management and agricultural planning.

CONCLUSIONS

This study provides a comprehensive assessment of precipitation and temperature trends in Telangana from 1990 to 2020, with a focus on understanding their regional variability and hydrological impacts. By integrating statistical analysis with flood occurrence data, the study highlights the increasing frequency and intensity of climate extremes and identifies districts that are most vulnerable to both floods and droughts.

- The analysis of precipitation trends revealed that most districts showed no significant long-term changes, indicating general seasonal stability. However, Wanaparthy, Nagarkurnool, and Mahabubnagar showed declining rainfall trends, signaling potential drought risks in southern Telangana.
- Central and southern districts exhibited the highest rainfall variability, with Coefficient of Variation (CV) values ranging from 34% to 38%, indicating a greater susceptibility to both rainfall deficits and extreme events.
- The Rainfall Anomaly Index (RAI) showed frequent positive anomalies in western and southern Telangana, aligning with flood-prone districts, while northern and northeastern regions showed negative anomalies, indicating drought sensitivity.
- The Precipitation Concentration Index (PCI) revealed that rainfall in northern and northeastern Telangana is highly concentrated in fewer events, elevating the risk of flash

floods during wet years and water scarcity in drought years.

- Integration of flood data from the NRSC-ISRO Flood Affected Area Atlas (2006–2020) with rainfall variability metrics confirmed that districts like Bhadradri Kothagudem, Mulugu, and Mancherial—which recorded high RAI, CV, and PCI—were also the most severely flood-affected. These districts reported over 10,000 hectares of inundation, with Bhadradri Kothagudem alone exceeding 20,000 hectares.
- Temperature trend analysis indicated consistent warming across Telangana, with the most rapid increases observed in Hyderabad, Rangareddy, and Medchal-Malkajgiri, largely due to urbanization and reduced vegetation. Rising minimum and maximum temperature anomalies, especially at night, have implications for evapotranspiration, soil moisture stress, and agricultural productivity.
- These findings highlight the need for targeted adaptation strategies such as efficient irrigation, groundwater conservation, improved flood mitigation infrastructure, and climate-sensitive urban planning to reduce climate risks.

The methods and conclusions presented in this study can support future research in climate risk modeling, hydrological impact assessment, and regional planning. By integrating statistical rainfall trend analysis with observed flood impact data, this framework offers a practical tool for identifying climate-vulnerable regions. It may also aid in the development of early warning systems, infrastructure planning, and policy interventions in other monsoon-influenced regions experiencing similar climate variability.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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