Open Access
Volume 5 Issue 1
Research Article

Journal of Water Engineering and Management
ISSN: 2582-6298

Assessment of Spatio-Temporal Rainfall Variability and Trends across West Bengal, India

Abhishekh Goyal[1], Pratibha Warwade[2]

[1]Ex MTech Student, Department of Civil Engineering, Central University of Jharkhand, India
[2]Assistant Professor, Department of Civil Engineering, Central University of Jharkhand, Jharkhand, India

Article Info

Article History:
Received on: January 10, 2024
Revised on: March 12, 2024
Accepted on: March 20, 2024
Published on: April 30, 2024

**Corresponding author:* Pratibha Warwade
Email: pratibha.warwade@cuj.ac.in

How to Cite:
Goyal, A. and Warwade, P. 2024. Assessment of Spatio-Temporal Rainfall Variability and Trends across West Bengal, India, Journal of Water Engineering and Management 5(1):1-16.
DOI: https://doi.org/10.47884/jweam.v5i1pp01-16

Abstract

Climate change manifests prominently through long-term variations in rainfall, influencing both spatial and temporal water availability. This study examines rainfall variability across 18 districts of West Bengal, India, using long-term records analysed at annual, seasonal, and monthly time scales. The Mann–Kendall test and Sen's Slope estimator were employed to assess the direction and magnitude of rainfall trends. The annual rainfall analysis revealed statistically significant trends in five districts: North 24 Parganas and South 24 Parganas exhibited increasing trends, whereas Birbhum, Maldah, and Uttar Dinajpur showed significant declines at the 95% confidence level. Seasonal analysis indicated that only the monsoon season experienced notable trends in several districts, while the post-monsoon period showed significance at just one location. Monthly trend evaluation reflected a heterogeneous pattern across the state, with no uniform direction of change. The findings support district-level water planning by highlighting zones of rising or diminishing rainfall, enabling better management of water resources under evolving climate conditions.

Keywords Rainfall variability: Mann–Kendall test: Sen's Slope estimator: West Bengal rainfall trends: Seasonal rainfall analysis.

Introduction

Climate change has significantly altered rainfall patterns, affecting water availability and agriculture worldwide. In India, where the economy is largely agro-based, rainfall—especially from the southwest monsoon—is vital. Rain-fed agriculture supports 68% of cultivated land and a large portion of the population and livestock. Variability in rainfall threatens food production and fresh water supply, making trend analysis essential for forecasting and planning. Trend analysis helps identify long-term changes in rainfall across time and regions, aiding policymakers in agricultural planning, water resource management, and disaster mitigation. The Intergovernmental Panel on Climate Change warns that shifting rainfall patterns could lead to severe water shortages, especially in developing countries. West Bengal, a key agricultural state in eastern India, exemplifies these challenges. With diverse geography—from the Himalayas to the Sundarbans—and a climate ranging from tropical to subtropical, the state relies heavily on monsoon rains from June to September. Districts like Darjeeling and Cooch Behar receive over 250 cm of rainfall annually. As climate change intensifies, understanding precipitation trends becomes crucial for ensuring sustainable development, food security, and economic stability.

Numerous studies have examined spatial and temporal variability in rainfall to assess the impacts of climate change globally. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), significant seasonal, annual, and spatial variations in rainfall trends have been observed across Asia over recent decades. Rainfall increased between 10°N and 30°N from 1900 onwards, followed by a decline after 1970. Nicholls and Lavery (1992) reported rising summer rainfall in eastern Australia during the 1950s, while Savelieva et al. (2000) and Peterson et al. (2002) noted a decline in annual precipitation in Russia.

Osborn et al. (2000) found that daily precipitation in the UK from 1961 to 2000 became more intense in winter and less intense in summer, with an increase in heavy rainfall events. Akinremi et al. (2001) identified seasonal and spatial rainfall differences in the Canadian Prairies. Shi et al. (2002) observed increasing annual precipitation in western China, while Hu et al. (2003) and Zhai and Pan (2003) reported declining trends in northern China. Studies in Brazil (Silva, 2004), the USA (Bruns et al., 2007), and Mexico (Gonzalez et al., 2008) also showed varied rainfall trends.

In southern Italy, Longobardi and Villani (2010) and Caloiero et al. (2011) found predominantly decreasing trends in annual and seasonal rainfall, except for summer, which showed an increase. Most studies employed the Mann-Kendall test and Sen's Slope Estimator to detect and quantify rainfall trends. These non-parametric methods are effective in identifying long-term variability across different time scales—monthly, seasonal, and annual. Rahman and Begum (2013) applied these techniques to Bhola Island in Bangladesh and found mixed trends, though not statistically significant. Rainfall fluctuations have direct implications for India's economy, particularly in agriculture and water resource management. Despite extensive global research, there is limited analysis of rainfall trends in West Bengal at seasonal and annual scales. Recognizing this gap, the present study investigates spatial and temporal rainfall variability across 18 districts of West Bengal over a 102-year period (1901–2002).

Using the Mann-Kendall test and Sen's Slope Estimator, the study aims to assess the magnitude and direction of rainfall trends to better understand climate change impacts and guide water resource planning.

Materials and Methods

Study Area

The Indian state of West Bengal is the subject of the current study. As seen in Fig. 1, it is situated in the eastern region of India between 85°50'E and 89°50'E and between 21°38'N and 27°10'N. West Bengal is located on India's eastern bottleneck. The entire area of the state is 88,752 km². Kolkata, the seventh largest city in India, serves as the capital of West Bengal. This state has eighteen districts (Table 1). West Bengal experiences a tropical climate. Except for the northern area, which is a part of the Himalayan Mountain Range, the majority of the land is plains. The northern region of Darjeeling is renowned for its superior teas. The Sundarbans delta lies to the south of West Bengal. West Bengal's climate varies from humid subtropical in the north to tropical savannah in the south. West Bengal experiences five distinct seasons: spring, summer, rainy season, brief fall, and winter. West Bengal receives 125 cm of rainfall on average, with North Bengal receiving the most, between 200 and 400 cm, while the middle region receives between 150 and 200 cm. While the Plateau region only receives 100 to 125 cm of rainfall, coastal areas receive roughly 200 cm.

Data Analysis

The Indian Metrological Department (IMD) page of the India Water Portal website (http://www.indiawaterportal.org/metdata) provided the long-term monthly rainfall data of 18 stations in West Bengal during a period of 102 years (1901-2002). In order to do a trend analysis of rainfall over the 18 districts in West Bengal, monthly rainfall data for each station were added up to obtain yearly and seasonal data. Four categories—pre-monsoon (March–May), post-monsoon (October–November), winter (December–February), monsoon (June–September), and annual basis—were used to examine variations in the rainfall series for various seasons. Rainfall analysis is done independently for each season and the entire year.

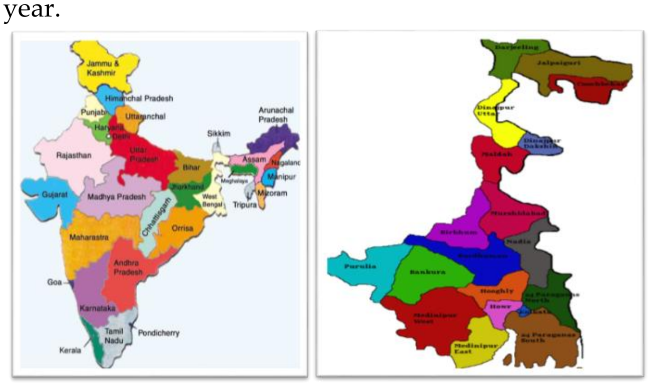

Fig.1 location map of study area

Table 1 Geographical coordinates of all the stations

S. No	Station name	Longitude	Latitude
1	Bankura	87.0786°E	23.2324°N
2	Bardhman	87.8615°E	23.2324°N
3	Birbhum	87.6186°E	23.8402°N

4	Dakshin Dinajpur	88.5565°E	25.3715°N
5	Darjeeling	88.2627°E	27.0360°N
6	Howrah	88.2636°E	22.5958°N
7	Hooghly	88.2461°E	22.8963°N
8	Jalpaiguru	88.7205°E	26.5435°N
9	Cooch Behar	89.4459°E	26.3357°N
10	Kolkata	88.3639°E	22.5726°N
11	Maldah	88.2461°E	25.1786°N
12	Medinipur	87.3215°E	22.4309°N
13	Murshidabad	88.2461°E	24.2290°N
14	Nadia	88.5565°E	23.4710°N
15	North24Parganas	88.3951°E	22.6342°N
16	Puruliya	86.3652°E	23.3321°N
17	South24 Parganas	88.4016°E	22.1352°N
18	Uttar Dinajpur	88.0510°E	25.9810°N

Methods

Trend analysis of a time-series involves assessing both the magnitude of change and its statistical significance. Numerous parametric and non-parametric approaches are available for detecting long-term rainfall trends. Parametric tests require the dataset to satisfy specific distributional assumptions, whereas non-parametric tests are more flexible, as they only require the observations to be independent and are robust to the presence of outliers (Lanzante, 1996). In this study, two widely used non-parametric methods—the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975) and Sen's slope estimator (Sen, 1968)—were applied to evaluate the direction and magnitude of rainfall trends. To further validate the MK results, a parametric linear regression analysis was also conducted for both seasonal and annual rainfall series. A brief description of the procedures adopted for the trend assessment is presented below.

Check for the Presence of Autocorrelation in the Rainfall Series

Finding a trend in a series is impacted by the presence of either positive or negative autocorrelation. A positively auto-correlated series increases the likelihood that a trend will be identified even if it may not exist. For negatively auto-correlated series, on the other hand, a trend cannot be identified. Equation 1 estimates the autocorrelation coefficient ρk of a discrete time series for lag-k.

$$\rho_k = \frac{\sum_{t=1}^{n-k}(x_t-\overline{x_t})(x_{t+k}-\overline{x_{t+k}})}{\sqrt{\sum_{t=1}^{n-k}(x_t-\overline{x_t})^2 * \sum_{t=1}^{n-k}(x_{t+k}-\overline{x_{t+k}})^2}} \quad \dots (1)$$

where, $\overline{x_t}$and $\mathrm{Var}(x_t)$ stand for the sample mean and sample variance of the first (n - k) terms, respectively, and $\mathrm{Var}(x_{t+k})$ are the sample mean and sample variance of the last (n- k) terms, respectively. Further, the no correlation hypothesis is checked by the lag-1 autocorrelation coefficient as H0: $\rho 1 = 0$ against H1: $|\rho 1| > 0$ using (Eq. 2).

$$t = |\rho_1|\sqrt{\frac{n-2}{1-\rho_1^2}} \quad \dots (2)$$

According to Cunderlik and Burn (2004), the test statistic t has a Student's distribution with (n − 2) degrees of freedom. The values of t_(α²2) are 1.645, 1.96, and 2.575 at the 10%, 5%, and 1% levels of significance, respectively. The null hypothesis regarding serial independence is rejected at the significance level α (in this case, 5%) if |t|≥t_ (α² (2)).

Determination of Significance of Trend

The statistical significance of rainfall trends in both seasonal and annual series was evaluated using the non-parametric Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975). The MK test is one of the most frequently applied tools for detecting monotonic trends in hydro-climatic time series, largely because it performs well even when datasets contain missing values or irregular sampling intervals. Numerous studies have adopted the MK approach to examine long-term changes in variables such as precipitation and temperature under climate-change conditions (Yu et al., 1993; Douglas et al., 2000; Yue et al., 2003; Burn et al., 2004; Singh et al., 2008). Compared to parametric trend-detection methods, the MK test offers several advantages (Duhan and Pandey, 2013). These include:
(1) no requirement for normally distributed data or homogeneous variance;
(2) reliance on medians rather than means, reducing sensitivity to extreme values;
(3) elimination of the need for data transformation;
(4) improved statistical power for skewed datasets; and
(5) the ability to incorporate censored observations without distortion (Helsel, 1987).

Despite these strengths, several researchers have shown that serial correlation within a time series can influence MK test results (Yue et al., 2002). The study by Yue et al. (2002) demonstrated that the test's power is affected by factors such as trend magnitude, series length, variability, and underlying distribution, and that its performance is comparable to that of Spearman's rho test. Von Storch (1995) and Yue and Wang (2002) further indicated that the standard MK test may falsely signal significant trends when data exhibit positive autocorrelation unless the test statistic's variance is properly adjusted—because autocorrelation increases the variance of the MK statistic (Yue et al., 2002a). Matalas and Sankarasubramanian (2003) also observed that serial dependence inflates the variability of slope estimates.

The Man-Kendall statistic (S) in this test quantifies the data's trend. A positive value denotes a rise over time, while a negative value denotes a drop. Finding the sign of the discrepancies between the outcomes of successive samples is the first stage. Sign (xj-xk) is an indicator function that, when j>k, yields the value -1, 0, or 1 based on the sign of xj-xk. The function is computed as follows (Eq. 3):

$$\mathrm{Sign(xj\text{-}xk)} = \begin{cases} 1 & \text{if } xj - xk > 0 \\ 0 & \text{if } xj - xk = 0 \\ -1 & \text{if } xj - xk < 0 \end{cases} \quad \ldots(3)$$

In the man Kendall statistics, (S) is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}(xj - xk)$$

where, N is the number of data points and sign (xj– xi) is the signum function.

This represents the number of positive and negative differences. For large samples, greater than 10, the test uses a normal distribution and the mean and the variance are determined as follows (Eq.4):

$$E[S]=0$$

$$\mathrm{var}(s) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_{k-1})(2t_k+5)}{18} \quad \ldots (4)$$

where, n is the length of data sets and t is the extent of any given tie or the number of data value in a group of determination. Normalized test statistic (Z) is calculated using the following equations (Eq 5):

$$Z_s = \begin{cases} \frac{s-1}{\sqrt{Var(s)}} & if\ s > 0 \\ \frac{s+1}{\sqrt{Var(s)}} & if\ s < 0 \\ o & if\ s = 0 \end{cases} \quad \ldots (5)$$

The test statistic Zs is utilized as a trend significance metric. Actually, the null hypothesis, H0, is tested using this test statistic. In a two-sided test, the null hypothesis is invalid if ∣ Zs∣ is greater than Zα/2, where α is the selected significance level (e.g., 5% with Z_0.025 = 1.96), suggesting that the trend is significant. An increasing or declining trend is indicated by a positive or negative value of Z. The following formulas (Eq. 6) are used to determine the probability density function for a normal distribution:

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{\frac{z^2}{2}} \quad \ldots (6)$$

Determination of Significance of Trend for Auto-Correlated Series Using Modified Man Kendall Test (MMK)

This technique eliminates the impact of all significant autocorrelation coefficients from a batch of data. In order to identify a trend line in a time series with autocorrelation, pre-whitening has been utilized (Cunderlik and Burn, 2004). As a result, the MMK test has been used to identify trends in auto-correlated series (Hamed and Rao, 1998; Rao et al., 2003). After deducting a non-parametric trend estimate, like Theil and Sen's median slope, from the data, the autocorrelation between ranks of the observations ρ_k are is assessed. Since the variance of S is underestimated when the data are positively auto correlated (Eq. 7), only significant values of ρ_k are employed to compute the variance correction factor n/ns*.

$$var(s) = \frac{n}{n^*} \quad \ldots (7)$$

where,n^* = effective sample size. The n/n^* ratio is computed directly from the equation (Eq. 8):

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k \quad \ldots (8)$$

where, n = actual number of observations, and ρ_k= lag k significant autocorrelation coefficient of rank k of time series. Var (S) was computed from the equation 8 and then it is substituted for Var (S) in Eq. 9. At last Man Kendall Z is tested for significance of trend comparing it with threshold levels i.e. 1.645 for 10%, 1.96 for 5% and 2.33 for 1% level of significance. The corrected variance is calculated by (Eq. 9):

$$V^*(S) = V(s) \times \frac{n}{n^*} \quad \ldots (9)$$

where, V(s) is from Eq. 10 and rest is as in the Man Kendall test.

Determination of Magnitude of Trend Using Sen's Slope Estimator

Sen's estimate was widely employed by many scholars in a hydro-meteorological time series to determine the amount of trend. Using the following formulas (Eq. 10), the slopes (T_i) of each pair of data are first determined in this method:

$$T_i = \frac{x_j - x_k}{j - k} \quad \ldots (10)$$

For i = 1, 2, 3……………………… N

where, x_j and x_k are data values at the time j and k (j>k) respectively. The median of these values of T_i is Sen's estimator of slopes which is calculated as (Eq. 11):

$$b = \begin{cases} T_{\frac{N+1}{2}} & \text{N is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{N is even} \end{cases} \quad \ldots (11)$$

After calculating β using a two-sided test at a 100 (1-α) % confidence interval, the non-parametric test can be used to determine the true slope. An upward (growing) trend in the time series is shown by a positive value of β, whereas a downward (decreasing) trend is indicated by a negative value.

Results and Discussion

The rainfall trend analysis over West Bengal for the period of 102 years (1901-2002) on monthly, seasonal and annual basis were carried by different methods such as Man-Kendall test, Sen's slope estimator. Rainfall characteristics of west Bengal for different stations is shown in Table 2. The maximum annual rainfall was found to be in Cooch Behar (3232.19 mm) and minimum were found to be in South 24 Parganas (797.57 mm). The maximum mean annual rainfall was found to be in Jalpaiguru (2346.86 mm) and minimum annual rainfall were found to be in Purulliya (1319.73 mm).

Table 2 Statistical properties of annual rainfall (mm)

S. NO.	Station	Maximum Rainfall	Minimum Rainfall	Mean(mm)	Standard Deviation
1	Bankura	2230.23	901.28	1412.52	121.54
2	Bardhman	2178.84	955.23	1418.21	2170.1
3	Birbhum	2178.79	925.11	1382.40	230.14
4	Dakshin Dinajpur	2020.91	917.84	1496.51	218.37
5	Darjeeling	2699.37	1435.21	2102.54	272.24
6	Howrah	2308.21	1002.37	1601.95	270.10
7	Hooghly	2263.89	1047.07	1540.79	252.45
8	Jalpaiguru	3192.19	1570.48	2346.86	300.80
9	Cooch Behar	3232.19	1370.27	2132.15	291.53
10	Kolkata	2326.69	1017.80	1585.32	274.69
11	Maldah	1894.37	902.28	1382.46	211.04
12	Medinipur	2297.89	1018.99	1570.03	233.91
13	Murshidabd	2044.69	941.70	1411.52	208.43
14	Nadia	2061.38	1011.22	1445.37	206.93
15	North 24 Parganas	2299.97	981.28	1607.67	270.11
16	Puruliya	2108.10	820.41	1319.73	201.80
17	South 24 Parganas	2006.28	797.57	1402.53	248.33
18	Uttar Dinajpur	2169.12	1037.80	1542.54	207.14

Estimation of Autocorrelation

To examine whether any inherent trend exists in the rainfall series, the lag-1 serial correlation was calculated prior to applying the MK test. The autocorrelation values for the monthly rainfall series are presented in Table 3. In January, six stations—Dakshin Dinajpur, Darjeeling, Jalpaiguri, Cooch Behar, Maldah and Uttar Dinajpur—exhibited significant positive autocorrelation at the 5% significance level. For February, three stations (Darjeeling, Jalpaiguri and Cooch Behar) showed significant autocorrelation at the same confidence level. Seasonal rainfall series covering pre-monsoon, monsoon, post-monsoon and winter were found to be free from serial dependence at the 5% significance level (Table 4). In the case of annual rainfall, all stations showed serial independence except Darjeeling and Cooch Behar, where significant lag-1 autocorrelation was detected.

Monthly, Seasonal and Annual Trend Analysis in 18 Stations from 1901-2002 using Man-Kendall / Modified and Sen's Estimator

Before applying the MK test all the series are tested for serial correlation using Lag-1 autocorrelation (Anderson, 1941) at 5% significance level to eliminate the effect of serial correlation. The MK test is applied directly to detect the trend to the series which are serially independent and the series which are auto-correlated, MMK test is applied. The results of MK/MMK test are shown in the Table 5. In the monthly rainfall series all the 18 stations in January, April, September and November showed the positive trend and none of the station showed significant trend at 95% confidence level. Month of February also showed non-significant trend in all the 18 stations. Maximum stations in the month of February showed decreasing trend except 3 stations (Jalpaiguru, North 24 Parganas and South 24 Parganas). In March season all the stations showed non-significant decreasing trend and maximum decreeing trend were found in Puruliya (1.001 mm). During the month of May, maximum stations were found to be non -significant and positive trend except 4 stations which showed decreasing trend (Hoogly, Kolkata, North 24 Parganas and South 24 Pargans).

In the month of June Maximum stations showed decreasing trend and Birbhum, Dakhsin Dinajpur, Darjeeling, Jalpaiguru, Cooch Behar, Maldah, Murshidabad and Uttar Dinajpur shows significantly decreasing trend at 95% confidence interval. Half of the stations during the month of July and August showed decreasing trend as well as half of the 18 stations showed increasing trend. In the month of October 16 stations showed positive trend except Darjeeling and Jalpaiguru which showed non- significant decreasing trend. Birbhum showed significant increasing trend in the month of October. In the month of December 1 station (Hoogly) showed no trend and 11 stations showed positive trend and rest 6 stations showed non-significantly decreasing trend. Table 6 presented the Z values seasonal and annual rainfall analysis.

In the annual rainfall series 5 stations out of 18 showed significant trend in which 2 stations showed increasing trend (North 24 parganas and south 24 Parganas) and 3 stations showed decreasing trend (Birbhum, Maldah and Uttar Dinajpur) at 95% confidence interval. Bankura, Bardhhaman, Dakshin Dinajpur, Darjeeling, Jalpaiguru, Cooch Behar, Murshidabad and Purulliya showed non- significant decreasing trend and Howrah, Hooghly, Kolkata, Medinipur, Nadia showed non-significant increasing trend in the annual rainfall series. In the Post Monsoon season 15 stations showed non-significant positive trend and 1 station (Birbhum) showed significant positive trend at 95% confidence interval and 2 stations (Darjeeling and Jalpaiguru) showed non-significant decreasing trend. None of the stations in the Pre Monsoon season and winter season showed significant trend. In the pre monsoon series out of 18 stations, 12 showed non-significant decreasing trend (Bankura, Bardhhaman, Birbhum, Howrah, Hooghly, Kolkata, Medinipur, Murshidabad, Nadia, North 24 Parganas, Purulliya, and South 24 Parganas) and 6 stations (Dakshin Dinajpur, Darjeeling, Jalpaiguru, Cooch Behar, Maldah and Uttar Dinajpur) showed non- significant increasing trend.

In the month of January all the 18 stations showed increasing trend and the magnitude of trend in the series was found to be 0.004 mm/year in South 24 Parganas to 0.048 mm/year in Puruliya (Table 7). In the month of February almost all the stations showed decreasing trend except Nadia (0.011 mm/year), North 24 Parganas (0.003 mm/year) and South 24 Parganas (0.01mm/year) and the magnitude of trend varied from -0.098 mm/year in Bankura to 0.011 mm/year in Nadia. In the month of March all the stations showed decreasing trend and the magnitude of trend varied from -0.072 mm/year in Hooghly to -0.02 mm/year in Darjeeling.

In the month of April all the stations showed increasing trend and the magnitude of trend ranged between 0.107 mm/year in Cooch Behar to 0.03 mm/year in Bankura district. Also in the month of May, maximum stations showed positive increasing trend except 3 stations (Hooghly, Kolkata, and North 24 Parganas) and the magnitude of trend in the month of May varied from 3.38E-4 mm/year in Howrah to -0.009 mm/year in Nadia. Almost all the stations showed decreasing trend in the month of June except 1 station (south 24 Pargans) and the magnitude of trend ranges from -1.166 mm/year to 0.13 mm/year in South 24 Parganas.

The magnitude of trend in the month of July ranged from -0.002 mm/year in Bankura to 0.547 mm/year in North 24 Parganas. In the month of August, the magnitude of trend varied from -0.519 mm/year in Maldah to 0.228 mm/year in north 24 Parganas. In the month of September and November all the stations showed increasing trend and the magnitude of trend in the month of September varied from 0.718 mm/year in North 24 Parganas to 0.101 mm/year in Uttar Dinajpur but in the month of November the magnitude of trend varied from 4.1E-4 mm/year in Darjeeling to 0.008 mm/year in Jalpaiguru. In the month of October, the magnitude of trend varied from -0.152 mm/year in Jalpaiguru to 0.464 mm/year in south 24 Parganas.in the month of December maximum station showed no trend except Darjeeling, north 24 Parganas and south 24 Parganas and the magnitude of trend varied form -1.72E-4 mm/year in south 24 Parganas to 4.78E-4 mm/year in north 24 Parganas.

In the pre monsoon season 6 of the stations showed positive trend and 12 stations showed negative trend (Table 8). The magnitude of trend varied from -0.207 mm/year in Kolkata to 0.27 mm/year in Jalpaiguru. In the post monsoon season out of 18 station 16 showed positive trend while 2 station showed negative trend (Darjeeling and Jalpaiguru) and the magnitude of trend varied from -0.108 mm/year in Jalpaiguru to 0.578 mm/year in south 24 Parganas. In the winter season the magnitude of trend varied from -0.109 mm/year in Birbhum to 8.630E-4 mm/year in Hooghly. In the monsoon season 11 station showed negative trend while 7 station showed positive trend and the magnitude of trend varied from -2.223 mm/year in Maldah to 1.511 mm/year in north 24 parganas and the maximum variation were showed in this season. In the annual rainfall series, the entire stations showed negative trend except 7 stations (Howrah, Hooghly, Kolkata, Medinipur, Nadia, North 24 Parganas and South 24 Parganas) and the magnitude of trend varied from -1.824 mm/year in Maldah to 2.051mm/year in North 24 Pargans.

Percentage Change of Rainfall for the Period of 102 Year

Table 9 depicted the percentage change of all the station considered for the study of duration of 102 years. In Pre monsoon rainfall series Kolkata (-8.515%) showed maximum decrease in percentage while Birbhum (-1.045%) showed minimum decrease in percentage. Also minimum decrease in percentage change while Jalpaiguru (-9.201%) showed maximum decrease in percentage change. Birbhum (38.427%) showed maximum significant increase in percentage change while Cooch Behar (6.754%) showed non-significant minimum increase in percentage change. In winter season all the stations showed non -significant increasing and decreasing percentage change. The maximum increase in percentage change was found in Darjeeling (13.296%) while minimum was found in South 24 Parganas (0.607%). The minimum percentage change was found in Howrah (-0.569%) while maximum was found in Bankura (-23.512%)

Table 3 Values of autocorrelation for ρ_k

S. No.	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bankura	0.018	-0.079	0.019	-0.111	0.037	-0.175	0.019	0.075	-0.125	0.024	-0.045	-0.010
2	Bardhman	0.040	-0.020	-0.003	-0.108	0.083	-0.161	0.000	0.055	-0.146	0.008	-0.054	-0.077
3	Birbhum	0.082	0.003	0.014	-0.082	0.105	-0.146	0.085	0.017	-0.112	0.011	-0.026	-0.074
4	Dakshin Dinajpur	0.251	0.049	-0.047	-0.114	0.132	-0.021	0.108	-0.093	-0.010	-0.109	-0.030	-0.101
5	Darjeeling	0.258	0.225	-0.038	-0.114	0.188	0.064	-0.058	-0.039	0.057	-0.098	0.032	0.036
6	Howrah	-0.021	-0.049	-0.036	-0.136	0.069	-0.111	-0.031	0.011	-0.162	-0.018	-0.087	-0.061
7	Hooghly	-0.008	-0.036	-0.028	-0.129	0.071	-0.133	-0.035	0.025	-0.158	-0.011	-0.084	-0.082
8	Jalpaiguru	0.230	0.258	-0.033	-0.039	0.136	0.046	0.031	-0.075	0.043	-0.107	0.051	0.036
9	Cooch Behar	0.244	0.267	-0.042	-0.009	0.106	0.068	0.079	-0.114	0.075	-0.098	-0.030	0.002
10	Kolkata	-0.015	-0.028	-0.037	-0.129	0.072	-0.118	-0.038	0.016	-0.153	-0.019	-0.087	-0.091
11	Maldah	0.277	0.036	-0.023	-0.092	0.103	-0.040	0.100	-0.052	-0.044	-0.056	-0.025	-0.112
12	Medinipur	-0.022	-0.108	-0.022	-0.146	0.058	-0.116	-0.008	0.002	-0.183	0.006	-0.078	0.026
13	Murshidabad	0.156	0.043	-0.018	-0.069	0.134	-0.134	0.068	-0.032	-0.079	-0.025	-0.039	-0.119
14	Nadia	0.085	0.026	-0.042	-0.095	0.125	-0.126	-0.039	-0.043	-0.102	-0.065	-0.073	-0.118
15	North24 Parganas	0.012	-0.032	-0.052	-0.119	0.101	-0.093	-0.058	0.011	-0.146	-0.054	-0.095	-0.095
16	Puruliya	0.008	-0.073	0.044	-0.074	0.012	-0.186	0.067	0.074	-0.048	0.037	-0.014	0.032
17	South24 Parganas	-0.018	-0.059	-0.048	-0.127	0.083	-0.079	-0.035	0.006	-0.161	-0.031	-0.087	-0.058
18	Uttar Dinajpur	0.284	0.109	-0.034	-0.112	0.123	0.082	-0.007	-0.015	0.006	-0.098	-0.056	-0.072

Table 4 Values of autocorrelation for annual and seasonal rainfall series

S.no	Station	Pre monsoon	Post monsoon	Winter	monsoon	annual
1	Bankura	0.025	0.039	0.019	-0.133	-0.164
2	Bardhman	-0.005	0.006	0.089	-0.173	-0.164
3	Birbhum	0.007	0.000	0.159	-0.094	-0.119
4	Dakshin Dinajpur	0.026	-0.120	0.115	0.085	0.015
5	Darjeeling	0.089	-0.093	0.094	0.191	0.210
6	Howrah	-0.042	0.001	0.005	-0.131	-0.089
7	Hooghly	-0.029	0.001	0.025	-0.152	-0.118
8	Jalpaiguru	0.103	-0.100	0.087	0.152	0.160
9	Cooch Behar	0.110	-0.090	0.118	0.163	0.211
10	Kolkata	-0.037	-0.005	0.023	-0.131	-0.098
11	Maldah	-0.002	-0.071	0.168	0.070	-0.027
12	Medinipur	-0.043	0.027	-0.053	-0.176	-0.121
13	Murshidabad	0.015	-0.048	0.174	-0.115	-0.164
14	Nadia	-0.005	-0.074	0.114	-0.193	-0.182
15	North 24 Parganas	-0.036	-0.034	0.008	-0.126	-0.096
16	Puruliya	0.052	0.054	-0.009	-0.035	-0.036
17	South 24 Parganas	-0.052	-0.005	-0.016	-0.108	-0.067
18	Uttar Dinajpur	0.028	-0.099	0.108	0.178	0.103

Table 5 Values of Z of monthly rainfall series (1901-2002) using MK/MMK test

SI no	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bankura	1.118	-1.27	-0.959	0.319	0.425	-1.669	-0.096	-1.035	1.311	1.540	1.645	-0.228
2	Bardhman	0.856	-1.200	-0.824	0.448	0.261	-1.293	-0.267	-1.070	1.082	1.851	1.776	0.140
3	Birbhum	1.056	-1.490	-0.938	0.624	0.309	**-2.215**	-1.628	-1.563	0.495	**2.039**	1.737	0.4520
4	Dakshin Dinajpur	0.00047	-1.681	-0.783	1.182	1.299	**-2.948**	-1.628	-1.704	0.777	1.634	1.717	0.684
5	Darjeeling	0.00062	-0.00056	-0.566	0.313	0.554	**-2.502**	-0.671	-0.806	0.824	-0.947	0.199	-0.801
6	Howrah	1.060	-0.085	-0.912	0.137	0.002	-0.114	1.170	0.243	1.722	1.640	1.747	0.451
7	Hooghly	0.96	-0.407	-0.874	0.225	-0.055	-0.352	0.701	-0.061	1.605	1.651	1.849	0
8	Jalpaiguru	0.00077	0.00043	-0.366	0.882	0.977	**-2.033**	-0.055	-0.677	1.135	-0.789	0.728	-0.497
9	Cooch Behar	0.00072	-0.00053	-0.519	0.812	1.270	**-1.986**	-0.202	-0.613	1.153	0.167	0.856	0.026
10	Kolkata	1.102	-0.090	-0.968	0.246	-0.114	-0.126	0.924	0.261	1.651	1.710	1.736	0.782
11	Maldah	0.00053	-1.769	-0.959	1.018	0.842	**-3.365**	-1.957	-1.728	0.396	1.781	1.846	0.595
12	Medinipur	0.983	-0.419	-0.751	0.096	0.308	-0.548	1.305	0.178	1.423	1.599	1.517	-0.263
13	Murshidabad	0.654	-1.464	-0.909	0.918	0.360	**-1.980**	-1.029	-1.610	0.977	1.628	1.870	0.567
14	Nadia	0.619	-0.739	-0.619	0.566	0.044	-0.642	0.325	-0.666	1.839	1.505	1.718	0.650
15	North 24 Parganas	0.589	0.093	-0.399	0.478	-0.255	0.267	1.546	0.595	1.957	1.499	1.511	0.443
16	Puruliya	1.623	-1.566	-1.001	0.225	0.701	-1.728	-0.366	-1.423	1.018	1.276	1.363	-0.352
17	South 24 Parganas	0.542	0.272	-0.580	0.149	-0.102	0.331	1.516	0.642	1.757	1.599	1.232	-0.302
18	Uttar Dinajpur	0.00057	-1.766	-0.853	0.801	1.035	**-3.559**	-1.417	-1.663	0.313	1.205	1.764	0.766

Table 6 Values of Z for seasonal and annual rainfall series using MK/MMK Test

S.no	Station	Pre monsoon	Post monsoon	Winter	monsoon	annual
1	Bankura	-0.302	1.646	-0.924	-0.707	-0.624
2	Bardhman	-0.460	1.974	-0.830	-1.006	-0.853
3	Birbhum	-0.255	**2.051**	-1.258	**-2.532**	**-2.185**
4	Dakshin Dinajpur	1.135	1.810	0.055	**-2.549**	-1.745
5	Darjeeling	0.396	-0.560	0.783	-1.693	-0.00063
6	Howrah	-0.490	1.851	0.184	1.569	1.634
7	Hooghly	-0.613	1.857	0.002	1.112	1.164
8	Jalpaiguru	0.965	-0.507	0.724	-1.100	-0.865
9	Cooch Behar	0.830	0.425	0.531	-0.795	-0.00032
10	Kolkata	-0.607	1.892	0..67	1.522	1.581
11	Maldah	0.384	1.681	-0.528	**-3.254**	**-2.649**
12	Medinipur	-0.055	1.822	-0.079	1.135	1.223
13	Murshidabad	-0.073	1.516	-0.789	-1.898	-1.734
14	Nadia	-0.366	1.540	-0.243	0.225	0.425
15	North 24 Parganas	-0.390	1.605	0.331	**1.968**	**2.092**
16	Puruliya	-0.085	1.170	-0.930	-1.229	-1.358
17	South 24 Parganas	-0.378	1.816	0.225	**2.074**	**2.391**
18	Uttar Dinajpur	0.748	1.270	0.108	**-3.001**	**-2.262**

Table 7 Shows the magnitude of trend (β) for monthly rainfall series

SI NO	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bankura	0.022	-0.098	-0.068	0.03	0.065	-0.526	-0.02	-0.322	0.367	0.285	0.02	0
2	Bardhhaman	0.014	-0.076	-0.065	0.046	0.041	-0.489	-0.067	-0.306	0.315	0.355	0.026	0
3	Birbhum	0.015	-0.087	-0.067	0.049	0.049	-0.747	-0.426	-0.476	0.176	0.405	0.027	0
4	Dakshin Dinajpur	0.023	-0.051	-0.029	0.114	0.211	-0.916	-0.545	-0.482	0.26	0.293	0.024	0
5	Darjeeling	0.03	-0.041	-0.02	0.036	0.141	-1.166	-0.334	-0.27	0.347	-0.156	4.1E-4	-1.3E-4
6	Howrah	0.008	-0.003	-0.065	0.016	3.38E-4	-0.041	0.438	0.106	0.628	0.451	0.031	0
7	Hooghly	0.013	-0.022	-0.072	0.025	-0.009	-0.126	0.284	-0.026	0.595	0.396	0.028	0
8	Jalpaiguru	0.025	-0.03	-0.022	0.097	0.251	-0.953	-0.026	-0.246	0.441	-0.152	0.008	0
9	Cooch Behar	0.023	-0.039	-0.028	0.107	0.357	-0.927	-0.093	-0.259	0.498	0.042	0.01	0
10	Kolkata	0.01	-0.003	-0.065	0.029	-0.021	-0.051	0.361	0.09	0.655	0.427	0.026	0
11	Maldah	0.033	-0.06	-0.036	0.078	0.12	-0.947	-0.62	-0.519	0.136	0.285	0.025	0
12	Mednipur	0.013	-0.028	-0.042	0.012	0.06	-0.175	0.396	0.058	0.457	0.399	0.046	0

13	Murshidabad	0.011	-0.069	-0.057	0.081	0.062	-0.538	-0.284	-0.47	0.286	0.297	0.03	0
14	Nadia	0.011	0.011	-0.048	0.063	0.009	-0.192	0.089	-0.225	0.527	0.292	0.026	0
15	North 24 Parganas	0.006	0.003	-0.029	0.054	-0.057	0.097	0.547	0.228	0.718	0.435	0.044	4.78E-4
16	Puruliya	0.048	-0.109	-0.053	0.017	0.082	-0.526	-0.119	-0.467	0.269	0.233	0.013	0
17	South 24 Parganas	0.004	0.01	-0.028	0.014	-0.023	0.13	0.478	0.21	0.579	0.464	0.041	-1.72E-4
18	Uttar Dinajpur	0.033	-0.05	-0.03	0.075	0.172	-1.067	-0.548	-0.41	0.101	0.186	0.016	0

Note: Bold values indicate the statistical significance at 95% level (+ve sign shows the increasing trend and –ve sign shows the decreasing trend).

Table 8 Shows the magnitude of trend (β) for annual and seasonal rainfall series

S.no	**Satiation**	**Pre monsoon**	**Post monsoon**	**Winter**	**monsoon**	**annual**
1	Bankura	-0.075	0.302	-0.089	-0.482	-0.473
2	Bardhman	-0.098	0.375	-0.072	-0.656	-0.646
3	Birbhum	-0.048	0.422	-0.109	-1.811	-1.63
4	Dakshin Dinajpur	0.246	0.351	0.002	-1.761	-1.306
5	Darjeeling	0.123	-0.097	0.046	-1.536	-1.456
6	Howrah	-0.134	0.577	0.021	1.097	1.616
7	Hooghly	-0.161	0.471	**8.630E-4**	0.614	1.047
8	Jalpaiguru	0.27	-0.108	0.038	-0.928	-0.879
9	Cooch Behar	0.267	0.101	0.028	-0.673	-0.608
10	Kolkata	-0.207	0.549	0.009	1.029	1.539
11	Maldah	0.071	0.345	-0.032	-2.223	-1.824
12	Medinipur	-0.019	0.483	-0.005	0.708	1.059
13	Murshidabad	-0.013	0.315	-0.061	-1.341	-1.22
14	Nadia	-0.115	0.333	-0.016	0.146	0.306
15	North 24 Parganas	-0.157	0.482	0.034	1.511	2.051
16	Puruliya	-0.018	0.201	-0.096	-0.856	-0.889
17	South 24 Parganas	-0.101	0.578	0.028	1.384	1.94
18	Uttar Dinajpur	0.14	0.217	0.007	-1.92	-1.624

Note: Bold value indicates the statistical significance at 95% level (+ve sign shows the increasing trend and –ve sign shows the decreasing trend).

Table 9 Percentage change for the period of 102 year

S.No	Station	Pre monsoon	Post monsoon	Winter	Monsoon	Annual
1	Bankura	-3.007	29.412	-23.512	-3.538	-2.488
2	Bardhman	-4.602	34.753	-23.460	-5.232	-3.751
3	Birbhum	-1.045	**38.427**	-22.550	**-14.57**	**-10.535**
4	Dakshin Dinajpur	15.712	29.618	-2.389	**-13.455**	-7.457
5	Darjeeling	8.075	-9.040	13.296	-7.530	-5.491
6	Howrah	-6.654	33.957	-0.569	8.611	9.237
7	Hooghly	-7.232	34.203	-5.181	4.849	6.551
8	Jalpaiguru	11.093	-9.201	12.269	-4.1334	-2.260
9	Cooch Behar	11.060	6.754	9.393	-3.1002	-1.803
10	Kolkata	-8.515	36.080	-2.725	7.858	8.918
11	Maldah	7.901	31.064	-14.55	**-1.8233**	**-12.158**
12	Medinipur	0.102	31.467	-5.918	5.487	6.569
13	Murshidabad	1.045	26.773	-20.028	-10.232	-7.529
14	Nadia	-3.957	27.663	-7.612	1.493	2.470
15	North 24 Parganas	-6.737	27.737	3.424	**11.314**	**11.974**
16	Puruliya	0.118	24.717	-22.45	-6.640	-5.969
17	South 24 Parganas	-6.737	33.107	0.607	**11.993**	**12.163**
18	Uttar Dinajpur	11.662	21.292	-1.843	**-13.732**	**-9.148**

Spatial Variation

Figures 2(a) to Fig 2 (e) illustrate the spatial variation in percentage change of rainfall across the study period for different seasons—pre-monsoon, post-monsoon, winter, monsoon—and annual totals. The southern region of West Bengal exhibits the greatest reduction in rainfall during the pre-monsoon season, whereas it shows a significant increase during the post-monsoon period. The spatial patterns of monsoon and annual rainfall are notably similar, highlighting the state's strong dependence on monsoonal precipitation. Overall, the northern part of West Bengal demonstrates a positive trend in rainfall variability, while the southern region shows a negative trend.

Conclusions

The Mann-Kendall (MK), Modified Mann-Kendall (MMK), and Sen's Slope estimator are effective non-parametric techniques for detecting rainfall trends and quantifying their magnitude. MMK was applied to auto correlated data for improved accuracy. On monthly time scale out of 18 stations, 9 showed statistically significant trends at the 95% confidence level. Eight stations showed significant trends in June, and Birbhum in October. Sen's Slope values ranged from 0.004 mm/year (South 24 Parganas) to 0.048 mm/year (Purulia). February and March showed mostly decreasing trends, while April and May showed increasing trends across most stations. June had predominantly decreasing trends, except South 24 Parganas. Post-monsoon season had mostly non-significant positive trends, with Birbhum showing a significant increase. No significant trends were observed during the pre-monsoon and winter seasons. Eleven stations showed negative trends during the monsoon, with four being statistically significant. North and South 24 Parganas showed significant increases, while others had non-significant positive trends. Five stations showed significant annual trends—North and South 24 Parganas with increasing trends, and Birbhum, Malda, and Uttar Dinajpur with decreasing trends. Other stations showed non-significant tren

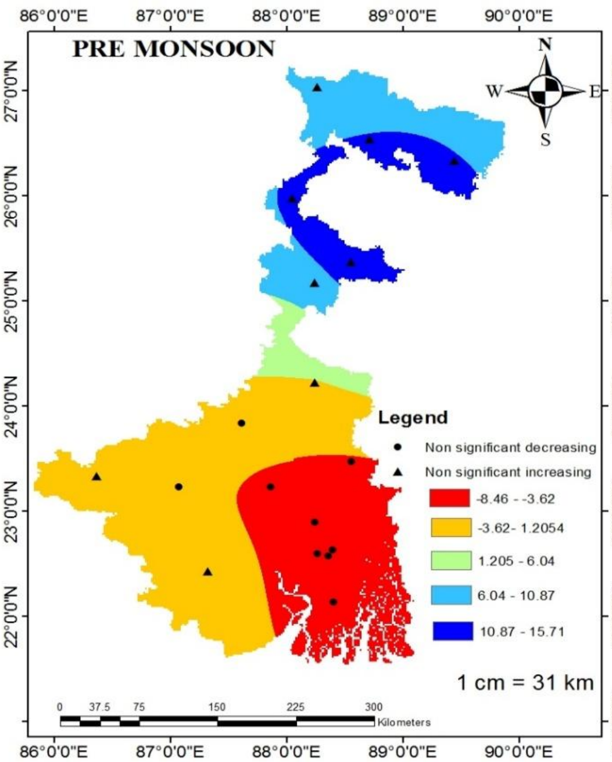

Fig.2(a) Percentage change of Pre-Monsoon

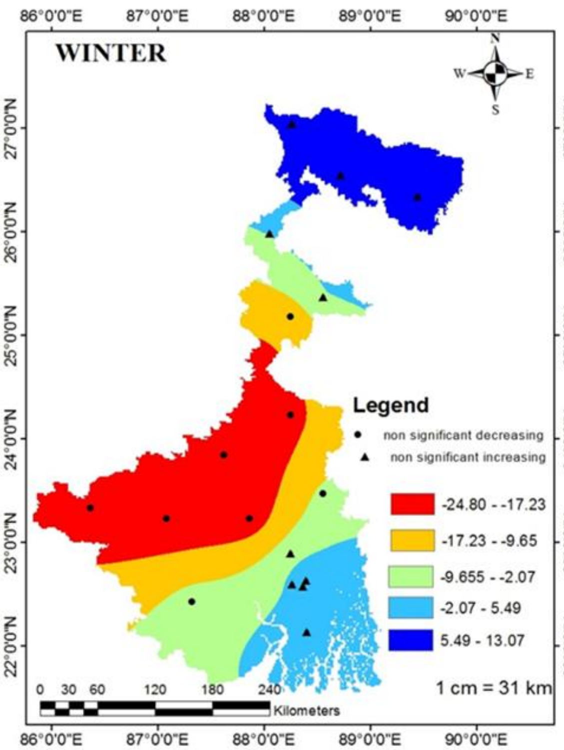

Fig.2 (c) Percentage change of winter

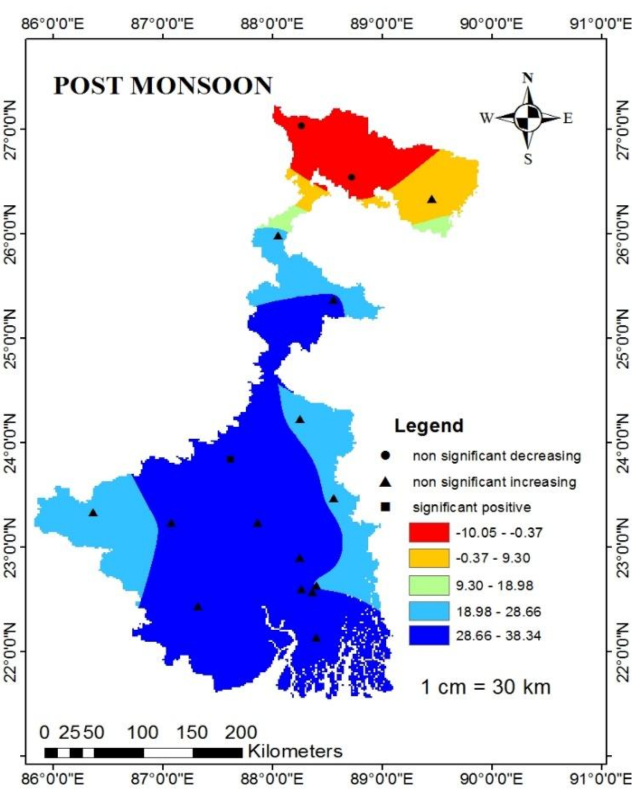

Fig.2 (b) Percentage change of Post Monsoon

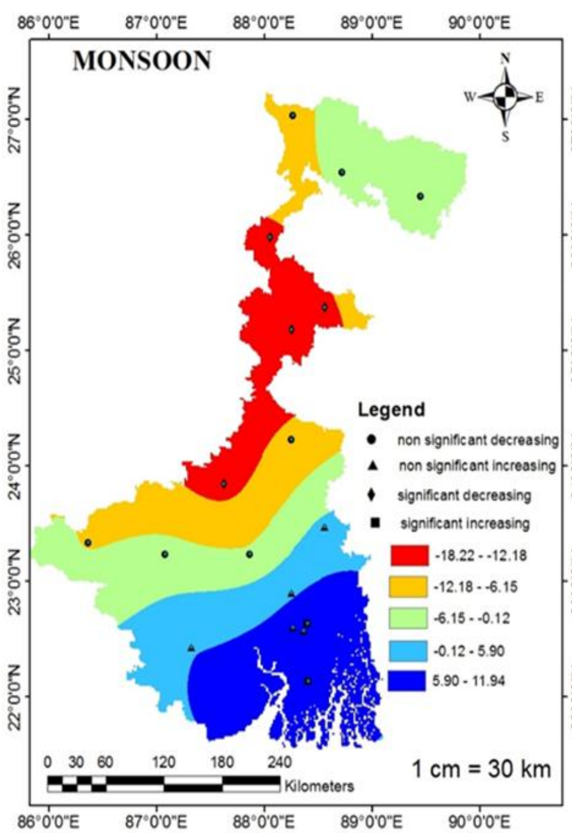

Fig.2 (d) Percentage change of Monsoon

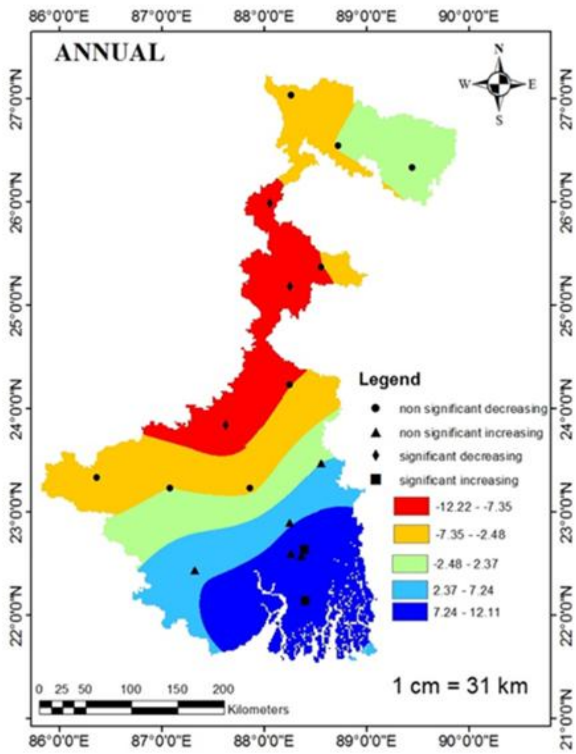

Fig.2 (e) Percentage change of Annual

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research received no external funding.

References

Akinremi, O. O., McGinn, S. M. and Cutforth, H. W. 2001. Seasonal and spatial patterns of rainfall trends on the Canadian prairies. International Journal of Climatology, 14(9): 2177-2182.

Bruns, T. E. 2007. Topology optimization of convection-dominated, steady-state heat transfer problems. International Journal of Heat and Mass Transfer, 50(15-16): 2859-2873.

Caloiero, T., Coscarelli, R., Ferrari, E. and Mancini, M. 2011. Trend detection of annual and seasonal rainfall in Calabria, Southern Italy. International Journal of Climatology, 31(1): 44-56.

Cunderlik, J. M. and Burn, D. H. 2004. Linkages between regional trends in monthly maximum flows and selected climatic variables. Journal of Hydrologic Engineering, 9(4): 246-256.

Da Silva, A. M. 2004. Rainfall erosivity map for Brazil. Catena, 57(3): 251-259.

Da Silva, R. M., Santos, C. A., Moreira, M., Corte-Real, J., Silva, V. C. and Medeiros, I. C. 2015. Rainfall and river flow trends using Mann-Kendall and Sen's slope estimator tests in the Cobres River basin. Natural Hazards, 77(2): 1205-1221.

Douglas, K. S., Guy, L. S. and Hart, S. D. 2009. Psychosis as a risk factor for violence to others: A meta-analysis. Psychological Bulletin, 135(5): 679.

Duhan, D. and Pandey, A. 2013. Statistical analysis of long-term spatial and temporal trends of precipitation during 1901-2002 at Madhya Pradesh, India. Atmospheric Research, 122: 136-149.

Hamed, K. H. and Rao, A. R. 1998. A modified Mann–Kendall trend test for autocorrelated data. Journal of Hydrology, 204: 182-196.

Helsel, D. R. 1987. Advantages of nonparametric procedures for analysis of water quality data. Hydrologic Sciences Journal, 32(2): 179-190.

Hu, J. Y., Ong, S. L., Ng, W. J., Lu, F. and Fan, X. J. 2003. A new method for characterizing denitrifying phosphorus removal bacteria. Water Research, 37(14): 3463-3471.

Lanzante, J. R. 1996. Resistant, robust and non-parametric techniques for analysis of climate data. International Journal of Climatology, 16: 1197-1226.

Longobardi, A. and Villani, P. 2010. Trend analysis of annual and seasonal rainfall in the Mediterranean area. International Journal of Climatology, 30: 1538-1546.

Matalas, N. C. and Sankarasubramanian, A. 2003. Effect of persistence on trend detection via regression. Water Resources Research, 39(12).

Nicholls, N. and Lavery, B. 1992. Australian rainfall trends during the twentieth century. International Journal of Climatology, 12(2): 153-163.

Osborn, A. M., Moore, E. R. and Timmis, K. N. 2000. Evaluation of terminal restriction fragment analysis for microbial community study. Environmental Microbiology, 2(1): 39-50.

Perez-Gonzalez, P. G., Trujillo, I., Barro, G., Gallego, J., Zamorano, J. and Conselice, C. J. 2008. Evolutionary paths of the most massive galaxies since z~2. Astrophysical Journal, 687(1): 50.

Peterson, B. M., Ferrarese, L., Gilbert, K. M., Kaspi, S., Malkan, M. A., Maoz, D. and others. 2004. Central masses and broad-line region sizes of active galactic nuclei. Astrophysical Journal,

Rao, S. M., Nestor, D. B., Turnshek, D. A., Lane, W. M., Monier, E. M. and Bergeron, J. 2003. Low-redshift damped Lyα galaxies. Astrophysical Journal, 595(1); 94.

Savelieva, N. I., Semiletov, I. P., Vasilevskaya, L. N. and Pugach, S. P. 2000. A climate shift in seasonal meteorological and hydrological parameters for Northeastern Asia. Progress in Oceanography, 47(2-4): 279-297.

Sen, P. K. 1968. Estimates of regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63(324): 1379-1389.

Shi, H., Quintero, F. J., Pardo, J. M. and Zhu, J. K. 2002. Na/H antiporter SOS1 controls Na transport in plants. Plant Cell, 14(2): 465-477.

Singh, P., Kumar, V., Thomas, T. and Arora, M. 2008. Basin-wise assessment of rainfall and temperature trends in north-west and central India. Hydrological Sciences Journal, 53: 421-433.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., and others. 2007. IPCC Fourth Assessment Report.

Trilling, L. 1941. Sherwood Anderson. The Kenyon Review, 3(3): 293-302.

Von Storch, H. and Navarra, A. 1995. Analysis of climate variability: Applications of statistical techniques. Springer-Verlag.

Yu, F. H., Shull, G. E. and Orlowski, J. 1993. Functional properties of rat Na/H exchanger NHE-2. Journal of Biological Chemistry, 268(34): 25536-25541.

Yue, S. and Hashino, M. 2003. Long-term trends of precipitation in Japan. Journal of Atmospheric Water Resources Association, 39(3): 587-596.

Yue, S. and Wang, C. 2004. Mann-Kendall test modified by effective sample size. Water Resources Management, 18(3): 201-218.

Yue, S., Pilon, P., Phinney, B. and Cavadias, G. 2002. Influence of autocorrelation on trend detection. Hydrological Processes, 16(9): 1807-1829.

Zhai, P. and Pan, X. 2003. Trends in temperature extremes in China. Geophysical Research Letters, 30(17).