Original Research Article

Rainfall Pattern Analysis and Change Point Detection: Kodagu District, Karnataka

Comment [A1]: Consider revising the topic to align it with include all results

Abstract

This study aims to analyze the long-term trends in monthly, seasonal, and annual rainfall in Kodagu district, Karnataka, from 1950 to 2023. The Wallis and Moore Phase-Frequency testwas employed to assess the randomness of the rainfall, while the linear regression trend line, Mann-Kendall (MK) test, and Modified-Mann Kendall (MMK) test were used to identify trends in the rainfall data. The MMK test revealed a significant increasing trend in rainfall during August (2.34 mm $year^{-1}$) and September (1.78 mm $year^{-1}$). Conversely, the other months, as well as the seasonal and annual rainfall, showed no significant trends. The Buishand U test identified August, September, and the monsoon season in the year 2003 as the trend change points, with no significant change points detected for the other months, seasons, or annual rainfall

Comment [A2]: I suggest to change this sentence to: "This study aims to analyze the long-term trends and Change Point Detectionin monthly, seasonal, and annual rainfall in Kodagu district, Karnataka, from 1950 to 2023"

Keywords: Rainfall, Trend Analysis, Mann-Kendall test, Sen's Slope estimator and Buishand U.

1. Introduction

Rainfall is a fundamental component of the hydrological cycle and plays a crucial role in sustaining agricultural productivity, water resources, and overall economic stability in India. As a predominantly agrarian country, India's economy is significantly influenced by the monsoon, which contributes to about 70-80% of the annual rainfall[9]. The spatial and temporal distribution of rainfall across India is highly variable, with certain regions experiencing abundant precipitation while others face frequent droughts. This variability in rainfall distribution not only

Comment [A3]: It appears that references where omitted affects agricultural output but also impacts water availability, hydroelectric power generation, and livelihoods across the country. The Indian economy, particularly in rural areas, is heavily reliant on consistent and timely rainfall; any deviation from the expected patterns can lead to significant economic losses and challenges in food security. Within this broader national context, the Kodagu district in Karnataka stands out as a region where rainfall is not only critical for agriculture but also for maintaining the delicate ecological balance of the Western Ghats. Kodagu, known for its coffee plantations, receives substantial rainfall due to its location in the Western Ghats[7]. This rainfall is essential for the cultivation of coffee, which is a major economic activity in the region. The district experiences a marked spatial gradient in rainfall, with the western parts receiving over 5000 mm of rain annually, while the eastern parts receive about 1200 mm[12]. This variation in rainfall has a direct impact on the agricultural productivity and water resources of the region. Given the importance of rainfall in Kodagu, there is a pressing need to analyze long-term trends and detect any significant changes in the rainfall patterns. Understanding these trends is crucial for planning and managing agricultural activities, ensuring sustainable water resources, and mitigating the potential impacts of climate change.

Various methods are available for trend analysis, with non-parametric methods like the Mann-Kendall (MK) and Spearman's rho (SR) tests being widely used due to their robustness and ability to handle non-normally distributed data. These methods are often paired with Sen's slope estimator, which provides a measure of the trend's magnitude. However, these traditional methods have certain limitations, including sensitivity to autocorrelation and challenges in detecting non-monotonic trends[11]. To address these issues, the Modified Mann-Kendall test has been developed, offering improvements over the traditional MK test by accounting for autocorrelation and providing more accurate trend detection in data sets with serial dependence[3]. In addition to trend analysis, detecting change points in rainfall data is equally important, as it helps identify sudden shifts in rainfall patterns that may indicate significant climatic changes. The Buishand U test is a well-established method for detecting change points in hydrological and climatic data, providing a robust statistical framework for identifying the timing of these shifts. By combining trend analysis with change point detection, this study aims to provide a comprehensive understanding of rainfall patterns in Kodagu District, contributing to better-informed decision-making for sustainable development in the region.

2. Methodology

2.1 Study area

Kodagu District, located in the Western Ghats of Karnataka, is a significant region in terms of biodiversity and agriculture, covering an area of approximately 4,102 km²(1,584 sq mi). The district lies between 11°56' to 12°52' North latitude and 75°22' to 76°11' East longitude. This region contributes to about 2.14% of Karnataka's total geographical area[10]. Kodagu is characterized by a varied topography, with its landscape predominantly covered by forests and coffee plantations. The elevation ranges from about 900 meters to 1,750 meters above sea level, which creates diverse climatic conditions across the district. The climate is typically tropical with a strong monsoonal influence, resulting in heavy rainfall predominantly during the southwest monsoon (June to September). For this study, the daily Rainfall (mm) data from 1950 to 2023 were obtained using the IMDLIB Python package, which facilitates downloading and handling gridded data from the India Meteorological Department (IMD). The daily Rainfall was converted into monthly and monsoon seasons for further analysis (https://doi.org/10.5281/zenodo.4405233). The study examines trends during the pre-monsoon (March-May),monsoon (June-September), post-monsoon (October-November), and winter

(December-February) seasons, along with annual rainfall trends.The Study area map was presented in Fig 1.

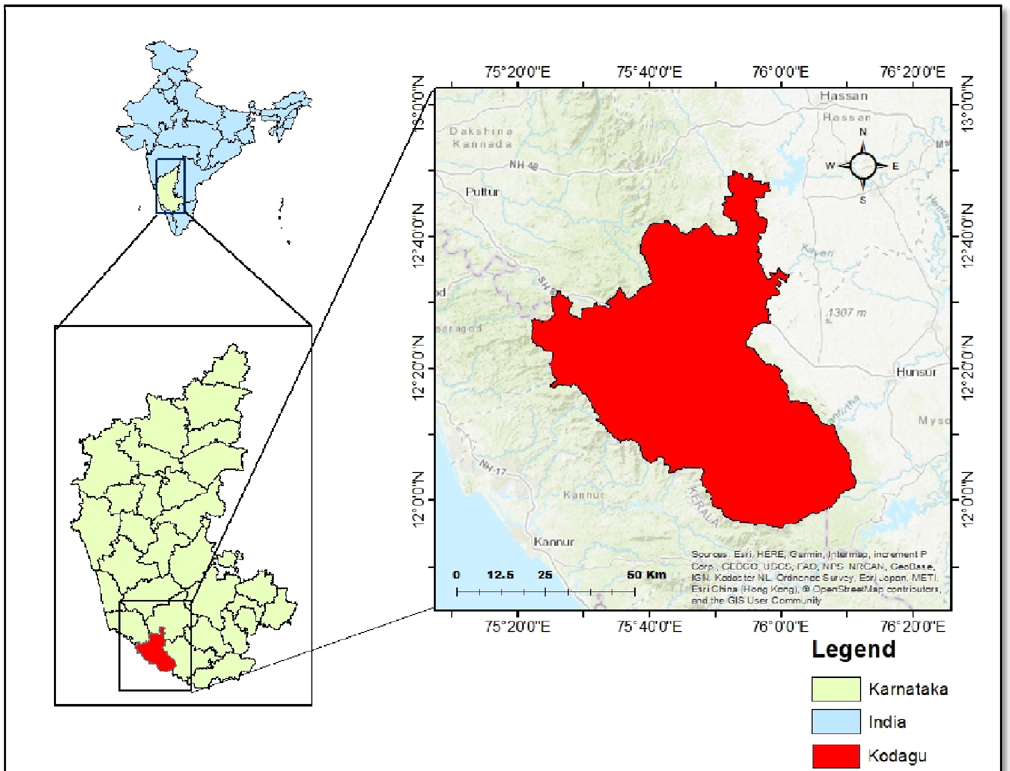

Fig 1: Study area map of Kodagu district, Karnataka

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2.2 Trend Analysis

A trend in a time series dataset represents a recognizable pattern, either upward or downward, indicating a positive or negative direction [6]. Estimating this trend requires the use of statistical tests, which can be either parametric or non-parametric. In this study, both parametric and non-parametric tests, including Linear Regression, the Wallis and Moore Phase-Frequency test, Mann-Kendall's test, Sen's slope estimator, and the Modified Mann-Kendall test, were applied to identify trends in the rainfall data. Additionally, the Buishand U test was utilized to detect change points over the observed period.

2.2.1 Wallis and Moore Phase-Frequency test

The Wallis and Moore Phase-Frequency test, often referred to as the Phase-Frequency test, is a parametric statistical method used to assess the randomness in a time series dataset. It helps determine whether observed fluctuations are random or exhibit a significant underlying pattern. By analyzing the phase and frequency of data points, the test can detect non-random behavior, indicating the presence of trends or cycles within the data[13].

Test procedure:

Null Hypothesis (H_0) = A time series exhibits inherent randomness.

Alternative Hypotheses (H_1) = A time series doesn't exhibit inherent randomness.

Test statistic:

$$Z = \frac{\left|h - \left(\frac{2n-7}{3}\right)\right|}{\sqrt{\frac{16n-29}{90}}}$$

Where, h is the number of phases.

2.2.2 Linear regression

Linear regression analysis is one of the most utilized parametric models for identifying trends in time series data. This model establishes a relationship between two variables-dependent and independent-by fitting a linear equation to the observed data[5]. The linear regression model is typically expressed by the equation:

$$Y = a + mX$$

Where, Y represents the dependent variable, X is the independent variable, a is the intercept constant, and m is the slope of the line (regression coefficient).

2.2.3 Mann-Kendall (MK) test

The Mann-Kendall (MK) trend test is a nonparametric alternative to parametric methods for trend analysis, particularly well-suited for detecting trends in rainfall data. The Mann-Kendall statistic (S) is calculated using the following equation:

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

Where,x_j and x_i are the annual values in years j and i (with $j > i$). The values of $sign(x_j - x_i) = 0$ represents the number of positive differences minus the number of negative differences for all pairs considered. For large samples (N > 10), the test is conducted using the Z statistic, with the mean and variance given by:

$$E(S) = 0$$

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

Computing the MK test statistic, Z_{MK}, is performed as follows:

$$z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \; if \; S < 0 \end{cases}$$

A positive z value indicates that the data tends to increase over time, while a negative z value suggests a decreasing trend. To determine whether there is a significant upward or downward trend at the α level of significance, the null hypothesis H_0 is rejected if $||z_{MK}| \geq z_{1-\alpha/2}$.

2.2.4 Modified Mann-Kendall (MMK) test

The Modified Mann-Kendall test is a non-parametric statistical method used to evaluate monotonic trends, whether increasing or decreasing, in time series data that exhibits positive autocorrelation. While the original Mann-Kendall test may produce misleading results in the presence of serial correlation, the MMK test addresses this by applying a variance correction factor. This adjustment accounts for the autocorrelation, providing more accurate trend detection[14]. The variance of the S statistic is calculated as follows:

$$V^*(S) = V(S).\frac{n}{n^*}$$

Where, n is the Actual Sample Size (ASS) of the data, and n/n^* is referred to as the Correction Factor (C.F). $V(S)$ represents the variance of S as calculated in the original MK test. The null hypothesis H_0 suggests that there is no trend in the data series. The null hypothesis is rejected when the Z-transformed statistic exceeds the critical Z value at a 5% significance level, i.e., $||z_{MMK}| \geq z_{1-\alpha/2}$.

2.2.5 Sen's Slope Estimator

Sen's slope estimator is frequently employed to measure the magnitude of a trend within a dataset. This linear slope estimator is particularly useful for monotonic data, offering robustness against errors, outliers, and missing values, unlike linear regression. The slope T_i for each pair of data points is computed using the formula:

$$T_i = \frac{x_j - x_i}{j - i} \quad \text{for } i = 1, 2, \ldots, n$$

Where, x_j and x_i represent the data values at times j and i (with j> i). The median of these n slope values T_i , known as Sen's slope estimator, is denoted as Q_{Med} and is calculated as follows:

$$Q_{Med} = \begin{cases} T_{\frac{N+1}{2}} \; if \; N \; is \; odd \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) \; if \; N \; is \; even \end{cases}$$

If N is odd, Sen's estimator Q_{Med} is equal to $T_{\frac{N+1}{2}}$; if NNN is even, it is the average of $T_{\frac{N}{2}}$ and $T_{\frac{N+1}{2}}$. Finally, the value of$Tmed$ is determined through a two-sided test at a $100(1 - \alpha)$ % confidence interval, which enables the estimation of the true slope using this non-parametric method[8].

2.2.6 Buishand U Test (Buishand, 1984)

The Buishand U test, introduced in 1984, is a non-parametric method designed to detect a shift in the mean of a hydrological time series, particularly effective for identifying a single abrupt change in the mean level. In this model, for a normal random variable X, the presence of a change-point is described as:

$$x_i = \begin{cases} \mu + \epsilon_i, & i = 1, \dots, m \\ \mu + \Delta + \epsilon_i, & i = m + 1, \dots, n \end{cases}$$

Where, errors $\epsilon_i's$ are normally distributed with mean zero and common unknown variance $\sigma.\mu$ and Δ are also unknown. The null hypothesis is $\Delta = 0$ is tested against the alternative hypothesis $\Delta \neq 0$. The test statistics usually written in terms the adjusted partial sums or cumulative deviations from the mean *i.e.*S_k.

The test statistics is

$$U = [n(n + 1)]^{-1} \sum_{k=1}^{n-1} (S_k/D_x)^2$$

Where, $S_k = \sum_{k=1}^{n}(x_i - \hat{x}) \quad (1 \le i \le n)$

and $D_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})}{n}}$ and the p value is estimated with a Monte Carlo simulation using m replicates. The maximum absolute value of U is the potential change point in the time series. The significance of this change point is evaluated by comparing them to critical values from statistical tables or using Monte Carlo simulations to assess its significance level. If the probability values were found to be less than 5% then there is a significant change point present in the rainfall pattern otherwise there is No significant change point in the rainfall pattern over a period of the study.

3. Results and discussion

3.1 Descriptive statistics

The descriptive statistics for Kodagu district, Karnataka, including mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis, are presented in Table 1. July recorded the highest average monthly rainfall of 588.34 mm contributing 28.46% to the annual rainfall, followed by August with 385.43 mm contributing 18.65%. The time plot of average monthly rainfall is shown in Fig 2. July and August make the largest contributions to the annual rainfall, accounting for 28.46% and 18.65%, respectively. Conversely, January and February contribute the least, with just 0.19% and 0.26% of the annual rainfall. Rainfall variability is assessed by the CV, where a CV of less than 20% indicates low variability, 20-30% indicates moderate variability, and greater than 30% indicates high variability. In this study, the CV for monthly rainfall ranged from 47.07% to 241.82%, reflecting significant variability in the rainfall data. Skewness values ranged from 0.64 to 4.76, with kurtosis values ranging from 0.14 to 28.88. March exhibited the highest skewness at 4.76, indicating a right skew, and a kurtosis of

Comment [A5]: The author did not describe the methodology used to generate the results presented in Table 1. These methods should be described in methodology section.

28.88, indicating a leptokurtic distribution. Table 2 summarizes the statistics for seasonal and annual rainfall. The annual rainfall in Kodagu had a CV of 30.58%, reflecting moderate variability. The standard deviation for annual rainfall was 631.97 mm, with a skewness of 0.68, suggesting a slight right skew, and a kurtosis of 0.25, indicating a distribution close to normal. Among the seasons, the monsoon season had the lowest CV at 34.67%, indicating relatively stable rainfall, whereas the winter season exhibited the highest CV at 116.17%, indicating high

Months	Mean	SD	CV	Skewness	Kurtosis	% Contribution to annual rainfall

variability. The monsoon season accounts for 74.71% of the total annual rainfall, whereas the winter season contributes just 1.16%. Fig 3 illustrates the distribution of annual and seasonal rainfall patterns.

Table 1: Descriptive statistics of monthly rainfall (mm) of Kodagu, Karnataka

January	3.86	9.35	241.82	2.99	9.07	0.19
February	5.41	10.65	197.07	2.56	6.86	0.26
March	20.38	39.80	195.32	4.76	28.88	0.99
April	81.58	47.70	58.47	0.64	0.14	3.95
May	151.32	107.95	71.34	2.59	11.36	7.32
June	379.28	178.53	47.07	0.74	0.29	18.35
July	588.34	285.85	48.59	1.45	3.87	28.46
August	385.43	229.28	59.49	1.75	3.55	18.65
September	191.16	113.87	59.57	1.08	0.85	9.25
October	177.82	91.59	51.51	1.09	1.77	8.60
November	67.72	59.49	87.85	1.39	2.21	3.28
December	14.59	23.44	160.63	2.45	6.75	0.71

3.2 Linear Regression Trend

The annual rainfall distribution patterns in Kodagu, Karnataka from 1950 to 2023 is depicted in Fig 4. The time series data is analyzed using linear regression, which is represented by the trend line in the graph. The trend line indicates a slight increase in rainfall over the years, as shown by the equation $Y = 1811.6 + 6.80\,X$. However, the low Coefficient of Determination (R^2=0.0537) suggests that the linear regression model does not provide a strong fit for the data, indicating that other methods might be better suited to capturing the variability and trends in this rainfall data.

Table 2: Descriptive statistics of seasonal and annual rainfall (mm) ofKodagu, Karnataka

Seasons	**Mean**	**SD**	**CV**	**Skewness**	**Kurtosis**	**% Contribution to annual rainfall**
Pre-monsoon	253.16	135.58	53.56	1.77	5.47	12.25
Monsoon	1544.28	535.48	34.67	0.71	0.21	74.71
Post-monsoon	245.53	112.58	45.85	0.67	0.08	11.88
Winter	23.93	27.80	116.17	1.86	3.59	1.16
Annual	2066.91	631.97	30.58	0.68	0.25	100.00

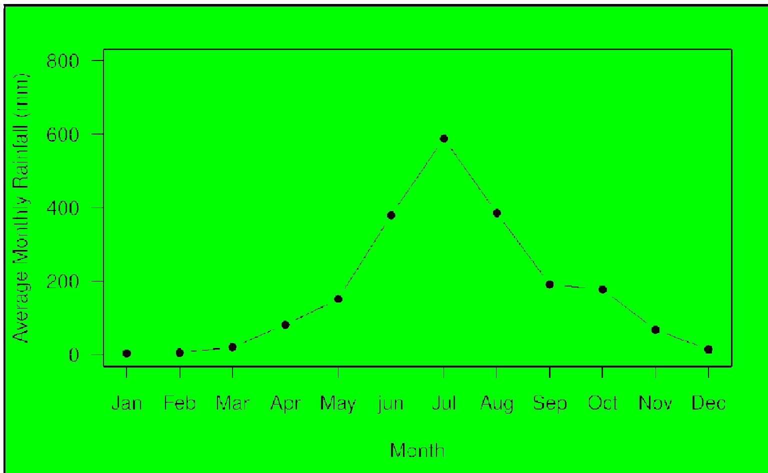

Fig 2: Time plot of the averagemonthly rainfall (mm) of Kodagu, Karnataka

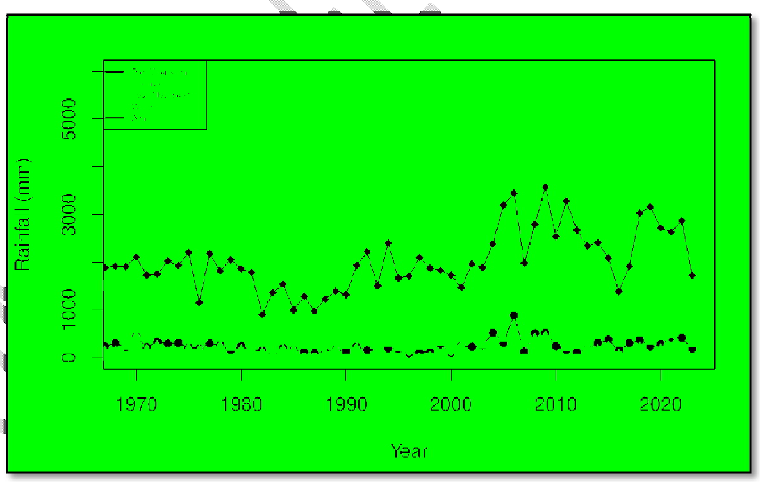

Fig 3: The distribution of Annual and Seasonal rainfall patternof Kodagu, Karnataka

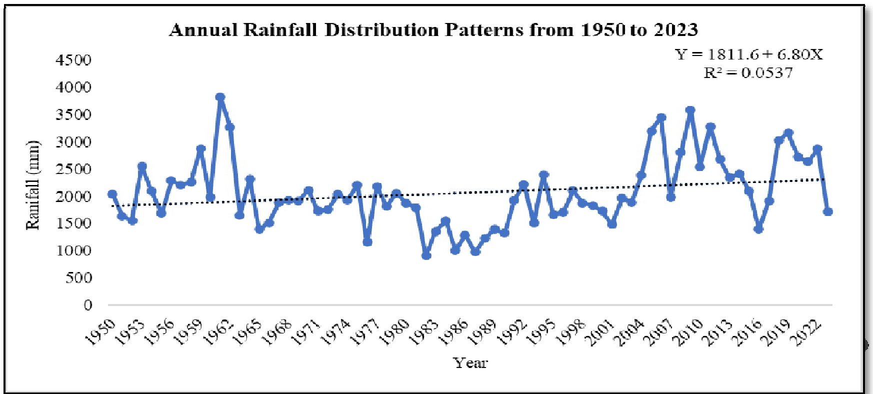

Fig 4: Trend of annual rainfall of Kodagu district from 1950 to 2023

3.3 Test for Randomness

The Wallis and Moore Phase-Frequency test was applied to assess the randomness of the time series for monthly, seasonal, and annual rainfall data, with results presented in Table 3 [4]. The findings indicate that the rainfall data exhibit random patterns at all levels, as the calculated significance levels for all series were greater than 5%, except for two months (January and February), where non-randomness was detected, with significance levels less than 5%.Hence along with MK test, the MMK test was utilized for the study since it was more efficient when autocorrelation was included in the data [14].

3.4 Trend Analysis

Determining trends in monthly, seasonal, and annual rainfall data typically involves using non-parametric tests like the Mann-Kendall (MK) and Modified Mann-Kendall (MM-K) tests. Table 4 presents the results of the Mk and MMK trend analysis for monthly rainfall in Kodagu, Karnataka. The analysis revealed a significant increasing trend in August, with a Sen's slope of 2.34 mm per year and a Z-value significant at the 5% level. Similarly, a significant increasing trend was observed in September, with a Sen's slope of 1.78 mm per year and a Z-value highly significant at the 1% level. For the other months, the Z-values were non-significant, indicating no significant trends during those periods; similar results were found by [1]. Similarly, the results of MK and MMK trend analysis for seasonal and annual rainfall were depicted in Table 5. The findings show no significant trend in the pre-monsoon, monsoon, post-monsoon, winter, and annual rainfall, as the Z-values for all these periods were non-significant. The lack of significant trends suggests that rainfall patterns during these seasons and on an annual basis have remained relatively stable over the study period.

Months/Seasons	**Z-value**	**p- value**
January	3.91	**<0.01**

Table 3: Wallis and Moore phase frequency test of monthly, seasonal and annual rainfall(mm) of in Kodagu district of Karnataka

February	2.23	**0.03**
March	0.28	0.78
April	0.28	0.78
May	1.95	0.06
June	0.84	0.40
July	0	1
August	1.12	0.26
September	1.12	0.26
October	0.56	0.58
November	0.84	0.40
December	0.28	0.78
Pre-monsoon	0.84	0.40
Monsoon	0.56	0.58
Post-monsoon	1.12	0.26
Winter	1.40	0.16
Annual	0	1

Table 4: Man-Kendall test, Modified Man-Kendall test of trend analysis and Sen's slope estimator of monthly rainfall(mm) in Kodagu district of Karnataka

Months	Mann Kendall Test			Modified Mann-Kendall Test			Trend	Sen's slope estimator
	Z-value	P-value	Tau value	Z-value	P-value	Tau value		
January	-0.03	0.98	< -0.01 NS	-0.03	0.98	< -0.01 NS	No Trend	0
February	0.24	0.81	0.02 NS	0.27	0.79	0.02 NS	No Trend	0
March	0.15	0.88	0.01 NS	0.16	0.88	0.01 NS	No Trend	0
April	-0.61	0.54	-0.05 NS	-0.61	0.54	-0.05 NS	No Trend	-0.13
May	-0.01	0.99	< -0.01 NS	-0.01	0.99	< -0.01 NS	No Trend	0
June	1.50	0.13	0.12 NS	1.50	0.13	0.12 NS	No Trend	1.38
July	-0.43	0.67	-0.03 NS	-0.31	0.76	-0.03 NS	No Trend	-0.58
August	**2.39**	**0.02**	**0.19***	**2.39**	**0.02**	**0.19***	**Increasing**	**2.34**
September	**3.06**	**<0.01**	**0.24****	**2.63**	**0.01**	**0.24****	**Increasing**	**1.78**
October	0.94	0.35	0.08 NS	0.60	0.55	0.08 NS	No Trend	0.39
November	-0.41	0.68	-0.03 NS	0.52	0.60	-0.03 NS	No Trend	-0.12
December	1.11	0.27	0.09 NS	1.43	0.15	0.09 NS	No Trend	0

NS: Non-significant trend

Z: normalized test statistics

*Statistically significant trends at the 5% significant level

**Statistically significant trends at the 1% significant level

Table 5: Man-Kendall test, Modified Man-Kendall test of trend analysis and Sen's slope estimator of seasonal and annual rainfall(mm) of Kodagu, Karnataka

Seasons	Mann Kendall Test			Modified Mann Kendall Test			Trend	Sen's slope estimator
	Z-value	p-value	Tau value	Z-value	p-value	Tau value		
Pre-monsoon	-0.07	0.94	-0.01 NS	-0.04	0.97	-0.01 NS	No Trend	-0.03
Monsoon	1.95	0.05	0.16 NS	1.35	0.18	0.16 NS	No Trend	5.78
Post-monsoon	0.71	0.48	0.06 NS	0.57	0.57	0.06 NS	No Trend	0.40
Winter	1.15	0.25	0.09 NS	1.21	0.22	0.09 NS	No Trend	0.10
Annual	1.80	0.07	0.14 NS	1.18	0.24	0.14 NS	No Trend	6.55

NS: Non-significant trend

3.5 Detection of change in point by using Buishand U test.

The detection of change points in monthly, seasonal, and annual rainfall (mm) was conducted using the Buishand U test. As presented in Table 6 and illustrated in Fig 5, significant change points were identified for August, September, and the monsoon season, with all these shifts occurring around the year 2003. This suggests a noticeable change in the rainfall pattern during these periods. On the other hand, the test results for the other months, pre-monsoon, post-monsoon, winter, and annual rainfall data were non-significant, indicating no notable change points were detected in these cases. The red vertical line in Fig 5 marks the identified change point, aligning with the significant findings in the corresponding data.

Table 6: Detection of change in point by using Buishand U test of monthly, seasonal and annual rainfall(mm) in Kodagu district of Karnataka.

Months / Seasons	Buishand U test		
	U	**p-value**	**Changepoint (Year)**
January	0.19	0.28	No
February	0.07	0.74	No
March	0.24	0.21	No
April	0.15	0.39	No
May	0.23	0.22	No
June	0.43	0.06	No
July	0.32	0.12	No
August	**0.68**	**0.01**	**2003**
September	**1.31**	**<0.01**	**2003**
October	0.35	0.10	No
November	0.04	0.92	No
December	0.10	0.57	No
Pre-monsoon	0.33	0.11	No
Monsoon	**0.81**	**<0.01**	**2003**
Post-monsoon	0.27	0.16	No
Winter	0.17	0.33	No
Annual	0.22	0.33	No

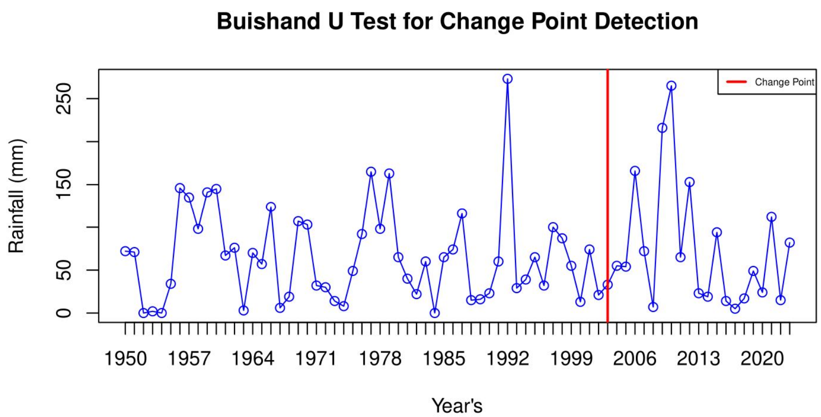

Fig 5: Graph showing Change in point identified using Buishand U test

4. Conclusions

The research analyzed monthly, seasonal, and annual rainfall trends (in mm) in Kodagu district, Karnataka, from 1950 to 2023. The Wallis and Moore Phase-Frequency test detected autocorrelation in the data. To assess long-term trends, both parametric methods, specifically linear regression, and non-parametric tests like the Mann-Kendall (MK) and Modified-Mann Kendall (MMK) tests were employed. Linear regression indicated a slight increase in rainfall over the years. The MMK test identified a significant upward trend in rainfall for August (2.34 mm/year) and September (1.78 mm/year). No statistically significant trends were found in other months, or in seasonal and annual rainfall. The Buishand U test detected notable change points in August, September, and during the monsoon season, all occurring around 2003, while no other months, seasons, or annual data exhibited such shifts. Rainfall variability is a significant concern, and these findings could help policymakers make informed decisions to address future climate risks and better understand the seasonal water budget, which is essential for crop planning, water security, and overall livelihood security for farmers.

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