Article

Long Term Homogeneity, Trend and Change-Point Analysis of Rainfall in the Arid District of Ananthapuramu, Andhra Pradesh State, India

Sandeep Kumar Patakamuri [1,*], Krishnaveni Muthiah[1] and Venkataramana Sridhar[2]

1 Centre for Water Resources, Anna University, Chennai, 600 025, India
2 Department of Biological Systems, Virginia Polytechnic Institute and State University, Blacksburg, USA
* Correspondence: sandeep.patakamuri@gmail.com or mkveni@annauniv.edu

Abstract: Daily rainfall data was collected for the arid district of Ananthapuramu, Andhra Pradesh state, India from 1981 to 2016 at the sub-district level and aggregated to monthly, annual and seasonal rainfall totals and the number of rainy days. The objective of this study is to evaluate the homogeneity, trend, and trend change points in the rainfall data. After quality checks and homogeneity analysis, a total of 27 rain gauge locations were considered for trend analysis. A serial correlation test was applied to all the time series to identify serially independent series. Non-Parametric Mann-Kendall test and Spearman's rank correlation tests were applied to serially independent series. The magnitude of the trend was calculated using Sen's slope method. For the data influenced by serial correlation, various modified versions of Mann-Kendall tests (Pre-Whitening, Trend Free Pre-Whitening, Bias Corrected Pre-Whitening and two variants of Variance Correction Approaches) were applied. A significant increasing summer rainfall trend is observed in 6 out of 27 stations. Significant decreasing trends are observed at two stations in the south-west monsoon season and at two stations in the north-east monsoon season. To identify the trend change-points in the time series, distribution-free Cumulative SUM test and sequential Mann-Kendall tests were applied. Two open-source library packages were developed in R language namely, 'modifiedmk' and 'trendchange' to implement the statistical tests mentioned in this paper. The study will benefit water resource management, drought mitigation, socio-economic development and sustainable agricultural planning in the region.

Keywords: Trend Analysis, Non-parametric trend tests, Mann-Kendall, Modified Mann-Kendall, Climate Change, modifiedmk, trendchange

1. Introduction

Hydrological regime is under a lot of stress due to climate change and gaining a lot of attention in the scientific community due to its potential adverse effects on the environment [1]. Rainfall variability plays a major role in the Indian economy and extreme rainfall events resulting in drought and floods impact the nation's food security and GDP [2]. India is quite vulnerable to climate change and its impacts on various sectors like water resources, agriculture, forestry, and health sector etc., are well documented by several researchers [3–10]. Detailed analysis of rainfall trend is useful in planning water resources development and management, designing water storage structures, irrigation practices and crop choices, drinking water supply, industrial development, and disaster management for current and future climatic conditions[11,12]. Evaluating past trends in the meteorological parameters at various spatial and temporal scales play a crucial role in understanding climate change and its impact on food security, energy security, natural resource management and sustainable development [13,14].

In order to represent the true variations in the weather and climate, the assumption of homogeneity in meteorological observations is quite important in climatological trend analysis. The direct methods of homogenization involve best management practices in data recording and archiving. Indirect methods of homogenization involve metadata analysis, creation of reference

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series, statistical tests for breakpoint detection and adjustment of the data records [15,16]. To identify the effects of non-climatic factors in the observations over time, homogeneity tests are performed on time series data. The homogeneity tests are of two types, namely absolute methods and relative methods. In the case of absolute homogeneity tests, each station is considered separately without considering the effect of neighboring stations. In relative homogeneity tests, neighboring reference stations are used. Several researchers have either assumed the data to be homogeneous or used absolute homogeneity tests alone in their research [17–22]. It is suggested to use the relative homogeneity tests if the neighboring stations are within the same climatic region [23,24].

In the literature, researchers have used parametric and non-parametric methods of trend detection in time series data. Parametric trend tests assume the data to be random, independent and normally distributed. Non-parametric trend tests are widely used in literature as they do not assume any statistical distribution in the data [25–30]. However, the assumption of serial independence and randomness stands unchanged for non-parametric trend tests. Serial correlation affects the power of trend tests in identifying trends correctly in the time series data [31,32]. Mann-Kendall test (MK) [33,34], Spearman's rank correlation coefficient test (SRC) [35,36] for trend detection and Sen's slope test (SS) for calculating trend magnitude [37,38] are perhaps the most widely used non-parametric tests in the previous studies. Power of Mann-Kendall test and Spearman's rho tests are positively affected by the sample size, magnitude of the trend, and significance level considered in the analysis; while it is negatively affected by time-series variations [39].

A majority of previous studies have used the Mann-Kendall test for trend detection and Sen's slope test to report trend magnitude in the case of serially independent data. To minimize the impact of serial correlation on trend detection, various methods like pre-whitening (PW) [32,40], trend free pre-whitening (TFPW) [41], bias-corrected pre-whitening (BCPW) [42], variance correction approach (VCA) [43,44] and block bootstrapping (BBS) [45,46] etc., were proposed in literature. When the timeseries are serially correlated, researchers have either ignored it or used one of several modified versions of Mann-Kendall tests to report trends. It is recommended to use a combination of statistical tests in trend analysis at various confidence intervals [25,47]. It is very important to study the change-point of the trend, along with trend analysis. Very few researchers have reported the time of trend change in their research [25].

Ananthapuramu district is an arid agro-ecological region of India, which is highly vulnerable to climate change [48]. Naveen et al., (1991) [49] have presented a detailed analysis of various climatological parameters like rainfall, temperature, wind speed, humidity, evaporation, solar radiation, etc., of Ananthapuramu. Rao et al., (2009) [50] have investigated the trends in heavy rainfall events of Ananthapuramu district using the rainfall data for the period 1971-2008. Reddy et al., (2008) [51] have presented a comprehensive study of drought conditions in Ananthapuramu district. The entire district of Ananthapuramu is declared as a hot-arid zone and several watershed management programs were initiated to mitigate the drought conditions. The majority of the farmers in the district are marginal or small farmers and are highly vulnerable to climate change. Climate resilient agriculture and best management practices in farming are required in the region for sustainable agriculture [52,53]. Groundwater quality is very alarming in many areas of the Ananthapuramu district, and the situation might worsen due to changes in the precipitation pattern [54].

The objective of the present study is to investigate the homogeneity, trends and trend change points in the rainfall time-series at Anantapuramu district. Very few studies on climatological trend analysis were carried out in this region [51]. In the present study, total rainfall and number of rainy days at monthly, annual and seasonal scale were thoroughly investigated for homogeneity using both absolute and relative tests. Prior to trend analysis, each series is subjected to serial correlation tests. For serially independent series, trend analysis is carried out using the Mann-Kendall test and Spearman's Rho test at various significance levels. When the series is serially correlated, five modified versions of Mann-Kendall tests were used in trend detection. The magnitude of the trend is calculated using Sen's slope method. Trend change-point analysis is carried out using the distribution-free CUSUM test (CUSUM) [55] and the Sequential Mann-Kendall test (SQMK) [56,57]. Two open-source software packages 'modifiedmk' [58] and 'trendchange' [59] were developed in R-language to implement the statistical tests mentioned in this study and are made available through CRAN

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repository. The present study will highly benefit the drought mitigation, irrigation water management, natural resource management and socio-economic development planning of the region.

2. Study Area and Data Used

Ananthapuramu district is in the southern part of India, in the state of Andhra Pradesh. The district lies between 13°40' N to 15°15' N latitude and 76°50' E to 78°30' E longitude. It is the largest district in the state with 63 sub-districts covering an area of 19,130 sq.km. The total population of the district is 4,081,148 with a sex ratio of 977 females for every 1000 males. The literacy rate of the district is 64.28 percent [60]. Most of the cultivated area in the district is rainfed and only a small portion of land is under irrigated agriculture. The soils in the district are majorly red soils with 76% of the total area, and the remaining 24% are black soils. The soil texture is predominantly sandy loam with low water retention capacity. Soil moisture deficiency is commonly observed in the area during all the stages of crop growth, leading to frequent crop failures [53]. The average elevation of the district is 610 m with the lowest elevation of 230 m at Tadipatri. Elevation at Anantapuramu city is 335 m. Climatologically the rainfall is divided into four seasons namely Winter (January-February), Summer (March to May), south-west monsoon (June to September) and north-East monsoon (October to December). The district receives a normal rainfall of 553 mm. South-west monsoon rainfall is predominant in the region, with normal rainfall of 338 mm and normal rainfall for north-east monsoon is recorded as 156 mm. Geographically, Ananthapuramu falls away from the east coast, causing it to receive less rainfall during north-east monsoons. Also, the district receives precarious rainfall due to less penetration of south-west monsoons caused by high Western Ghats [60]. The annual mean maximum temperature is 33.7° C and the minimum mean temperature is 22.0° C [49]. Potential evapotranspiration during south-west monsoon is higher than the total rainfall, causing serious crop stress conditions during the growing season[53]. Location map of the study area with the spatial distribution of rain gauge stations is shown in Figure 1.

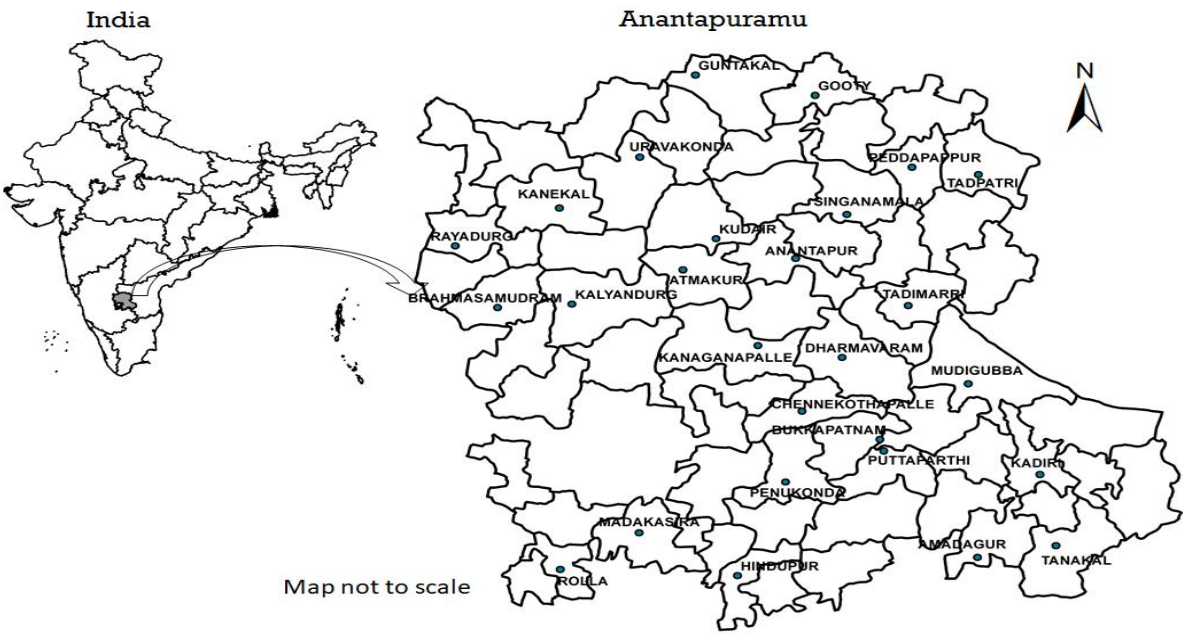

Figure 1. Location map of the study area and rain gauge stations

Daily rainfall data for 63 sub-district rain gauge locations are collected for the period 1981 to 2016 from the Department of Statistics and Planning, Ananthapuramu. After careful pre-processing for missing data and quality checks, a total of 27 rain gauge locations were selected for homogeneity and trend analysis. Daily rainfall data is aggregated to the number of rainy days and total rainfall at monthly, seasonal and annual scale. India Meteorological Department's (IMD) high resolution, gridded rainfall data at 0.25° x 0.25° resolution [61] is used in the study to validate the rain gauge level

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findings. The daily gridded data is also aggregated to monthly, seasonal and annual scale for the purpose of analysis. Geographical location and elevation information of the rain gauge stations and the corresponding length of the data record is provided in Table 1.

Table 1. Description of rain gauge locations in the study area considered for analysis

S.No.	Station	Latitude	Longitude	Elevation (in meters)	Record period
1	Amadagur	13° 53'	78° 01'	675	1987-2016
2	Anantapur	14° 40'	77° 36'	352	1981-2016
3	Atmakur	14° 38'	77° 21'	497	1981-2016
4	Brahmasamudram	14° 32'	76° 56'	511	1987-2016
5	Bukkapatnam	14° 11'	77° 48'	445	1981-2016
6	Chennekothapalle	14° 16'	77° 37'	438	1981-2016
7	Dharmavaram	14° 24'	77° 43'	376	1981-2016
8	Gooty	15° 07'	77° 38'	384	1981-2016
9	Guntakal	14° 09'	77° 23'	456	1981-2016
10	Hindupur	13° 49'	77° 29'	626	1981-2016
11	Kadiri	14° 06'	78° 09'	520	1981-2016
12	Kalyandurg	14° 32'	77° 06'	556	1981-2016
13	Kanaganapalle	14° 26'	77° 31'	436	1981-2016
14	Kanekal	14° 48'	77° 04'	456	1981-2016
15	Kudair	14° 43'	77° 25'	422	1981-2016
16	Madakasira	13° 56'	77° 16'	664	1981-2016
17	Mudigubba	14° 20'	77° 57'	404	1987-2016
18	Peddapappur	14° 55'	77° 51'	262	1987-2016
19	Penukonda	14° 04'	77° 35'	566	1981-2016
20	Puttaparthi	14° 10'	77° 48'	459	1987-2016
21	Rayadurg	14° 41'	76° 51'	555	1981-2016
22	Rolla	13° 50'	77° 06'	715	1987-2016
23	Singanamala	14° 48'	77° 43'	310	1981-2016
24	Tadimarri	14° 33'	77° 51'	317	1987-2016
25	Tadpatri	14° 54'	78° 00'	238	1981-2016
26	Tanakal	13° 55'	78° 11'	612	1981-2016
27	Uravakonda	14° 56'	77° 15'	479	1981-2016

3. Methodology

Various statistical tests were performed to analyze the homogeneity, trends and trend change-points in the timeseries data, after thorough quality checks and pre-processing. The sequential stages in data analysis are

- Homogeneity tests
- Testing for serial correlation
- Trend tests
- Trend change-point tests

3.1. Homogeneity tests

Homogeneity testing is very crucial in climatological studies, to represent the real variations in weather and climate. Inhomogeneity occurs in climate data due to several reasons including instrumentation error, changes in the adjacent areas of the instrument and mishandling of the human. If the homogeneity is not tested prior to trend analysis, the results will indicate erroneous trends. In the present study, absolute homogeneity tests were performed on individual station records and

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relative homogeneity tests were performed by generating a reference series using Anclim software package and calculating the ratio of observed series to the reference series [62–64]. Four widely used statistical tests mentioned below were applied to the data to test for homogeneity. All the four tests used in the present study assume the null hypothesis of data being homogeneous.

- Alexandersson's Standard Normal Homogeneity Test [62,63]
- Buishand's range test [65]
- Pettitt's test [66]
- Von Neumann's ratio test [67]

3.1.1. Alexandersson's Standard Normal Homogeneity Test

For an annual series X_i (i is the year from 1 to n) with mean '$\overline{X}$' and standard deviation 's', Alexandersson (1986) [62,63] describes a statistic $T(k)$ to compare the mean of first 'k' years of the record with that of last '$n-k$' years as

$$T(k) = k\overline{z}_1^2 + (n-k)\overline{z}_2^2 \text{ for } k = 1, 2, \ldots, n \quad (1)$$

where,

$$\overline{z}_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(X_i-\overline{X})}{s} \text{ and } \overline{z}_2 = \frac{1}{(n-k)}\sum_{i=k+1}^{n}\frac{(X_i-\overline{X})}{s} \quad (2)$$

If a break is located at year 'K' then $T(k)$ reaches maximum near the year k = K. The test statistic T_0 is defined as

$$T_0 = \max_{1\le k<n} T(k) \quad (3)$$

The null hypothesis is rejected when T_0 is above the critical value, which depends on the sample size.

3.1.2. Buishand's range test

In Buishand's range test [65], for an annual series X_i (i is the year from 1 to n) with mean '$\overline{X}$' and standard deviation 's' the adjusted partial sums are defined as

$$S_0^* = 0 \; and \; S_k^* = \sum_{i=1}^{k}\left(X_i - \overline{X}\right) \text{ where } k = 1, 2, \ldots, n \quad (4)$$

For a homogeneous series, the value of S_k^* fluctuates around zero, as no systematic deviations of the X_i values with respect to their mean will appear. When a break-point is present in the series, S_k^* value reaches a maximum value (negative shift) or minimum value (positive shift) near the year k = K. The $(S_k^*/s)/\sqrt{n}$ is depicted in the graphs representing the results of this test. The significance of the shift can be tested using 'rescaled adjusted range' denoted as R, which is the difference between the maximum and minimum of the S_k^* values scaled by the sample standard deviation.

$$R = \left(\max_{0\le k\le n} S_k^* - \min_{0\le k\le n} S_k^*\right)/\ s \quad (5)$$

$R/\sqrt{n}$ value is compared with the critical values of Buishand (1982) [65] to test for significance.

3.1.3. Pettitt's test

Pettitt's test [66] is a non-parametric rank test. The ranks $r_1, r_2, \ldots, r_n$ of the series $X_1, X_2, \ldots, X_n$ are used to calculate the test statistics as

$$Y_k = 2\sum_{i=1}^{k} r_i - k(n+1) \text{ where } k = 1, 2, \ldots, n \quad (6)$$

When a break occurs at year K, the statistic is maximum or minimum at year k = K,

$$Y_K = \max_{1\le k\le n}|Y_k| \quad (7)$$

The value of Y_K is compared with critical values given by Pettitt (1979) [66] to test for statistical significance.

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3.1.4. Von Neumann's ratio test

For an annual series X_i (i is the year from 1 to n) with mean '$\overline{X}$', The von Neumann ratio 'N' is defined as the ratio of the mean square successive (year to year) difference to the variance, given as

$$N = \sum_{i=1}^{n-1}(X_i - X_{i+1)})^2 \ / \sum_{i=1}^{n}(X_i - \overline{X})^2 \tag{8}$$

If there is a break in the series, the value of N tends to be lower than the expected value. If there is rapid variation in the mean, the values of N may rise above 2. This test does not indicate the exact location of the break year.

3.2. Testing for Serial Correlation

For detecting the trend in time series, the statistical tests assume the subsequent data in the series to be independent. The power of trend tests is highly influenced by the presence of serial correlation in the data [41,68]. Positive serial correlation leads to wrongful rejection of the null hypothesis of no trend when it is true (type I error). Similarly, negative serial correlation leads to accepting the null hypothesis of no trend when it is false (type II error). To test for serial correlation in the data, lag-k serial correlation coefficients are calculated [69–73]. In several of the trend studies, the time series is tested for serial correlation by calculating lag-1 serial correlation coefficient ρ_1 [74–77]. For any timeseries $X_i = x_1, x_2, \ldots, x_n$, lag-1 serial correlation coefficient (ρ_1) is calculated as

$$\rho_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}(x_i - E(x_i)).(x_{i+1} - E(x_i))}{\frac{1}{n}\sum_{i=1}^{n}(x_i - E(x_i))^2} \tag{9}$$

where, $E(x_i)$ is the mean of the sample and n is the sample size

$$E(x_i) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{10}$$

The probability limits for ρ_1 on the correlogram of an independent series is given by Anderson (1941) [73] as

$$\rho_1 = \begin{cases} \frac{-1+1.645\sqrt{n-2}}{n-1}, \text{for the one} - \text{tailed test} \\ \frac{-1\pm1.96\sqrt{n-2}}{n-1}, \text{for the two} - \text{tailed test} \end{cases} \tag{11}$$

Significance of serial correlation was evaluated by comparing ρ_1 value with the critical values of Student's t-distribution values.

3.3. Trend Tests

Trends tests are applied on time-series data to identify significant positive or negative trends. All the trend tests in this section assume null hypothesis of no trend and alternative hypothesis of existence of monotonic increasing or decreasing trend. When the timeseries are serially independent, the Mann-Kendall test [33,34] and Spearman's Rho test [35,36] were applied to test for trends. These two tests are very robust in detecting the trends and are widely used in literature. The magnitude of the trend was estimated using Sen's slope method [37,38]. From the extensive literature survey, it is evident that there is no universal solution to account for serial correlation present in the timeseries. It is always suggested to apply various statistical tests to analyze the trends in serially correlated data. In the present study, when the timeseries exhibit significant serial correlation, the following modified versions of Mann-Kendall tests were used.

- Pre-whitening [32,40]
- Trend free pre-whitening [41]
- Bias-Correction applied to pre-whitening [42]
- Variance correction approach suggested by Hamed and Rao (1998) (MMKH) [43]
- Variance correction approach suggested by Yue and Wang (2004) (MMKY) [44]

3.3.1. Mann-Kendall Test

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Mann-Kendall test [33,34] is perhaps the most widely used non-parametric test for detecting trends in hydro-meteorological and environmental data. Mann-Kendall test is a non-parametric test for monotonic trend detection. It doesn't assume the data to be normally distributed and is flexible to outliers in the data. The test assumes a null hypothesis H_0 of no trend and alternate hypothesis H_A of increasing or decreasing monotonic trend.

For a timeseries $X_i = x_1, x_2, \ldots, x_n$, Mann-Kendall test statistic S is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{12}$$

where, n is the number of data points, x_i and x_j are the data values in timeseries i and j $(j > i)$, respectively. $sign(x_j - x_i)$ is the sign function as

$$Sign(x_i - x_j) = \begin{cases} -1 & if\ (x_j - x_i) < 0 \\ 0 & if (x_j - x_i) = 0 \\ 1 & if\ (x_j - x_i) > 0 \end{cases} \tag{13}$$

Statistics S will be normally distributed with parameters $E(S)$ and variance $V(S)$ as given below

$$E(S) = 0 \tag{14}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(k)(k-1)(2k+5)}{18} \tag{15}$$

where, n is the number of data points, m is the number of tied groups and t_k denotes the number of ties of extent k. Standardized test statistic Z is calculated using the formula below

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{var(S)}} & if\ S < 0 \end{cases} \tag{16}$$

To test for a monotonic trend at an α significance level, the alternate hypothesis of trend is accepted if the absolute value of standardized test statistic Z is greater than $Z_{1-\alpha/2}$ value obtained from standard normal cumulative distribution tables. A positive sign of the test statistic indicates an increasing trend and a negative sign indicates a decreasing trend.

3.3.2. Spearman's Rank Correlation Coefficient Test

Spearman's Rho test [35,36] is another widely used non-parametric test. The power of this test is comparable with the Mann-Kendall test [39]. For a given timeseries $X_i = x_1, x_2, \ldots, x_n$, the spearman rank correlation coefficient $\mathrm{r_{SRC}}$ is given as

$$\mathrm{r_{SRC}} = 1 - \left\{ \frac{6 \sum_{i=1}^{n} [d_i]^2}{\mathrm{n(n^2 - 1)}} \right\} \tag{17}$$

where, $d_i = (RX_i - RY_i)$. RX_i is the rank of the variable X_i and RY_i is the chronological order of observations. $i = 1, 2, \ldots, n$ in series of size n. The test statistic $\mathrm{t_{SRC}}$ is given by Equation (18).

$$\mathrm{t_{SRC}} = \mathrm{r_{SRC}} \sqrt{\frac{\mathrm{(n-2)}}{1 - \mathrm{r_{SRC}^2}}} \tag{18}$$

Test statistic $\mathrm{t_{SRC}}$ follows t-distribution with the degree of freedom ν and significance level α. The null hypothesis of no-trend is rejected when $|\mathrm{t_{SRC}}| > \mathrm{t}_{\nu,1-(\alpha/2)}$.

3.3.3. Sen's Slope Estimator

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Sen's slope method is a robust non-parametric method of estimating the magnitude of trend slope [37,38]. For a given timeseries $X_i = x_1, x_2, \ldots, x_n$, with N pairs of data, the slope is calculated as given in Equation (19)

$$\beta_i = \frac{x_j - x_k}{j-k}, \forall\, k \leq j \ \text{ and } \ i = 1, 2, \ldots, N \tag{19}$$

Median of N values of β_i gives the Sen's estimator of slope β.

$$\beta = \begin{cases} \dfrac{\beta_{N+1}}{2} & \text{if N is odd} \\ \dfrac{\left(\dfrac{\beta_{\mathrm{N}}}{2} + \dfrac{\beta_{N+2}}{2}\right)}{2} & \text{if N is even} \end{cases} \tag{20}$$

3.3.4. Pre-whitening

For a given timeseries $X_i = x_1, x_2, \ldots, x_n$, with lag-1 serial correlation coefficient ρ_1 as mentioned in Equation (9), pre-whitened series X_t' is given by von Storch (1995) [32,40] as

$$X_t' = X_t - \rho_1 X_{t-1} \tag{21}$$

3.3.5. Trend Free Pre-whitening

In Trend free pre-whitening [41] of a given timeseries $X_t = x_1, x_2, \ldots, x_n$, the first step is to calculate Sen's slope using equations (19) and (20). Monotonic trend β is removed from X_i to form a trend free series Y_t

$$y_t = x_t - \beta t \tag{22}$$

where, x_t is the series value at time t and y_t is the de-trended series and β is the trend slope.

In the next stage, lag 1 serial correlation coefficient ρ_1 of the detrended series y_t is calculated as mentioned in equation (9). If ρ_1 is not significant, the trend detection is performed on the detrended series. In case of significant serial correlation at lag 1, de-trended series is pre-whitened and the residual series y_t' is calculated as

$$y_t' = y_t - \rho_1 y_{t-1} \tag{23}$$

In the final stage, the monotonic trend component is added back to residual series y_t' to generate trend free pre-whitening series X_t^*

$$X_t^* = y_t' + \beta t \tag{24}$$

3.3.6. Bias Corrected Pre-whitening

A timeseries $X_t = x_1, x_2, \ldots, x_n$, assumed to follow a first ordered serial correlation process including a linear trend can be modeled as

$$X_t = \rho \mathrm{X}_{t-1} + \alpha + \beta t + \varepsilon_t \tag{25}$$

where, X_t and X_{t-1} are observations at times t and t-1 respectively; ρ is the serial correlation coefficient, α is constant intercept term, β is trend slope with respect to time and ε_t is an uncorrelated noise term. Estimated values of ρ, α *and* β are given by the matrix calculation below

$$[\rho \quad \alpha \quad \beta]^T = (Z^T Z)^{-1} Z^T y \tag{26}$$

where Z is the matrix of size $(n-1) \times 3$ whose second column contains $(n-1)$ values equal to 1, and the third column contains the numbers 2 to n and y is a vector of size $(n-1) \times 1$ containing the observations x_2 to x_n. Bias corrected serial correlation coefficient ρ^* [42,78] is calculated using

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the formula mentioned in Equation (27). This value is used in bias-corrected pre-whitening and trend detection studies.

$$\rho^* = \frac{(n\hat{\rho} + 2)}{n - 4} \tag{27}$$

3.3.7. Variance Correction Approaches

In a timeseries $X_t = x_1, x_2, \ldots, x_n$, with n number of observations, effective information is contained in n^* number of observations. Effective sample size n^* is always less than the original sample size n. In the presence of positive or negative serial correlation, the variance of Mann-Kendall test statistic S will increase or decrease respectively. This effect can be reduced by calculating the modified variance $V^*(S)$.

$$V^*(S) = V(S) * CF \tag{28}$$

Correction factors (CF) proposed by Hamed and Rao (1998) [43] and Yue and Wand (2004) [44] termed as CF1 and CF2 respectively are

$$CF_1 = 1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2) r_k^R \tag{17}$$

$$CF_2 = 1 + 2 \sum_{k=1}^{n-1} \left(1 - \frac{k}{n}\right) r_k \tag{18}$$

where, r_k *and* r_k^R are the $lag\text{-}k$ serial correlation coefficients of data and ranks of data respectively and n is the total length of the series. In the case of CF_1, only significant correlation coefficients are used. For calculating CF_2, $lag\text{-}1$ serial correlation coefficient is used. Mann-Kendall trend test is calculated by using corrected variance $V^*(S)$.

3.4. Trend Change-Point Tests

In hydroclimatic trend analysis, identifying the trends and time of trend change both play a significant role. Any trend detection study is incomplete without reporting the time of trend change. Unfortunately, none of the previous studies in the region have reported the starting time of significant rainfall trends. In the present study, distribution-free CUSUM test [55] and sequential Mann-Kendall test [56,57] were employed in trend change-point analysis. Both these tests are non-parametric tests and are very useful in identifying sequential step changes in the timeseries. The CUSUM test [55] is based on cumulative sum charts and the sequential Mann-Kendall test [56,57] considers each sample point sequentially considered in both progressive and retrograde manner.

3.4.1. Distribution Free CUSUM Test

Distribution free CUSUM test [55] checks for differences in the mean values in two parts of a series are different for an unknown time. The median value of the series is compared with successive values in order to detect the change after a number of observations. The test statistic V_k is the maximum value of the cumulative sum (CUSUM) of the k signs of differences from the median (which is a series of -1 or +1) starting from the beginning of the series. For a timeseries $X_t = x_1, x_2, \ldots, x_n$, the test statistic V_k is given as

$$V_k = \sum_{i=1}^{k} sign(x_i - x_{median}) \text{ where, } \quad k = 1, 2, \ldots, n \tag{31}$$

where, $k = 1, 2, \ldots, n$ and $sign(x_i - x_{median})$ is given as

$$Sign(x_i - x_{median}) = \begin{cases} -1 & if\ (x_i - x_{median}) < 0 \\ 0 & if\ (x_i - x_{median}) = 0 \\ 1 & if\ (x_i - x_{median}) > 0 \end{cases} \tag{32}$$

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Distribution of V_k follows the Kolmogorov-Smirnov two-sample statistic $KS = \left(\frac{2}{n}\right)\max|V_k|$, with a critical value of $\max|V_k|$ given at various significance levels as in Equation (33)

$$\begin{gathered} 1.22\sqrt{n}\ at\ \alpha = 0.10 \\ 1.36\sqrt{n}\ at\ \alpha = 0.05 \\ 1.63\sqrt{n}\ at\ \alpha = 0.01 \end{gathered} \tag{33}$$

3.4.2. Sequential Mann-Kendall Test

For a series $X_t = x_1, x_2, \ldots, x_n$, Sequential Mann-Kendall test is a rank-based test to identify the change-point in the time series. From Taubenheim (1989) and Sneyers (1990), the first step is to arrange the series as ranked order and calculating the test statistic t_j

$$t_j = \sum_{i}^{j} n_j \tag{34}$$

where, n_j is the number of times $x_{j>}x_i$ under the condition $j > i$ with $j = 1, 2, \ldots, n$ and $i = 1, 2, \ldots, j-1$.

Distribution of test statistic is asymptotically normal with mean $E(t_{j)} = \frac{j(j-1)}{4}$ and variance $VAR(t_{j)} = \frac{j(j-1)(2j+5)}{72}$. A reduced variable called prograde series $u(t)$ is calculated for each of the test statistic variable t_j as

$$u(t) = \frac{t_j - E(t_j)}{\sqrt{VAR(t_j)}} \tag{35}$$

In a similar way, retrograde series $u'(t)$ is calculated from the end of the series. In absence of a trend, the series will intersect at several locations. In the presence of a significant trend, the point of intersection of the prograde series and the retrograde series will indicate the trend change-point.

3.5. Software Packages – 'modifiedmk' and 'trendchange'

Two open-source library packages namely 'modifiedmk' and 'trendchange' were developed in R-language [79]. The package 'modifiedmk' was used to perform the non-parametric Mann-Kendall test, Spearman's Rank Correlation Coefficient test and all modified versions of Mann-Kendall tests mentioned in the present study. Another package 'trendchange' was used for change-point analysis. These packages are now freely available via CRAN repository and Github version control platform [58,59].

4. Results and Discussion

Each station will contain 17 series (12 monthly, 1 annual and 4 seasonal series), and a total of 459 time-series generated from 27 rain gauge locations (27 x 17) were subjected to statistical tests and the analysis is provided in this section. Absolute homogeneity and relative homogeneity tests were reported at a confidence interval of 95%. Results of the trend tests are reported at 90%, 95%, and 99% confidence intervals. Trend change-points are reported when there is any significant positive or negative trend observed in the time-series.

4.1. Homogeneity of Rainfall Data

The results of absolute homogeneity tests and relative homogeneity tests are grouped into three classes as

- Useful – If none or only one of the above four tests reject the null hypothesis
- Doubtful – If two of the four tests reject the null hypothesis
- Suspect – If three or all the tests reject the null hypothesis

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A similar type of classification is observed in Schönwiese and Rapp (1997) [80] and Wijngaard et al., (2003) [81]. Out of 459 series, all the records of Bukkapatnam, Dharmavaram, Hindupur, Kadiri, Madakasira, Puttaparthi, Rolla, and Tanakal stations found as 'Useful' in both absolute and relative homogeneity tests and hence are not mentioned in the summary of homogeneity analysis as depicted in Table 2.

Table 2. Summary of homogeneity results

Station name	**Absolute homogeneity**		**Relative homogeneity**	
	Doubtful	**Suspect**	**Doubtful**	**Suspect**
Amadagur	-	-	January	-
Anantapur	-	-	September	-
Atmakur	May October	Annual Summer South-west monsoon	-	January September
Brahmasamudram	-	-	Annual North-east monsoon	January
Chennekothapalle	January September October	-	-	Annual
Gooty	April Summer	-	April	-
Guntakal	January	April May Summer	-	-
Kalyandurg	-	Summer	-	-
Kanaganapalle	-	Summer	North-east monsoon	-
Kanekal	December	Summer	-	-
Kudair	March	August Annual Summer	September	January
Mudigubba	-	-	-	January
Peddapappur	February March	-	Annual	February
Penukonda	April October Summer	-	-	-
Rayadurg	December	Summer	-	September
Singanamala	May October	-	October North-east monsoon	Annual
Tadimarri	-	January	Annual	January
Tadpatri	October	-	-	Annual
Uravakonda	Summer	-	Winter	-

Absolute homogeneity test results indicated 20 series as 'Doubtful' and 14 series as 'Suspect' and all the remaining as 'Useful'. Relative homogeneity test results indicated 12 series to be "Doubtful" and 11 series to be 'Suspect' and the remaining series to be 'Useful'. Any series classified as a suspect is considered inhomogeneous and excluded from trend analysis.

4.2. Serial Correlation Analysis

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The serial correlation test is highly influenced by the confidence interval used in the statistical tests. The results of the present study indicated 26 series out of 459 series found to be serially correlated at a 90% confidence interval. At a confidence interval of 95%, the number of series influenced by serial correlation reduced drastically by half to 13. Analysis at 99% confidence interval indicated only two series were affected by serial correlation.

4.3. Rainfall Trend Analysis

Trend analysis is performed on monthly, annual and seasonal rainfall series, and the results of serially independent annual and seasonal rainfall alone are shown in Table 3. The spatial location of the stations with increasing and decreasing rainfall trends are as shown in Figure 2.

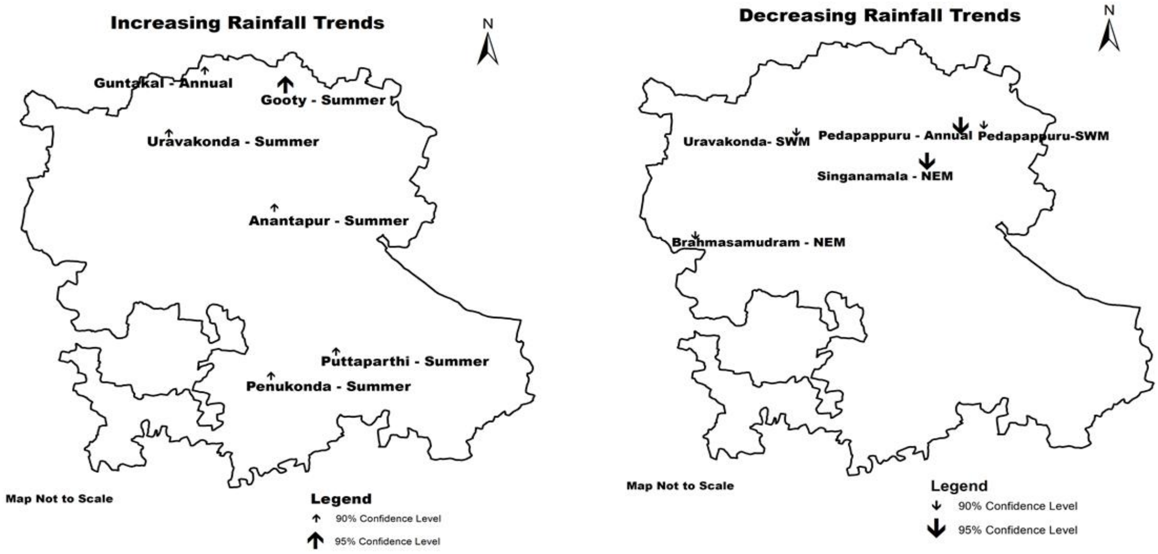

Figure 2. Spatial representation of increasing and decreasing rainfall series in Anantapuramu

Trend analysis indicated both increasing and decreasing trends in annual rainfall. Increasing annual rainfall trend is observed at Guntakal station at 90% confidence interval (4.8 mm/year) whereas, Pedapappuru annual rainfall indicated a decreasing trend at 95% confidence interval (-7.6 mm/year). Spearman's rank correlation coefficient test result at Rolla indicated decreasing annual rainfall trend at a confidence interval of 90% (-7.1 mm/year), while the Mann-Kendall test does not indicate any significant trend. IMD Gridded rainfall data analysis at river basin scale by Bisht et al., (2017) [8] and climate projections used in Jaspers et al., (2012) [82] showed an increasing annual rainfall trend. It is to be noted that, though the interpolated and projected climate data showed an increasing trend, the trend analysis using station level data as in Rao et al., (2009) [8] indicated similar increasing annual rainfall trend at Guntakal and decreasing annual rainfall trend at Pedapappuru as in the present study.

In the study area, very sparse rainfall is observed during the winter season. Mann-Kendall test results do not indicate any significant trend in winter rainfall. Spearman's rank correlation coefficient test result of Atmakur indicated an increasing winter rainfall trend at a confidence interval of 90% and Chennekottapalle, Kudair and Tadimmari stations showed an increasing trend at a confidence interval of 95%. The magnitude of the winter rainfall trends is too small and closer to zero.

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Table 3. Results of Mann-Kendall (MK) test, Sen's Slope test (SS) and Spearman's Rank Correlation Coefficient (SRC) test without considering the effect of serial correlation

Station name	Annual			Winter			Summer			South-West monsoon			North-East monsoon		
	MK	SS	SRC	MK	SS	SRC	MK	SS	SRC	MK	SS	SRC	MK	SS	SRC
Amadaguru	-1.070	-3.674	-1.120	0.946	0.000	1.462	0.946	1.417	1.010	-0.856	-2.552	-0.837	-0.357	-0.933	-0.213
Anantapur	0.150	0.349	0.307	1.158	0.000	1.473	**1.703***	1.825	**1.750***	-0.477	-1.254	-0.338	-0.708	-0.767	-0.745
Atmakur	*IH*	*IH*	*IH*	1.090	0.000	**1.724***	*IH*	*IH*	*IH*	*IH*	*IH*	*IH*	0.913	1.008	0.953
Brahmasamudram	-1.534	-5.906	-1.622	0.535	0.000	0.801	0.999	1.129	1.244	-1.285	-4.447	-1.171	**-1.820***	-3.165	**-1.705***
Bukkapatnam	0.150	0.583	0.173	0.150	0.000	0.295	1.267	0.974	1.569	-0.014	-0.073	0.116	-0.449	-0.787	-0.499
Chennekottapalle	*IH*	*IH*	*IH*	1.539	0.000	**2.131#**	0.844	0.495	0.746	-0.341	-0.729	-0.278	-0.640	-1.005	-0.797
Dharmavaram	0.000	-0.102	-0.077	0.504	0.000	0.554	1.171	1.030	1.213	-0.313	-0.827	-0.171	*SC*	*SC*	*SC*
Gooty	-0.218	-0.711	-0.179	0.163	0.000	0.318	**2.438#**	1.811	**2.673⸸**	-1.022	-2.051	-0.843	-0.014	-0.007	-0.094
Guntakal	**1.839***	4.805	**1.822***	1.131	0.000	1.642	*IH*	*IH*	*IH*	0.613	1.123	0.666	0.804	0.819	0.817
Hindupur	-0.204	-0.675	-0.272	*SC*	*SC*	*SC*	1.566	1.490	1.616	-0.817	-2.299	-0.773	-0.177	-0.176	-0.028
Kadiri	-0.259	-0.776	-0.202	-0.014	0.000	-0.041	1.444	1.243	**1.729***	-0.286	-1.118	-0.536	0.000	0.004	0.253
Kalyanadurg	1.076	3.322	1.215	0.395	0.000	0.729	*IH & SC*	*IH & SC*	*IH & SC*	0.477	0.855	0.633	0.000	0.060	0.402
Kanaganapalle	0.041	0.124	0.236	1.022	0.000	1.394	*IH*	*IH*	*IH*	-0.232	-0.578	-0.202	-0.885	-0.894	-0.547
Kanekal	*SC*	*SC*	*SC*	0.095	0.000	0.231	*IH*	*IH*	*IH*	0.232	0.758	0.283	-0.041	-0.106	-0.317
Kudair	*IH*	*IH*	*IH*	1.553	0.000	**2.525#**	*IH*	*IH*	*IH*	0.477	0.942	0.573	0.558	0.461	0.528
Madakasira	-0.150	-0.296	-0.187	0.790	0.000	1.243	1.566	1.726	1.636	-0.422	-0.950	-0.581	0.259	0.467	0.746
Mudigubba	-0.963	-4.740	-0.949	0.553	0.000	0.783	0.321	0.250	0.301	-1.213	-4.088	-0.974	*SC*	*SC*	*SC*
Pedapappuru	**-2.034#**	-7.648	**-2.053#**	0.517	0.000	0.633	0.517	0.447	0.656	**-1.820***	-4.750	**-1.827***	-1.606	-3.189	-1.449
Penukonda	*SC*	*SC*	*SC*	1.131	0.000	1.514	**1.866***	1.901	**2.080#**	*SC*	*SC*	*SC*	0.831	1.166	1.033
Puttaparthi	*SC*	*SC*	*SC*	0.571	0.000	0.887	**1.659***	1.763	**1.716***	-0.285	-1.413	-0.269	-0.731	-1.308	-0.760
Rayadurg	0.667	2.201	0.663	0.313	0.000	0.512	*IH*	*IH*	*IH*	-0.082	-0.207	-0.078	*SC*	*SC*	*SC*
Rolla	-1.606	-7.135	**-1.688***	-0.054	0.000	-0.061	0.178	0.240	0.335	-0.821	-3.933	-0.879	-1.392	-3.300	-1.444
Singanamala	*IH*	*IH*	*IH*	1.158	0.000	1.465	0.000	-0.005	-0.041	-1.103	-2.429	-1.032	**-2.411#**	-2.716	**-2.221#**
Tadimarri	-0.285	-1.175	-0.264	1.463	0.000	**2.172#**	0.821	0.692	1.032	-0.071	-0.117	0.001	*SC*	*SC*	*SC*
Tadipatri	*IH*	*IH*	*IH*	0.640	0.000	0.852	0.123	0.074	0.139	-0.749	-2.002	-0.678	-0.736	-1.179	-0.826
Tanakal	-0.245	-1.052	-0.211	0.913	0.000	1.280	0.640	0.504	0.601	-0.504	-1.506	-0.443	-0.667	-0.799	-0.615
Uravakonda	*SC*	*SC*	*SC*	0.613	0.000	1.011	**1.812***	1.241	**1.961#**	**-1.703***	-3.706	**-1.883***	-1.076	-1.633	-0.934

* - significant at 90% confidence interval, # - significant at 95% confidence interval and ⸸ - significant at 99% confidence interval; *IH* – Inhomogeneous; *SC* – Serially Correlated

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Mann-Kendall test and Spearman's rank correlation coefficient test indicated increasing summer rainfall at Anantapur (1.8 mm/year) and Puttaparthi (1.7 mm/year) stations at a confidence interval of 90%. Increasing summer rainfall at Penukonda (1.9 mm/year) and Uravakonda (1.2 mm/year) stations at 90% confidence interval were reported by the Mann-Kendall test. Whereas, Spearman's rank correlation coefficient test indicated increasing trends at a confidence interval of 95% for the same stations. SRC test results for Gooty (1.8 mm/year) station reported increasing summer rainfall at a confidence interval of 95%, whereas the Mann-Kendall test indicates a significant increasing trend at a confidence interval of 99%. Summer rainfall series at Kadiri indicated an increasing trend at a 90% confidence interval (1.2 mm/year) with Spearman's rank correlation coefficient test, whereas the Mann-Kendall test doesn't indicate any significant trend. IMD gridded rainfall data [61] and the results of Bisht et al (2017) [8] at river basin level also indicated increasing summer rainfall in the region.

Both the MK test and SRC test indicated decreasing south-west monsoon rainfall trend at Pedapappuru (-4.7 mm/year) and Uravakonda (-3.7 mm/year) stations at a confidence interval of 90%. The north-east monsoon rainfall trend is decreasing at Brahmasamudram (-3.1 mm/year) and Singanamala (-2.7 mm/year) at a confidence interval of 90% and 95% respectively. The findings of the monsoon rainfall trend analysis are similar to the results of Bisht et al (2017) [8] and Malla Reddy et al., (2015) [83]. The decrease south-west monsoon rainfall can be attributed to the geographical positioning of the district in the rain shadow region of Western Ghats. As the district is away from the coastal area, the district receives very little rainfall during the north-east monsoon season [84].

Previous studies in this region by Malla Reddy et al., (2015) [83] reported a decreasing rainfall trend during the crop growing season and increasing rainfall outside the cropping season. It is also reported that September rainfall, which is very crucial for Kharif cropping is declining. Early-onset of summer and an increase in the temperature are causing severe soil moisture deficiency and crop failures in this region.

If a series is influenced by serial correlation, five modified versions of the Mann-Kendall test are used to examine the trends. Results of modified Mann-Kendall tests applied to the serially correlated series at a confidence interval of 90% are shown in Table 4. A series is said to have a significant trend only if at least three of the five tests suggest a significant trend. The results of modified versions of the Mann-Kendall test indicated an increasing trend in May rainfall at Hindupur and Uravakonda stations and a decreasing rainfall trend in October rainfall at Tadimarri station. The variance correction approach suggested by Yue and Wang (2004) indicated a significant trend in most of the cases as compared to other tests.

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Table 4. Results of modified versions of the Mann-Kendall test applied to serially correlated data

Station name	Time series	PW	TFPW	BCPW	MMKH	MMKY
Amadaguru	August	-0.47	-0.17	-0.51	-1.17	**-2.45**#
Brahmasamudram	June	0.54	0.51	0.43	-0.10	-0.30
Chennekothapalle	May	0.06	0.00	0.09	0.31	0.86
Dharmavaram	May	0.65	0.48	0.68	0.79	**1.85***
Dharmavaram	North-east monsoon	-0.48	-0.37	-0.51	-0.54	-1.15
Gooty	October	0.48	0.28	0.51	0.71	0.69
Hindupur	February	-0.06	-0.06	-0.06	0.51	0.88
Hindupur	May	**1.96**#	1.51	**2.07**#	1.42	**3.19**⸸
Hindupur	June	0.17	0.31	0.06	0.65	1.16
Hindupur	Winter	0.30	0.30	0.30	1.40	**1.79***
Kalyanadurg	Summer	*IH*	*IH*	*IH*	*IH*	*IH*
Kanekal	Annual	0.28	0.28	0.48	-0.01	-0.02
Mudigubba	May	0.28	0.13	0.28	0.68	**1.68***
Mudigubba	North-east monsoon	-0.51	-0.51	-0.58	-0.10	-0.11
Pedapappuru	November	-0.09	-0.09	-0.09	-0.21	-0.50
Penukonda	Annual	0.71	1.14	0.60	0.84	**1.87***
Penukonda	South-west monsoon	0.00	-0.17	-0.03	-0.40	-0.73
Puttaparthi	Annual	-0.54	-0.43	-0.51	-0.78	-1.32
Puttaparthi	North-east monsoon	-1.18	-0.96	-1.14	-0.73	**-2.25**#
Singanamala	May	-0.13	-0.23	-0.18	-0.64	-0.92
Tadimarri	October	**-1.74***	-1.44	**-1.86***	-1.64	**-2.45**#
Tadimarri	North-east monsoon	-0.96	-0.81	-0.99	-0.96	**-2.21**#
Tadipatri	November	-0.77	-0.77	-0.82	-0.38	-0.95
Uravakonda	May	**1.73***	1.45	**1.85***	**1.66***	1.33
Uravakonda	October	-0.09	-0.03	-0.09	-0.42	-0.88
Uravakonda	Annual	-0.03	-0.57	0.00	-0.90	**-2.30**#

* - significant at 90% confidence interval, # - significant at 95% confidence interval and ⸸ - significant at 99% confidence interval; *IH* – Inhomogeneous.

4.4. Total Rainfall Trend vs Trend in Number of Rainy Days

In the present study, we tried to examine the trend in the number of rainy days when any significant annual and seasonal trend is observed in the total rainfall. The purpose of this analysis is to examine if the trends in the number of rainy days are decreasing or increasing with the increase or decrease in the trends in the total amount of rainfall. It is observed that for winter series at Atmakur, Kudair, Tadimarri; summer series at Gooty, Kadiri; and annual series at Guntakl, significant increasing trends are observed in both the number of rainy days and total rainfall. At Brahmasamudram, both trends in the number of rainy days and total rainfall are observed to be decreasing. It is observed that the number of rain days are increasing or decreasing when total rainfall is increasing or decreasing respectively.

4.5. Trend Change-Point Analysis

The purpose of change-point analysis is to identify the probable time where a significant change occurred in the series. Trend change point analysis is carried out for all the series exhibiting significant trend and the results of the Distribution-free CUSUM test and Sequential Mann-Kendall test are shown in Table 5. CUSUM test indicated significant change points in summer series at Anantapur, Gooty and Puttaparthi stations, and north-east monsoon series at Brahmasamudram and Singanamala stations.

Table 5. Trend change-point summary

Stations	Series	CUSUM	SQMK
Anantapur	Summer	**1995**#	1998
Atmakur	Winter	2015	-
Brahmasamudram	North-east monsoon	**2003***	2011
Chennekottapalle	Winter	2012	-
Gooty	Summer	**1997**#	2000
Guntakal	Annual	1995	1995
Kadiri	Summer	1999	1995
Kudair	Winter	2012	-
Pedapappuru	Annual	2001	2011
Pedapappuru	South-west monsoon	2001	2001
Penukonda	Summer	1999	2003
Puttaparthi	Summer	**1999***	2013
Rolla	Annual	1991	1993
Singanamala	North-east monsoon	**2002***	2013
Tadimarri	Winter	2012	-
Uravakonda	Summer	2001	2001
Uravakonda	South-west monsoon	2001	2012

* - significant change point at 90% confidence interval, # - significant change point at 95% confidence

Sequential Mann-Kendall test results as shown in Figure 3 are based on interactions between prograde and retrograde series. The series will intersect at several locations in the absence of a significant trend. When there is a significant intersection is observed in the plot, it indicates the probable change year of trend change. The plots mentioned in Figure 3 are the significant trend change-points observed with distribution-free CUSUM tests.

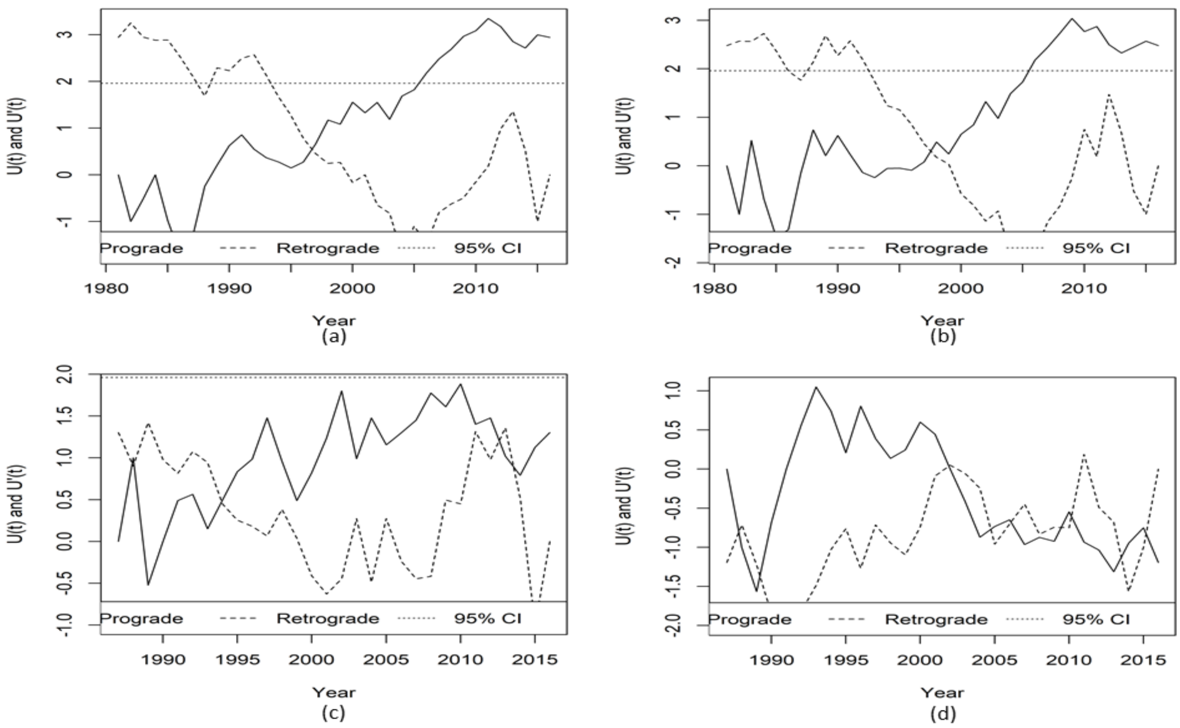

Figure 3. Sequential Mann-Kendall plots for (a). Anantapur - Summer, (b). Gooty - Summer, (c). Puttaparthi - Summer and (d) Brahmasamudram - North-east monsoon

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5. Conclusions

Daily rainfall data is collected for the district of Ananthapuramu, Andhra Pradesh, India for a period of 36 years starting from 1981 and is aggregated to monthly, annual and seasonal totals and a number of rainy days. Both absolute and relative homogeneity tests were performed on the data and inhomogeneous series were excluded from trend and change point analysis. To implement the trend tests and change point tests mentioned in this study, two open-source libraries were developed in R-language and are made available via CRAN repository.

Trend analysis showed increasing summer rainfall in the study area at all the stations, except for Singanamala. Six stations out of 27 stations indicated significant increase in summer rainfall. South-west monsoon and North-east monsoon rainfall trend is decreasing in most of the stations. Nineteen out of 27 stations indicated decreasing south-west monsoon rainfall trend and significant decrease is observed at Pedapappuru and Uravakonda. North-east monsoon rainfall trend is decreasing at 20 stations and significant decrease is observed at Brahmasamudram and Singanamala. Increase in the summer rainfall trends and decreasing monsoon rainfall trends will impact the agriculture sector in the region.

The serial correlation was analyzed at various confidence intervals and an ensemble of modified trend tests were applied to the serially correlated data. The present study is perhaps one of the few studies which considered using multiple modified versions of trend tests when the series are serially correlated. Identifying the trend change point is as crucial as studying the trends in hydro-meteorological data. The present study used two non-parametric tests to report the trend change points. Significant change points are observed in the summer season at Anantapur, Gooty, Puutaparthy and north-east monsoon season at Brahmasamudram and Singanamala.

For an arid district like Ananthapuramu, where rainfed agriculture is widely practiced, a decreasing trend in monsoon rainfall is an alarming indication. By assessing the rainfall variability, this study offers insights into distinguishing vulnerable zones within the study area so that better water management decisions, storage and irrigation infrastructure, cropping choices and water security policies for sustainable land and water resources management can be implemented.

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