Rainfall Trend Analysis by Mann-Kendall Test and Sen's Slope Estimator: A Case Study of Gummidipoondi Sub-basin, Tamil Nadu, India

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Abstract — Trend analysis in the rainfall provides us information for effective planning and designing the availability of the water resources. The study investigates the effect of climate variability on the rainfall in Gummidipoondi Sub-basin of Tiruvallur district located in Tamil Nadu which consists of three influencing rain gauging stations. Daily rainfall data for 30 years (1990 to 2019) has been processed in this study to find out the trends in Monthly, annual, seasonal and Annual Daily Maximum Rainfall (ADMR). The same is used to find the trend and its magnitude respectively. In North East monsoon season a significantly falling trend is observed. It is also observed that the trend analysis of rainfall series from 1990 to 2019 did not show any significant trend for the study area as a whole, although there are both increasing and decreasing trends for seasons and months in all the three gauging stations which suggests overall insignificance in rainfall variability in the Gummidipoondi Sub-Basin.

Index Terms — Climate Change, Mann-Kendall test, Modified Mann-Kendall test, Rainfall, Sen's Slope, Statistical analysis, Trend Analysis

1 Introduction

Rainfall is an important meteorological parameter and any change in its pattern would directly affect the availability of the water resources thus affecting urban, industrial and agricultural uses [1]. The hydrological cycle and its processes are under major threat due to the climate change and the Studies to detect trends in hydrologic series and its impact on agriculture, increased risk of hunger and water scarcity, rapid melting of glaciers, and uncertainty in the river flows deserves an urgent attention [2]. Changes in frequency of rainfall and its temporal variation would modify the pattern of stream flows, spatial and temporal distribution of runoff, soil moisture, and depletion of groundwater resources. A detailed trend analysis on rainfall will lead to a better understanding of the problems associated with floods, droughts, and the availability of water with respect to future climate scenarios. The evaluation of past trends of meteorological parameters at various spatial and temporal scales plays a crucial role in understanding climate change and its impact on food security, energy security, natural resource management, and sustainable development.

Trend detection of stream flow and rainfall is an active area of interest for both hydrology and climatology particularly in the context of climate change. Trend analysis of rainfall is defined as the use of statistical approaches to quantify the magnitude of changes in a long-term rainfall series over a given period of time. The purpose of trend analysis is to determine if the rainfall pattern is generally increasing or decreasing over a period of time. Various statistical tests are used to detect trends in hydrological and hydro-meteorological time series; these are widely classified as parametric and nonparametric tests. Parametric tests are carried out when the distribution of time-series is known, they are more powerful but require that data be random, independent and normally distributed, which is rarely true for hydrological time series data. In the absence of information on time series distribution, the Non – Parametric tests are generally used. For nonparametric tests, data must be independent, but outliers are better tolerated. Nonparametric trend tests are widely used in the literature as they do not assume any statistical distribution in the data. The most common non-parametric tests for working with time series trends are the Mann-Kendall tests. The Mann-Kendall test is the most common one used by researchers in studying hydrologic time series trends.

The objective of this present study is to investigate the presence of trend in the rainfall time series in the Gummidipoondi Sub-Basin located in Tiruvallur District. Very few studies on climatological trend analysis have been carried out in this region. In this study, the rainfall is investigated for the presence of trend at a monthly, annual, and seasonal scale. In addition to this, the presence of trend is also investigated for Annual Daily Maximum Rainfall Series (ADMR).

2 Study Area Description

The Gummidipoondi Sub-basin is one of the eight sub-basins of Chennai. It is located mainly in Gummidipoondi Taluk under Tiruvallur District of Tamil Nadu, India. The sub-basin is situated between 79˚52′00″ E to 80˚10′00″ E longitudes and 13˚20′00″ N to 13˚33′00″ N latitudes. The Sub-basin comprises an area of about 412 sq. km. and falls within River Araniyar Sub-basin. Gummidipoondi sub-basin drains into Bay of Bengal near Pulicat Lake. The Maximum rainfall occurs during North-East monsoon. There is no perennial river flowing in Tiruvallur district. However, considerable number of tanks are present which takes care of domestic and agricultural water requirement. The major soil type is clayey soil followed by Sandy coastal alluvium soil. The predominant land

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use in the sub-basin is agriculture with some rural and urban built-up areas. The index map of the study area is shown in Figure 1.

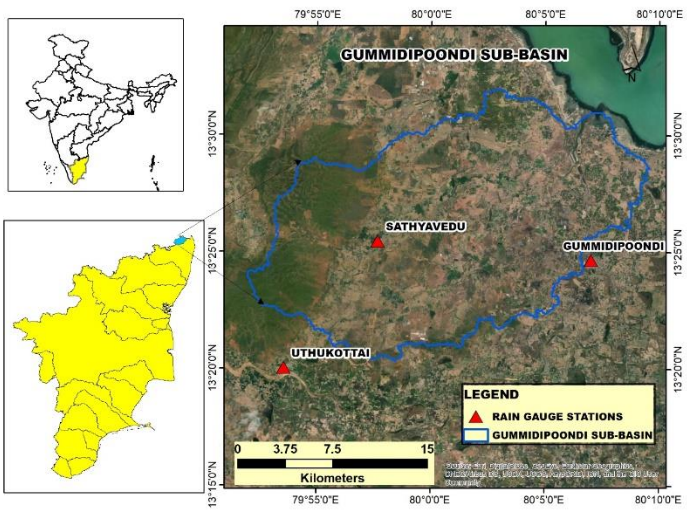

Fig. 1. Index Map of the study area

3 MATERIALS AND METHODS

This study mainly focusses on the trend analysis by using the Man-Kendall method along with Sen's Slope estimate method over the Gummidipoondi Sub-basin region. The methodology adopted for trend analysis of rainfall is shown in the Figure 2.

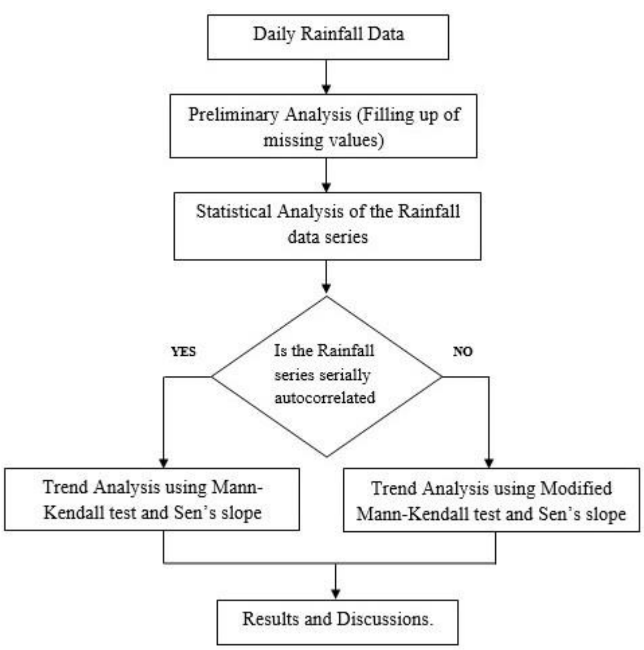

Fig. 2. Methodology Flowchart

3.1 Meteorological data

The daily rainfall data for 30 years (1990 to 2019) for the Tiruvallur District comprising of a total of 18 rain gauge stations was collected from the office of State Surface & Ground Water Data Centre, Public Works Department, Chennai, Tamil Nadu. From the available stations, the most influencing rain gauge stations are identified using Thiessen Polygon method. The missing values of the influencing Rain gauge stations were filled using Inverse Distance Weighted (IDW) method. Among the 18 identified stations, the three rain gauge stations located in Gummidipoondi, Sathyavedu and Uthukottai are the most influencing rainfall stations and the same are used in this study to analyse the trend in Rainfall.

3.2 Analysis of Data

The rainfall observed for a 30-year period were analysed for monthly and annual seasonal timescale. In addition to this, the trend was investigated for another factor called Annual Daily Maximum Rainfall (ADMR), which is the maximum single day rainfall event of the year. For Seasonal analysis, each year was divided into four climatic seasons, as per the classification suggested by India Meteorological Department, IMD for Tamil Nadu namely South West Monsoon (June – September), North East Monsoon (October – December), Winter (January – February) and Summer (March – May). The Gummidipoondi Sub-basin receives majority of rainfall in North- East monsoon followed by South-west monsoon.

In this present study, the magnitude of trend in the rainfall data series was determined using Sen's estimator and statistical significance of the trend in the rainfall data was investigated using Mann – Kendall (MK) test. This technique makes use of Variance correction approaches proposed by Hamed and Rao [3].

3.3 Mann – Kendall test

Mann-Kendall test had been proposed by Mann [4] as a non-parametric test for detecting trends in the data series and later Kendall [5] formulated test statistic distribution for testing on non-linear trends and turning point. It statistically checks the monotonic upward and downward trends in climatic data series over the time. To discover the existence of statistically significant or insignificant trends in hydrologic climate variables such as precipitation, streamflow, temperature under the context of climate change, the Mann – Kendall test has been effectively used in various studies. (Mondal et al. [6], S.K Jain et al. [7], Abeysingha et al. [8], Bhabishya Khaniya et al. [9]). The MK test checks the null hypothesis (No Trend) versus the alternate Hypothesis (Presence of trend). The Mann-Kendall test statistic (S) is estimated by the following equation as follows:

$$S = \sum_{i=1}^{N-1} \sum_{J=i+1}^{N} sgn\,(x_j - x_i) \qquad (1)$$

Where x_i and x_j are the time series and N is the number of data points in the time series. The sign function 'sgn' can be further expressed as

$$sgn\left(x_j - x_i\right) = \begin{cases} +1 & ,\text{if } \left(x_j - x_i\right) > 0 \\ 0 & ,\text{if } \left(x_j - x_i\right) = 0 \\ -1 & ,\text{if } \left(x_j - x_i\right) < 0 \end{cases} \quad (2)$$

This statistic represents the difference between the number of positive and negative differences. If the number of samples 'N' exceeds 8, Statistics S approximates to a normal distribution with the mean and the variance as follows

Mean, E(S)=0

The variance of the Mann – Kendall's test is acquired using the following formula

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

Where n is the number of tied groups (i.e., Zero difference between tied values) and t_i is the number of data points in the i^{th} tied group. The standard normal deviate also known as standard test statistic Z_c is calculated as follows:

$$Z_C = \begin{cases} \dfrac{S-1}{\sqrt{Var\ (s)}} & ,\text{for } S > 0 \\ 0 & ,\text{for } S = 0 \\ \dfrac{S+1}{\sqrt{Var\ (s)}} & ,\text{for } S < 0 \end{cases} \quad (4)$$

Z_C is a measure of significance in trends. It tends to follow the standard normal distribution. If $Z_C > 0$, it indicates an increasing trend in the series and vice versa. A significance level α is used to test an upward or downward monotone trend (a two – tailed test). If $Z_C > Z\ \alpha/2$, then the trend is considered significant and vice versa. In this study 5% significant level is used. If the Rainfall series is serially autocorrelated, the existence of trend is found using Modified Mann – Kendall's (MMK) test.

3.4 Sen's Slope Estimator Test

The magnitude of trend is predicted by the Sen's Method [10]. This method assumes a linear trend in the time series and has been widely used for determining the magnitude of trend in hydro-meteorological time series (Jayawardene et al. [11], Martina Isabella et al. [12] and Patakamuri S.K et al. [13]. This test calculates both the slope and intercept using Sen's Slope estimator test. Initially, a set of linear slopes for all data pairs is calculated using the following equation.

$$T_i = \frac{x_j - x_k}{j-k} \quad \text{for i = 1,2, 3, …., n, j > k,} \quad (5)$$

Where, T_i is the Slope and x_j and x_k are the data values at time j and k, respectively. The median of the n values of T_i is symbolised as Sen's slope estimator (Q_i) and given by

$$Q_i = \begin{cases} T_{(n+1)/2} & ,n\ is\ odd \\ \frac{1}{2}(\ T_{n/2} + T_{(n+2)/2} & ,n\ is\ even \end{cases} \quad (6)$$

Positive value of Q_i indicates upwards or increasing trend and a negative value Q_i represents a presence of downward or decreasing trend in the time series of the data.

In this study, the Mann – Kendall test along with Sen's slope estimator is carried out using Addinsoft's XLSTAT 2012. The null hypothesis is tested at 95% confidence level for the rainfall data for monthly, annual and Seasonal timescale. In addition to this, trend was also checked for Annual Daily Maximum Rainfall (ADMR) values as it gives an idea on the temporal trend in the rainfall data for the three rain gauge selections.

4 Results and Discussions

4.1 Preliminary statistical Analysis

Before the trend analysis, a preliminary statistical analysis which consists of estimation of important statistical parameters is done to the rainfall series. The results are shown in Table 1.

TABLE 1
RAINFALL STATISTICS

SEASON	Minimum	Maximum	Mean (mm)	S. D	CV	Skewness	Kurtosis
GUMMIDIPOONDI (1990-2019)							
Annual	646.2	2144.1	1204.2	394.2	0.33	0.71	-0.35
SWM	155.1	888.7	411.7	162.2	0.39	1.60	3.45
NEM	277.8	1630.2	724.9	337.4	0.47	1.11	1.02
Winter	0.0	201.7	14.3	39.6	2.77	4.08	18.37
Summer	0.0	318.8	53.3	78.5	1.47	1.94	3.66
ADMR	40.0	309.0	118.0	57.7	0.49	1.52	3.34
SATHYAVEDU (1990-2019)							
Annual	542.2	2096.0	1217.3	397.7	0.32	0.64	0.01
SWM	120.9	979.0	407.0	163.5	0.39	1.30	4.02
NEM	202.0	1499.0	726.4	334.6	0.45	0.53	-0.16
Winter	0.0	88.6	14.9	23.7	1.56	1.80	2.62
Summer	0.0	356.9	69.0	90.1	1.29	2.06	4.38
ADMR	44.0	225.0	122.7	49.0	0.39	0.41	-0.77
UTHUKOTTAI (1991-2019)							
Annual	398.0	1865.6	1063.9	356.0	0.33	0.37	0.15
SWM	112.0	881.0	410.6	162.8	0.39	0.79	1.12
NEM	138.0	1165.4	553.5	257.4	0.46	0.66	0.06
Winter	0.0	129.4	17.0	35.1	2.03	2.34	4.65
Summer	0.0	334.2	82.9	86.4	1.02	1.46	1.70
ADMR	50.0	211.2	102.4	35.4	0.34	1.05	1.77

S.D = Standard Deviation, CV = Coefficient of Variation

The statistical parameters (mean, standard deviation, skewness, kurtosis and coefficient of variation) of annual, seasonal and ADMR series were computed for each station over the period of 1990 to 2019. The skewness, which is a measure of asymmetry in a frequency distribution around the mean. All the rainfall series show positive skewness indicating that annual precipitation during the period is asymmetric and it lies to the right of the mean over all the stations. Kurtosis is a statistic describing the peakiness of a symmetrical frequency distribution, varied from −0.16 to 18.37 with predominantly positive values of skewness. The coefficient of variation (CV), which is measure of the dispersion of data points in a data series around the mean, was computed for all stations in order to investigate spatial pattern of inter-annual variability of annual precipitation over the study area. The annual rainfall series of all the three stations showed the coefficient of variation of 0.32. It can be concluded from the results that the season in which major precipitation occurs show least variability. On the other hand, winter and summer season shows comparatively higher variability.

The annual rainfall of Gummidipoondi, Sathyavedu and Uthukottai over a period of 30 years is shown in Figure 3, Figure 4 and Figure 5 respectively.

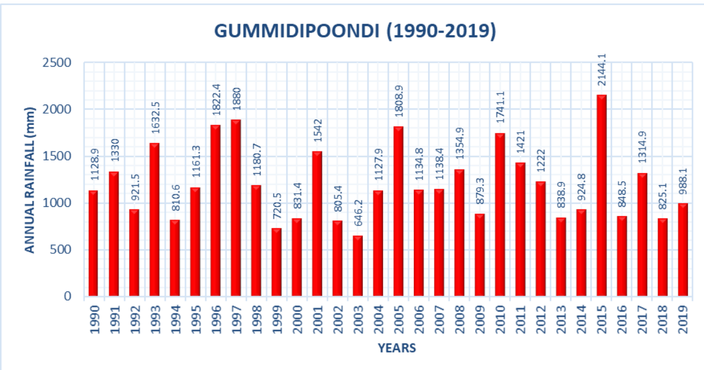

Fig. 3. Annual Rainfall (1990 to 2019) for Gummidipoondi station

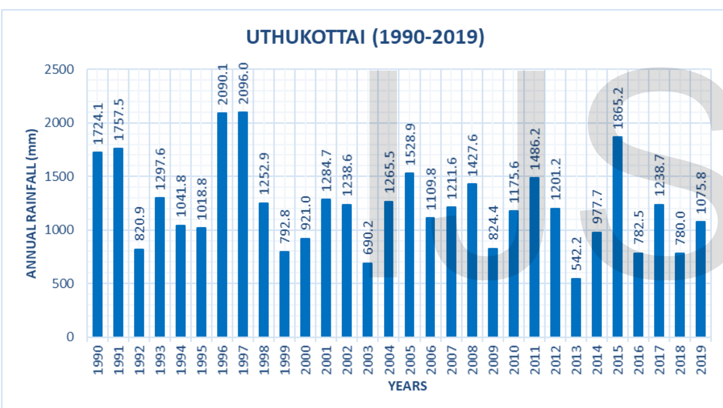

Fig. 4. Annual Rainfall (1990 to 2019) for Uthukottai station

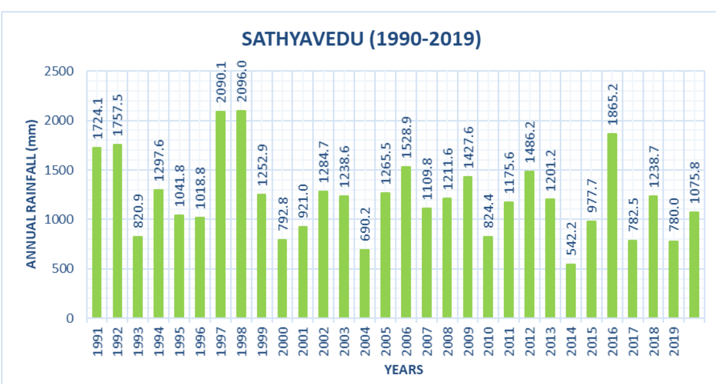

Fig. 5. Annual Rainfall (1990 to 2019) for Sathyavedu station

4.2 Trend Analysis of Monthly Rainfall Analysis

The Mann-Kendall (MK) test and Sen's slope test were applied on a monthly rainfall data to detect the trends in the precipitation series at Gummidipoondi, Sathyavedu and Uthukottai rain gauge stations. Table 2 presents the results of Mann-Kendall's Statistic (Z_C) and its corresponding Sen's slope factor (S) along with the significance of the trend.

TABLE 2
TREND ANALYSIS OF MONTHLY RAINFALL

Month	Rain Gauge Stations								
	Gummidipoondi			Sathyavedu			Uthukottai		
	Z_C	S	T	Z_C	S	T	Z_C	S	T
January	0.56	0	NS	0.44	0	NS	-1.15	0.000	NS
February	0.31	0	NS	0.25	0	NS	-0.73*	0.000	NS
March	0.58	0	NS	0.91	0	NS	-0.17	0.000	NS
April	-0.35	0	NS	0.79	0	NS	-0.54	0.000	NS
May	0.94	0	NS	0.85	0	NS	**-2.78***	**-1.317**	**S**
June	1.36	1.195	NS	1.09	1.036	NS	1.71	1.225	NS
July	1.09	1.071	NS	0.37	0.6	NS	-0.62*	-0.267	NS
August	0.18	0.305	NS	0.45	0.992	NS	0.24*	0.504	NS
September	0.71	0.873	NS	1.3	1.633	NS	-0.45	-0.561	NS
October	0.04	0.105	NS	-1.32	-3.994	NS	-1.48	-3.389	NS
November	-1.71	7.482	NS	**-2.57**	**-10.850**	**S**	**-2.38**	**-7.742**	**S**
December	0.71	1.636	NS	-0.43	-1.081	NS	0.71	1.694	NS

NS – Non Significant trend S – Significant trend at 5% level of Significance. The values marked with (*) indicates the series for which Modified Mann – Kendall test is used for trend analysis.

For Gummidipoondi Rain gauge station, no significant trend either positive or negative was observed for 5% level of significance. However, the analysis has detected insignificant trends in the series. Both positive and negative trends are identified, the majority of being positive trends, which indicates there is an insignificant rising trend in the non-monsoon months. The months of April and November have shown evidence of negative trends although insignificant. The Sen's slope statistic shows no magnitude of trend for the months of January to May. The Major rising trend is observed in the month of July, having Z_C of 1.36 and its corresponding Sen's slope value of 1.195 and the major falling trend is observed in the month of November with Z_C of 1.36 and corresponding Sen's slope value of 1.195. The monthly, annual, seasonal and ADMR variation in Z_C is shown in Figure 6.

The rainfall recorded at Sathyavedu rain gauge station shows a significant falling trend at the month of November with Z_C of -2.57 and its corresponding Sen's slope value of -10.85. The significantly high magnitude indicates that the rainfall is significantly decreasing in the month of November, which is a major monsoon month. The other months show both positive and negative insignificant trends. The major observation in this series is that it shows negative trends for the months of October to December, during which the North-East monsoon is prevalent. The Major rising trend is observed in the month of September, having Z_C of 1.3 and its corresponding Sen's slope value of 1.633. Figure 7 shows the variation in Z_C values in monthly, annual, seasonal and ADMR series.

In Uthukottai station, the monthly rainfall series of February, May, July, August were serially autocorrelated. Hence, Modified Mann-Kendall test is used for trend analysis. The Analysis shows evidence of significant falling trends in the months of May and November. The major falling trend is observed in the month of November having Z_C value of -2.38 and its corresponding magnitude of -7.742. Both the stations of Sathyavedu and Uthukottai showed significant falling trend in the month of November which confirms the presence of a falling trend in the amount of monthly rainfall in North-East Monsoon. And out of 12 months, 9 months shows downward trend in the rainfall both significant and insignificant. The rising trend is observed only in the months of June, August and December.

4.3 Trend Analysis of Annual, Seasonal and ADMR Rainfall

The Mann-Kendall test and Sen's slope test were applied on an Annual, Seasonal time scale in addition with Annual Daily Maximum Rainfall to detect the trends in the precipitation series at Gummidipoondi, Sathyavedu and Uthukottai Rain gauge stations. Table 3 presents the results of Mann-Kendall's Statistic (Z_C) and its corresponding Sen's slope factor (S) along with the significance of the trend.

TABLE 3
TREND ANALYSIS OF ANNUAL AND SEASONAL RAINFALL

Month	Rain Gauge Stations								
	Gummidipoondi			Sathyavedu			Uthukottai		
	Z_C	S	T	Z_C	S	T	Z_C	S	T
Annual	-0.25	-2.482	NS	-1.59	-11.317	NS	**-1.97**	-15.585	S
SWM	0.149	2.619	NS	1.28	3.343	NS	-0.02	-0.543	NS
NEM	-0.099	-5.208	NS	**-2.55**	-16.750	S	**-2.04**	-11.665	S
Winter	0.069	0	NS	-0.62	0	NS	-0.91	0	NS
Summer	0.169	0.358	NS	1.47	1.267	NS	-1.35	-2.014	NS
ADMR	0.023	0.257	NS	**-2.36**	-2.631	S	-0.96	-0.668	NS

NS – Non Significant trend S – Significant trend at 5% level of Significance

Annual Rainfall: Trend analysis indicated a significant decreasing trend in annual rainfall in Uthukottai station having ZC value of -1.97 (negative trend) with its corresponding Sen's slope value of -15.585 which indicates a downward trend of significant magnitude. The Gummidipoondi and Sathyavedu stations showed negative trend however insignificant. This decreasing trend in all the stations results in the fact that annual rainfall is reducing in the Gummidipoondi sub-basin over a period of 30 years.

South West Monsoon: No significant trend is observed in all the three stations for southwest monsoon season. The stations of Gummidipoondi and Sathyavedu observed increasing trend although insignificant. Only the Uthukottai station showed insignificant decreasing trend. The maximum trend is observed in Sathyavedu station (S = 3.343), and the minimum trend Is Observed in Uthukottai station (S = -0.543). The trend analysis for this season concludes with the fact that there is no significant rise or fall in the quantum of rainfall in three decades.

North East Monsoon: All the three stations show downward trend in this season. The stations of Sathyavedu (S=-16.750) and Uthukottai (S=-11.665) shows a significant downward trend. As the district of Tiruvallur receives maximum rainfall in the north east monsoon season, the downward trend results of the analysis indicate a significant impact of climate change on the rainfall in the district.

Winter Season: Very scanty rainfall is observed during the winter season. Also, the trend analysis indicated very insignificant trends with almost zero magnitude of trend. Hence it is concluded that there is no significant trend in the rainfall patterns during winter season.

Summer Season: The summer season follows the path of trend observed in winter season. No significant trends were observed with the maximum trend found in Sathyavedu (S = 1.267) and negative trend being detected in Uthukottai station (S = -2.014).

Annual Daily Maximum Rainfall: The ADMR values showed a mixed trend with a significant negative trend observed in Sathyavedu (S = -2.631). An insignificant negative trend is observed in Uthukottai (S = -0.668) and the insignificant positive trend in Gummidipoondi (S = 0.257). The mixed trend results show spatial as well as temporal variability in rainfall within same sub-basin. Further analysis with larger data series and trend detection in other hydrological parameters will result in more detailed understanding of the rainfall patterns and its impacts due to climate change.

5 CONCLUSION

The present study analysed the rainfall data for 30 years from 1990 to 2019 of Gummidipoondi Sub-Basin for the determining the trend in precipitation. Daily Rainfall data is collected from three influencing rain gauge stations of Gummidipoondi, Sathyavedu and Uthukottai. The daily rainfall data is aggregated to Annual, Seasonal and ADMR time series. The data is initially checked for serial correlation, and the presence of trend is detected using Mann-Kendall test and Modified Mann-Kendall tests for serially correlated series and the magnitude of the trend is estimated using Sen's Slope method.

The results of the trend analysis indicate that there is a major decreasing trend in Uthukottai station, both in monthly and seasonal data series, followed by Sathyavedu. Gummidipoondi has maximum increasing trends, which shows spatial and temporal variation in rainfall within an individual watershed. Further analysis with larger data series and trend detection in other hydrological parameters and using other trend detection methods will result in more detailed understanding of the rainfall patterns and its impacts due to climate change. This will extensively aid in framing better water management strategies, water securities, cropping practices and a sustainable development altogether.

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