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What do century-long rainfall trends reveal about climate change in Bihar's Makhana-growing wetland districts?

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सार – यह अध्ययन 1901 से 2022 तक के डेटा का उपयोग करके बिहार, भारत के प्रमुख मखाना उत्पादक आर्द्रभूमि (Wetland) जिलों में वर्षा की स्थानिक-कालिक परिवर्तनशीलता और दीर्घकालिक प्रवृत्तियों की जांच करता है। मौसमी और वार्षिक वर्षा में प्रवृत्तियों का पता लगाने के लिए, मान-कैंडल (MK) परीक्षण, प्रवृत्ति-मुक्त प्री-व्हाइटेंड MK (TFPW-MK) परीक्षण, सेन का ढलान अनुमानक (Sen's slope estimator), और सरल रेखीय प्रतिगमन (Simple Linear Regression - SLR) जैसी सांख्यिकीय विधियों को नियोजित किया गया था। प्रवृत्ति व्यवहार की व्याख्या को बढ़ाने के लिए एक पूरक ग्राफिकल विधि के रूप में अभिनव प्रवृत्ति विश्लेषण (Innovative Trend Analysis - ITA) लागू किया गया था। 1%, 5%, और 10% सार्थकता स्तरों पर पेटिट (Pettitt's) और संचयी योग (CUSUM) परीक्षणों का उपयोग करके परिवर्तन-बिंदु पहचान (Change-point detection) आयोजित की गई थी। विश्लेषण ने सुपौल को छोड़कर अधिकांश जिलों में वार्षिक और मानसूनी वर्षा में मुख्य रूप से नकारात्मक प्रवृत्तियों का खुलासा किया, जिसने सांख्यिकीय रूप से महत्वपूर्ण बढ़ती प्रवृत्ति प्रदर्शित की। सेन के ढलान अनुमानों ने प्रवृत्ति परिमाणों में स्थानिक विषमता का संकेत दिया, जिसमें अररिया में सबसे स्पष्ट गिरावट देखी गई। परिवर्तन-बिंदु विश्लेषण ने महत्वपूर्ण अस्थायी बदलावों की पहचान की, विशेष रूप से मानसूनी वर्षा में, जिसने वार्षिक योग को दृढ़ता से प्रभावित किया। ITA ने सांख्यिकीय परीक्षणों के परिणामों की प्रभावी ढंग से पुष्टि की, जिससे प्रवृत्ति प्रतिरूपों की एक सूक्ष्म दृश्य समझ प्राप्त हुई। सांख्यिकीय और ग्राफिकल दृष्टिकोणों का एकीकृत उपयोग वर्षा की गतिकी का एक व्यापक मूल्यांकन प्रदान करता है, जिसका बिहार के आर्द्रभूमि कृषि-पारिस्थितिकी प्रणालियों में जलवायु-अनुकूल कृषि योजना और जल संसाधन प्रबंधन के लिए निहितार्थ हैं।

ABSTRACT. This study investigates the spatio-temporal variability and long-term trends in rainfall across the major Makhana-growing wetland districts of Bihar, India, using data spanning from 1901 to 2022. To detect trends in seasonal and annual rainfall, statistical methods such as the Mann-Kendall (MK) test, trend-free pre-whitened MK (TFPW-MK) test, Sen's slope estimator, and simple linear regression (SLR) were employed. Innovative Trend Analysis (ITA) was applied as a complementary graphical method to enhance interpretation of trend behavior. Change-point detection was conducted using Pettitt's and the cumulative sum (CUSUM) tests at 1%, 5%, and 10% significance levels. The analysis revealed predominantly negative trends in annual and monsoon rainfall across most districts, except for Supaul, which exhibited a statistically significant increasing trend. Sen's slope estimates indicated spatial heterogeneity in trend magnitudes, with the most pronounced decline observed in Araria. Change-point analysis identified significant temporal shifts, particularly in monsoon rainfall, which strongly influenced annual totals. ITA effectively corroborated the results of the statistical tests, offering a nuanced visual understanding of trend patterns. The integrated use of statistical and graphical approaches provides a comprehensive assessment of rainfall dynamics, with implications for climate-resilient agricultural planning and water resource management in Bihar's wetland agro-ecosystems.

Key words – Climate change, trend detection, Mann-Kendall test, Sen's slope, Change point detection.

1. Introduction

Wetlands are among the world's most vital and productive ecosystems, contributing significantly to climate change mitigation regulating hydrological and biogeochemical cycles, and supporting livelihoods (Garba *et al.*, 2023; Madane and Bajirao, 2024). A significant portion of freshwater aquatic and wetland ecosystems is situated within agricultural landscapes, where commodity production (agricultural produce) constitutes the largest water use (King *et al.*, 2021). Global system variations can result in long-lasting alterations to climatic factors, which can significantly affect regional water supplies (Nistor *et al.*, 2020). The weather patterns on Earth are altered by climate change, which has an impact on regional climates, particularly with regard to factors like precipitation (Patel and Mehta, 2023). The amount of water available is determined by rainfall, which is a key component of hydrological cycles. Climate change has resulted in variations in rainfall quantity, intensity, seasonality, droughts, and flooding (Milly and Dunne, 2016; Surendran *et al.*, 2017). Inadequate rainfall results in decreased streamflow, lower moisture content, lower reservoir levels, and groundwater depletion (Kumar *et al.*, 2021). Changes in both the amount and frequency of rainfall have a direct effect on streamflow patterns and the distribution of runoff over both time and space (Kim and Kang, 2020), groundwater reserves (Toure *et al.,* 2016; Alifujiang *et al.*, 2020), and soil moisture levels (Wasko and Nathan, 2019). Understanding these changes is crucial for maintaining terrestrial ecosystems, managing water resources, safeguarding the environment, fostering biodiversity, assuring agricultural productivity, and advancing food security (Abbot and Marohasy, 2017; Tarate *et al.,* 2024). Droughts and floods, which are often caused by sudden variations in rainfall, pose significant threats. During a drought, insufficient rainfall restricts plant growth, which in turn reduces crop yields. On the other hand, floods caused by too much rainfall might damage crops (Liu *et al.*, 2017; Muthoni *et al.*, 2019). In this context, arid or semi-arid regions should be prioritized due to the irregular, insufficient, and unpredictable nature of rainfall occurrences in these areas (Patel and Mehta, 2023). The effects of climate extremes are influenced by agroecology, regional characteristics, farming methods, and farmers' capacity for adaptability (Zampieri *et al.*, 2017). Temporal variations in rainfall intensity can have a major effect on agricultural productivity, as rainfall is essential to the hydrological cycle. Furthermore, the emergence of novel pests and crop diseases may be influenced by variations in rainfall patterns (Shahzad *et al.,* 2021; Skendžić *et al.,* 2021). It is essential to assess rainfall trends and characteristics in order to improve water resource management and assist decision-makers in planning and resource development (Hu *et al.*, 2019). Rainfall data analysis offers useful information that can improve strategies for managing water resources, safeguard the environment, encourage agricultural scheduling, and promote regional economic growth (Jain *et al.,* 2013).

Several techniques for trend analysis of rainfall datasets have been reported, including both parametric (Zakwan and Ara, 2019; Malik and Kumar, 2020) and nonparametric approaches (Mondal *et al.*, 2015). Notably, the most popular nonparametric tests for identifying trends in time series data are the MK test and Sen's slope test (Chen *et al.*, 2016; Fan *et al.*, 2018; Tan *et al.*, 2019; Ali *et al.*, 2019; Sediqi *et al.*, 2019; Patakamuri *et al.*, 2020; Patel and Mehta, 2023). However, it is crucial to remember that the rainfall time series must be free from autocorrelation effects to allow for the MK test to be valid (Patel and Mehta, 2023). In order to solve this problem Şen (2012) invented an innovative graphical method called as innovative trend analysis (ITA). Different researchers used ITA for trend analysis of rainfall time series data (Caloiero *et al*., 2018; Marak *et al*., 2020; Aher and Yadav, 2021; Pastagia and Mehta, 2022). It has been popular recently to use an ITA that uses graphical representations to examine trends in time series data without requiring any underlying assumptions (Şen, 2014; Ali *et al.,* 2019).

Extreme wet or dry monsoon season events have increased noticeably in India and East Asia (Nistor *et al.*, 2020). Therefore, evaluating rainfall trends is essential for better water resource development, management, and planning. The technique of analyzing current and historical trends in order to predict future trends is known as trend analysis (Jain *et al.*, 2013). Understanding challenges with flooding, droughts, and water availability in light of future climate scenarios can be assisted by the analysis of rainfall trends. Analyzing trends in rainfall contributes to the sustainable management of water resources. Therefore, in order to take the appropriate actions to avoid future drought and flood-like conditions, it is essential to understand rainfall characteristics, the magnitude of change, the nature of the trend, and fluctuations in seasonal and annual rainfall. It is also significant from a socioeconomic perspective (Aher and Yadav, 2021). Rai and Singh (2009) analysed rainfall variability and probability for crop planning at Madhepura in Bihar. Zakwan and Ara (2019) conducted a statistical analysis of rainfall in Bihar from 1950 to 2016, which revealed a significant long-term decline in annual precipitation, high intra- and inter-annual variability, and pronounced rainfall concentration during the monsoon months, emphasizing the urgent need for rainwater harvesting and the application of sustainable water management strategies. Sharma and Priya (2023) conducted a long-term assessment of precipitation behaviour in Bihar from 1901 to 2021, revealing a significant declining trend in annual rainfall across most districts, with pronounced reductions in the eastern region, highlighting increasing variability and potential risks to the hydrological balance and agricultural sustainability under changing climate conditions. Singh *et al.* (2024) highlighted increasing spatiotemporal variability in rainfall patterns across different districts in Bihar, with a growing negative trend in recent years, underscoring the need for region-specific water resource and risk management strategies. A comprehensive spatiotemporal analysis by Kumar and Thangavel (2025) revealed significant seasonal and annual shifts in rainfall patterns across Bihar over the past 72 years, marked by increasing pre-monsoon rainfall and declining monsoon and annual precipitation, highlighting critical implications for water resource management and climate-resilient agricultural planning.

Important aquatic crops like Makhana (*Euryale ferox* Salisb.) grow in wetlands like stagnant water of lakes and lowland area particularly Mithila region in the Bihar state of India. In addition to being an excellent non-cereal aquatic food crop, its cultivation area is decreasing because of the high temperatures, low relative humidity, and limited supply of water, which are the main causes of decrease in its yield (Jana *et al.*, 2018). Therefore, this study is proposed to analyze the spatio-temporal variability and trend of long-term rainfall time series in the major Makhana growing wetland districts of the Bihar state in India. Thus, this study is formulated with the following objectives: (a) To identify the long-term trends of rainfall time series (1901-2022) using statistical methods (MK, pre-whitened MK test, Sen's slope, SLR) and graphical methods (ITA) on seasonal and annual time scale; (b) To find the magnitude of trend of rainfall time series using Sen's slope estimator; (c) To detect the change point of the rainfall time series using Pettitt test and distribution-free cumulative sum (CUSUM) test (d) To compare the results obtained from statistical and graphical methods for the study area. To the best of our knowledge, there is no such comprehensive analysis carried out for rainfall analysis in this study area. The major novelty of the study is to compare the results of the ITA approach to that of conventional parametric and non-parametric tests at 1%, 5% and 10% level of significance. The results revealed that the hidden trends in rainfall time series can be identified with only ITA compared to other methods. Although several studies have explored rainfall variability in Bihar, most have relied solely on conventional statistical approaches and have largely overlooked the identification of trend change points or the application of novel graphical tools like ITA. This study not only applies a holistic suite of parametric (SLR), non-parametric (MK, pre-whitened MK, Sen's slope), and graphical (ITA) techniques but also incorporates change point detection methods (Pettitt and CUSUM), which have not been simultaneously applied in this region's context. Additionally, the study focuses specifically on wetland districts of Bihar, which are ecologically and agriculturally unique due to their dependence on stable hydrological regimes for Makhana cultivation. The comparative evaluation of ITA and traditional methods at different confidence levels further distinguishes this research by demonstrating the capacity of ITA to uncover hidden or non-monotonic trends. ITA offers a significant advantage as it does not require any assumptions about the data distribution or autocorrelation and can detect hidden, non-monotonic, and segment-specific trends that traditional methods may overlook. This is especially important in Makhana growing wetland districts of Bihar where rainfall variability is high, and hydrological shifts critically impact Makhana cultivation. Furthermore, ITA's graphical nature allows for a more intuitive interpretation of trend directions by comparing the behaviour of two halves of the time series. In our analysis, ITA was able to identify trends during specific seasons and in certain districts that were not captured by MK or Sen's slope, thereby demonstrating its greater sensitivity and suitability for analysing complex rainfall dynamics in ecologically sensitive regions. By bridging a methodological and geographic gap, this work significantly enhances the understanding of rainfall dynamics in wetland agro-ecosystems under changing climatic conditions, offering critical insights for climate-resilient planning and water management.

2. Data and methodology

2.1. *Study area*

Aquatic crops like Makhana are grown in the wetland districts like Darbhanga, Madhubani, Sitamarhi, Araria, Madhepura, Saharsa, Supaul, Purnea, Kishanganj and Katihar districts of the north Bihar, India. The geographical location of these districts of the north Bihar is shown in Fig. 1. Elevation in the study area varies from -1 to 104 m above mean sea level. Average annual rainfall in the study area varies from 1205 to 2162 mm. The study area experiences a humid subtropical climate characterized by distinct seasonal variations. The winter season extends from November to February, with January being the coldest month. During this time, average daily temperatures range from 5 °C to 10 °C, while maximum daily temperatures in summer reach up to 41°C. The summer season spans from March to June, transitioning into the monsoon season, which persists until September.

2.2. *Data collection*

This study employed daily rainfall data from the India Meteorological Department (IMD) with a grid resolution of 0.25° × 0.25° for the 122-year period 1901–2022. The district shapefile of Bihar state was directly projected with this data, and the analysis was conducted using the zonal-statistical average of the confined district region. Using daily rainfall data gathered from a network of 6,955 rain gauge stations throughout India, this high-resolution gridded dataset was created (Pai *et al.*, 2014).

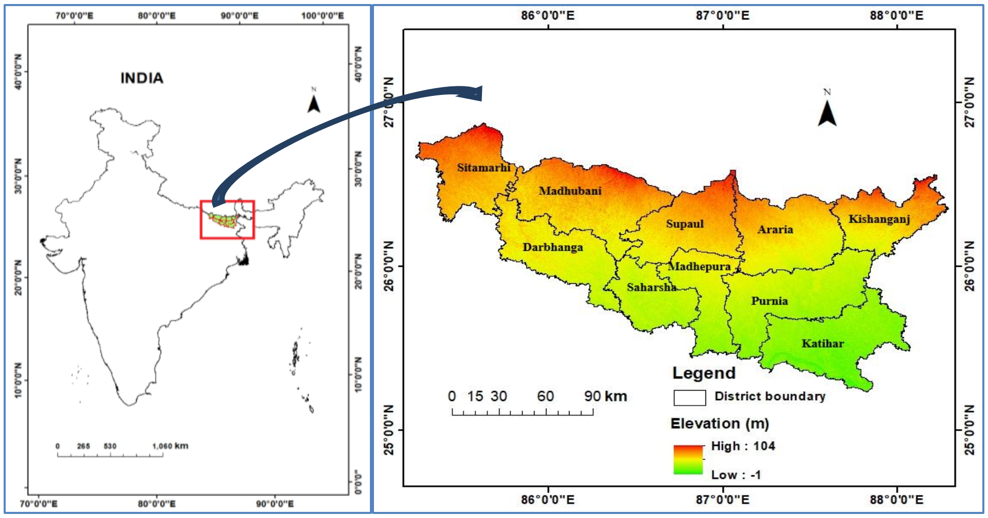

Fig. 1. Geographical location of the Makhana growing wetland districts of Bihar

The daily rainfall data for all districts were converted into seasonal and annual series. The entire year was divided into four meteorological seasons, as defined by the IMD in India namely monsoon (June to September), post-monsoon season (October to December), winter (January to February) and pre-monsoon season (March to May) in preparation for conducting rainfall trend analysis (Chauhan *et al.,* 2022).

2.3. *Trend detection tests*

2.3.1. *MK test*

The MK test, a rank-based non-parametric technique, is widely used to find monotonic trends in hydro-meteorological data (Kendall, 1938; Mann, 1945). The key benefit of non-parametric approaches is that they are not affected by a small number of abnormal values and do not require the sample to have a specific distribution (Chauhan *et al.,* 2022). The assumptions of the MK test are that the data are independent and arranged in a random order (Marak *et al.*, 2020). The presence of a monotonic trend (either gradually increasing or decreasing) within the time series is the alternative hypothesis, which is then evaluated against the null hypothesis (no trend). The standardized test statistic Z_{MK} is computed as:

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \quad (1)$$

2.3.2. *Sen's slope estimator*

The magnitude of trend changes cannot be measured by the MK test. As a result, the slope of a linear trend in the rainfall data is estimated using Sen's slope, which was proposed by Sen (1968). This can be ascertained by using the following formula:

$$SS_i = median\ \frac{(R_i - R_j)}{(i-j)} \quad j < i \quad (2)$$

where, SS_i is the slope, R is the variables, i and j are indices. If $SS_i > 0$, it indicates increasing trends. Otherwise, negative trend during the period when $SS_i < 0$.

2.3.3. *Autocorrelation test & trend-free pre-whitening Mann-Kendall trend test (TFPW-MK)*

Pre-whitening is a filtering method used to alter a series with autocorrelation into one without correlation, often referred to as "white noise" (Yue *et al.,* 2002). This procedure is carried out prior to doing a trend test. The lag-1 serial correlation components were eliminated from the series before to the MK test in this investigation using the Trend-Free Pre-whitening technique. The serial independence of trends within the rainfall time series was determined using the autocorrelation test. This test relies on the autocorrelation function which operates on the rainfall time series $R_1, R_2, ..., R_n$ at corresponding times $t_1, t_2, ..., t_n$ given as:

$$r_k = \frac{\sum_{i=1}^{n-k} (R_i - \bar{R})(R_{i+k} - \bar{R})}{\sum_{i=1}^{n} (R_i - \bar{R})^2} \quad (3)$$

The rainfall time series were tested for lag-1 (k=1) autocorrelation at 1%, 5 % and 10 % significance level.

2.3.4. *SLR*

It is a parametric test and most commonly used for trend analysis of time series data (Malik and Kumar, 2020). The mathematical expression for the linear regression model is as follows (Meshram *et al.,* 2017);

$$y = mX + C \quad (4)$$

where y indicate the dependent variable, X represent the independent variable, m is the slope of straight line and C is the intercept.

2.3.5. *ITA*

When compared to the MK test, ITA is a superior trend analysis tool mainly because it can identify non-monotonic trends. MK can only identify monotonic trends; ITA is a powerful trend analysis method that can identify trends at different levels of a given time series, including both low and high points (Agbo *et al.,* 2023). ITA has been widely employed for various climate measurements and can spot more trends than MK, covering more parameters (Akçay *et al.*, 2022). Furthermore, ITA is robust against limitations like data length, distribution patterns, and serial correlation, making it a flexible and reliable approach for trend detection. Notably, ITA's utility extends to the classification of drought severity, enabling the depiction of trends across different drought categories within a single graphical representation, thereby enhancing the understanding of drought dynamics over time. In summary, ITA presents a more innovative and holistic approach for trend analysis in contrast to the conventional MK test (Sinam, 2022).

$$ITAs = \frac{2\,(\bar{R}_j - \bar{R}_i)}{n} \quad (5)$$

where, ITA_S represents the slope in ITA method, n is the sample size, $\bar{R}_i$ and $\bar{R}_j$ represent the mean values of the first and second half of the time series, respectively. Using ITA, the study assessed the significance of the variation in seasonal and annual rainfall at 1%, 5%, and 10% significant levels. The ITA was carried out using “trendchange” package in RStudio software. In cases where a single monotonic trend (either increasing or decreasing) is evident, there's no need to categorize data into "low," "medium," and "high" categories, as the trend itself indicates the direction. However, when scatter points deviate from a consistent trend, indicating non-parallel patterns with varying degrees of increase or decrease, its categorization becomes essential. For instance, in this study, rainfall amounts were categorized as low ($R < \bar{R} - R_{sd}$), medium ($\bar{R} - R_{sd} < R < \bar{R} + R_{sd}$), and high ($R > \bar{R} + R_{sd}$), where R represents the first half of the time series, $\bar{R}$ denotes the mean, and Rsd represents the standard deviation (Alifujiang *et al.,* 2020).

2.4. *Change point detection*

Trend detection and trend change timing are important aspects of hydro-climatic trend analysis. Determining the onset of notable rainfall trends is an essential component of any comprehensive trend detection investigation. In this study, the distribution-free CUSUM test (Patakamuri *et al.*, 2020) and Pettitt’s Test (Madane *et al.*, 2023) were used in the change-point analysis of time series.

2.4.1. *Distribution free CUSUM test*

The distribution-free CUSUM test focuses at whether mean value discrepancies between two series parts change over an arbitrary time period. It detects changes beyond a predetermined number of data points by comparing the series median value with later observations. Starting from the beginning of the series, the cumulative sum (CUSUM) of the K signs of deviations from the median (forming a series of -1 or +1) yields the highest value, which is represented by the test statistic, W_k. For a rainfall time series $R_t = R_1, R_2, \ldots, R_n$, the expression for test statistics W_k is as (Patakamuri *et al.,* 2020);

$$W_k = \sum_{i=1}^{k} sign\,(R_i - R_{median}) \quad (6)$$

where, K = 1, 2, 3…n and $sign\,(R_i - R_{median})$ is given as:

$$sign(R_i - R_{median}) = \begin{cases} 1 & if\ (R_i - R_{median}) > 0 \\ 0 & if\ (R_i - R_{median}) = 0 \\ -1 & if\ (R_i - R_{median}) < 0 \end{cases} \quad (7)$$

2.4.2. *Pettitt's Test:*

Pettitt (1979) method is a well-suited procedure for detecting unexpected abrupt changes within long-term time series data. The null hypothesis that the variable retains the same positional constraint (i.e., no change point) regardless of the distribution is assessed by this test. On the other hand, the alternative hypothesis implies the time series data contains a change point. A test statistic known as K_T indicates where the change point is located in the provided data as (Pettitt, 1979):

$$K_T = max|Y_{t,T}| \quad (8)$$

$$Y_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(R_j - R_i) \quad (9)$$

The approximate p value of the test is given as (Pettitt 1979):

$$p \approx 2\,exp\left(\frac{-6K_T^2}{T^3 + T^2}\right) \quad (10)$$

The change point identified by the K_T test statistic gives statistically significant results at different significance levels α when $p < \alpha$.

2.5. *Percentage of change*

The change percentage is determined through an approximation based on a linear trend analysis. The

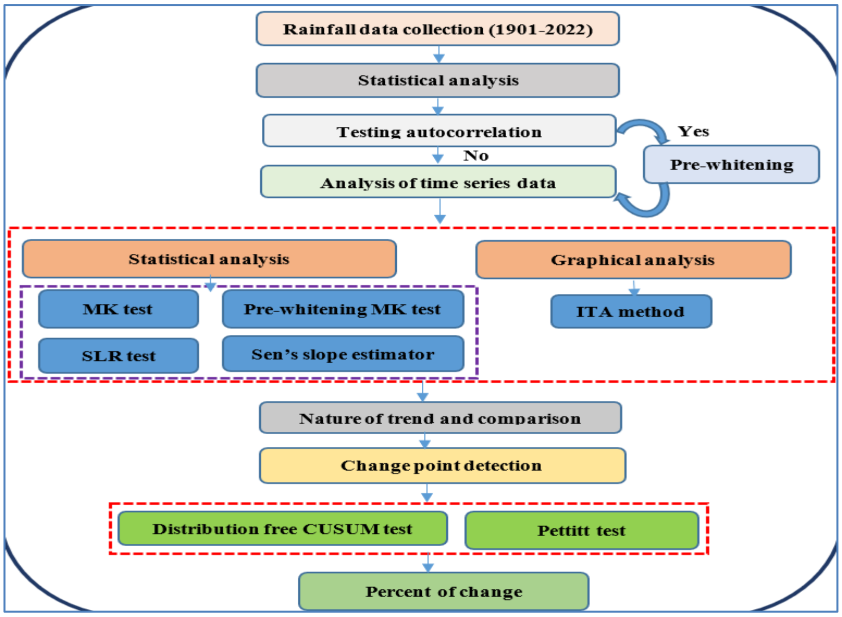

Fig. 2. Flowchart of the methodology adopted in this study

TABLE 1

Lag-1 autocorrelation coefficient for the annual and seasonal rainfall in the study area

District / time scale	Annual	Winter	Pre-monsoon	Monsoon	Post-monsoon
Araria	0.2013**	0.0239	0.0175	0.1078	-0.1106
Darbhanga	0.1901**	0.068	0.133	0.1535*	-0.0584
Katihar	0.1237	0.0606	0.107	0.0803	-0.0332
Kishanganj	0.1145	0.0915	0.106	0.029	-0.1093
Madhepura	0.0672	0.0271	0.0188	0.0492	-0.0721
Madhubani	0.1181	-0.0833	0.1267	0.0214	0.0181
Purnia	0.1556*	0.0789	0.1455	0.1273	-0.1121
Saharsa	0.1038	-0.0629	0.0524	0.0757	0.0187
Sitamarhi	0.1447	0.0265	0.0326	0.175*	-0.0279
Supaul	0.1392	0.0417	0.0773	0.0606	-0.0803

***, **, * statistically significant trend at level of significance (α) = 1%, 5 % and 10 %, respectively.

median slope is multiplied by the duration of the observation period for this computation, and the result is then divided by the corresponding mean value, which is reported as a percentage (Yue *et al.*, 2003):

$$Percentage\ change\ (\%) = \frac{SS_i \times (Data\ length)}{\text{mean value}} \times 100 \qquad (11)$$

The complete flowchart of the approach used in this investigation is depicted in Fig. 2. The analysis of this study was carried out using 'trend' and 'trendchange' packages in RStudio software.

3. Results and discussion

Box plots of annual and seasonal rainfall over the period of 122 years (1901 to 2022) for different districts of study area are shown in Fig. 3. The statistical parameters of rainfall like mean, standard deviation (SD), coefficient of skewness (CS) and coefficient of kurtosis (CK) for annual and seasonal rainfall over period were also determined. Here it was observed that in the study area, for annual scale the mean rainfall, SD, CS and CK varies from 1204.5 to 2162 mm, 290.1 to 459.4 mm, -0.32 to 0.31, -0.4 to 1.17, respectively. Mean rainfall, SD, CS and CK of winter season varies from 18.44 to 22.81 mm, 17 to 22.15 mm, 0.83 to 1.61, -0.32 to 4.17, respectively in the study area. Mean rainfall, SD, CS and CK of pre-monsoon season varies from 104.71 to 295.84 mm, 55.24 to 110.89 mm, 0.32 to 1.24, -0.28 to 4.19, respectively. Monsoon seasonal rainfall mean, SD, CS and CK varies from 1004.49 to 2052.29 mm, 330.59 to 303.15 mm, 0.28 to 0.42, -0.18 to 0.37. Mean rainfall, SD, CS and CK of post-monsoon season varies from 71.38 to 132.69 mm, 69.69 to 111.31 mm, 1.07 to 1.72, 0.41 to 3.14.

3.1. *Calculation of autocorrelation coefficient*

The acf function in the R programming language was used to determine the lag-1 autocorrelation coefficient for the annual & seasonal rainfall data for each district in the study area. The lag-1 autocorrelation coefficient values for the seasonal, and annual time series rainfall data at 1%, 5 % and 10 % significance level are presented in Table 1. The TFPW-MK trend test was employed to identify the trend in the rainfall data series in the study area since the lag-1 autocorrelation coefficient revealed that the rainfall series of some districts are serially correlated.

3.2. *Temporal variation of annual and seasonal rainfall trend in the study area*

Temporal trend analysis was carried out using the MK, TFPW-MK, SLR, Sen's slope, and ITA tests separately at 1%, 5%, and 10% significance levels for all the districts in the study area. The district-wise results of trends and their magnitudes (slope) are presented in Table 2. The MK, TFPW-MK, SLR, Sen's slope, and ITA tests were applied to annual and seasonal rainfall series, and their test statistics are presented in Table 2.

The test statistics of the MK test (Z_{mk}), TFPW-MK test ($Z_{tfpw\text{-}mk}$), SLR (m), Sen's slope (SS_i), and ITA (ITA_s) revealed a significant negative trend in annual and monsoon rainfall series at the 1%, 5%, and 10% significance levels for all districts except Supaul. A significant negative trend was observed for annual and monsoon rainfall data across different districts, with Supaul being the exception. All the tests consistently indicated either increasing or decreasing rainfall trends in the study area during the monsoon, winter, and annual scales. During the winter season, the values of test statistics from different tests indicated a negative slope, signifying decreasing rainfall across all districts in the study area. In the pre-monsoon season, rainfall is decreasing in Araria, Katihar, and Madhubani, but increasing in other districts according to the test statistics at different significance levels (Table 2). In the post-monsoon season, rainfall is decreasing in various districts except for Madhepura, Purnia and Katihar.

According to Sen's slope, the magnitude (mm/year) of decrease in annual rainfall was observed highest in Araria (-3.22), followed by Darbhanga (-2.59), Kishanganj (-1.60), Saharsa (-1.38), Sitamarhi (-1.34), Madhubani (-0.96), Madhepura (-0.78), Purnia (-0.48), and Katihar (-0.40). An increasing trend (mm/year) in annual rainfall was observed only in Supaul (1.59). For winter rainfall, Sen's slope indicated the highest magnitude of decrease in Kishanganj (-0.11), followed by Darbhanga (-0.09), Purnia (-0.06), Saharsa (-0.06), Araria (-0.05), Sitamarhi (-0.05), Madhubani (-0.04), Madhepura (-0.04), Katihar (-0.04), and Supaul (-0.02). In the pre-monsoon season, a decreasing trend (mm/year) in rainfall was observed only in Araria (-0.006), while the highest increasing trend was found in Purnia (0.54), followed by Katihar (0.43), Supaul (0.36), Sitamarhi (0.21), Madhepura (0.20), Madhubani (0.14), Darbhanga (0.12), Saharsa (0.11), and Kishanganj (0.07). During the monsoon season, the highest decreasing trend (mm/year) in rainfall was observed in Araria (-2.91), followed by Darbhanga (-2.19), Sitamarhi (-1.36), Saharsa (-1.27), Madhepura (-1.22), Purnia (-1.19), Kishanganj (-1.18), Madhubani (-0.77), and Katihar (-0.75). An increasing trend (mm/year) in monsoon rainfall was observed only in Supaul (1.34). In the post-monsoon season, a decreasing trend (mm/year) was observed in Kishanganj (-0.24), Araria (-0.10), Madhubani (-0.09), Sitamarhi (-0.09), Darbhanga (-0.07), Saharsa (-0.05), and Supaul (-0.04). An increasing trend was found in Madhepura (0.05), Purnia (0.04), and Katihar (0.03) according to Sen's slope. These findings highlight the variability in rainfall trends across different districts and seasons within the study area.

The results of the percentage change in annual and seasonal rainfall series as per Sen's slope in the study area from 1901 to 2022 reveal a statistically significant decrease in annual rainfall, with the highest reductions observed in Darbhanga (-26.23%), followed by Araria (-22.58%), Sitamarhi (-13.40%), Saharsa (-12.74%), Madhubani (-9.01%), Kishanganj (-7.8%), Madhepura (-6.67%), Purnia (-3.53%) & Katihar (-3.38%). Conversely, an increase in annual rainfall was observed only in Supaul (12.31%). A similar trend was observed for monsoon rainfall, with percentage changes are in the order of Darbhanga (-26.6%), Araria (-24.96%), Sitamarhi (-16.25%), Saharsa (-14.26%), Madhepura (-12.78%), Supaul (12.57%), Purnia (-10.80%), Madhubani (-8.71%), Katihar (-7.87%), and Kishanganj (-7.01%). For winter rainfall, a decreasing percentage change was observed across all districts, with the highest reduction in Kishanganj (-62.19%), followed by Darbhanga (-50.31%), Purnia (-34.81%), Saharsa (-32.10%), Sitamarhi (-30.60%), Araria (-26.93%), Madhubani (-26.46%), Katihar (-23.82%), Madhepura (-21.63%) & Supaul (-12.94%). Regarding pre-monsoon rainfall, a decrease was noted only in Araria (-0.38%), while increases were highest in Purnia (35.31%), followed by Katihar (34.10%), Supaul (25.37%), Sitamarhi (23.84%), Madhepura (16.94%), Darbhanga (13.98%), Madhubani (13.21%), Saharsa (11.10%) & Kishanganj (2.89%). For post-monsoon rainfall, decreases were found in Kishanganj (-22.07%), Sitamarhi (-15.38%), Madhubani (-14.80%), Araria (-12.13%), Darbhanga (-11.62%), Saharsa (-6.71%) & Supaul (-5.82%), while increases were observed in Madhepura (6.31%), Purnia (4.54%), & Katihar (3.48%).

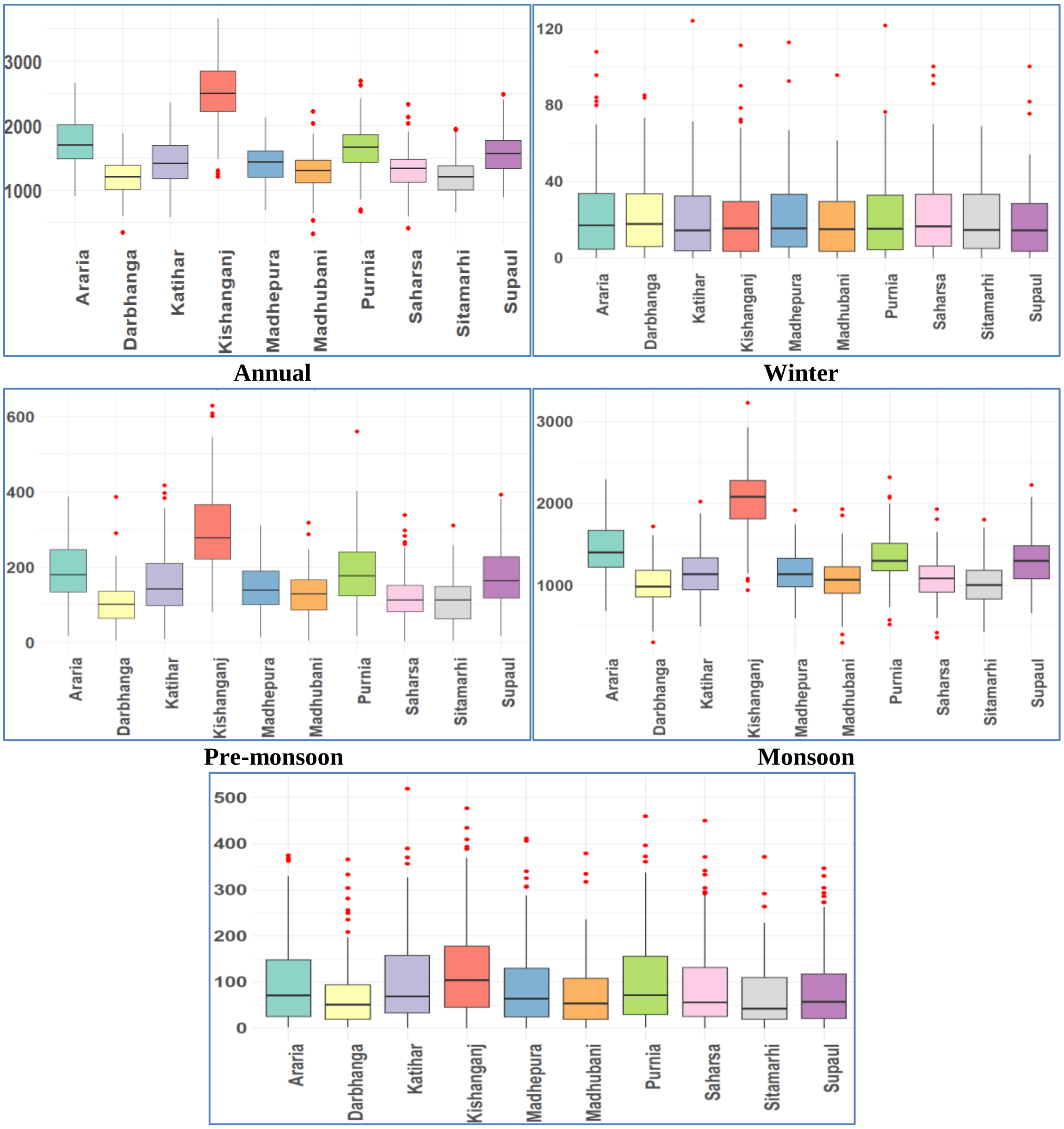

Fig. 3. Box plots of annual and seasonal rainfall (mm) over year 1901 to 2022 (122 years) for different districts of study area

The ITA test revealed statistically significant trends at the 1%, 5%, and 10% significance levels on different seasonal and annual scales across the study area (Table 2). In the study area, a statistically significant decreasing annual rainfall trend was observed for all districts except Supaul at the 1% significance level. The magnitude of the decrease (mm/year) in annual rainfall was found to be highest in Araria (-4.457), followed by Darbhanga (-2.649), Saharsa (-1.269), Madhubani (-1.217), Madhepura (-1.109), Purnia (-1.083), Katihar (-0.900), Kishanganj (-0.765), and Sitamarhi (-0.600). A significant increasing trend in annual rainfall was detected only for Supaul (2.343) at the 1% significance level.

A statistically significant decreasing trend in winter season rainfall was found for all districts in the study area (Table 2). The magnitude (mm/year) of the decrease in winter rainfall was highest in Darbhanga (-0.200), followed by Kishanganj (-0.191), Purnia (-0.172), Saharsa (-0.170), Madhepura (-0.149), Katihar (-0.143), Araria (-0.136), Madhubani (-0.113), Sitamarhi (-0.110), and Supaul (-0.082) at the 1% significance level.

TABLE 2

Annual and seasonal trend test results in the study area

District	Araria	Darbhanga	Katihar	Kishanganj	Madhepura	Madhubani	Purnia	Saharsa	Sitamarhi	Supaul
					Annual					
Z_{mk}	-3.19***	-3.37***	-0.47	-1.42	-1.06	-1.34	-0.57	-1.78*	-1.71*	1.56
$Z_{tfpw-mk}$	-2.71***	-2.94***	-0.58	-1.58	-1.18	-1.34	-0.77	-1.73*	-1.59	1.16
m	-3.06	-2.06	-0.05	-1.49	-0.73	-0.70	-0.27	-0.92	-0.84	1.53
SS_i	-3.22	-2.59	-0.40	-1.60	-0.78	-0.96	-0.48	-1.38	-1.34	1.59
ITA_s	-4.46***	-2.65***	-0.90***	-0.76***	-1.11***	-1.21***	-1.08***	-1.27***	-0.60***	2.34***
					Winter					
Z_{mk}	-1.60	-2.30**	-1.39	-3.08***	-1.11	-1.39	-1.87*	-1.64	-1.50	-0.95
$Z_{tfpw-mk}$	-1.42	-1.79*	-1.12	-2.38**	-1.00	-1.27	-1.43	-1.62	-1.20	-0.75
m	-0.09	-0.12	-0.07	-0.15	-0.07	-0.06	-0.09	-0.1	-0.07	-0.04
SS_i	-0.05	-0.09	-0.04	-0.11	-0.04	-0.04	-0.06	-0.06	-0.05	-0.02
ITA_s	-0.14***	-0.20***	-0.14***	-0.19***	-0.15***	-0.11***	-0.17***	-0.17***	-0.11***	-0.08***
					Pre-monsoon					
Z_{mk}	-0.04	0.80	2.01**	0.30	1.22	0.81	2.48**	0.70	1.51	1.74*
$Z_{tfpw-mk}$	-0.21	0.60	1.93*	0.19	1.04	0.72	1.96**	0.55	1.44	1.50
m	-0.05	0.20	0.50	0.03	0.22	0.15	0.58	0.14	0.27	0.41
SS_i	-0.006	0.12	0.43	0.07	0.20	0.14	0.54	0.11	0.21	0.36
ITA_s	-0.24***	0.12***	-0.14***	0.13***	0.18***	-0.04***	0.48***	0.15***	0.22***	0.40***
					Monsoon					
Z_{mk}	-3.27***	-3.32***	-0.96	-1.03	-1.65*	-1.06	-1.50	-1.89*	-1.93*	1.65*
$Z_{tfpw-mk}$	-3.02***	-2.98***	-1.12	-1.25	-1.86*	-1.35	-1.54	-1.98**	-1.78*	1.28
m	-2.80	-2.04	-0.57	-1.20	-0.99	-0.74	-0.81	-0.92	-0.97	1.11
SS_i	-2.91	-2.19	-0.75	-1.18	-1.22	-0.77	-1.19	-1.27	-1.36	1.34
ITA_s	-3.91***	-2.42***	-1.13***	-0.55***	-1.17***	-0.93***	-1.39***	-1.11***	-0.65***	1.52***
					Post-monsoon					
Z_{mk}	-0.68	-0.69	0.19	-1.12	0.34	-0.89	0.27	-0.38	-0.84	-0.34
$Z_{tfpw-mk}$	-0.88	-0.84	0.05	-1.15	0.23	-1.09	0.18	-0.62	-1.06	-0.51
m	-0.12	-0.09	0.08	-0.16	0.13	-0.04	0.07	-0.03	-0.08	0.05
SS_i	-0.10	-0.07	0.03	-0.24	0.05	-0.09	0.04	-0.05	-0.09	-0.04
ITA_s	-0.17***	-0.25***	-0.05	-0.16***	0.02*	-0.14***	-0.002	-0.13***	-0.06***	0.07*

***, **, * statistically significant trend at $\alpha = 1\%$, 5 % and 10 %, respectively. Negative (−) and positive (+) values indicate the decreasing and increasing trends, respectively

The results of the trend analysis using ITA for pre-monsoon season rainfall are presented in Table 2. A statistically significant decreasing trend (mm/year) in pre-monsoon season rainfall was found to be highest in Araria (-0.240), followed by Katihar (-0.143) and Madhubani (-0.036) at the 1% significance level. Conversely, a significant increasing trend in pre-monsoon rainfall was observed in Purnia (0.479), Supaul (0.401), Sitamarhi (0.222), Madhepura (0.185), Saharsa (0.147), Kishanganj (0.135), and Darbhanga (0.122) at the 1% significance level. These findings indicate that while some districts experienced a decrease in pre-monsoon rainfall, others showed an increasing trend during the pre-monsoon season.

The results of the trend analysis using ITA for monsoon season rainfall are presented in Table 2. In the study area, a statistically significant decreasing trend in monsoon season rainfall was observed for all districts except Supaul at the 1% significance level. The magnitude of the decrease (mm/year) in rainfall is highest in Araria (-3.906), followed by Darbhanga (-2.418), Purnia (-1.388), Madhepura (-1.168), Katihar (-1.129), Saharsa (-1.117), Madhubani (-0.928), Sitamarhi (-0.647) and Kishanganj (-0.547). A statistically significant increasing trend in monsoon season rainfall is found only in Supaul (1.518) at the 1% significance level. These findings highlight the variability in monsoon rainfall trends across different districts within the study area.

In the study area, a statistically significant decreasing trend in post-monsoon season rainfall was observed for all districts except Madhepura and Supaul (Table 2). The magnitude (mm/year) of the decrease in rainfall is found to be highest in Darbhanga (-0.255), followed by Araria (-0.175), Kishanganj (-0.162), Madhubani (-0.139), Saharsa (-0.129), Sitamarhi (-0.065), Katihar (-0.054), and Purnia (-0.002). The decreasing rainfall trends in Katihar and Purnia districts were observed statistically non-significant. A statistically significant increasing trend (mm/year) in post-monsoon season rainfall was found only in Supaul (0.073) and Madhepura (0.023) districts at the 10% significance level. These findings highlight the variability in post-monsoon rainfall trends across different districts within the study area. The comparative assessment of different trend test results is represented in Table 3. These results indicated that ITA detects trends more sensitively than MK and TFPW-MK tests.

3.3. *Graphical analysis of ITA results*

3.3.1. *Annual rainfall*

The graphical plots of the ITA method at an annual scale for different districts of the study area are depicted in Fig. 4 for additional visual analysis. Here, a monotonically decreasing trend of annual rainfall is clearly observed in Araria district. The results illustrate a clear decreasing trend of all rainfall values in the low, medium, and high categories in Araria district. In the case of Darbhanga district, a non-monotonic trend is evident as the low and medium values fall within the decreasing trend categories, while high values are scattered around the no-trend line, indicating no discernible trend in the high values categories. A non-monotonically increasing trend is observed in the Katihar, Kishanganj, and Madhepura districts where no clear trend is observed in the low category except Kishanganj (decreasing trend), and a weak decreasing trend is observed in the medium category, while an increasing trend is observed in the high category. In Madhubani and Purnia districts, a non-monotonic increasing trend is observed, where medium and high rainfall values are scattered around the no-trend line, indicating no discernible trend, while low rainfall values show a decreasing trend. A non-monotonic increasing trend is observed in Saharsa and Sitamarhi districts, where low and medium values exhibit a decreasing to no-trend nature (weak decreasing), while high category values indicate an increasing trend. In the Supaul district, a non-monotonic increasing trend is observed, where an increasing trend is observed in high categories, while a weaker increasing trend is observed in the low and medium categories. Weak trend magnitudes have scatter points closer to the no-trend line.

3.3.2. *Winter season rainfall*

The ITA results of winter season rainfall in different districts are graphically depicted in Fig. 5. Here, all districts of the study area exhibit a monotonic decreasing trend, as evidenced by decreasing rainfall across all categories: low, medium, and high. However, a weaker decreasing trend in the low rainfall category was detected in Araria, Katihar, Madhepura, Madhubani, Saharsa, and Supaul districts, as rainfall data points are closer to the no-trend line. Weaker decreasing trends in medium and high rainfall magnitudes were detected in Supaul and Sitamarhi districts, respectively, of the study area.

3.3.3. *Pre-monsoon season rainfall*

The ITA results of pre-monsoon season rainfall in different districts are graphically depicted in Fig. 6. A non-monotonic decreasing trend was detected in Araria district, where low and high magnitude rainfall showed a decreasing trend, while the medium category showed no trend. In Darbhanga, low and medium category rainfall showed no trend, as the data points are uniformly distributed around the no-trend line, while high category rainfall showed an increasing trend, overall representing a non-monotonic increasing trend. In Katihar, a non-monotonic increasing trend was detected according to ITA. Here, low rainfall showed a decreasing trend, while medium and high category rainfall indicated increasing trends. In Kishanganj district, low magnitude rainfall showed a weak decreasing trend, while medium category rainfall showed a weak increasing trend, and high category rainfall showed no trend. In Madhepura, low, medium, and high rainfall showed weaker decreasing, increasing, and increasing trends, respectively, overall indicating a non-monotonic increasing trend. In Madhubani, low magnitude rainfall showed a decreasing trend, while medium and high category rainfall showed no trend. A non-monotonic increasing trend was observed in Purnia district, as the low, medium, and high magnitude rainfall fell under decreasing, increasing, and increasing trend categories, respectively. In Saharsa, high category rainfall showed an increasing trend, while low and medium categories showed no trend. In Sitamarhi, a weak increasing trend was observed in the medium rainfall category, while no trend and increasing trends were observed for low and high category rainfall, respectively. A non-monotonic increasing trend was detected in Supaul district, as the low category rainfall showed a weaker decreasing trend, while medium and high category rainfall showed increasing trends.

3.3.4. *Monsoon season rainfall*

The ITA results of different districts for detecting monsoon seasonal rainfall trends are graphically depicted in Fig. 7. Here, Araria and Darbhanga districts exhibit a monotonic decreasing trend, as evidenced by decreasing rainfall across all categories: low, medium, and high. In Katihar district, all rainfall categories demonstrate no clear trend, as indicated by the close scattering of data points around the no-trend line. In Kishanganj, ITA analysis reveals a non-monotonic increasing trend. Low rainfall values exhibit a decreasing trend, medium values show no discernible trend, and high values indicate a weaker increasing trend. In Madhepura district, a non-monotonic increasing trend is evident. Low rainfall demonstrates a weak decreasing trend, medium rainfall shows a decreasing trend, and high rainfall presents an increasing trend, suggesting a non-monotonic pattern. In Madhubani, a decreasing trend is detected for low rainfall, while no clear trend is observed for both medium and high rainfall, as data points cluster around the no-trend line. A non - monotonic increasing trend is detected in Purnia

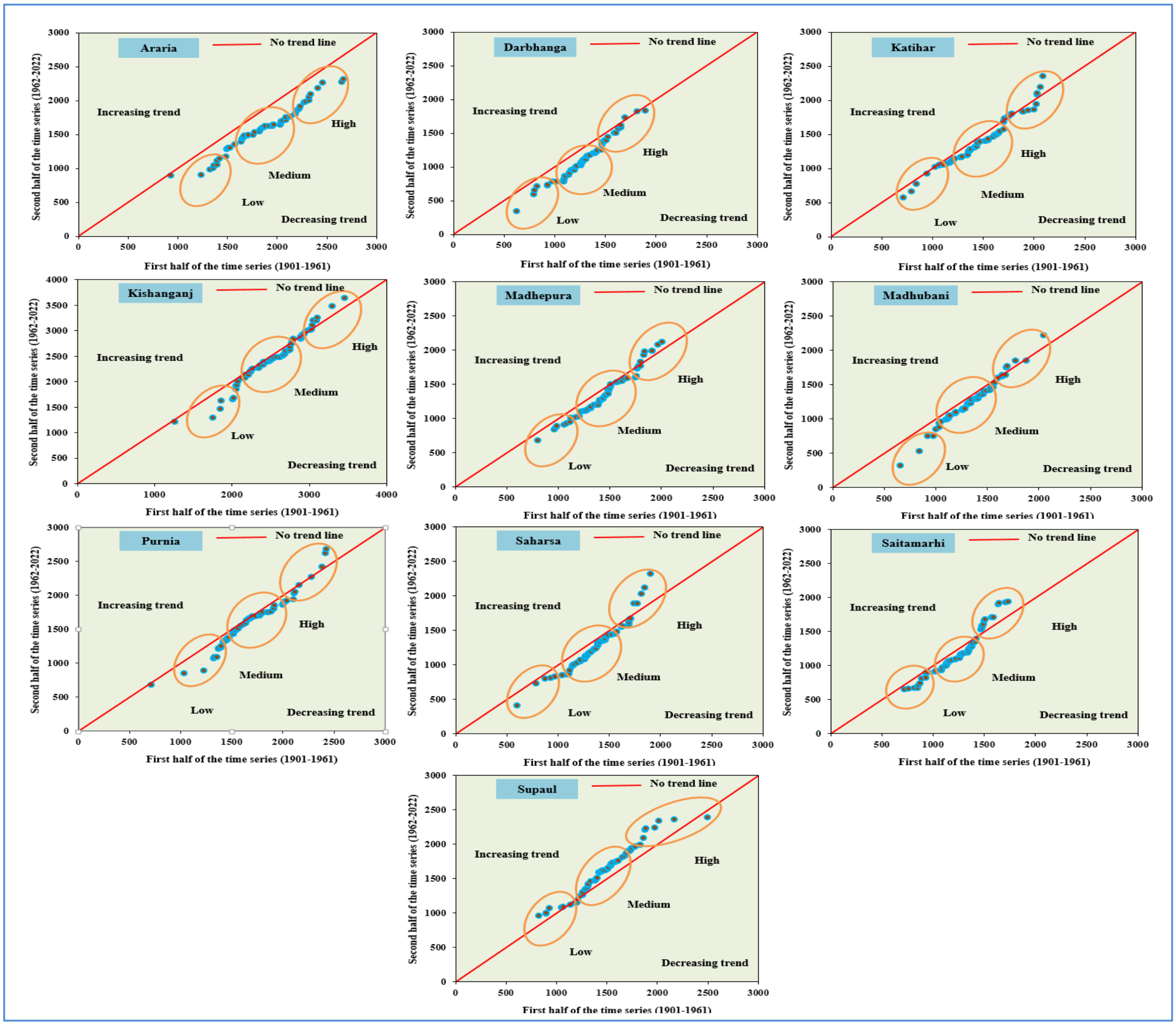

Fig. 4. Graphical plots of ITA method for annual rainfall at different districts of the study area

TABLE 3

Comparative assessment of different trend methods

Stations	MK test					TFPW-MK test					ITA test				
	A	W	Pre-m	M	Post-m	A	W	Pre-m	M	Post-m	A	W	Pre-m	M	Post-m
Araria	Decreasing			Decreasing		Decreasing			Decreasing		Decreasing	Decreasing	Decreasing	Decreasing	Decreasing
Darbhanga	Decreasing	Decreasing		Decreasing		Decreasing	Decreasing		Decreasing		Decreasing	Decreasing	Increasing	Decreasing	Decreasing
Katihar			Increasing					Increasing			Decreasing	Decreasing	Decreasing	Decreasing	
Kishanganj		Decreasing					Decreasing				Decreasing	Decreasing	Increasing	Decreasing	Decreasing
Madhepura				Decreasing					Decreasing		Decreasing	Decreasing	Increasing	Decreasing	Increasing
Madhubani											Decreasing	Decreasing	Decreasing	Decreasing	Decreasing
Purnia		Decreasing	Increasing					Increasing			Decreasing	Decreasing	Increasing	Decreasing	Decreasing
Saharsa	Decreasing			Decreasing		Decreasing			Decreasing		Decreasing	Decreasing	Increasing	Decreasing	Decreasing
Sitamarhi	Decreasing			Decreasing					Decreasing		Decreasing	Decreasing	Increasing	Decreasing	Decreasing
Supaul			Increasing	Increasing							Increasing	Decreasing	Increasing	Increasing	Increasing

*A- Annual, *W-Winter, *Pre-m- Pre-monsoon, *Post-m- Post-monsoon

Increasing	No trend	Decreasing

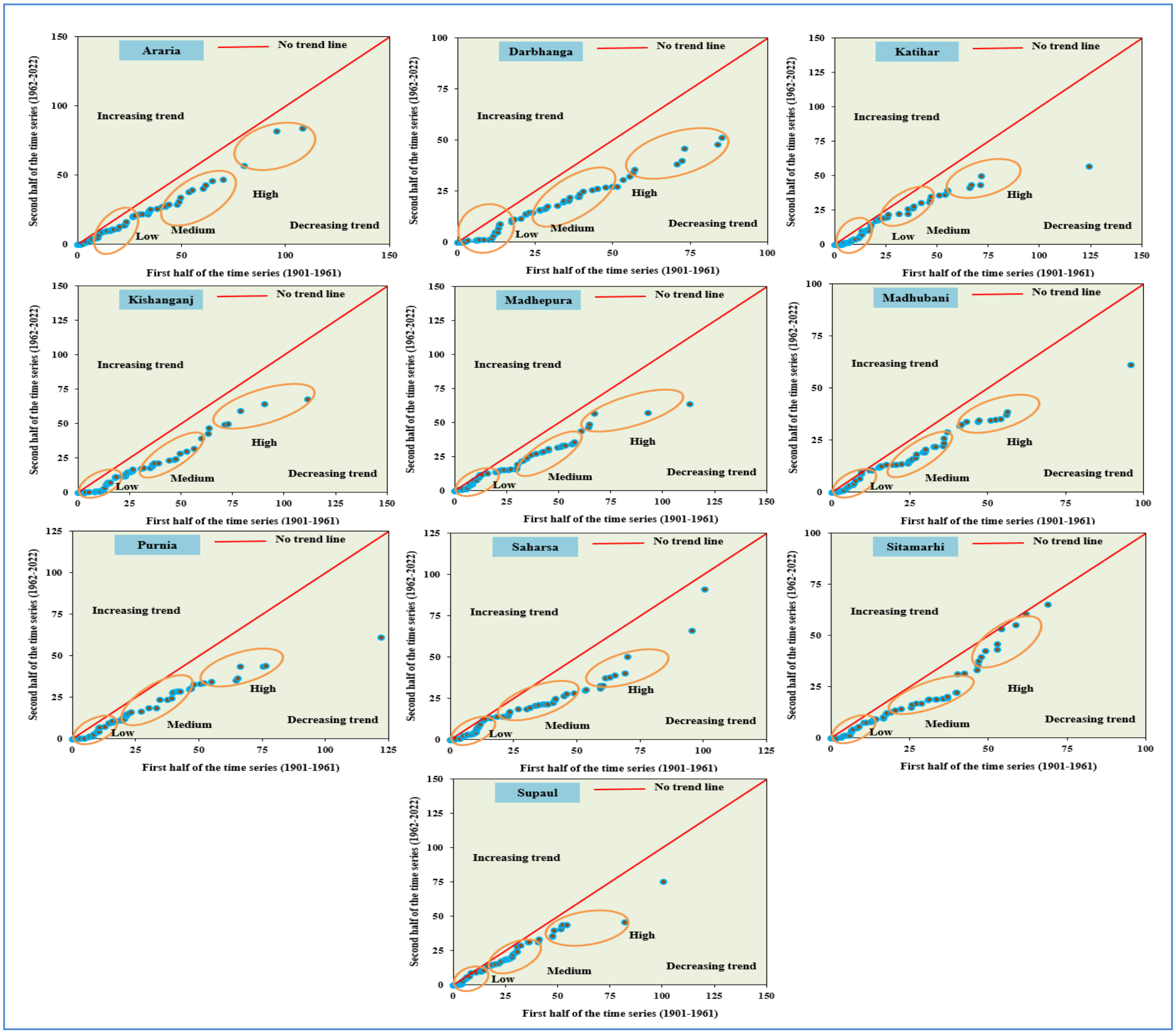

Fig. 5. Graphical plots of ITA method for winter season rainfall at different districts of the study area

TABLE 4

Summary of the rainfall change-point detection using Pettitt's test and distribution free CUSUM test

District	Annual		Winter		Pre-monsoon		Monsoon		Post-monsoon	
	Pettitt's test	CUSUM	Pettitt's test	CUSUM	Pettitt's test	CUSUM	Pettitt's test	CUSUM	Pettitt's test	CUSUM
Araria	1956***	1956***	1946	1946	1949	1949	1956***	1956***	1939	1949
Darbhanga	1949***	1949***	1959**	1959	2009	2009	1956***	1963***	1979	1979
Katihar	1956	1956*	1962	1962	1972**	1972**	1956	1956*	1908	1963
Kishanganj	1991**	1991*	1945**	1945	1968	1968	2000*	2000	1939	1949
Madhepura	2004	2004	1959	1962	1972	1972	2004*	2004	1927	1927
Madhubani	1949	1949	1962	1962	1998	1979	1965	1965	1963	1963
Purnia	1956	1970	1962*	1962	1972**	1972**	1956	1956	1927	1941
Saharsa	1950	1950	1959	1962	1973	1973*	1956	1956	2004	1911
Sitamarhi	1949	1949*	1996	1991	1979	1974*	1949	1943	1979	1988
Supaul	1972*	1972**	1962	1974	1973*	1973	1973*	1973***	1937	1937

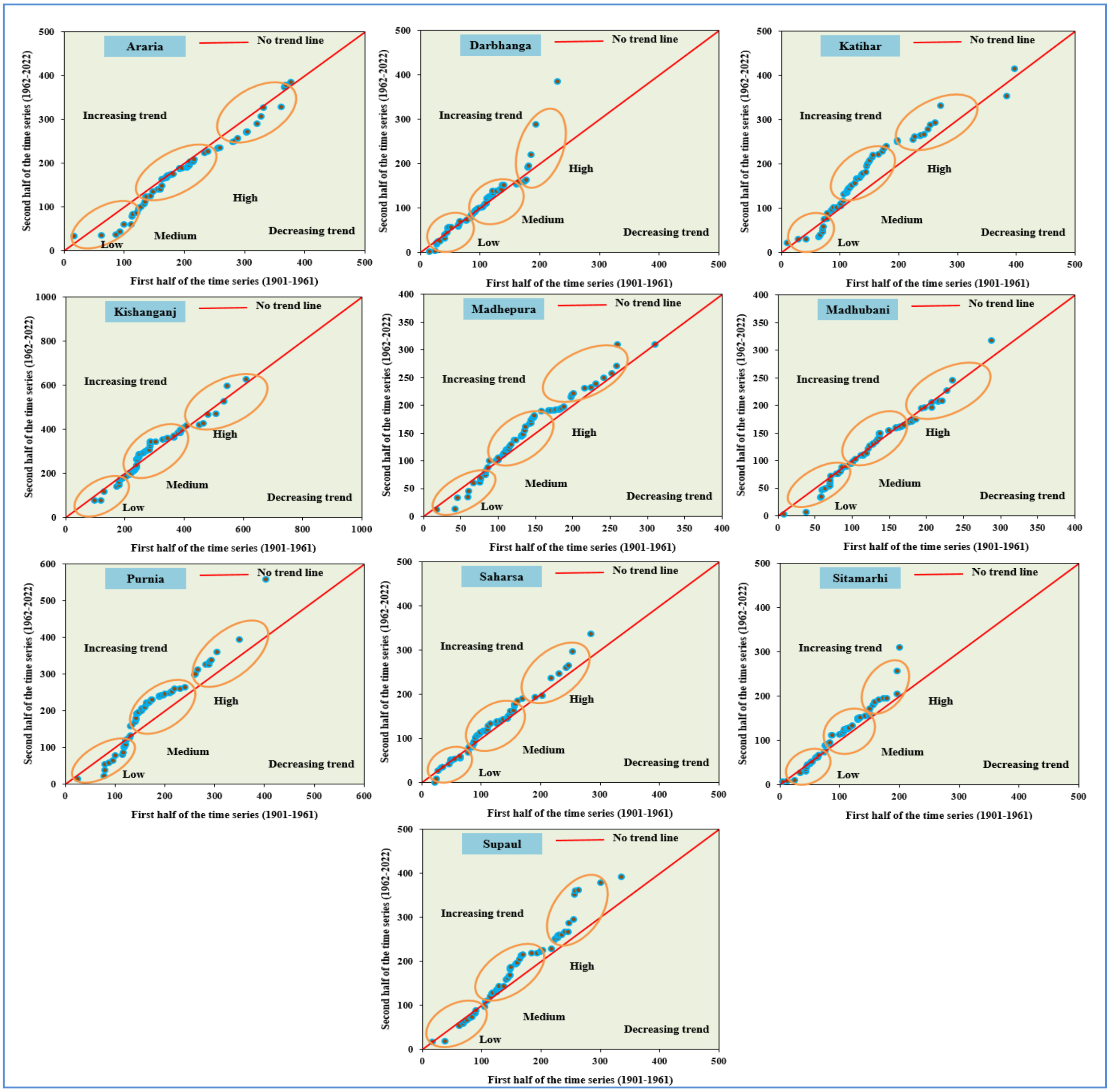

Fig. 6. Results of ITA method for pre-monsoon season rainfall at different districts of the study area

district, characterized by a weak decreasing trend for small and medium categories and a weak increasing trend for high rainfall categories. Similarly, in Saharsa and Sitamarhi districts, a non-monotonic increasing trend is observed. A weak decreasing trend is evidenced for low and medium rainfall, while an increasing trend is observed for high rainfall categories. In Supaul district, low, medium, and high rainfall categories exhibit no trend, a weak increasing trend, and an increasing trend, respectively, indicating a non-monotonic increasing trend in rainfall.

3.3.5. *Post-monsoon rainfall*

The ITA results of post-monsoon seasonal rainfall in different districts are graphically depicted in Fig. 8. A non-monotonic decreasing trend was detected in Araria district during the post-monsoon season. Here, low, medium, and high rainfall fall under the no-trend, decreasing, and decreasing trend categories, respectively. A monotonic decreasing trend was detected in Darbhanga district, as medium and high rainfall categories showed decreasing rainfall trends, while low rainfall showed no

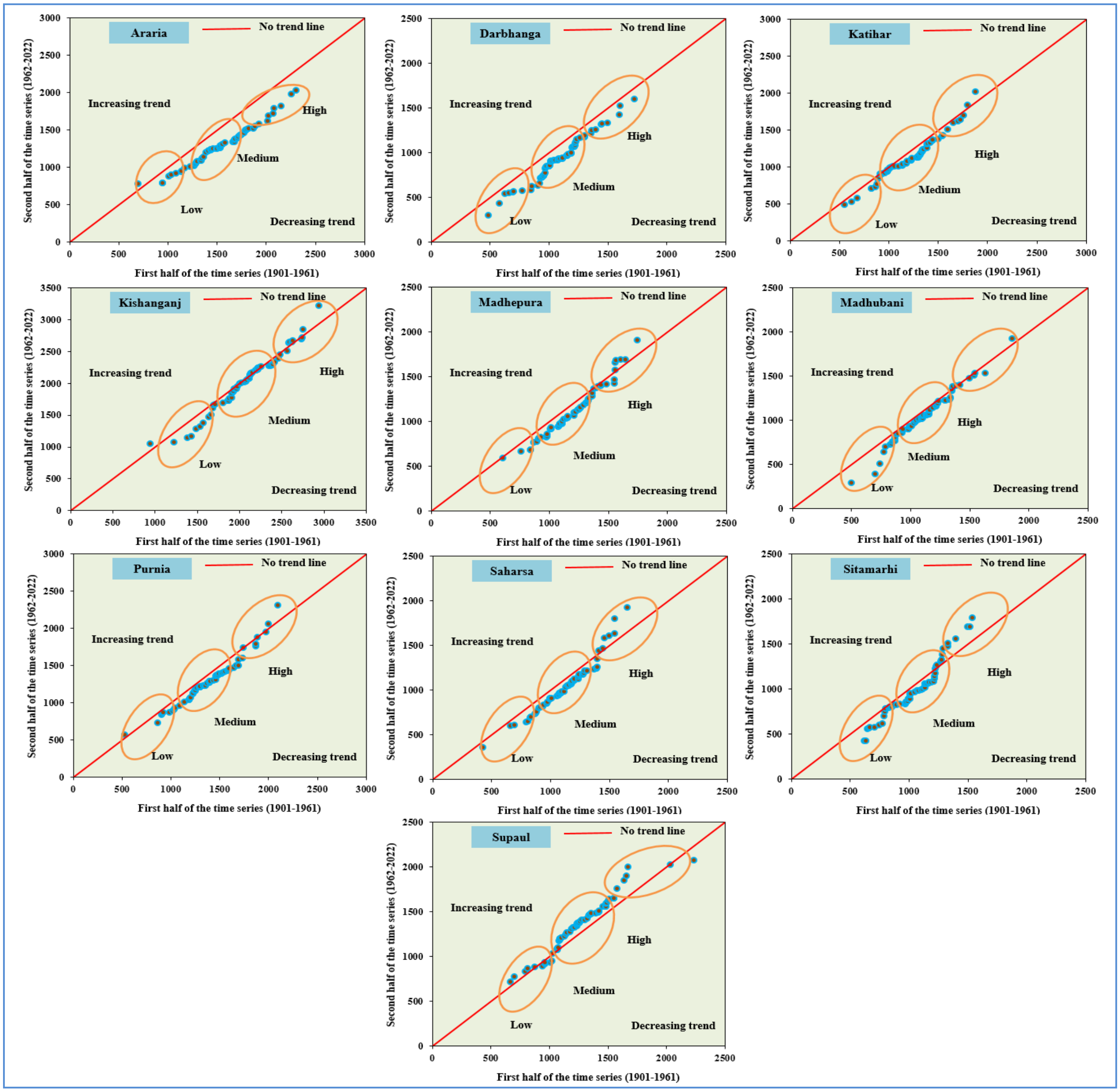

Fig. 7. Graphical plots of ITA method for monsoon season rainfall at different districts of the study area

trend. In Katihar, a non-monotonic increasing trend was detected because medium and high category rainfall showed decreasing and increasing trends, respectively. In Kishanganj, low magnitude rainfall showed a decreasing trend, while medium and high rainfall data points are uniformly distributed around the no-trend line, indicating no trend. In Madhepura and Sitamarhi districts, data points are well distributed around the no-trend line, indicating no trend for low, medium, and high rainfall categories. In Madhubani, low and medium rainfall falls under weaker decreasing trend categories, while high rainfall showed no trend. A non-monotonic increasing trend was observed in Purnia, where low, medium, and high rainfall categories fall under no-trend, decreasing, and increasing trend categories, respectively. In Saharsa, low and medium category rainfall showed no trend, while high rainfall showed a decreasing trend, overall indicating a non-monotonic decreasing trend. In Supaul, medium category rainfall showed an increasing trend, while low and high rainfall showed no trend, as the data points are well distributed on both sides of the no-trend line.

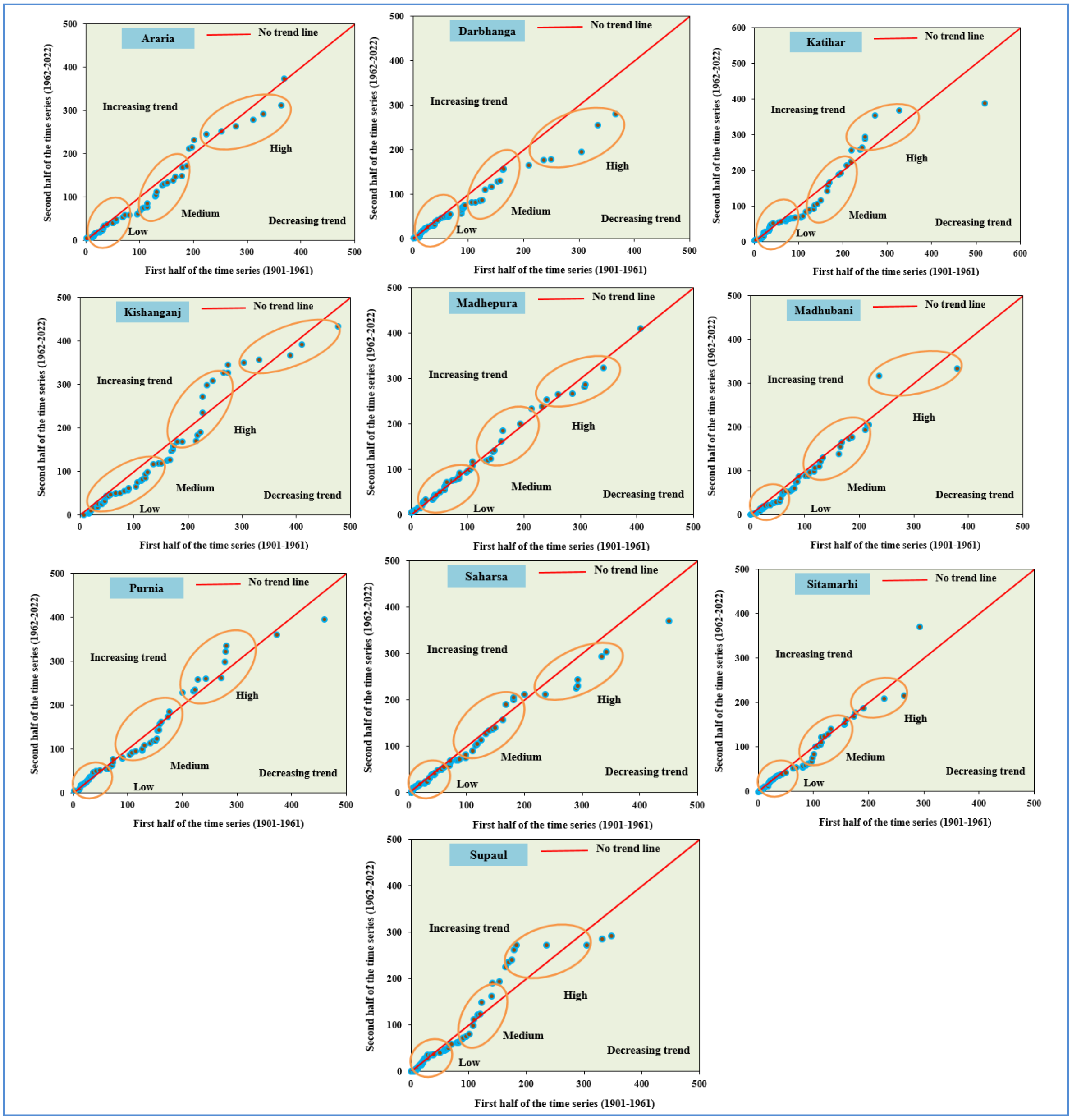

Fig. 8. Graphical plots of ITA method for post-monsoon season rainfall at different districts of the study area

As per ITA, the nature of trend in low, medium and high rainfall categories at annual and seasonal scale in the study area is depicted in Fig. 9. Here, it was observed that hidden trends in low, medium and high rainfall categories can be identified with only ITA than that of other methods.

The observed increasing rainfall trend in Supaul district is likely influenced by several localized climatic and geographical factors. Supaul is situated within the floodplain dynamics which may enhance moisture availability through increased local recycling, thereby contributing to higher precipitation levels. Additionally, alterations in monsoon circulation patterns due to climate change may be shifting rainfall distribution, resulting in region-specific increases. Land use changes, including variations in vegetation cover, can modify evapotranspiration rates and atmospheric moisture content, further impacting rainfall amounts. Moreover, human activities such as deforestation and shifts in agricultural practices can influence local microclimates, potentially affecting the spatial and temporal distribution of rainfall in the districts.

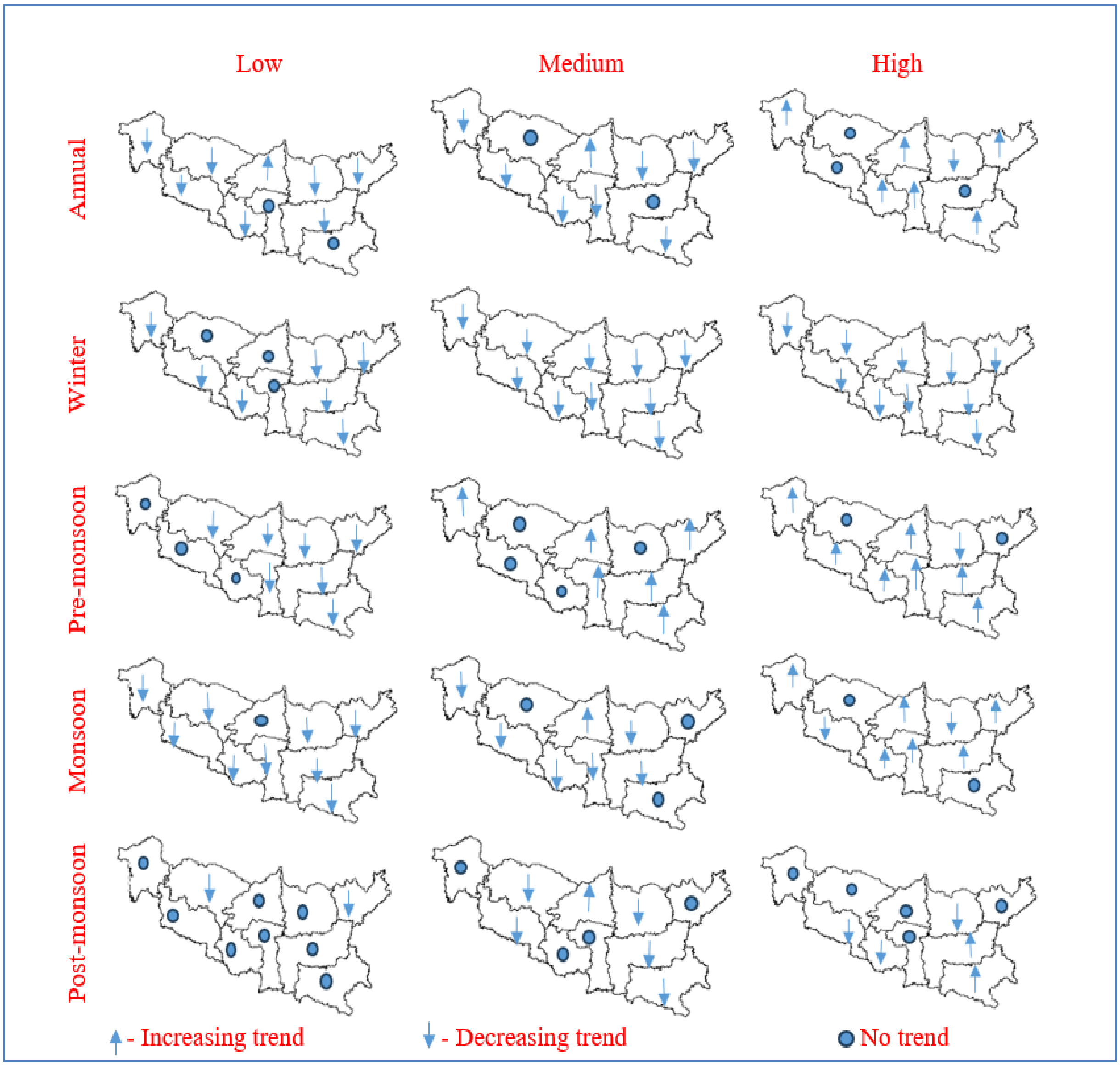

Fig. 9. Nature of trend in low, medium and high rainfall categories at Annual and seasonal scale in the study area as per ITA

3.4. *Analysis of change-point detection tests of rainfall in the study area*

Identifying the point in a time series where a significant change has occurred is the purpose of change-point analysis. Trend change-point analysis was performed for all series that showed a significant trend. Table 4 demonstrates the findings of the distribution-free CUSUM test and Pettitt's test for annual and seasonal change-point detection across the study area with different significance levels. These tests were applied to detect shifts in annual and seasonal rainfall patterns from 1901 to 2022. The change-point detection analysis revealed that most districts exhibited similar shift years for both annual and monsoon rainfall, with some exceptions. The analysis strongly indicates that changes (increases or decreases) in monsoon rainfall are ultimately reflected in the annual rainfall, highlighting the significant influence of monsoon rainfall on the study area. Notable variations were observed in winter, pre-monsoon, and post-monsoon rainfall from 1901 to 2022. In most cases, both tests indicated similar change points for annual and seasonal rainfall in the study area, except for a few districts at different significance levels. For annual, monsoon, and pre-monsoon rainfall, a shift in rainfall patterns was observed after 1949. In contrast, the winter and post-monsoon seasons showed shifts in rainfall patterns after 1945 and 1908, respectively.

This study recommends implementing adaptive water resource management strategies, including rainwater harvesting, construction of check dams, and the promotion of water-efficient irrigation systems to mitigate the impact of decreasing rainfall trends in the study area. It is necessary to adopt climate-resilient agricultural practices, such as the use of drought-resistant crop varieties, altering cropping patterns, and practicing conservation agriculture to sustain Makhana cultivation in varying climatic conditions in the wetland area. It is important to develop and enhance disaster preparedness plans to address the increased risk of droughts and floods due to significant changes in rainfall patterns. It is essential to promote afforestation and soil conservation initiatives to enhance soil moisture retention and prevent soil erosion, thus supporting agricultural productivity in the face of changing rainfall patterns. It is necessary to formulate and implement policies that support sustainable water use, conservation agriculture, and disaster resilience to address the challenges posed by changing rainfall patterns. In order to enhance the sustainability of aquatic crop cultivation under changing rainfall regimes, it is crucial to integrate integrated wetland management approaches that prioritize maintaining the hydrological integrity of Makhana-growing ecosystems. This includes seasonal water budgeting based on rainfall forecasts and real-time monitoring of water levels to optimize the timing of sowing and harvesting. Promotion of community-based water governance models, where local farmers collectively manage wetland resources, can improve water distribution equity and system resilience. Additionally, establishing early warning systems and climate information services can support informed decision-making at the farm level. Long-term strategies should focus on the research and development of aquatic crop varieties that are genetically adapted to withstand fluctuating hydrological conditions.

4. Conclusions

In this study, an extensive analysis of spatio-temporal variability and trend identification was conducted for long-term rainfall time series across the major wetland districts in Bihar, India, spanning from 1901 to 2022. Statistical methods including the MK, TFPW-MK, Sen's slope and SLR tests were utilized to discern trends in both seasonal and annual rainfall data, providing quantitative insights into their direction and significance over time. ITA was employed to visually illustrate these trends, enhancing understanding of temporal changes in rainfall patterns throughout the study period. Sen's slope estimator was applied to quantify the magnitude of trends across different districts and seasons, revealing variations in the rates of change indicative of significant increases or decreases in rainfall. Pettitt's test and the distribution-free CUSUM test were employed at significance levels of 1%, 5%, and 10% to detect change points in rainfall patterns. These tests identified specific years where significant shifts occurred in annual and seasonal rainfall, reflecting changes in climatic conditions over the 122-year period. The analysis revealed significant negative trends in annual and monsoon rainfall at 1%, 5%, and 10% significance levels across all districts except Supaul. Most districts experienced a decreasing trend in annual, monsoon, winter, and post-monsoon rainfall. However, Supaul exhibited an increasing trend in both annual and monsoon rainfall, while some districts showed increasing trends in pre-monsoon rainfall. The highest decrease in annual rainfall was observed in Araria, whereas the highest decline in monsoon rainfall occurred in Darbhanga. Winter rainfall showed a declining trend in all districts, with the most significant reduction recorded in Kishanganj. The spatial distribution of rainfall changes indicated significant variability across different districts and seasons. Additionally, Pettitt's and distribution-free CUSUM tests identified significant change points in annual and seasonal rainfall patterns from 1901 to 2022. Furthermore, shifts in monsoon rainfall were found to be closely linked to annual rainfall changes, highlighting the strong influence of monsoon rainfall on overall annual totals. Significant shifts in annual, monsoon, and pre-monsoon rainfall patterns were observed after 1949, while winter rainfall shifts occurred after 1945. Post-monsoon rainfall showed noticeable shifts as early as 1908. Most districts exhibited similar change-point years for annual and monsoon rainfall, with a few exceptions at different significance levels. Additionally, notable changes in rainfall patterns were observed across different seasons, reflecting varying climatic influences over the study period.

Regarding ITA analysis for annual rainfall, most districts exhibited non-monotonic trends with mixed decreasing and increasing patterns. Araria indicated a clear decreasing trend, whereas Supaul showed a non-monotonic increasing trend. Pre-monsoon rainfall analysis indicated predominantly non-monotonic trends, with Araria showing decreases in low and high categories and Supaul indicating increases in medium and high categories. Winter rainfall consistently showed a monotonic decreasing trend across all districts, albeit with weaker decreases observed in some low, medium, and high categories. For monsoon rainfall, Araria and Darbhanga exhibited decreasing trends, while other districts demonstrate non-monotonic patterns, varying across low, medium, and high categories. Post-monsoon rainfall similarly showed predominantly non-monotonic trends, with Araria and Darbhanga indicated decreasing trends in medium and high categories, and other districts showing mixed patterns. This integrated approach of statistical and graphical methods provides a robust analysis of long-term rainfall variability and trends, offering valuable insights for climate assessment and water resource management strategies in Bihar's wetland districts. Future study should be focused to incorporate climate change projections to assess future rainfall scenarios and their potential impacts on water resources and agriculture. This will help in developing long-term adaptation strategies. It is essential to conduct comprehensive assessments of how changes in rainfall patterns affect socio-economic factors, including farmer livelihoods, food security, and regional economies, particularly in the context of aquatic crops cultivation in the wetland area. Detecting trends in extreme rainfall events like heavy downpours or long dry periods is important for understanding climate impacts.

Data availability

Data is available from the corresponding author upon reasonable request.

Competing Interests

The authors declare no competing interests.

Authors' Contributions

Suryakant Bajirao Tarate: Manuscript writing, conceptualization, methodology, data analysis and reviewing. (*email: taratesuryakant01@gmail.com*).
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