Journal of Agrometeorology

(A publication of Association of Agrometeorologists)

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 28 (3) : 415-421 (September - 2026)
https://doi.org/10.54386/jam.v28i3.3270
https://journal.agrimetassociation.org/index.php/jam

Research paper

Rainfall Analysis for Crop Planning for Paddy Grown in Cauvery Delta Zone of Tamil Nadu

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ABSTRACT

The Cauvery Delta Zone (CDZ) of Tamil Nadu is highly dependent on rainfall variability for paddy production. The long-term daily rainfall data (1991–2024) from three representative districts (Thanjavur, Tiruvarur, and Nagapattinam) were analysed to evaluate the rainfall trends, regime shifts, and assured rainfall for crop planning. Non-parametric Mann–Kendall and Sen's slope tests were used to detect monotonic trends, while Innovative Trend Analysis (ITA) and Pettitt's change-point test identified non-linear trends and structural shifts. Weekly rainfall probabilities were estimated using the incomplete gamma distribution. Results indicated a statistically significant increase in Northeast Monsoon rainfall (Sen's slope: +3.1 to +3.7 mm yr^{-1}; $p \leq 0.05$) and a weak decline in Southwest Monsoon rainfall (−0.9 to −1.4 mm yr^{-1}). Pettitt's test detected a significant rainfall regime shift around 2005 ($p < 0.05$), marking increased interannual variability. District-wise probability analysis showed that Standard Meteorological Weeks (SMW) 42–48 provide assured rainfall ≥75 mm at 75% probability, suitable for Samba paddy transplanting, whereas Navarai season rainfall was unreliable (<10 mm $week^{-1}$). Regression analysis revealed that El Nino-Southern Oscillation Index (INSO) and Indian Ocean Dipole (IOD) together explained 82% of interannual rainfall variability ($R^2 = 0.82$; $p < 0.01$). The study provides statistically robust, rainfall-responsive insights for paddy crop planning in the Cauvery Delta Zone.

Keywords: Cauvery Delta Zone; ENSO; IOD; Innovative Trend Analysis; Mann–Kendall test; Rainfall probability; Sen's slope

Rainfall is the principal climatic determinant of agricultural productivity and water management in monsoon-dependent ecosystems such as Tamil Nadu (Sathyamoorthy *et al.,* 2016; Pavithrapriya *et al.,* 2022). The Cauvery Delta Zone (CDZ), comprising Thanjavur, Tiruvarur, and Nagapattinam districts, is one of the most important rice-growing regions in southern India, where paddy cultivation is strongly influenced by the temporal distribution of Southwest Monsoon (SWM) and Northeast Monsoon (NEM) rainfall (Sathyamoorthy *et al.,* 2016; Barati *et al.,* 2022; Prabakar *et al.,* 2024). In recent studies, it has been reported that the rainfall variability has increased, the intensity of the monsoon has shifted and the frequency of high-intensity rainfall events of short duration has increased over the Cauvery basin, challenging the conventional crop calendars (Ghosh *et al.,* 2023; Manivasagam *et al.,* 2025; Niraimathi & Saravanan, 2024).

Several earlier investigations in the CDZ have documented rainfall trends using classical non-parametric methods such as the Mann–Kendall test and Sen's slope estimator (Mann, 1945; Sen, 1968; Pavithrapriya *et al.,* 2022). However, these approaches primarily detect linear trends and may fail to capture non-linear changes or abrupt regime shifts (Deka *et al.,* 2013; Saravanakumar *et al.,* 2022). Innovative Trend Analysis (ITA) and Pettitt's change-point test offer complementary insights by identifying hidden trends and structural discontinuities in hydro-climatic time series (Saravanakumar *et al.,* 2022; Manivasagam *et al.,* 2025; Sellaperumal *et al.,* 2025; Pettitt, 1979).

The novelty of the present study lies in:

(i) the district-wise detection of non-linear rainfall trends and regime shifts in the CDZ using ITA and Pettitt's test, (ii) the integration of trend diagnostics with ENSO and IOD teleconnections to explain interannual rainfall variability, and (iii) the development of district-specific, probability-based rainfall windows for paddy crop planning.

This study aims to (a) quantify long-term rainfall

Article info - DOI: *https://doi.org/10.54386/jam.v28i3.3270*
Received:21 November 2025; Accepted: 15 July 2026; Published online : 7 September 2026

variability (1991–2024), (b) detect linear and non-linear rainfall trends and change points, and (c) identify statistically assured rainfall periods for paddy cultivation in the Cauvery Delta Zone.

MATERIALS AND METHODS

Study Area

The study was conducted in the Cauvery Delta Zone (CDZ) of Tamil Nadu, India, comprising three major rice-growing districts: Thanjavur, Tiruvarur, and Nagapattinam (Fig. 1) (Sathyamoorthy *et al.,* 2016; Pavithrapriya *et al.,* 2022; Nair *et al.,* 2024). The area lies between 10.5° - 11.1° N latitude, and 78.9° - 79.9° E longitude and is under tropical wet–dry climate. Average yearly temperature is 27-29 °C and the relative humidity is ~75-80%. The total annual rainfall in the region is divided between the Northeast monsoon (NEM) season (October-December) and Southwest monsoon (SWM) season (June-September) with NEM accounting for 50-55% and SWM accounting for 45-47% of the total annual rainfall (Sathyamoorthy *et al.,* 2016; Bama *et al.,* 2021; Barati *et al.,* 2022).

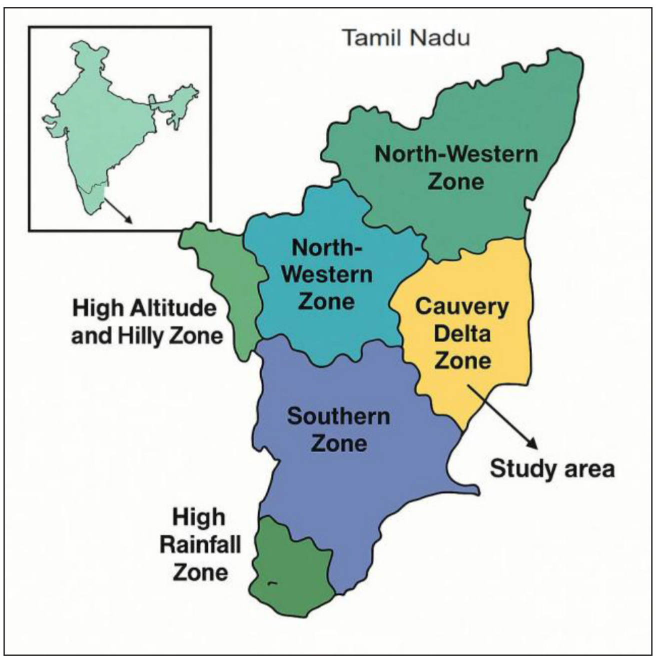

Fig. 1: Study Area: Cauvery Delta Zone

Rainfall Data and Quality Control

The daily rainfall data for the last 34 years (1991-2024) were collected from the India Meteorological Department (IMD), Chennai, for one representative station in each district: Thanjavur (10.78° N, 79.13° E), Tiruvarur (10.77° N, 79.64° E), and Nagapattinam (10.76° N, 79.84° E).

The selected stations of India Meteorological Department (IMD) stations which represent the agro-climatic conditions of the central part of each district. The stations were selected because they had long-term rainfall data (1991–2024) that were continuous, had few missing observations, and were widely used in regional climatological and agrometeorological studies. The selected stations are representative of the rainfall variability at the district level in the Cauvery Delta Zone.

The data for each day was summed to monthly, seasonal and Standard Meteorological Week (SMW) totals for analysis. Data quality control was performed for continuity, outliers, and missing values. The ratio-to-mean interpolation method (Deka *et al.,* 2013; Pavithrapriya *et al.,* 2023) was used to infill missing observations (<0.5%).

The Standard Normal Homogeneity Test (SNHT) and Buishand range test (Alexandersson, 1986; Buishand, 1982; Deka *et al.,* 2013) were used to test the homogeneity of rainfall series. All series were found to be homogeneous at the 5% significance level, in the homogeneity test, and thus suitable for trend and change-point analysis.

Descriptive Statistics

The mean, standard deviation (SD) and coefficient of variation (CV) were used to quantify the seasonal and annual rainfall variability, computed as:

$$CV = \frac{SD}{\bar{X}} \times 100$$

where is the average rainfall.CV values below 30% are considered as stable rainfall and above 50% are considered as high interannual variability (Sathyamoorthy *et al.,* 2016).

Mann–Kendall Trend Test

Non-parametric Mann-Kendall (MK) test was used to detect the monotonic trends in the annual and seasonal rainfall series (Mann, 1945). The test statistic S for MK was calculated as well as the standardized normal statistic Z and the significance level by the 95% and 99% confidence levels. If necessary, variance correction for tied values was performed (Deka *et al.,* 2013).

Sen's Slope Estimator

Sen's slope (β) which is the median of all pairwise slopes were used as an estimate of the magnitude of the detected trends (Sen, 1968). Along with the slope estimates, 95% confidence limits were computed to give an idea of the uncertainty in the magnitude of the trend.

Innovative Trend Analysis (ITA)

To find the non-linear and hidden trends that are not identified by MK test, innovative Trend Analysis (ITA) method was used (Pavithrapriya *et al.,* 2022). The rainfall series has been divided into two equal parts and paired values have been plotted against the 1:1 reference line. ITAs (C_ITA) were calculated at the district level for each season to provide an indication of the direction and strength of the trend. If the value is positive it means the trend is increasing and negative if the trend is decreasing (Manivasagam *et al.,* 2025).

Pettitt's Change-Point Test

Rainfall regime change detection was done using the Pettitt non-parametric test (Saravanakumar *et al.,* 2022). The statistical significance level was set at $p < 0.05$ and the test statistic Ut and the corresponding year of the change-point were calculated. The change points identified were considered as structural changes in the rainfall series.

Rainfall Probability Analysis

The incomplete gamma distribution, which is suitable to model positively skewed rainfall data, was used to estimate weekly rainfall probabilities for each district separately (Sahu *et al.,* 2022). The method of moments was used for estimating shape and scale parameters. For the paddy crop planning, assured rainfall amounts were calculated at 50, 75 and 90 probability levels for each SMW (Ahmed *et al.,* 2009).

Linkage with Global Climate Indices

The annual Niño 3.4 (ENSO) data for the period of 1991-2024 and Dipole Mode Index (IOD) data for the same period were retrieved from the National Oceanic and Atmospheric Administration (NOAA) (Arunima *et al.,* 2023) and Japan Agency for Marine–Earth Science and Technology (JAMSTEC) respectively (Prayag *et al.,* 2023; Sarma *et al.,* 2025). A multiple linear regression model was used to quantify the relative contribution of large-scale ocean–atmosphere oscillations and non-linear rainfall trends to the annual rainfall variability in Cauvery Delta Zone, a multiple linear regression model was employed:

$$R = a + b_1(ENSO) + b_2(IOD) + b_3(C_{ITA}) + \varepsilon$$

where R is annual rainfall, a is the intercept, b_1-b_3 are the regression coefficients, C_{ITA} is the trend coefficient derived from Innovative Trend Analysis and ε is the random error term. For evaluating the robustness and performance of the models, the coefficient of determination (R^2), residual standard error, variance inflation factor (VIF), and residual normality diagnostics were used (Saravanakumar *et al.,* 2022; Ramanathan, 2021; Susmitha *et al.,* 2025). All differences were considered statistically significant at 5% level.

Software Used

All analyses were performed using R (v4.3.2) and Python (v3.12). Rainfall probability estimation was carried out using Weather Cock software, and figures were prepared using OriginPro 2023.

RESULTS AND DISCUSSION

Descriptive Statistics of Rainfall

Long-term (1991–2024) mean annual rainfall varied moderately across the Cauvery Delta Zone districts (Table 1). Thanjavur recorded the highest mean annual rainfall (1042 mm), followed by Nagapattinam (1038 mm) and Tiruvarur (1034 mm). Interannual variability was moderate, with annual CV values ranging from 15 to 19%. The Northeast Monsoon (NEM) contributed the largest share of rainfall (50–55%), whereas winter rainfall (January–February) showed very high variability (CV > 100%), indicating unreliable rainfall during the Navarai season.

Trend Analysis Using Mann–Kendall Test and Sen's Slope

Results of the Mann–Kendall (MK) test and Sen's slope estimator are summarized in Table 2. Annual rainfall exhibited a weak, non-significant decreasing trend across all districts ($Z = -0.62$ to -0.88; $p > 0.05$), with Sen's slope values ranging from −0.9 to −1.2 mm yr^{-1}. In contrast, NEM rainfall showed a statistically significant increasing trend ($Z = 2.12$–2.45; $p \leq 0.05$), with Sen's slope estimates between +3.1 and +3.7 mm yr^{-1}. The 95% confidence intervals of Sen's slope did not include zero, confirming trend robustness. The rainfall of Southwest Monsoon showed a weak negative trend (−1.0 to −1.4 mm yr^{-1}), but the trend was not statistically significant.

Innovative Trend Analysis (ITA)

The scatter plots (Fig. 2) showed non-linear behaviour of rainfall that was not adequately represented by MK statistics. NEM rainfall points were mostly above the 1:1 line for all districts, showing an upward trend, while SWM and annual rainfall points were slightly below the 1:1 line, showing a slight downward trend.

These trends were quantified by the ITA coefficients (NEM: +0.028 to +0.034, SWM: -0.018 to -0.024, Annual: -0.010 to -0.015). Positive values for NEM confirm intensification of rainfall in recent decades, while negative coefficients for SWM reflect reduced early-season rainfall.

Pettitt's Change-Point Detection

The results of Pettitt's test showed that there were statistically significant change points in the annual rainfall series in all districts between 2004 and 2007 (Fig. 3) ($p < 0.05$). The maximum Pettitt U-statistics were 312, 346 and the corresponding change-point years were 2005 (Thanjavur), 2006 (Tiruvarur) and 2005 (Nagapattinam). The change points suggest a shift from a relatively stable rainfall regime (1991–2003) to a high-variability regime (2004–2024).

District-Wise Rainfall Probability Analysis

The weekly assured rainfall calculated from the incomplete gamma distribution was different across the various districts (Table 3). In all the districts, SMW 42-48 had the highest assured rainfall with 75% probability which is more than 75 mm week-1, which is favourable for Samba paddy transplanting. On the other hand, SMWs 1-12 had a positive outlook with rainfall less than 10 mm $week^{-1}$, which indicated a high risk for rainfed Navarai cultivation.

Association with Global Climate Indices

Multiple regression analysis showed that the ENSO, IOD and the non-linear trend coefficient derived from ITA explained a significant amount of interannual rainfall variability in the Cauvery Delta Zone ($R^2 = 0.82$; $p < 0.01$). The annual rainfall was found to be negatively associated with ENSO with a statistically significant value ($b = -0.41$; $p = 0.004$), suggesting that during El Niño

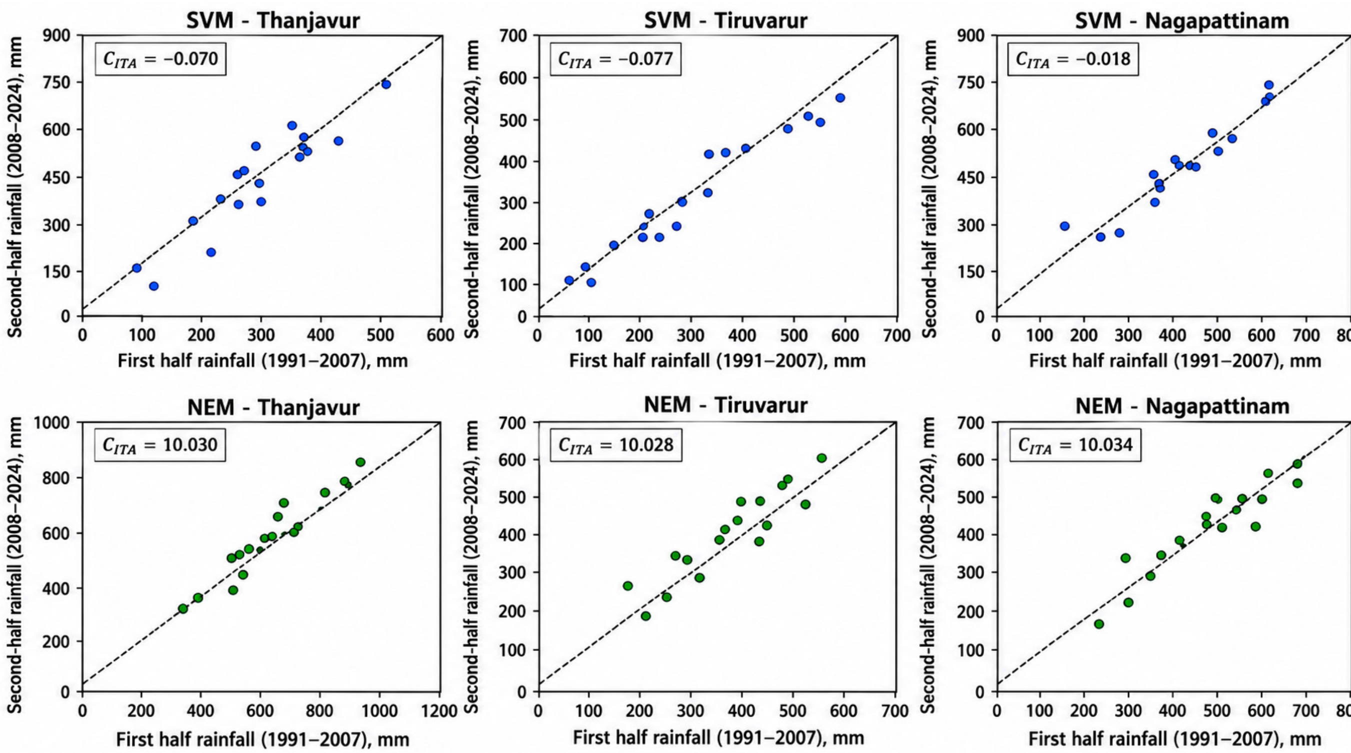

Fig. 2: Innovative Trend Analysis (ITA) plots for seasonal rainfall in the Cauvery Delta districts.

Table 1: Seasonal and annual rainfall statistics (1991–2024)

Season	Thanjavur		Tiruvarur		Nagapattinam	
	(Mean ± SD)	CV (%)	(Mean ± SD)	CV (%)	(Mean ± SD)	CV (%)
Winter (Jan–Feb)	38 ± 41	108	41 ± 46	112	43 ± 45	105
Summer (Mar–May)	135 ± 72	53	142 ± 77	54	147 ± 71	48
SWM (Jun–Sep)	328 ± 125	38	333 ± 131	39	339 ± 120	35
NEM (Oct–Dec)	541 ± 155	29	518 ± 163	31	509 ± 149	29
Annual	1042 ± 182	17	1034 ± 194	19	1038 ± 160	15

(CV = coefficient of variation (%). High CV during winter indicates unreliable rainfall for Navarai season.)

Table 2: Mann–Kendall Z-values, Sen's slope and 95% confidence intervals (1991–2024)

Season	District	MK Z-value	p-value	Sen's slope (mm yr⁻¹)	95% CI
Winter	Thanjavur	−0.54	0.59	−0.7	−1.8 to +0.4
	Tiruvarur	−0.61	0.54	−0.9	−2.1 to +0.3
	Nagapattinam	−0.58	0.56	−0.8	−1.9 to +0.4
SWM	Thanjavur	−1.21	0.22	−1.3	−2.6 to +0.2
	Tiruvarur	−1.34	0.18	−1.4	−2.8 to +0.1
	Nagapattinam	−1.10	0.27	−1.0	−2.4 to +0.3
NEM	Thanjavur	2.45	0.014	+3.4	+1.2 to +5.6
	Tiruvarur	2.12	0.034	+3.1	+0.9 to +5.2
	Nagapattinam	2.58	0.010	+3.7	+1.4 to +6.1
Annual	Thanjavur	−0.78	0.43	−1.0	−2.3 to +0.4
	Tiruvarur	−0.62	0.53	−0.9	−2.1 to +0.5
	Nagapattinam	−0.88	0.38	−1.1	−2.5 to +0.3

phases, annual rainfall is reduced. IOD, on the other hand, had a significant positive influence (b = +0.38; p = 0.006) indicating that positive IOD events are associated with increased rainfall. The ITA coefficient was also significant (b = +0.29, p = 0.008), suggesting that non-linear rainfall intensification plays a part in the interannual variability.

The regression relationship based on the estimated coefficients is:

$$\hat{R} = a - 0.41(\mathrm{ENSO}) + 0.38(\mathrm{IOD}) + 0.29(C_{ITA})$$

Where is the estimated annual rainfall variability, There was no evidence of multicollinearity between predictors (variance

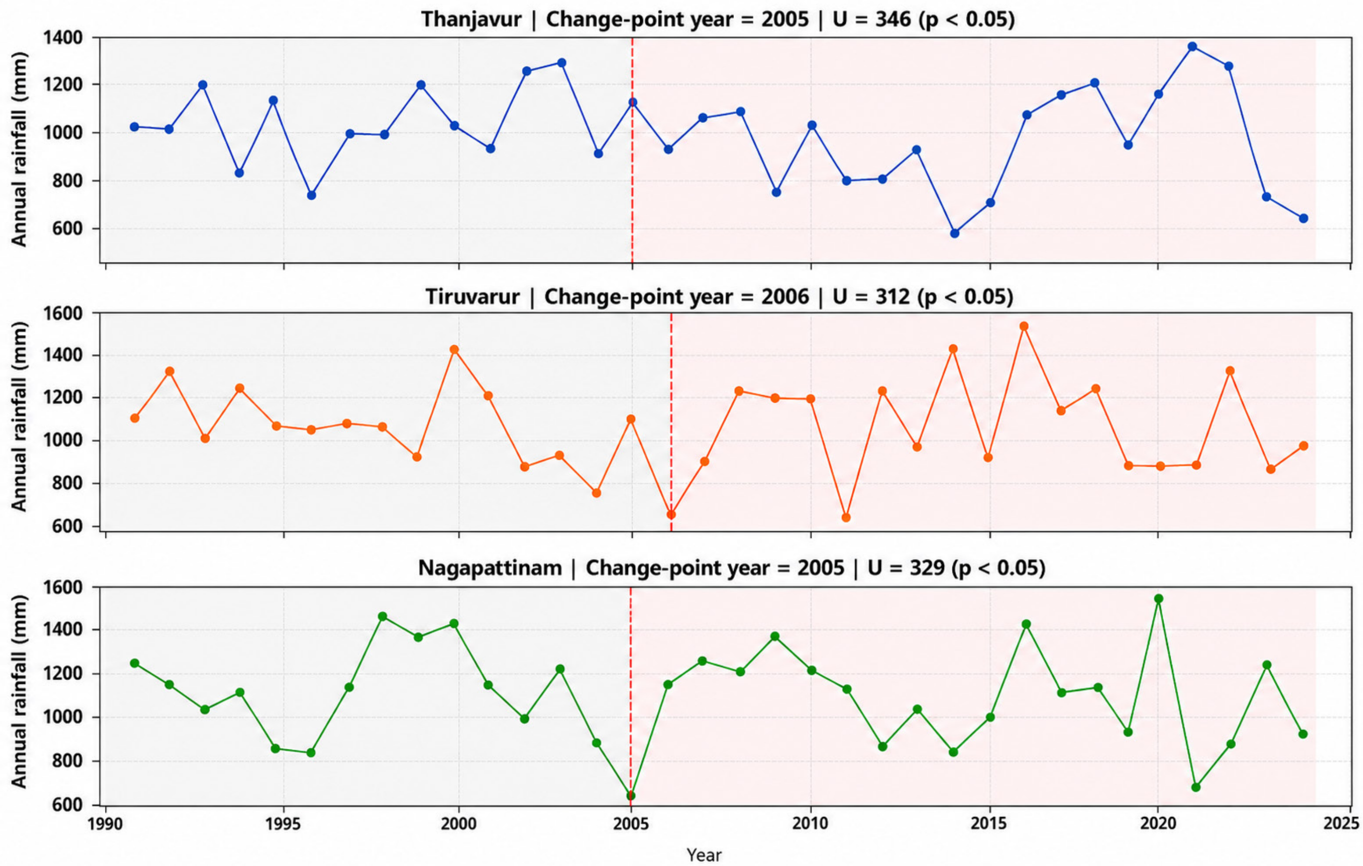

Fig. 3: Pettitt's change-point detection for annual rainfall in the Cauvery Delta Zone.

inflation factors <2.0) and the residuals were homoscedastic and approximately normally distributed, so the regression model was robust.

Discussion

Long-term rainfall analysis (1991-2024) shows statistically significant changes in the rainfall regime in the Cauvery Delta Zone (CDZ) with distinct seasonal difference between South West Monsoon (SWM) and North East Monsoon (NEM). The Mann-kendall and Sen's slope results suggest that there is no significant monotonic trend in the annual rainfall series for all three districts, while the NEM rainfall series suggests a statistically significant increasing trend which is consistent across the districts. The differences between the two are reflected in the fact that the total rainfall has not shown any significant change over the years, even though there have been significant changes in the distribution of the rainfall throughout the year.

The negative trend in SWM rainfall, though not statistically significant, is consistent for all districts and seasons, indicating a gradual reduction in the contribution of early monsoon. This is also supported by the negative ITA coefficients, which reflect non-linear declines in recent decades that are not necessarily identified by linear trend tests. The agreement of the MK and ITA results increases the robustness of the identified seasonal differences.

The innovative Trend Analysis gave valuable information about the non-linear nature of rainfall, for NEM rainfall, positive ITA coefficients show an intensification in the second part of the studied period. The aggregation of ITA scatter points above the 1:1 line since the mid-2000s implies that recent increases in NEM rainfall are not continuous but through episodic high-intensity events. Indeed, such behaviour is consistent with the observed increase in rainfall variability (as evidenced by the moderate coefficients of variation of NEM rainfall).

The change-point test performed by Pettitt identified statistically significant shifts in rainfall regime between 2004 and 2007 in all districts, indicating a shift from a relatively stable rainfall regime to a high variability regime. The timing of the change points in the different districts suggests a basin-wide climatic change and not just anomalies. The overlap of these change points with the changes in ITA trends indicates that the post 2005 period is associated with a change in monsoon dynamics, further justifying the use of a non-stationary rainfall series.

These results are further supported by district-wise rainfall probability analysis which shows that SMWs 42–48 is the most reliable rainfall window over the Cauvery Delta Zone. The high assured rainfall at 75% probability for these weeks is an indication of the growing influence of NEM rainfall, while the low assured rainfall for SMWs 1-12 is an indication of the lack of reliability of winter rainfall. The results of these probability-based analyses are quantitative support for the seasonal trends identified by the MK, ITA, and Pettitt analyses.

Table 3: District-wise assured weekly rainfall (mm) at different probability levels (1991–2024)

SMW Range	District	50%	75%	90%	Interpretation
1–12	Thanjavur	14.1	7.2	3.4	Dry (Navarai)
	Tiruvarur	12.8	6.5	3.1	Dry
	Nagapattinam	13.6	6.9	3.3	Dry
23–28	Thanjavur	41.2	27.5	16.8	Kuruvai onset
	Tiruvarur	39.4	25.1	15.2	Kuruvai onset
	Nagapattinam	43.1	28.4	17.5	Kuruvai onset
42–48	Thanjavur	105.6	81.4	58.2	Peak NEM
	Tiruvarur	98.7	76.3	53.6	Peak NEM
	Nagapattinam	103.2	79.1	55.9	Peak NEM

The regression model ($R^2 = 0.82$) shows that the annual rainfall variability in the CDZ is closely related to the global ocean–atmosphere interactions, as represented by the strong relationship between the annual rainfall variability and the large-scale climate indices (ENSO and IOD). The strong negative impact of ENSO and positive impact of IOD support the observed interannual variability and give a physical basis for the observed regime shifts.

Overall, the linear trend analysis, non-linear diagnostics, change-point detection and probability assessment suggest that there is a measurable shift in rainfall behaviour in the Cauvery Delta Zone since the mid-2000s. These complementary statistical methods enhance the accuracy of rainfall characterization and mitigate the uncertainties of using a single method.

CONCLUSION

The study was carried out on the basis of analysing the daily rainfall of 34 years' data (1991 to 2024) for variability, trend and predictable time windows for paddy is crop being grown in the Cauvery Delta Area of Tamil Nadu. The results show a statistically significant shift in rainfall around the year 2005 identified by the change-point test of Pettitt ($p < 0.05$), suggesting the shift from a relatively stable to a high variability rainfall regime. The seasonal analysis showed that there was a clear difference in the monsoon activity. The rainfall of the Northeast Monsoon showed a significant positive trend (Sen's slope of +3.1 to +3.7 mm yr^{-1}) with positive ITA coefficients in the last decades, suggesting rainfall intensification. On the other hand, Southwest Monsoon rainfall exhibited a slight decreasing trend, which resulted in less early rainfall. District-wise rainfall probabilities analysis revealed that the most reliable period for rainfall was Standard Meteorological Weeks (SMW) 42 – 48 with rainfall above 75 mm assured with 75% probability in all the districts while the winter season was very unreliable for rainfall. The regression analysis showed that the interannual rainfall variability was well explained by the combination of ENSO, IOD and non-linear rainfall trend coefficient ($R^2 = 0.82$), suggesting that large-scale ocean–atmosphere interactions play an important role in influencing regional rainfall patterns. The use of linear trend analysis, non-linear diagnostics, change-point detection and probability assessment has been integrated to provide a statistically sound framework for the characterization of the non-stationary behaviour of rainfall in the Cauvery Delta Zone, which will serve as a reliable scientific basis for planning rain-fed crops.

ACKNOWLEDGMENT

The authors express their gratitude to the Thiagarajar College of Engineering (TCE) for supporting us to carry out this research work.

Author's certificate: The manuscript or its part is not under consideration for publication elsewhere and the same has been approved by all co-authors.

Conflict of Interests: The authors declare that there is no conflict of interest regarding the publication of this article.

Funding: No external funding was involved in this work.

Data Availability: Indicates the availability of data upon request from the corresponding author.

Authors contribution: **B. Johnson:** Conceptualization, writing original draft preparation, reviewing; **T. Chandrakumar:** Conceptualization, supervision, editing, reviewing; **D. Sakthipriya:** Data curation, methodology, formal analysis, visualization, and manuscript refinement.

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