Meteoric Water Trend Analysis using Statistics and GIS for Drought Condition Assessment on Climate Change Aspects in Thoothukudi District, Tamil Nadu, India

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Abstract
Precipitation is the most important variable for climate change studies, and also mostly determines the drought conditions on the Earth's surface. The present study assessed rainfall variation and monitored drought conditions in the Thoothukudi district of Tamil Nadu, India. In this study, various statistical methods are employed to determine the annual average rainfall and seasonal rainfall over 30 years. The monthly rainfall variation was computed using Standard Deviation (SD) and Coefficient of Variation (CV), and trends in monthly rainfall were estimated using the Mann-Kendall and Sen's Slope test for three decades from 1990 to 2019. The drought condition in the study area

was also monitored. The study's findings indicate that the annual average rainfall has varied to some extent from year to year. Its variation has increased since 2008. Seasonally, NE monsoons have had a high amount of rainfall inall four seasons over the last 30 years. Other seasons have less rainfall variability during the years 1999 to 2011. The rainfall variation has increased to be more extreme than the state's seasonal average, except in summer. In the SW monsoon, rainfall has increased slightly, but it's also below the state's seasonal average due to the dynamic changes in monthly rainfall. The monthly rainfall variation over three decades, significantly consistent in April, May, August, September, October, and November, and January, February, March, and June, shows dispersion, with CV mostly below 100% and above 100% respectively during the I and II decades.In the III decade, all the month's rainfall variation is dispersed except Nov. Whereas, in July and Dec, the rainfall variation has been changing every decade, with its dispersion or consistent variation. The Mann-Kendall and Sen's Slope test indicates that the trend is decreasing or increasing witha 95% confidence level of significance. Generally, excessive rainfall is recorded during the NE monsoon season in Tamil Nadu. During the first three decades, excess rainfall has been reported in Kayalpattinam, Tiruchendur, Kulasekarapattinam, and Santhankulam, whereas scanty to deficient rainfall has been reported in the other two decades.

Keywords: Rainfall, Drought, Mann-Kendall, Sen's Slope, Climate Change, Meteoric Water

Introduction

Rainfall is a crucial component of the environmental hydrological cycle. It is the primary basis of fresh water on the Earth. Rainfall plays a major role in climate change. Climate change can easily wreak havoc on agricultural growth over a period of time [1-4] and is vulnerable to agricultural production, such as crops, livestock, fisheries, and forestry [5-7]. Furthermore, various studies have shown that rainfall patterns have become more extreme, leading to increased drought events, which in turn contribute to global warming [8-11]. Unpredictable high frequency and intensity of rainfall lead to abrupt flooding and devastation of livelihoods [12]. Therefore, the impact of climate change isa domain of hypothetical vulnerability assessment [13,14]. Consequently,an accurate understanding of rainfall variability across a wide range of temporal measurements will enable better risk management practices. Joshi and Pandey [15] attempt to deliver India's sub-regions annual rainfall sequence to classify climate change (drought condition). Sarkar and Kafatos [16] have explained the Indian rainfall system and its relationship with ENSO and Tamil Nadu practices with four monsoons, viz, Winter, Summer, NE monsoon, and SW monsoon. Drought is a severe environmental risk that is significantly influenced by agricultural production in tropical countries, such as India [17]. The lack of rainfall leads to drought compared to usual circumstances [18,19]. Human migration and natural ecosystem changes are evidence of the impact of drought on water availability [20,21]. Very few water resources are identified in the Barren areas, rock surfaces, shrublands, and grasslands [86]. Due to urbanisation and industrial growth, there is a need to address the loss of agricultural land, vegetation, forest land, water bodies, and mineral wealth [87].

Surface hydroclimatic changes, precipitation variations, prolonged dry spells, and increased evaporation, driven by global climate change and global warming,lead to long-term drought spells in various parts of the world[22]. Drought conditions have been evaluated by many researchers using multiple indices, like Crop Moisture Index[23], Palmer drought severity index [24,25], Palfaiaridity index [26,27], Standardised precipitation index (SPI) [28-36], Surface water supply index [37], atmospheric crop moisture index [38],and rainfall anomaly index [39]. Masroor [40] examined the drought conditions affecting groundwater potential in the middle sub-basin of theGodavari using an analytical hierarchy process (AHP) and a random forest machine-learning algorithm. Groundwater is very precious for supporting human health, ecological diversity, and economic development [85]. Balaganesh [41] shot a new composite drought vulnerability index (CDVI) for 30 districts in Tamil Nadu, India. Kumar [42] proposed the Integrated Drought Monitoring Index (IDMI) to examine the spatial and temporal changes in farming drought during the northeast monsoon in the southeastern

Indian state of Tamil Nadu between 2000 and 2016.The present study of 30 years of rainfall data collected from the 20stations in the Thoothudkudi district to determine monthly rainfall variations, annual average, and trends in rainfall using non-parametric statistical methods of Mann-Kendall test [43, 44] and Sen's slope method[45] used to determine the magnitude of changes in rainfall time series. Moreover, the drought conditions in the Thoothukudi district, Tamil Nadu, India, should be monitored.

Study Area

Thoothukudi district lies between 77°39'E to 78°22'E Longitude and 8°18'N to 9°21' N Latitude (Fig.1)in the southern part of Tamil Nadu, South India. The crescentic coast is famous for several economically important activities, including salt pans, fisheries, industries, ports,and urban settlements. The Tamirabarani is a major river that controls drainage patterns, as well as minor streams such as the Palaiyar, Nambiyar, and Hanuman Nadhi. The study area falls under a semi-tropical environment,like a hot and dry climate. May to August is the hottest month, and December to February is the coldest month of the year[46]. The Thoothukudi district receivedthe maximum amount of rainfall in November and the minimum in June [47]. The study area encompasses 20 rain gauge stations, including Surangudi, Vaippar, Vedanatham, Arasadi, Thoothukudi, Kayalpattinam, Tiruchendur, Kulasekarapattinam, Kadalkudi, Vilathikulam, Ottapidaram, Srivaigundam, Sathankulam, Ettayapuram, Kadambur, Kalampatti, Kayathar, Kazhugumalai, Kovilpatti, and Maniyachi (Fig. 1).

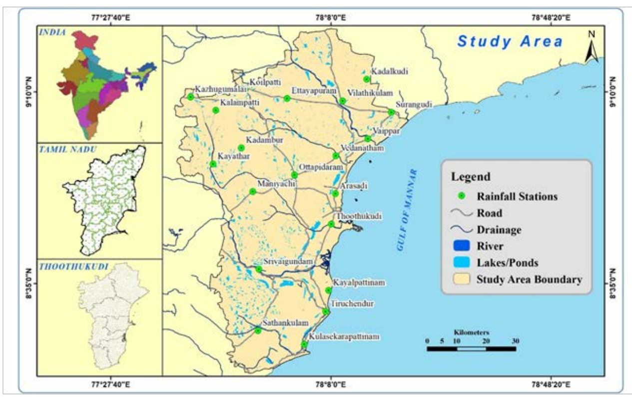


Figure 1 Study Area

Methods and Materials

Precipitation is the primary climate variable for climate change studies. The study was conductedto assess rainfall variation and monitor drought conditions in the Thoothukudi district over three decades, based on precipitation changes. For this study, 30 years (1990 - 2019) of 20 stations' daily observation rainfall data were used to estimate the 30 years of average annual rainfall and seasonal rainfall examined for four seasons,namely Winter (January and February), Summer (March, April, and May), SW monsoon (June, July, August, and September), and NE monsoon (October, November, and December). Moreover,monthly precipitation variation was computed for three decades, namely the I-Decade (1990-1999), the II-Decade (2000-2009), and the III-Decade (2010-2019), using mean, standard deviation, and coefficient of variation. The coefficient of variation (CV) measures the relative dispersion of a series of data around its mean. It is defined as the ratio of the standard deviation to the mean. It is often used to compare the degree of variability between series. The coefficient of variation is a measure of the dispersion from the mean or the variability of the data. The non-parametric Mann-Kendall test and Sen's slope test are used to analyse the decade of the monthly rainfall trend. The Mann-Kendall test has been used to analyse time series exhibiting regularly rising or dropping trends that are significant at various probability levels [48–50]. Statistics S can be obtained by following Eq.

$\sum_{t=1}^{n-1} \sum_{t'=t+1}^{n} \text{sig}\ (R_{t'}-R_t)$

sign $(R_{t'}-R_t)$ = {(+1 if $(R_{t'}-R_t)$>0@0 if (R_t'-X_t)=0@-1 if (R_t'-R_t)<0)

Where n is the number of years, Rt and Rt' are months of rainfall at time t=1, 2, …, n-1 and t'= t+1, …, n. The S is the significance of the trend in the rainfall pattern. Normalised test statistic Z is computed as follows Eq.

Z={((s-1)/√(VAR(S)) If S>0@0 If S=0@(s-1)/√(VAR(S)) If S< 0)

The magnitude of precipitation change is estimated as an upward or downward slope based on the positive and negative values of β [51], using Sen's slope method [45].

S_m= $((R_{t'}-R_t))/((t'-t))$ for i=1,2,………,n

where S_m is the median value of Sen's estimate slope. It's the relationship between the month of rainfall ($R_{t'}$, R_t) and its time (t', t).

β = Sen' Slope = {$S_{m(n+1/2)}$, & if n is Odd@(1/2)(S_m(n/2)+$S_{m((n+2)/2)}$)) & if n is Even)

The positive and negative values of the β are indicated by an upward and downward trend in a time series.

Moreover, the drought condition (DC) was estimated to be three decades. It calculated the difference between the Tamil Nadu state average of each seasonal precipitation and the decadal seasonal mean rainfall.

DC=((Mean Rainfall-State mean rainfall))/(State mean rainfall) ×100

Accordingly, the DC has been classified into four classes: excess, normal, deficient, and scanty, as shown in Table 1. GIS is an efficient tool for mapping and analysing spatial data sets [88, 89, 93] and determining the spatial distribution of parameters. The feature class weights are easy and useful for overlay analysis [90, 91, 92]. The DC spatial distribution maps were prepared using the multivariate interpolation technique of Inverse Distance Weighting (IDW) in the Arc GIS platform. In this technique, known sample points can be converted into weighted average values assigned to unknown sample points near them in the study area[52]. The methodological innovation of geographical information system mapping the results confers additional advantages of simplicity and clear communication to policy actors [53-56].

Table 1 Classification of Drought

Classes	Range
Excess	>+20%
Normal	+ 19 to -19%
Deficient	-20 to -59%
Scanty	< -60 %

Results and Discussion

Annual Average Rainfall (1990 - 2019)

In the study area, many regions failed to receive regular monsoon rainfall, and abnormally intense rainfall was reported during the last decade due to climate change and global warming. The study area's annual rainfall has varied from 646 to 1,389 mm over 102 years (1901-2002) [50]. Between 2000 and 2010, rainfall varied from 550 to 789mm, with an average annual rainfall of 680mm. It is less than the state's average rainfall[47]. The study period also had less annual average rainfall than Tamil Nadu, with an annual average rainfall of 960mm for 30 years,except in the year 2008 (1002mm), as shown in Fig. 2. The minimum amount of rainfall (< 250mm) was noticed in the years 1990, 1995, 1999, 2006, and 2016. The maximum rainfall (482mm – 795mm) was reported in 1993, 1997, 2004, 2005, 2010, 2015, and 2019. The intensity of rainfall varies from year to year, and the variation in rainfall has been increasing since 2006. It leads to extreme floods or drought. It affects the environmental livelihood and ecosystem.[57] It also states that the dynamics of extreme weather conditions cause flooding and drought, resulting in economic losses for the nation.

Seasonal Variation of Precipitation (1990 - 2019)

The Thoothukudi district has experienced some significant irregularities noted in all monsoon seasons[50]. The NE monsoon contributes 43%, and the least contributes 6% during the winter season over 102 years (1901-2002). From2000 to 2010, the NE monsoon contributed 65.4%, and the SW monsoon contributed 8.06% [36].The irregularities in rainfall have persisted throughout the seasons in the Thoothukudi district for 30 years (1990-2019).The rainfall was significantly lower from 1990 to 2012 compared to the average seasonal rainfall in Tamil Nadu (Fig. 3). Meanwhile, the seasonal rainfall rose to an extreme levelfrom2013 onwards. The high intensity of rainfall was observed in all seasons except the southwest monsoon from 2013 to 2015, as shown in Fig. 3(A,B,D). The unpredictable rainfall has affected the environment and livelihood due to the flood. In the winter season, extreme rainfall was noted in 2013 and 2014 (Fig. 3A). In the summer season, the rainfall was high in 2013, 2014, and 2018 (Fig. 4B). In 2014, 2015, and 2019, the high amount of rainfall was absorbed in the NE monsoon (Fig. 3D). Whereas, in the SW monsoon, the amount of rainfall was significantly less from 1990 to 2013. Afterwards, the rainfall slightly increased in the southwest monsoon (Fig. 3C). The physiographic settings have been significantly affecting the average winter rainfall [58].The seasonal rainfall pattern may have changed due to summer rainfall. [59-67] also specified that the weakening of the summer monsoon affects the frequency of monsoon rainfall. The Indian summer monsoon may have a severe impact due to reduced meridional gradient flow resulting from warming in the Asian region [62]. The Indian monsoon system is a prominent cycle of global climate circulation, and the dynamics of the Indian summer monsoon are particularly peculiar because the Indian summer monsoon has significant implications for El Niño and ENSO events. The rainfall changes affect ocean and land surface temperatures.

Decadal Monthly Variation of Precipitation

Rainfall change is one of the phenomena of climate change, and it leads to drought. The regional drought has been dependent on monthly rainfall. The intensity of monthly rainfall in the regional area leads to seasonal monsoon variations, whether they are high or low. In the study area, the monthly average rainfall was generally high in October and November, among the 12 months, over 30 years. The coefficient of variation (CV) in the monthly rainfall in the Thoothukudi district for three decades reveals that, during the I decade, the monthly rainfall CV is less (<100%) in Apr, May, Aug, Sep, Oct, and Nov (Fig.4A), due to SD close to the mean rainfall (Table 2). Whereas the rainfall CV is high (>100%) in January, February, March, June, July, and December, due to the SD spread out from the mean rainfall in every month of the decade.

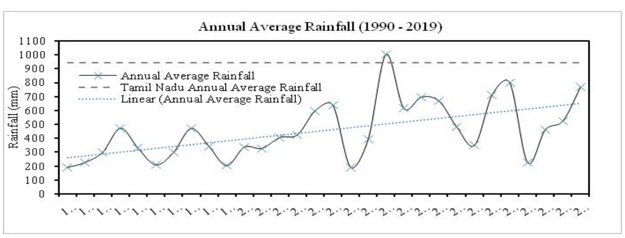
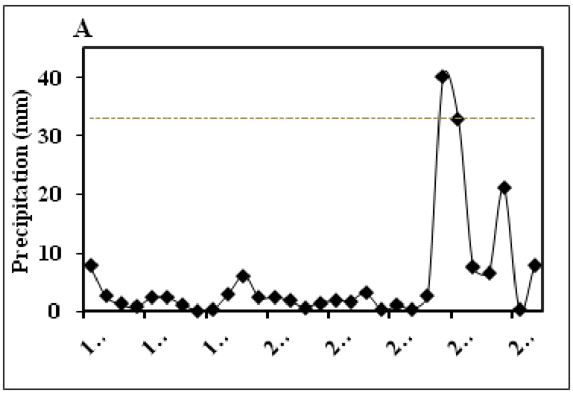
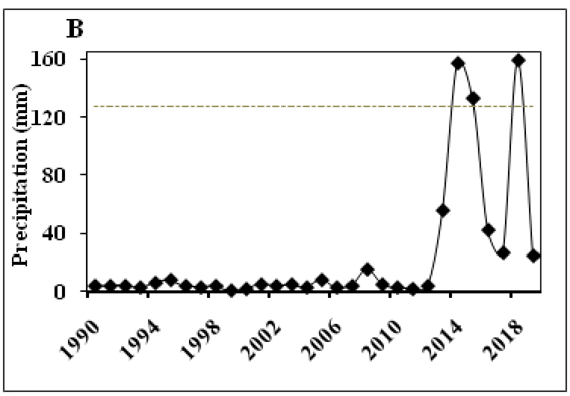


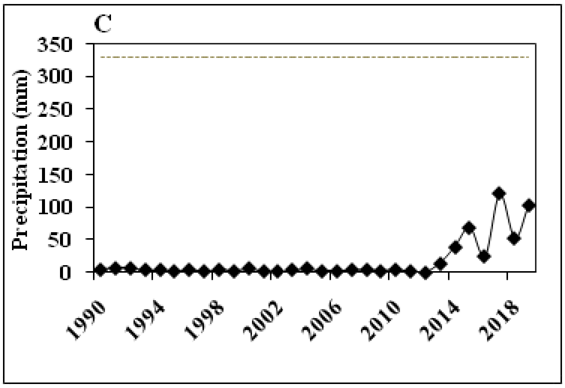
Fig 2 Thoothukudi District Annual Average Rainfall (1990 – 2019)

Table 2 Monthly Average Rainfall (1990 - 2019)

Month	Decade-I			Decade-II			Decade-III		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
JAN	34	48	141	13	13	104	135	211	156
FEB	12	15	129	33	34	102	119	214	180
MAR	18	18	101	36	81	227	339	500	148
APR	32	27	85	57	36	63	279	334	120
MAY	33	19	57	22	18	82	658	898	136
JUN	11	17	149	4	4	104	74	87	118
JUL	15	18	121	9	7	81	77	107	140
AUG	20	17	83	21	20	97	264	274	104
SEP	37	19	52	35	33	94	487	593	122
OCT	159	72	45	168	103	61	2488	2586	104
NOV	187	99	53	194	83	43	2803	2282	81
DEC	96	106	111	62	47	76	1401	1525	109







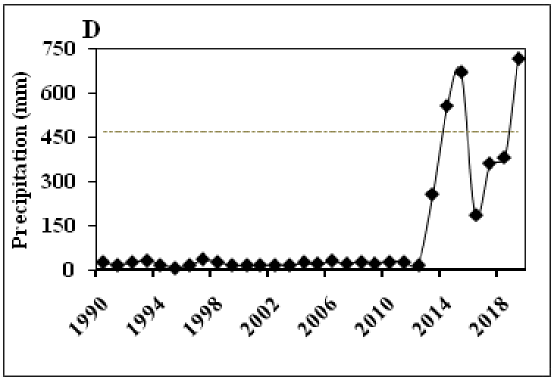


Figure 3 Seasonal Average Rainfall (1990 – 2019) Winter B) Summer C) South West Monsoon D) North-East Monsoon. The Dashed Line is the Seasonal Average Rainfall of Tamil Nadu

In the II decade, Apr, May, and Jul to Dec, the rainfall variation has less than 100% of CV due to the minimum SD of mean rainfall, and in the remaining months of Jan, Feb, Mar, and Jun, rainfall CV is >100% (Fig. 4B). It means monthly rainfall variation is high in every year. In the III-decade, high intensity of rainfall was reported, so a high variation of SD has been noted in the months (Table 2 and Fig. 4C). While in Nov, rainfall CV has been noticed <100%, and in all the months the rainfall CV is >100% (Table 2). It means the month of Nov, rainfall SD is minimum to the mean of the decade, and the remaining months of rainfall SD are spread out from the mean (Fig. 4C). Overall, the results show that Apr, May, Aug, Sep, Oct and Nov, the intensity and frequency of rainfall were reported as a significantly consistent variation. While in January, February, March, and June, the rainfall variation is dispersed for the I and II decades. This rainfall pattern changed in the third decade; all the months of rainfall variation are dispersed, except November. In July and December, rainfall variation has changed dynamically every decade, either in terms of dispersion or consistent variation. Generally, the Thoothukudi district received a good amount of rainfall in October and November. During the study period, the first and second decades of rainfall intensity were lower than in the third decade.

Mann-Kendall and Sen's slope Trends in Rainfall

The decadal monthly rainfall variation trends were estimated using the Mann-Kendall test, and the magnitude of the rainfall change was determined using Sen's slope test (Table 3). The results of the Mann-Kendall and Sen's Slope test statistics confirm that the three decades of rainfall trends are consistent with an alternative hypothesis of both increasing and decreasing trends. Because Sen's slope β-values are less than the significance level (Table 3), it indicates upward and downward trends of rainfall for the three decades of months. The 95% confidence level of the Decreasing Trend was significantonly in January, and the increasing trend was not significant, as noticed in February, April, and December. The remaining months confirm a decreasing trend, which was significant during the first decade. In the II decade, an increasing trend has not been significant. Jan, May, Jun, Jul, Sep, Dec, a decreasing trend was not significant, and increasing and decreasing trends were significant at a 90% confidence level as reported in Nov and Feb respectively (Table 3). In contrast, in III decade, the trend is positive of all the month, the level of confidence is 90% in Apr, Aug, Dec, and 95% in Jun, Jul, and Sep – Nov, the remaining of the month has increasing trend not significant (Table. 3). Overall, of the rainfall trend is upward from Decreasing significant at 95% to Increasing trend significant at 95% confidence level during the three decades form 1990 – 2019. On the contrary, no significant trend was reported in all months except January, where a significant decreasing trend was observed over the past 102 years (1901-2002)[50]. The trends have to change into increasing trends.

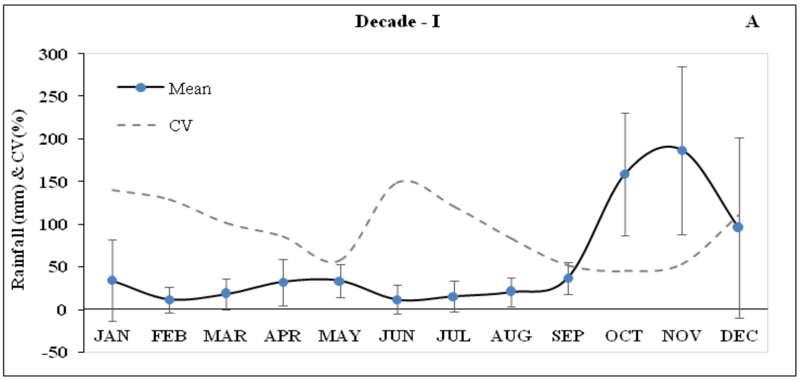
Table 3 Mann-Kendall and Sen's Slope Test for Thoothukudi

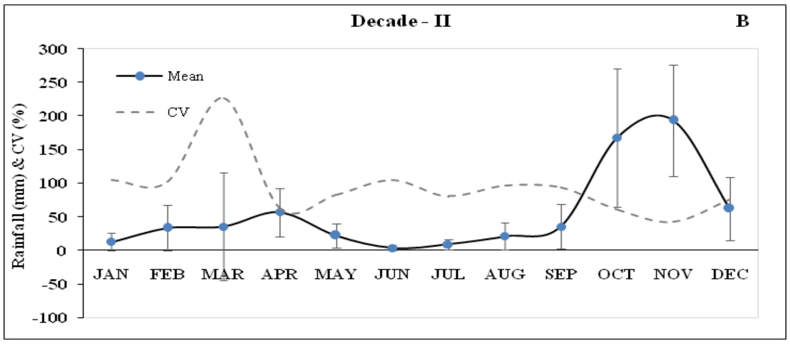
Decade – I (1990 - 1999)				
Month	**Z - Value**	**Sm**	**β-Value**	**Confidence Level**
JAN	-2.15	-5.34	0.03	Decreasing Trend Significant at 95% confidence Level
FEB	0.99	1.23	0.32	Increasing trend not Significant
MAR	-1.25	-1.90	0.21	Decreasing Trend Significant
APR	0.36	0.40	0.72	Increasing trend not Significant
MAY	-0.54	-2.20	0.59	Decreasing Trend Significant
JUN	-1.07	-1.10	0.28	Decreasing Trend Significant
JUL	-0.09	-0.20	0.93	Decreasing Trend Significant
AUG	-1.25	-2.70	0.21	Decreasing Trend Significant
SEP	-1.07	-3.03	0.28	Decreasing Trend Significant
OCT	-0.89	-11.91	0.37	Decreasing Trend Significant
NOV	-0.72	-10.31	0.47	Decreasing Trend Significant
DEC	0.89	3.37	0.37	Increasing trend not Significant
Decade – II (2000 - 2009)				
Month	**Z - Value**	**Sm**	**β-Value**	**Confidence Level**
JAN	-0.36	-0.24	0.72	Decreasing trend not Significant
FEB	-1.79	-6.71	0.07	Decreasing Trend Significant at 90% Confidence Level
MAR	1.53	1.69	0.13	increasing trend not Significant
APR	0.89	5.21	0.37	increasing trend not Significant
MAY	-0.72	-0.40	0.47	Decreasing trend not Significant
JUN	-0.54	-0.15	0.59	Decreasing trend not Significant
JUL	-0.72	-0.47	0.47	Decreasing trend not Significant
AUG	1.25	2.90	0.21	Increasing trend not Significant

SEP	-0.89	-2.03	0.37	Decreasing trend not Significant
OCT	1.25	21.52	0.21	Increasing trend not Significant
NOV	1.79	22.06	0.07	Increasing Trend Significant at 90% Confidence Level
DEC	-0.36	-5.25	0.72	Decreasing trend not Significant
Decade – III (2010 - 2019)				
Month	**Z - Value**	**Sm**	**β-Value**	**Confidence Level**
JAN	0.36	2.29	0.72	Increasing trend not Significant
FEB	0.27	3.22	0.79	Increasing trend not Significant
MAR	1.00	25.99	0.32	Increasing trend not Significant
APR	1.79	40.29	0.07	Increasing Trend Significant at 90% Confidence Level
MAY	1.25	56.68	0.21	Increasing trend not Significant
JUN	2.42	14.13	0.02	Increasing Trend Significant at 95% Confidence Level
JUL	2.50	13.37	0.01	Increasing Trend Significant at 95% Confidence Level
AUG	1.79	61.95	0.07	Increasing Trend Significant at 90% Confidence Level
SEP	2.33	138.69	0.02	Increasing Trend Significant at 95% Confidence Level
OCT	2.15	573.37	0.03	Increasing Trend Significant at 95% Confidence Level
NOV	1.97	474.44	0.05	Increasing Trend Significant at 95% Confidence Level
DEC	1.61	351.35	0.11	Increasing Trend Significant at 90% Confidence Level

Drought Conditions of Thoothukudi District

Drought is a deficiency occurring in the natural climatic phenomenon of precipitation and is difficult to monitor due to minor changes [68]. [69] state that rainfall discrepancies are one of the high climatic factors. It strongly influenced the intensity and frequency of climate extremes when the impact of climate change was observed using rainfall data. Besides, greenhouse gases in the atmosphere also contribute to climate change. These gas concentrations help to magnify higher rainfall events. Meanwhile, low-intensity rainfall events lead to Earth warming in many parts of the world, even in small areas [70,71]. [67] addressed the changes in the Indian summer monsoon from the modelling studies, emphasising the expected rise in greenhouse gas emissions. Numerous studies suggest that Indian rainfall has decreased significantly in most places over the past 50 years [72-78].





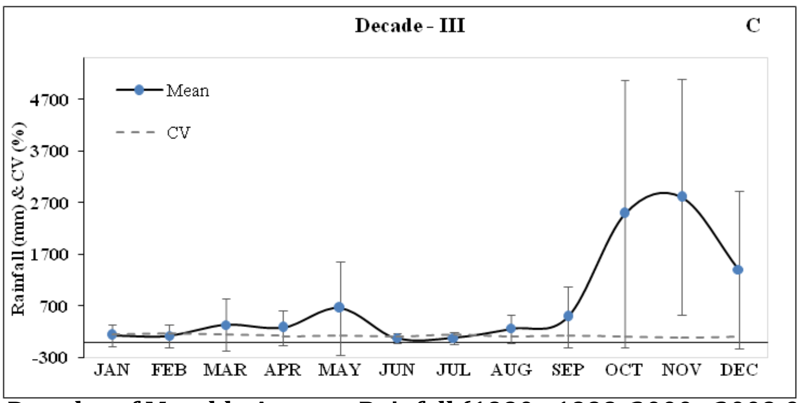


Figure 4 (A-C) Decades of Monthly Average Rainfall (1990 - 1999, 2000 - 2009 & 2010 - 2019) and its Standard Deviation and Coefficient of Variation in Thoothukudi District

Table 4 Decade of Seasonal Precipitation and Drought Condition in Tuticorin District (1990 - 1999)

Rain-Gauge Stations	Winter	Drought Condition		Summer	Drought Condition		SW Monsoon	Drought Condition		NE Monsoon	Drought Condition	
Surangudi	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty
Vaippar	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty
Vedanatham	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty
Arasadi	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty	0	-100	Scanty
Tuticorin	51	56	Excess	39	-70	Scanty	41	-88	Scanty	359	-23	Deficient
Kayalpattinam	20	-41	Deficient	0	-100	Scanty	2	-99	Scanty	0	-100	Scanty

Tiruchendur	73	123	Excess	44	-66	Scanty	58	-82	Scanty	534	14	Normal
Kulasekarapattinam	15	-56	Deficient	6	-95	Scanty	5	-98	Scanty	100	-79	Scanty
Vilathikulam	22	-34	Deficient	33	-74	Scanty	100	-70	Scanty	310	-34	Deficient
Ottapidaram	39	19	Normal	101	-21	Deficient	152	-54	Deficient	310	-34	Deficient
Srivaigundam	44	33	Excess	83	-34	Deficient	64	-81	Scanty	380	-19	Normal
Sathankulam	36	8	Normal	77	-39	Deficient	87	-74	Scanty	476	2	Normal
Ettayapuram	4	-88	Scanty	42	-67	Scanty	57	-83	Scanty	166	-65	Scanty
Kadalkudi	17	-47	Deficient	44	-65	Scanty	109	-67	Scanty	194	-59	Deficient
Kadambur	5	-85	Scanty	37	-71	Scanty	30	-91	Scanty	148	-68	Scanty
Kalampatti	0	-100	Scanty	0	-100	Scanty	13	-96	Scanty	62	-87	Scanty
Kayathar	15	-56	Deficient	124	-2	Normal	88	-73	Scanty	336	-28	Deficient
Kazhugumalai	1	-98	Scanty	6	-95	Scanty	0	-100	Scanty	28	-94	Scanty
Kovilpatti	43	29	Excess	130	2	Normal	165	-50	Deficient	440	-6	Normal
Maniyachi	0	-100	Scanty	2	-98	Scanty	0	-100	Scanty	96	-80	Scanty
State Seasonal Average	33			127			331			468		

Table 5 II Decade of Seasonal Precipitation and Drought Condition in Tuticorin District (2000 - 2009)

Rain-Gauge Stations	Winter	Drought Condition		Summer	Drought Condition		SW Monsoon	Drought Condition		NE Monsoon	Drought Condition	
Surangudi	4	-87	Scanty	50	-61	Scanty	7	-98	Scanty	102	-78	Scanty
Vaippar	5	-85	Scanty	57	-55	Deficient	17	-95	Scanty	134	-71	Scanty
Vedanatham	2	-95	Scanty	51	-60	Scanty	8	-98	Scanty	104	-78	Scanty
Arasadi	9	-73	Scanty	44	-65	Scanty	4	-99	Scanty	115	-75	Scanty
Tuticorin	73	123	Excess	135	6	Normal	35	-89	Scanty	354	-24	Deficient
Kayalpattinam	48	46	Excess	140	10	Normal	10	-97	Scanty	353	-25	Deficient
Tiruchendur	98	198	Excess	141	11	Normal	37	-89	Scanty	503	7	Normal
Kulasekarapattinam	46	40	Excess	136	7	Normal	16	-95	Scanty	382	-18	Normal
Vilathikulam	41	25	Excess	122	-4	Normal	85	-74	Scanty	335	-28	Deficient
Ottapidaram	21	-35	Deficient	95	-25	Deficient	59	-82	Scanty	230	-51	Deficient
Srivaigundam	60	82	Excess	133	5	Normal	70	-79	Scanty	356	-24	Deficient
Sathankulam	67	103	Excess	156	22	Excess	65	-80	Scanty	416	-11	Normal
Ettayapuram	47	43	Excess	134	5	Normal	132	-60	Scanty	318	-32	Deficient
Kadalkudi	31	-5	Normal	105	-17	Normal	69	-79	Scanty	274	-41	Deficient
Kadambur	22	-34	Deficient	153	20	Excess	93	-72	Scanty	272	-42	Deficient
Kalampatti	17	-49	Deficient	114	-10	Normal	87	-74	Scanty	212	-55	Deficient
Kayathar	41	25	Excess	163	28	Excess	163	-51	Deficient	348	-26	Deficient
Kazhugumalai	18	-46	Deficient	128	1	Normal	54	-84	Scanty	310	-34	Deficient
Kovilpatti	41	23	Excess	162	28	Excess	140	-58	Deficient	340	-27	Deficient
Maniyachi	4	-88	Scanty	118	-7	Normal	19	-94	Scanty	200	-57	Deficient
State Seasonal Average	33			127			331			468		

Table 5 III Decade of Seasonal Precipitation and Drought Condition in Tuticorin District (2010 - 2019)

Rain-Gauge Stations	Winter	Drought Condition		Summer	Drought Condition		SW Monsoon	Drought Condition		NE Monsoon	Drought Condition	
Surangudi	4	-87	Scanty	50	-61	Scanty	7	-98	Scanty	102	-78	Scanty
Vaippar	5	-85	Scanty	57	-55	Deficient	17	-95	Scanty	134	-71	Scanty
Vedanatham	2	-95	Scanty	51	-60	Scanty	8	-98	Scanty	104	-78	Scanty
Arasadi	9	-73	Scanty	44	-65	Scanty	4	-99	Scanty	115	-75	Scanty
Tuticorin	73	123	Excess	135	6	Normal	35	-89	Scanty	354	-24	Deficient
Kayalpattinam	48	46	Excess	140	10	Normal	10	-97	Scanty	353	-25	Deficient
Tiruchendur	98	198	Excess	141	11	Normal	37	-89	Scanty	503	7	Normal
Kulasekarapattinam	46	40	Excess	136	7	Normal	16	-95	Scanty	382	-18	Normal
Vilathikulam	41	25	Excess	122	-4	Normal	85	-74	Scanty	335	-28	Deficient
Ottapidaram	21	-35	Deficient	95	-25	Deficient	59	-82	Scanty	230	-51	Deficient
Srivaigundam	60	82	Excess	133	5	Normal	70	-79	Scanty	356	-24	Deficient
Sathankulam	67	103	Excess	156	22	Excess	65	-80	Scanty	416	-11	Normal
Ettayapuram	47	43	Excess	134	5	Normal	132	-60	Scanty	318	-32	Deficient
Kadalkudi	31	-5	Normal	105	-17	Normal	69	-79	Scanty	274	-41	Deficient
Kadambur	22	-34	Deficient	153	20	Excess	93	-72	Scanty	272	-42	Deficient
Kalampatti	17	-49	Deficient	114	-10	Normal	87	-74	Scanty	212	-55	Deficient
Kayathar	41	25	Excess	163	28	Excess	163	-51	Deficient	348	-26	Deficient
Kazhugumalai	18	-46	Deficient	128	1	Normal	54	-84	Scanty	310	-34	Deficient
Kovilpatti	41	23	Excess	162	28	Excess	140	-58	Deficient	340	-27	Deficient
Maniyachi	4	-88	Scanty	118	-7	Normal	19	-94	Scanty	200	-57	Deficient
State Seasonal Average	33			127			331			468		

The decreasing rainfall is an indicator of drought. It is essential for drought monitoring [79]. Moreover, the decadal monthly rainfall variation leads to drought conditions, which can be either scanty or excessive. The drought conditions varied across different regional areas at the same time of precipitation. Spatially, the study area has 20 rain-gauge stations. The drought conditions varied from station to station due to variations in monthly precipitation. During the last decade, most of the study area was affected by scanty drought in all seasons due to the meagre amount of rainfall in these regions, and excess rainfall was noted only in the winter season. Whereas, Normal and Deficient drought conditions have been noticed in a few more areas (Table 4 and Fig.5). Spatially, Surangudi, Vaippar, Vedanatham, Arasadi, Ettayapuram, Kadambur, Kalampatti, Kazhugumalai, and Maniyachi have been affected by scanty drought in all the seasons (Fig.8). Tuticorin, Tiruchendur, Srivaigundam, and Kovilpatti have an excess rainfall absorbed, and the normal rainfall was reported at Ottapidaram and Sathankulam regions, and the remaining stations reported from deficient to scanty rainfall in the winter season. In the summer, Kayathar and Kovilpatti experience normal rainfall, while Ottapidaram, Srivaigundam, and Sathankulam report deficient drought conditions (Fig. 8). During the southwest monsoon, Ottapidaram and Kovilpatti receive deficient rainfall. In contrast, the remaining stations are reported as scanty. During the NE monsoon, the Tiruchendur, Srivaigudam, Sathankulam, and Kovilpatti regions experienced normal drought conditions, while the rest of the stations reported scanty or deficient rainfall (Table 4).

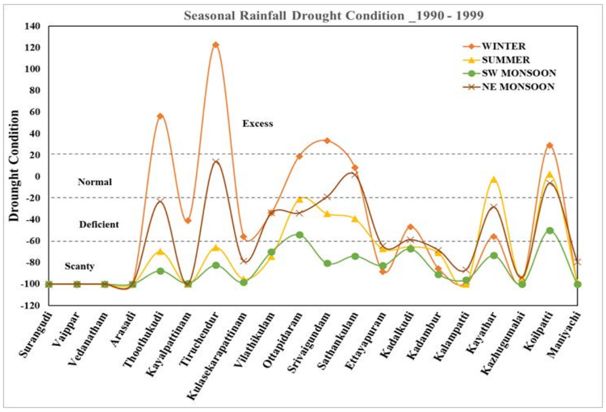


Figure 5 Seasonal Precipitation Changes and Drought Condition (1990 - 1999)

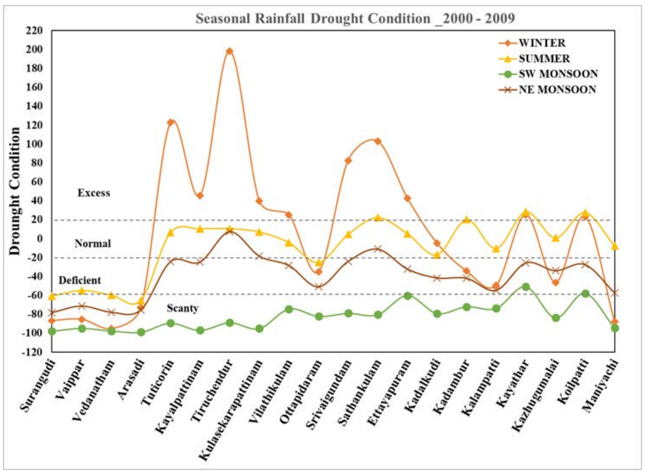


Figure 6 Seasonal Precipitation Changes and Drought Condition (2000 - 2009)

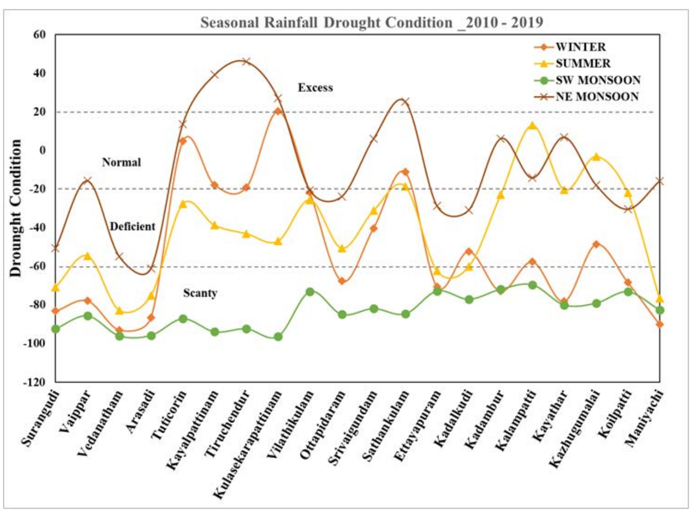


Figure 7 Seasonal Precipitation Changes and Drought Condition (2010 - 2019)

In the II decades (2000 – 2009), excess to normal rainfall was ruled in the winter and summer seasons, whereas deficient to scanty drought was dominant in the SW and NE monsoon (Table 5 and Fig. 6). Surangudi, Vaippar, Vedanatham, and Arasadi have scanty drought in all seasons (Fig.9). Ottapidaram has a deficient drought in all seasons except the SW Monsoon is scanty drought. In the winter season, Kadambur, Kalampatti, and Kazhugumalai have reported drought. Kadalkudi and Maniyachi have Normal and Scanty droughts, respectively. Excess rainfall was reported in the remaining stations. In the summer, excess rainfall was recorded in Sathankulam, Kadambur, Kayathar, and Kovilpatti, while the remaining stations experienced normal rainfall. In the Southwest Monsoon, Kayathar and Kovilpatti experienced deficient conditions, while the rest of the stations reported scanty drought. During the NE monsoon, Tiruchendur, Kulasekarapattinam, and Sathankulam experienced normal droughts, while the rest of the stations recorded deficient rainfall (Fig. 9).

During the III-Decade (2010 - 2019), scanty was reported in all the stations in SW-Monsoon (Table6 and Fig.7). In NE-Monsoon, Arasadi was only affected by scanty drought and the rest of the stations recorded as Excess to Deficient (Fig.10). Kulasekarapattinam has Excess rainfall in the winter season, and Tuticorin, Kayalpattinam, Tiruchendur, and Sathankulam have reported as Normal rainfall. Scanty to Deficient rainfall was reported at the remaining stations. During the summer season, Sathankulam, Kalampatti, and Kazhugumalai experience normal rainfall, while the rest of the stations receive scanty to deficient rainfall (Fig. 10). The changes in rainfall patterns impact agriculture and scheduled irrigation plans, which are dependent on the monsoons [50]. Moreover, seawater intrusion is also caused by the low and erratic rainfall in the coastal areas [80-85]. Thoothukudi district has major industrialisations, including a harbour, Thermal power plants, the Sterlite copper industry, a Petrochemical industry, Alkali Chemicals and fertilisers, SPIC, spinning mills, etc., which also contribute to climate change. It affects weather conditions, such as precipitation patterns, surface temperature, and humidity.

Conclusion

This study analyses the 30 years (1990-2019) of rainfall variation and its associated drought conditions in the Thoothukudi district, using various statistical methods. Over the past 30 years, the annual average rainfall has varied from year to year. The variation of annual average rainfall has shown an increasing trend since 2006. Seasonally, the NE monsoon received a higher amount of rainfall than the other seasons. The amount of rainfall has increased in all seasons since 2013, except in summer. It has increased to more extreme than the seasonal state average rainfall, due to systematic changes in monthly rainfall. The monthly rainfall variation over three decades, significantly consistent in April, May, August, September, October, and November, and January, February, March, and June, shows dispersion, with CV mostly below 100% and above 100% respectively during the I and II decades.

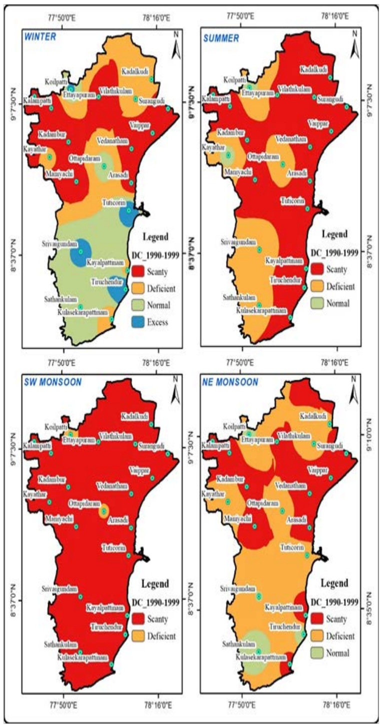


Figure 8 Seasonal Drought Condition (1990 – 1999)

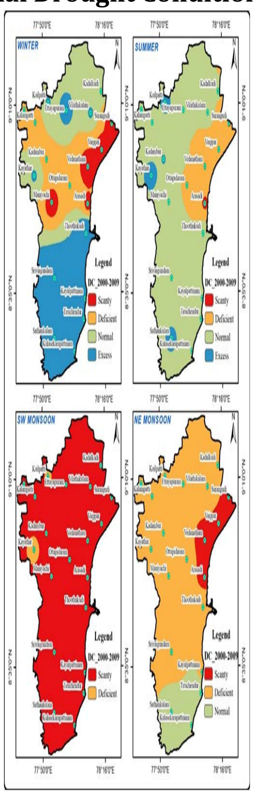


Figure 9 Seasonal Drought Condition (2000 – 2009)

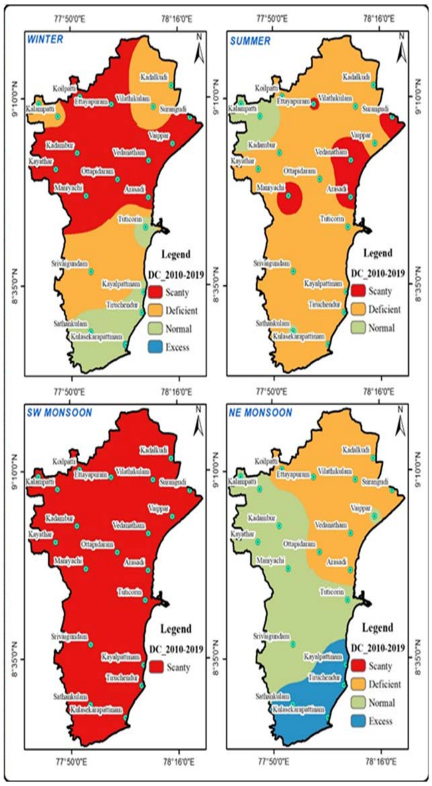


Figure 10 Seasonal Drought Condition (2010 - 2019)

In the 3rd decade, the monthly rainfall variation is dispersed except for November. In contrast, in July and December, the rainfall variation has changed every decade, with either dispersion or consistent variation. The Mann-Kendall and Sen's slope test has concluded that the rainfall trends in every month of each decade in this study area support the alternative hypothesis that rainfall trends increase or decrease in each decade. This variation leads to drought, which can be either excessive or insufficient. In this study, drought conditions in the Thoothukudi district experienced scanty rainfall in the SW Monsoon for the last 30 years. While most of the area experiences scant and deficient rainfall in the I and II decades, the winter and summer seasons have normal and excess rainfall in the II decade. Generally, an excess amount of rainfall occurs during the northeast monsoon in Tamil Nadu; however, the study area has experienced scanty to deficient rainfall in the first and second decades. Moreover, during the Third Decade, the areas of Kayalpattinam, Tiruchendur, Kulasekarapattinam, and Santhankulam recorded excess rainfall due to changes in the precipitation pattern. It affects land and sea livelihood due to the high intensity of rainfall during unexpected seasons. The present study demonstrates that the district's rapid industrialisation is a significant contributor to climate change, leading to drought in the study area. This can be overcome by regularly monitoring the impacts and controlling the effects of industrial activities, which will greatly control the study area's drought.

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