

THE SPATIO-TEMPORAL CHARACTERISTICS OF SOIL MOISTURE AND ITS PERSISTENCE OVER TAMIL NADU

Rajavel M¹, Dhivya R², Venkatesa Palanichamy N³, Amirtha Devi M⁴, Amirtha Shivani J⁴, Amirtha Varshini P⁴, Anandhakumar G⁴, Sivakumar K^{5*} and Balakrishnan N^{5*}

¹Associate Professor & PRO, Agricultural College & Research Institute, Coimbatore-3

²Assistant Professor, PSGR Krishnammal College for Women, Coimbatore³Former Dean & ³Professor (ARM), Agricultural College & Research Institute, Coimbatore-3

⁴Research Scholars, Agricultural College & Research Institute, Coimbatore-3

⁵Dept of Soil Science & Agrl. Chemistry, Agricultural College & Research Institute, Coimbatore-3

*Corresponding Author: bala.n@tnau.ac.in, sivakumar.k@tnau.ac.in

ABSTRACT

Soil moisture is a key regulator of land–atmosphere interactions, crop productivity, and drought development, yet its spatial variability and persistence remain poorly characterised for Tamil Nadu, a state marked by diverse rainfall regimes across the Western Ghats, coastal plains, and interior districts. This study used district-wise, gridded rainfall (IMD, 0.25°×0.25°) and soil moisture (ESA CCI, 0.25°×0.25°) data for 1991–2020 to examine (i) the spatial distribution and variability of rainfall and soil moisture, (ii) soil moisture persistence, and (iii) the relationship between rainfall and soil moisture across the state. Monthly and annual means, coefficients of variation, seasonal soil moisture, anomaly-based autocorrelation, e-folding persistence duration, and Pearson lag correlation were computed for each district. Mean annual rainfall was 883.2 mm, highest in The Nilgiris and Kanniyakumari and lowest in Karur and Tiruppur, with annual CV ranging 18.9–34.6%. Soil moisture (0.10–0.36 m³/m³) followed a distinct seasonal cycle, peaking during the Northeast Monsoon (mean 0.296) and lowest during the Hot Weather Period (0.188), confirming the Northeast Monsoon as Tamil Nadu's principal recharge season. Lag-1 autocorrelation of soil moisture anomalies ranged from 0.338 to 0.650 (state average ≈ 0.506) and was positive in every district, with persistence durations of 1–4 months (2–3 months in 86% of districts) — longest in Tirunelveli, Chengalpattu, Thiruvallur and Vellore, and shortest in The Nilgiris. Contemporaneous rainfall–soil moisture correlation was weak and non-significant ($r = 0.144$, $p = 0.394$), while a significant positive correlation emerged only at an 11-month lag ($r = 0.407$, $p = 0.039$), indicating a delayed rather than immediate coupling. These findings demonstrate that Tamil Nadu's soil moisture is spatially heterogeneous, monsoon-dependent, and characterised by short- to intermediate-term memory, providing district-level diagnostics valuable for drought monitoring, irrigation scheduling, and agricultural planning across the state.

KEYWORDS: Spatial, Temporal, Soil moisture, Persistence, Tamil Nadu

1. INTRODUCTION:

Soil moisture is a key component of the terrestrial hydrological cycle and mediates interactions among the land surface, atmosphere, and biosphere. It refers to the water content in active soil layers, specifically the total water held in the spaces between soil particles and serves as an indicator of soil wetness. Although soil moisture makes up only a small portion of the Earth's total water, its spatial and temporal variability significantly affects weather, climate, agriculture, drought development, and ecosystem functioning (1).

Soil moisture distribution depends on factors such as rainfall, soil properties, topography, vegetation, land use, temperature, and evaporative demand. Precipitation is the main driver of short-term variability. Understanding this variability is essential for agricultural and water-resource management because soil water availability directly affects crop growth and productivity (Dorigo et al., 2017). Over 95% of agricultural land relies on rainfall for soil moisture, and agriculture uses about 70% of global freshwater resources to maintain adequate levels. Spatial variations result from differences in terrain, soil characteristics, vegetation cover, and rainfall distribution. These differences support mapping soil properties and assessing irrigation needs. Seasonal fluctuations are mainly driven by changes in precipitation, temperature, and evapotranspiration throughout the year (2,3).

An important characteristic of soil moisture is its ability to retain the influence of previous hydrological conditions, commonly referred to as soil moisture persistence or soil moisture memory (1, 4). Soil moisture memory can also influence the persistence of hydrological processes, such as evapotranspiration and runoff, and may contribute to the predictability of drought and other hydroclimatic conditions (5,6).

The interaction between soil moisture and the atmosphere is crucial to understanding regional climate variability. Soil moisture affects evapotranspiration and surface energy partitioning. Atmospheric conditions control rainfall and evaporative demand (4). Research shows that strong land-atmosphere coupling can occur where soil moisture variations affect atmospheric processes and precipitation (3,1). Analyzing soil moisture persistence provides insights into how long the impacts of wet or dry conditions last in the land surface system and how they may influence vegetation and atmospheric processes (7).

Traditional ground-based soil moisture observations are limited in spatial coverage and continuity. Satellite remote sensing and reanalysis datasets have improved the monitoring of soil moisture conditions over large areas and extended periods (8). Long-term satellite-based products, like those from the European Space Agency Climate Change Initiative (ESA CCI), combine data from multiple microwave sensors to offer consistent soil moisture records (9,2). These datasets help analyze regional soil moisture patterns and their connections to rainfall and vegetation in areas with limited continuous ground observations (12).

Studying soil moisture dynamics is crucial in the state of Tamil Nadu. The state exhibits considerable variability in rainfall, agro-climatic conditions, topography, soil types, and land-use systems. Rainfall in the region is influenced by both the southwest and northeast monsoons, which have distinct contributions and varying regional patterns (13). The Western Ghats, coastal plains, interior districts, and rain shadow regions have distinct rainfall patterns. Spatial variations in soil moisture availability are created by these differences. The variability of rainfall is critical in Tamil Nadu as many agricultural areas rely on seasonal rainfall and soil water during the most important crop growth stages (10, 11).

Despite the importance of soil moisture for agriculture, drought monitoring, and water-resource management, a detailed understanding of its spatial variability and persistence across Tamil Nadu remains essential. Integrating spatial distribution, temporal variability, persistence characteristics, rainfall, and vegetation response can therefore provide a more comprehensive understanding of soil moisture dynamics across the state. Hence, the present study, entitled “The Spatio-Temporal Characteristics of Soil Moisture and Its Persistence over Tamil Nadu,” aims to characterize the spatial and temporal behaviour of soil moisture across Tamil Nadu.

2. MATERIALS AND METHODS:

2.1. Study Area

The present study was carried out for the state of Tamil Nadu, with the analysis conducted on a district-wise basis to capture the spatial variability in rainfall and soil moisture across the state's diverse agro-climatic zones.

2.2. Study Period

A thirty-year period from 1991 to 2020 was selected for the analysis. This period is consistent with the World Meteorological Organization (WMO) standard for defining a climatological normal, and is long enough to reliably characterize long-term average conditions, inter-annual variability, and persistence behaviour of soil moisture.

2.3. Data Parameters

Two primary data parameters were used in this study:

- Rainfall
- Soil Moisture

2.4. Data Sources

Both datasets were obtained at a matching spatial resolution of $0.25^\circ \times 0.25^\circ$ to allow direct comparison between rainfall and soil moisture across districts.

Parameter	Source	Spatial Resolution
Rainfall	India Meteorological Department (IMD)	$0.25^\circ \times 0.25^\circ$
Soil Moisture	European Space Agency (ESA)	$0.25^\circ \times 0.25^\circ$

2.5. METHODOLOGY

The gridded rainfall and soil moisture data were processed district-wise for the period 1991–2020 following the sequence of statistical procedures described below, progressing from basic monthly averaging to the characterization of soil moisture memory through autocorrelation analysis.

1. Monthly Mean of Soil Moisture and Rainfall

$$SM_m = (\sum SM_i) / n$$

Where:

- SM_m = Monthly mean soil moisture ($m^3 m^{-3}$)
- SM_i = Individual soil moisture observations within the month
- n = Number of valid observations in that month

The monthly mean is calculated by averaging all valid daily/sub-daily observations within a given month. This monthly series forms the basis for all subsequent climatology and anomaly calculations. The same formula, applied to rainfall observations, gives the monthly mean rainfall.

2. Monthly Soil Moisture Climatology

$$\bar{SM}_m = (\sum SM_{m,y}) / N$$

Where:

- $\bar{SM}_m$ = Long-term mean soil moisture for a particular calendar month
- $SM_{m,y}$ = Monthly mean for month m in year y
- N = Number of years in the study period ($N = 30$, for 1991–2020)

The climatology represents the long-term average condition for each calendar month (e.g., the average January soil moisture over 1991–2020) and serves as the reference or 'normal' condition against which individual months are compared.

3. Soil Moisture Anomaly

$$SM'_t = SM_t - \bar{SM}_m$$

Where:

- SM'_t = Soil moisture anomaly for month t
- SM_t = Observed monthly soil moisture for month t
- $\bar{SM}_m$ = Monthly climatology for the corresponding calendar month

The anomaly is the departure of the observed monthly value from its climatological normal. A positive anomaly indicates wetter-than-normal conditions, while a negative anomaly indicates drier-than-normal conditions. This de-trended, de-seasonalized series is used for the subsequent persistence analysis.

4. Autocorrelation Function (ACF)

$$r(k) = \frac{\sum[(SM'_t - \mu)(SM'_{t+k} - \mu)]}{\sum[(SM'_t - \mu)^2]}$$

Where:

- $r(k)$ = Autocorrelation coefficient at lag k
- k = Time lag, expressed in months
- μ = Mean of the soil moisture anomaly series

The ACF quantifies the degree to which soil moisture anomalies in one month are correlated with anomalies in preceding months. It provides the basis for characterizing soil moisture 'memory' — the tendency of wet or dry conditions to persist over time.

5. Lag-1 Autocorrelation

$$ACF(1) = \text{Corr}(SM'_t, SM'_{t+1})$$

Where:

- $ACF(1)$ = Correlation between soil moisture anomalies in consecutive months

Lag-1 autocorrelation specifically measures month-to-month persistence. A higher $ACF(1)$ value indicates stronger persistence; for instance, an $ACF(1)$ of 0.65 reflects stronger month-to-month memory than a value of 0.34.

6. E-folding Threshold

$$\text{Threshold} = 1/e = 0.368$$

Where:

- e = Base of the natural logarithm (2.71828)
- Persistence is considered to have ended once $ACF(k) \leq 0.368$

The e-folding criterion is a standard reference threshold used to define the characteristic memory timescale of a decaying autocorrelation series. It is used here as a decay criterion and is not a test of statistical significance.

7. Soil Moisture Persistence Time

$$T_p = \text{First lag } (k) \text{ at which } ACF(k) \leq 0.368$$

Where:

- T_p = Persistence time, expressed in months
- k = Monthly lag at which the ACF first falls to or below the e-folding threshold

The persistence time is identified as the first monthly lag at which the autocorrelation function falls below the e-folding threshold of 0.368. This value represents the characteristic duration of soil moisture memory for each district and is the key metric used to compare persistence behaviour across the study area.

Analytical Sequence

- Compute monthly means of rainfall and soil moisture from raw gridded data
- Derive the 30-year (1991–2020) monthly climatology for each calendar month
- Calculate monthly soil moisture anomalies relative to climatology
- Compute the autocorrelation function of the anomaly series at increasing monthly lags
- Extract the lag-1 autocorrelation as an index of immediate month-to-month persistence
- Apply the e-folding threshold ($1/e = 0.368$) as the decay criterion
- Determine the soil moisture persistence time for each district as the first lag at which ACF falls to or below 0.368.
- This sequence was applied uniformly to each district of Tamil Nadu, enabling a spatial comparison of soil moisture memory and its relationship with rainfall patterns across the state for the period 1991–2020.

3. RESULTS

3.1. Spatial distribution and variability of rainfall and soil moisture

3.1.1 Spatial distribution and variability of mean monthly rainfall

The mean monthly rainfall for the districts of Tamil Nadu during 1991–2020 showed temporal and spatial variability (Fig. 1). The Tamil Nadu mean rainfall increased from relatively low during January–March to a maximum rainfall during October–November.

January: During January, rainfall across Tamil Nadu is largely governed by the residual influence of the retreating northeast monsoon and occasional winter disturbances associated with the northeast trade winds. Nagapattinam

recorded the highest mean rainfall (38.6 mm), attributable to its exposed coastal location along the Bay of Bengal, which continues to receive moisture-laden winds even after the peak monsoon withdrawal. In contrast, Karur, situated in the interior plains and shielded by the surrounding hill ranges, recorded the lowest rainfall (12.4 mm), characteristic of its rain-shadow positioning relative to both monsoon systems.

February: Rainfall activity declines further as the northeast monsoon fully withdraws, leaving only sporadic winter showers. Tirunelveli recorded the highest rainfall (32.5 mm), likely influenced by its proximity to the southern hill ranges that induce localized orographic lifting even during the dry season. Karur again recorded the lowest value (11.2 mm), reaffirming its consistent dry interior climatic regime throughout the winter months.

March: As pre-summer convective activity begins to intensify in the southern peninsula, Tirunelveli continued to record the highest rainfall (49.7 mm), reflecting increased thermal convection interacting with the Western Ghats' rain-shadow-adjacent terrain. Karur remained the driest district (17.9 mm), indicating that its low rainfall regime persists independent of seasonal transitions, primarily due to its inland location away from major moisture sources.

April: With the gradual build-up of pre-monsoon showers, Kanniyakumari recorded the highest rainfall (84.1 mm), a pattern consistent with its unique geographical position at the confluence of the Arabian Sea, Bay of Bengal, and Indian Ocean, which enhances convective rainfall generation. Villupuram recorded the lowest rainfall (21.3 mm), reflecting the delayed onset of convective activity in the northern interior districts.

May: Rainfall intensifies further as pre-monsoon convective systems mature ahead of the southwest monsoon onset. Kanyakumari again recorded the highest rainfall (110.1 mm), sustaining its position as the wettest district due to continuous maritime influence from multiple directions. Kancheepuram recorded the lowest rainfall (39.6 mm), indicative of the relatively delayed pre-monsoon activity along the northeastern coastal plains.

June: With the onset of the southwest monsoon, rainfall patterns shift markedly toward the Western Ghats region. The Nilgiris recorded the highest rainfall (152.9 mm), a direct consequence of orographic uplift as moisture-laden southwest winds are forced upward along the steep Ghat terrain, resulting in intense precipitation. Virudhunagar, positioned within the rain-shadow zone east of the Ghats, recorded the lowest rainfall (25.0 mm), illustrating the strong orographic rainfall gradient characteristic of peninsular India.

July: July marks the peak phase of the southwest monsoon, and The Nilgiris continued to record the highest rainfall (191.0 mm), the highest value observed for this district across the monsoon season, underscoring the sustained intensity of orographic precipitation. Virudhunagar remained the driest (30.0 mm), reflecting the persistent rainshadow effect that suppresses southwest monsoon rainfall in the southern interior plains.

August: As the southwest monsoon begins to show intra-seasonal variability, The Nilgiris again recorded the highest rainfall (148.0 mm), maintaining its dominant position due to continued orographic influence, albeit with a slight decline from the July peak. Thoothukudi recorded the lowest rainfall (37.6 mm), consistent with its location in a rain-shadow coastal belt that remains largely unaffected by southwest monsoon currents.

September: As the southwest monsoon begins its withdrawal phase and transitional weather systems emerge, Vellore recorded the highest rainfall (134.3 mm), likely influenced by localized convective activity and early interaction with incoming northeast monsoon currents. Thoothukudi continued to record the lowest rainfall (49.6 mm), reflecting its persistent low-rainfall regime across both monsoon phases.

October: October marks the onset of the northeast monsoon, which brings a substantial and widespread increase in rainfall across the state, particularly in southern and coastal districts. Kanniyakumari recorded the highest rainfall (216.3 mm), benefiting from its coastal exposure to moisture-rich easterly and northeasterly winds. Karur recorded the lowest rainfall (107.1 mm) among all districts; however, it is notable that even the lowest ranked district received substantially more rainfall than in preceding months, reflecting the widespread influence of the northeast monsoon.

November: November represents the climatic peak of the northeast monsoon and the wettest period of the year for Tamil Nadu as a whole. Nagapattinam recorded the highest rainfall of the entire annual cycle (375.4 mm), a value reflecting its direct exposure to intense northeast monsoon depressions and cyclonic systems that frequently make landfall along the central Tamil Nadu coast. Krishnagiri, an interior district shielded from direct northeast monsoon influence by distance and topography, recorded the lowest rainfall (91.2 mm), highlighting the sharp spatial gradient in northeast monsoon rainfall distribution between coastal and interior regions.

December: As the northeast monsoon gradually withdraws, rainfall intensity diminishes but remains concentrated along the coast. Nagapattinam continued to record the highest rainfall (199.8 mm), sustaining its position as one of the principal recipients of northeast monsoon rainfall throughout the season. Erode recorded the lowest rainfall (37.3 mm), reflecting its interior location and minimal exposure to the retreating monsoon systems.

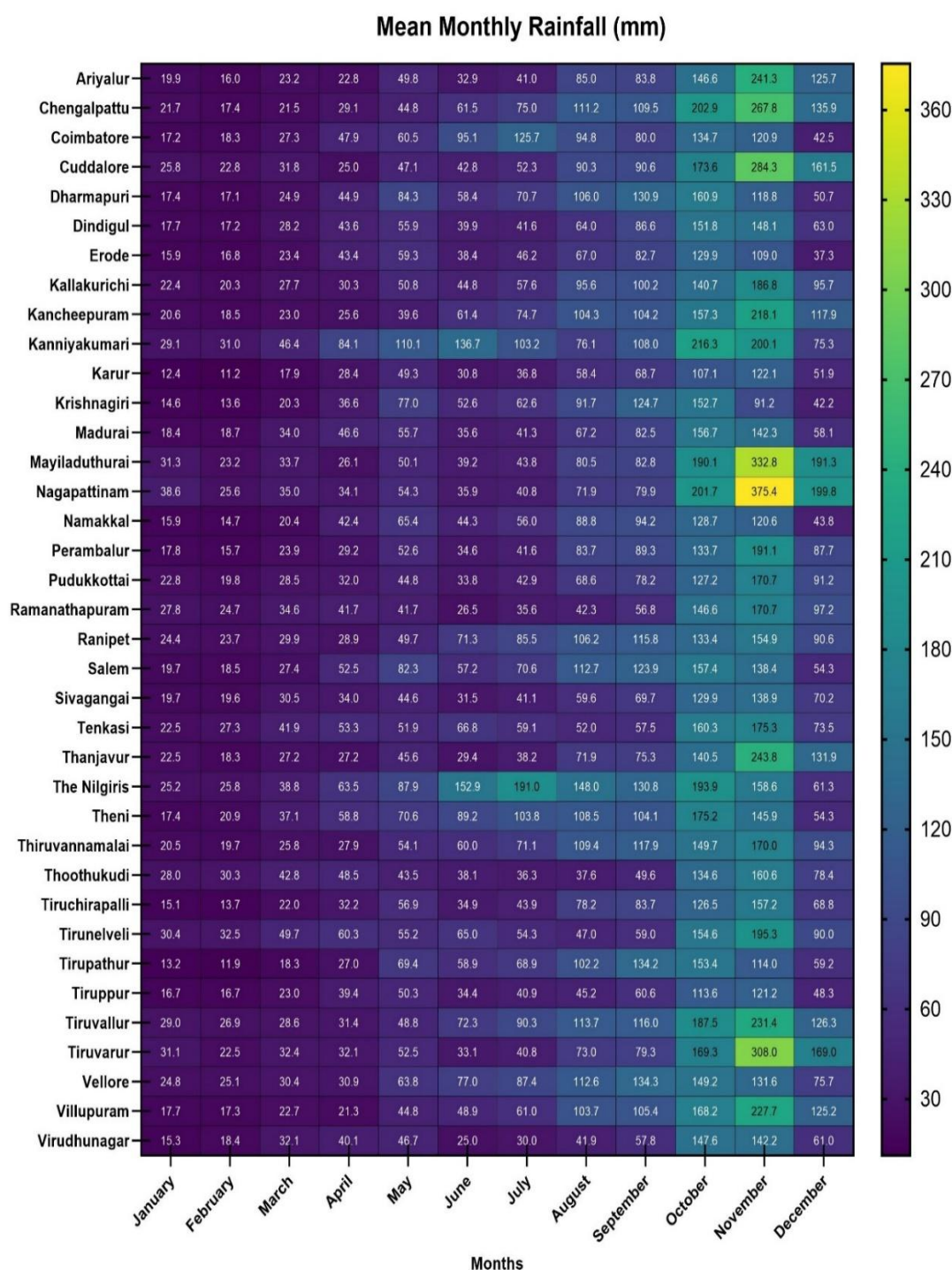


Fig. 1. Mean Monthly Rainfall

3.2. Spatial distribution and variability of mean seasonal rainfall

Seasonal rainfall analysis revealed distinct spatial and temporal variations across Tamil Nadu (Table 1). The Northeast Monsoon (NEM) was the dominant rainfall season, contributing an average of 425.2 mm, accounting for nearly half of the state's annual rainfall. Coastal and delta districts such as Nagapattinam, Mayiladuthurai, Tiruvavur, and Cuddalore received the highest NEM rainfall, highlighting their strong dependence on northeast monsoon systems and cyclonic weather events. In contrast, western districts such as Erode, Karur, and Tiruppur received comparatively lower NEM rainfall.

The Southwest Monsoon (SWM) was the second-largest contributor to annual rainfall, with a state average of 291.2 mm. Districts located along the Western Ghats, particularly The Nilgiris, Kanniyakumari, Theni, and Vellore, received substantially higher SWM rainfall due to orographic influences. Conversely, Ramanathapuram and Virudhunagar recorded the lowest southwest monsoon rainfall, reflecting the rain-shadow effect experienced in southeastern Tamil Nadu.

The Hot Weather Period (HWP) contributed a moderate amount of rainfall (124.9 mm), mainly through convective thunderstorms and localized weather systems. Higher rainfall during this season was observed in Kanniyakumari, The Nilgiris, and Theni, while lower rainfall occurred in northern districts such as Kancheepuram and Villupuram. The Cold Weather Period (CWP) contributed the least rainfall (42.0 mm) and exhibited the highest variability, indicating the sporadic and uncertain nature of winter rainfall across the state.

The coefficient of variation showed that rainfall variability was highest during the Cold Weather Period (74.2%), followed by the Northeast Monsoon (33.9%) and Hot Weather Period (38.3%), whereas the Southwest Monsoon exhibited the lowest variability (25.4%). This suggests that southwest monsoon rainfall is relatively more stable and dependable, while winter rainfall is highly erratic. Overall, the analysis demonstrates that Tamil Nadu's rainfall regime is strongly influenced by both monsoon systems, with the Northeast Monsoon playing the most critical role in supporting agriculture, water resources, and livelihood security, particularly in the coastal and delta regions.

3.3. Annual distribution and variability of rainfall across the Tamil Nadu

The mean annual distribution and variability of rainfall across the Tamil Nadu was given under Table 1. The mean annual rainfall of Tamil Nadu during 1991–2020 was 883.2 mm. Among the districts, The Nilgiris recorded the highest mean annual rainfall (1277.6 mm), followed by Kanniyakumari (1216.4 mm) and Nagapattinam (1193.1 mm). In contrast, Karur (595.0 mm), Tiruppur (610.2 mm), and Virudhunagar (658.1 mm) received the lowest mean annual rainfall. The higher rainfall observed in coastal and hilly districts can be attributed to the influence of monsoon systems and orographic effects, whereas the lower rainfall in interior districts reflects their semi-arid climatic conditions.

The standard deviation of annual rainfall indicates the extent of year-to-year fluctuation in rainfall amounts. Cuddalore recorded the highest standard deviation (312.8

mm), closely followed by Mayiladuthurai (309.5 mm) and Nagapattinam (308.9 mm), suggesting substantial annual rainfall variability in these coastal districts. Conversely, Karur (163.5 mm), Namakkal (172.9 mm), and Madurai (182.3 mm) exhibited lower standard deviation values, indicating relatively stable annual rainfall conditions. The greater variability in coastal districts may be associated with the irregular occurrence of cyclones and northeast monsoon rainfall.

Annual rainfall variability across Tamil Nadu during 1991–2020 exhibited considerable spatial differences among districts. The annual coefficient of variation (CV) ranged from a minimum of 18.9% in Theni to a maximum of 34.6% in Tiruppur, indicating moderate to high inter-annual variability in rainfall distribution across the state. The state average annual rainfall was 883.2 mm with a standard deviation of 187.4 mm and a CV of 21.3%, suggesting relatively stable annual rainfall at the state level despite local fluctuations.

Districts such as Tiruppur (34.6%), Sivagangai (31.1%), Cuddalore (29.9%), Villupuram (29.8%), and Pudukkottai (29.3%) recorded the highest annual CV values, reflecting greater year-to-year rainfall uncertainty and a stronger influence of irregular monsoon and cyclonic rainfall events. In contrast, Theni (18.9%), Salem (21.2%), The Nilgiris (21.6%), Kanniyakumari (22.0%), and Dharmapuri (22.5%) exhibited lower annual CV values, indicating comparatively more reliable rainfall regimes due to the influence of both southwest and northeast monsoons and local topographic effects.

Table 1. Mean Seasonal and Annual Rainfall of Tamil Nadu during 1991-2020

District	CWP			HWP			SWM			NEM			Annual		
	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
Ariyalur	35.9	34.4	95.9	95.7	55.5	58.0	242.7	83.8	34.5	513.6	223.1	43.4	887.9	244.0	27.5
Chengalpattu	39.1	33.4	85.4	95.4	69.0	72.3	357.2	112.5	31.5	606.5	278.6	45.9	1098.2	300.5	27.4
Coimbatore	35.5	32.5	91.5	135.7	59.2	43.6	395.6	120.7	30.5	298.1	114.0	38.2	864.9	212.3	24.5
Cuddalore	48.5	40.1	82.7	103.9	64.7	62.2	276.0	94.8	34.4	619.4	266.4	43.0	1048.0	312.8	29.8
Dharmapuri	34.5	37.8	109.3	154.2	51.8	33.6	365.9	96.5	26.4	330.3	119.9	36.3	885.0	199.1	22.5
Dindigul	34.9	28.8	82.4	127.8	48.8	38.2	232.0	82.1	35.4	363.0	155.8	42.9	757.7	188.1	24.8
Erode	32.7	35.3	108.2	126.1	57.2	45.3	234.4	85.8	36.6	276.2	102.6	37.1	669.4	186.2	27.8
Kallakurichi	42.8	42.3	99.0	108.9	55.1	50.6	298.3	76.4	25.6	423.2	176.8	41.8	873.1	212.6	24.4

Kancheepuram	39.1	43.3	110.8	88.2	64.1	72.7	344.6	112.2	32.6	493.4	231.5	46.9	965.2	270.4	28.0
Kanniyakumari	60.1	40.7	67.8	240.6	90.8	37.7	424.0	124.7	29.4	491.7	189.5	38.5	1216.4	267.3	22.0
Karur	23.6	28.4	120.3	95.6	42.6	44.5	194.6	83.1	42.7	281.1	122.9	43.7	595.0	163.5	27.5
Krishnagiri	28.3	29.8	105.4	134.0	43.5	32.5	331.6	104.4	31.5	286.1	109.2	38.2	780.0	191.5	24.5
Madurai	37.1	29.4	79.3	136.3	55.4	40.7	226.6	88.0	38.8	357.2	131.8	36.9	757.2	182.3	24.1
Mayiladuthurai	54.4	49.2	90.4	109.9	76.4	69.5	246.4	89.1	36.2	714.1	267.4	37.5	1124.8	309.5	27.5
Nagapattinam	64.2	72.7	113.2	123.4	77.9	63.1	228.5	110.3	48.3	777.0	270.6	34.8	1193.1	308.8	25.9
Namakkal	30.6	33.3	108.8	128.1	51.2	40.0	283.3	83.7	29.5	293.1	111.2	38.0	735.1	172.9	23.5
Perambalur	33.5	35.8	106.9	105.7	49.7	47.0	249.1	76.7	30.8	412.6	174.8	42.4	800.9	198.3	24.8
Pudukkottai	42.6	38.5	90.5	105.3	52.6	49.9	223.5	87.8	39.3	389.1	162.8	41.8	760.5	222.3	29.2
Ramanathapuram	52.5	35.1	66.9	118.0	76.9	65.2	161.2	89.0	55.2	414.5	160.4	38.7	746.2	208.7	28.0
Ranipet	48.1	46.8	97.3	108.6	66.1	60.9	378.8	116.5	30.8	379.0	151.2	39.9	914.4	252.6	27.6
Salem	38.3	39.4	103.0	162.3	54.0	33.3	364.5	85.0	23.3	350.0	124.6	35.6	915.1	193.3	21.1
Sivagangai	39.3	33.3	84.9	109.1	61.7	56.6	201.8	94.9	47.0	338.9	134.1	39.6	689.1	214.0	31.0
Tenkasi	49.8	34.7	69.6	147.1	67.1	45.6	235.5	107.4	45.6	409.1	142.8	34.9	841.4	221.4	26.3
Thanjavur	40.9	42.0	102.8	100.0	48.2	48.2	214.9	87.9	40.9	516.2	216.8	42.0	871.9	244.1	28.0
The Nilgiris	51.0	41.3	81.1	190.2	77.3	40.7	622.7	158.0	25.4	413.7	129.8	31.4	1277.6	274.7	21.5
Theni	38.3	28.3	73.9	166.6	53.4	32.1	405.5	113.2	27.9	375.3	137.0	36.5	985.7	185.8	18.8
Thiruvannamalai	40.2	44.8	111.5	107.8	57.8	53.7	358.4	101.0	28.2	414.1	168.8	40.8	920.5	242.7	26.4
Thoothukudi	58.3	33.8	57.9	134.8	70.8	52.6	161.6	75.5	46.7	373.6	123.5	33.0	728.3	193.8	26.6
Tiruchirapalli	28.8	31.1	108.0	111.0	45.0	40.5	240.7	70.6	29.3	352.5	151.3	42.9	733.0	187.0	25.5
Tirunelveli	62.9	37.6	59.8	165.2	85.6	51.8	225.4	94.1	41.7	439.9	141.4	32.1	893.4	233.9	26.2
Tirupathur	25.1	32.3	128.7	114.7	46.6	40.6	364.1	118.1	32.4	326.6	118.6	36.3	830.4	210.3	25.3
Tiruppur	33.4	40.6	121.5	112.6	63.1	56.0	181.1	93.3	51.5	283.0	117.3	41.4	610.2	210.8	34.5
Tiruvallur	55.9	39.3	70.3	108.7	62.1	57.1	392.2	109.2	27.8	545.2	246.0	45.1	1102.0	257.2	23.3
Tiruvarur	53.6	57.2	106.7	117.0	63.2	54.0	226.2	100.9	44.6	646.2	238.7	36.9	1043.0	264.6	25.4
Vellore	49.9	40.8	81.8	125.2	68.1	54.4	411.4	129.8	31.6	356.6	123.0	34.5	943.0	246.7	26.2
Villupuram	35.1	34.2	97.7	88.8	56.0	63.1	318.9	85.0	26.6	521.0	235.8	45.3	963.8	287.1	29.8

Virudhunagar	33.6	28.2	83.8	118.9	62.8	52.9	154.7	85.2	55.0	350.8	130.2	37.1	658.1	187.9	28.5
Tamil Nadu	42.0	31.1	74.2	124.9	47.7	38.2	291.2	73.7	25.3	425.2	144.0	33.9	883.2	187.3	21.2

3.4. Monthly distribution and variability of soil moisture (m^3/m^3)

The mean monthly soil moisture across the districts of Tamil Nadu for the period 1991–2020 is presented in Fig. 2. Soil moisture values ranged from 0.10 to 0.36 m^3/m^3 across the state, with a distinct and consistent seasonal cycle observed in nearly all districts.

The lowest mean soil moisture was recorded during March (0.165) and February (0.179), representing the peak of the dry summer period following the retreat of the northeast monsoon, when evapotranspiration losses exceed the limited moisture reserves. Values began rising sharply from April–May onward with the onset of pre-monsoon and southwest monsoon showers and continued to build steadily through the southwest monsoon season (June–September).

Soil moisture increased during November (0.309) and October (0.303), coinciding with the northeast monsoon — the principal rainfall season for Tamil Nadu — followed closely by December (0.276) and September (0.279). This confirms that soil moisture recharge in the state is predominantly governed by the northeast monsoon rather than the southwest monsoon, consistent with Tamil Nadu's unique rainfall climatology compared to most other Indian states.

Spatially, Kanniyakumari (0.279), The Nilgiris (0.276), Madurai (0.273), Erode (0.268) and Tiruvallur (0.267) recorded the highest annual mean soil moisture, reflecting either high and well-distributed rainfall (Kanniyakumari, The Nilgiris) or favourable soil and irrigation conditions sustaining higher retention through the year. In contrast, Ramanathapuram (0.178), Cuddalore (0.190), Tirupathur (0.201), Mayiladuthurai and Nagapattinam (0.202 each) recorded the lowest mean soil moisture, indicating chronically drier soil regimes. Notably, Ramanathapuram — situated in the rain-shadow tract of the state — recorded the lowest values in almost every month, underscoring its persistent moisture-deficit status.

The difference between the wettest and driest months (seasonal amplitude) also varied across districts. Kanniyakumari, Theni, The Nilgiris, Tirupathur and Tenkasi showed the narrowest amplitude (0.12–0.13), suggesting comparatively stable moisture retention across seasons — largely due to more evenly distributed rainfall or better soil moistureholding capacity. Conversely, Tiruppur, Virudhunagar, Karur, Krishnagiri and Namakkal exhibited the widest amplitude (0.17–0.18), reflecting a sharper contrast between the dry summer trough and the post-monsoon peak, typical of the semi-arid interior districts.

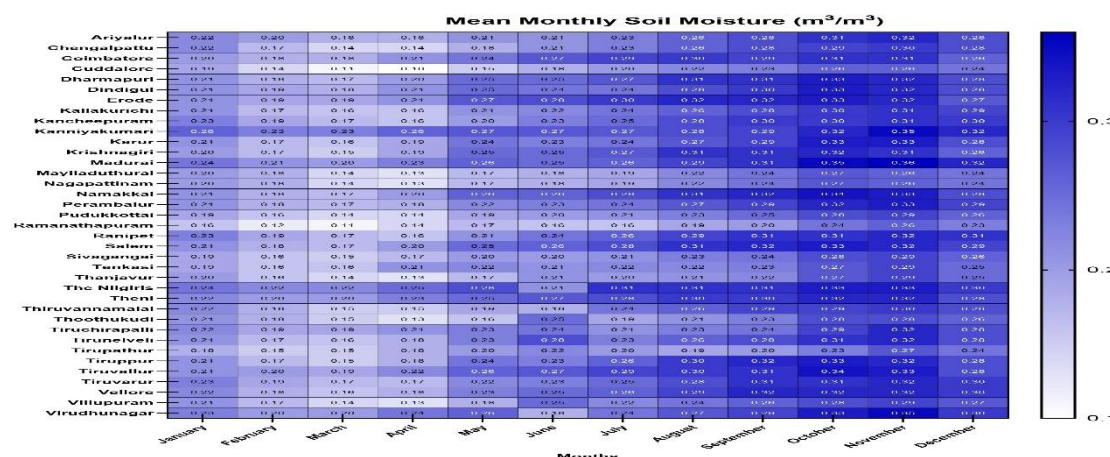


Fig. 2. Mean Monthly Soil Moisture

3.5. Season-wise Mean and Variability of Soil Moisture

3.5.1. Cold Weather Period (CWP)

During the Cold Weather Period, the mean soil moisture across districts averaged 0.196, ranging from 0.14 (Ramanathapuram) to 0.25 (Kanniyakumari) (Table 2). Variability in this season was comparatively high, with a mean SD of 0.025 (range 0.01–0.04), indicating relatively inconsistent moisture retention year-to-year. Ramanathapuram, Cuddalore, and Tirupathur recorded the lowest moisture levels, while Kanniyakumari, The Nilgiris, and Madurai recorded the highest — reflecting the influence of residual northeast monsoon moisture that persists into this period in the southern and hilly districts.

3.5.2. Hot Weather Period (HWP)

The Hot Weather Period recorded the lowest overall mean soil moisture (0.188) among all four seasons, ranging from 0.12 (Cuddalore) to 0.25 (Kanniyakumari and The Nilgiris). This decline reflects intense evapotranspiration losses coupled with minimal rainfall input characteristic of summer. Variability remained moderately high (mean SD 0.023), with Cuddalore, Ramanathapuram, and Thanjavur showing the driest conditions, while Virudhunagar, Kanniyakumari, and The Nilgiris retained comparatively higher moisture, aided by better soil-moisture-holding capacity or localized rainfall.

3.5.3. Southwest Monsoon (SWM)

Soil moisture improved markedly during the Southwest Monsoon, with a mean of 0.253 (range 0.18–0.31), as monsoon rainfall began replenishing soil profiles across the state. Notably, this season recorded the lowest variability of all seasons (mean SD 0.015), indicating a fairly stable and predictable moisture build-up year after year. Ramanathapuram, Thanjavur, and Thoothukudi recorded the lowest moisture, while The Nilgiris, Erode, and Tiruvallur recorded the highest, benefiting from more effective rainfall utilization and soil retention during this season.

Table 2. Mean Seasonal Soil Moisture of Tamil Nadu during 1991-2020

District	CWP		HWP		SWM		NEM	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ariyalur	0.21	0.02	0.19	0.02	0.24	0.01	0.3	0.02
Chengalpattu	0.2	0.02	0.15	0.02	0.24	0.01	0.29	0.02
Coimbatore	0.19	0.02	0.21	0.01	0.29	0.02	0.29	0.02
Cuddalore	0.16	0.03	0.12	0.03	0.21	0.01	0.25	0.02
Dharmapuri	0.2	0.02	0.2	0.02	0.28	0.02	0.31	0.02
Dindigul	0.2	0.02	0.21	0.02	0.27	0.02	0.31	0.02
Erode	0.2	0.01	0.22	0.02	0.3	0.01	0.31	0.02
Kallakurichi	0.19	0.03	0.18	0.03	0.25	0.01	0.3	0.02
Kancheepuram	0.21	0.02	0.18	0.03	0.27	0.02	0.31	0.02
Kanniyakumari	0.25	0.03	0.25	0.03	0.28	0.02	0.33	0.02
Karur	0.19	0.03	0.2	0.02	0.26	0.02	0.31	0.03
Krishnagiri	0.19	0.02	0.19	0.02	0.28	0.01	0.29	0.02
Madurai	0.23	0.03	0.23	0.02	0.28	0.02	0.34	0.03
Mayiladuthurai	0.19	0.02	0.15	0.03	0.21	0.01	0.26	0.02
Nagapattinam	0.19	0.02	0.15	0.03	0.21	0.01	0.26	0.02
Namakkal	0.19	0.02	0.21	0.02	0.29	0.02	0.32	0.02
Perambalur	0.2	0.03	0.19	0.02	0.26	0.01	0.31	0.02
Pudukkottai	0.18	0.04	0.16	0.03	0.22	0.01	0.28	0.02
Ramanathapuram	0.14	0.03	0.14	0.03	0.18	0.01	0.24	0.02
Ranipet	0.21	0.03	0.18	0.03	0.27	0.02	0.31	0.02
Salem	0.2	0.02	0.2	0.02	0.29	0.01	0.31	0.02
Sivagangai	0.18	0.03	0.17	0.02	0.22	0.01	0.28	0.02
Tenkasi	0.17	0.03	0.19	0.02	0.22	0.02	0.27	0.02
Thanjavur	0.18	0.03	0.14	0.02	0.2	0.01	0.27	0.02
The Nilgiris	0.23	0.02	0.25	0.02	0.31	0.01	0.32	0.01

Theni	0.21	0.01	0.23	0.02	0.28	0.02	0.31	0.02
Thiruvannamalai	0.2	0.03	0.16	0.03	0.26	0.02	0.29	0.03
Thoothukudi	0.2	0.02	0.15	0.02	0.2	0.01	0.27	0.02
Tiruchirapalli	0.2	0.02	0.21	0.02	0.22	0.02	0.3	0.02
Tirunelveli	0.19	0.03	0.19	0.02	0.25	0.01	0.3	0.02
Tirupathur	0.16	0.04	0.17	0.03	0.2	0.02	0.25	0.02
Tiruppur	0.19	0.03	0.19	0.02	0.28	0.02	0.31	0.02
Tiruvallur	0.21	0.01	0.22	0.01	0.29	0.02	0.32	0.02
Tiruvarur	0.21	0.03	0.19	0.03	0.27	0.01	0.31	0.02
Vellore	0.2	0.03	0.19	0.02	0.28	0.02	0.31	0.03
Villupuram	0.19	0.03	0.15	0.03	0.23	0.01	0.28	0.02
Virudhunagar	0.22	0.02	0.23	0.02	0.26	0.02	0.33	0.02

3.5.4. Northeast Monsoon (NEM)

The Northeast Monsoon emerged as the wettest season overall, with the highest mean soil moisture (0.296), ranging from 0.24 (Ramanathapuram) to 0.34 (Madurai). This confirms the NEM's role as the principal moisture-recharging season for Tamil Nadu. Variability during this season (mean SD 0.021) was lower than in the CWP and HWP but slightly higher than the SWM, suggesting consistent though occasionally erratic rainfall performance. Ramanathapuram, Cuddalore, and Tirupathur remained the driest districts even in this peak season, while Madurai, Kanniyakumari, and Virudhunagar recorded the highest moisture levels, reflecting strong NEM rainfall influence over the southern and central interior districts.

3.6. Annual Mean and Variability of Soil Moisture

The annual mean soil moisture distribution across Tamil Nadu during 1991–2020 exhibited noticeable spatial variation among districts (Table 3). The state average soil moisture ranged from 0.21 to 0.25, with a mean value of 0.24 and a standard deviation of 0.01, indicating relatively stable soil moisture conditions at the state level. Among the districts, Kanniyakumari and The Nilgiris recorded the highest mean annual soil moisture (0.28), followed by Madurai, Erode, Theni, Tiruvallur, and Virudhunagar (0.26). The higher soil moisture levels in these districts can be attributed to higher rainfall, favorable topography, and enhanced water retention capacity of soils. In contrast, Ramanathapuram recorded the lowest mean soil moisture (0.17), followed by Cuddalore (0.18) and several coastal and dryland districts such as Mayiladuthurai, Nagapattinam, Thanjavur, Thoothukudi, and Tirupathur (0.20). Lower soil moisture in these regions may be associated with higher evapotranspiration rates, coarse-textured soils, and limited moisture storage capacity.

The maximum annual soil moisture was observed in Kanniyakumari (0.31), followed by The Nilgiris (0.30) and Madurai and Virudhunagar (0.29). Conversely, Ramanathapuram recorded the lowest minimum soil moisture (0.15), followed by Cuddalore and Tirupathur (0.16). These observations indicate the susceptibility of southeastern districts to moisture stress during dry periods. The standard deviation values ranged from 0.01 to 0.02. Districts such as Kanniyakumari, Karur, Namakkal, Pudukkottai, Ramanathapuram, Ranipet, Sivagangai, Thiruvannamalai, Tirupathur, Tiruppur, and Vellore exhibited relatively higher standard deviation values (0.02), indicating greater year-to-year fluctuations in soil moisture. In contrast, most districts recorded lower standard deviation values (0.01), suggesting comparatively stable soil moisture conditions over the study period.

Table 3. Mean Annual Soil Moisture of Tamil Nadu during 1991–2020

District	Soil Moisture (m ³ /m ³)			
	Min	Max	Mean	SD
Ariyalur	0.21	0.25	0.24	0.01
Chengalpattu	0.2	0.24	0.22	0.01
Coimbatore	0.2	0.26	0.24	0.01
Cuddalore	0.16	0.21	0.18	0.01
Dharmapuri	0.22	0.27	0.25	0.01

Dindigul	0.22	0.26	0.25	0.01
Erode	0.23	0.28	0.26	0.01
Kallakurichi	0.2	0.25	0.23	0.01
Kancheepuram	0.21	0.26	0.24	0.01
Kanniyakumari	0.25	0.31	0.28	0.02
Karurl	0.2	0.27	0.24	0.02
Krishnagiri	0.21	0.26	0.24	0.01
Madurai	0.24	0.29	0.27	0.01
Mayiladuthurai	0.18	0.23	0.2	0.01
Nagapattinam	0.18	0.23	0.2	0.01
Namakkal	0.21	0.28	0.25	0.02
Perambalur	0.22	0.25	0.24	0.01
Pudukkottai	0.17	0.24	0.21	0.02
Ramanathapuram	0.15	0.2	0.17	0.02
Ranipet	0.19	0.27	0.24	0.02
Salem	0.22	0.27	0.25	0.01
Sivagangai	0.18	0.24	0.21	0.02
Tenkasi	0.18	0.23	0.21	0.01
Thanjavur	0.17	0.23	0.2	0.01
The Nilgiris	0.25	0.3	0.28	0.01
Theni	0.22	0.28	0.26	0.01
Thiruvannamalai	0.19	0.25	0.23	0.02
Thoothukudi	0.18	0.23	0.2	0.01
Tiruchirapalli	0.2	0.26	0.23	0.01
Tirunelveli	0.2	0.25	0.23	0.01
Tirupathur	0.16	0.22	0.2	0.02
Tiruppur	0.2	0.26	0.24	0.02
Tiruvallur	0.23	0.28	0.26	0.01
Tiruvarur	0.22	0.26	0.24	0.01
Vellore	0.2	0.27	0.25	0.02
Villupuram	0.19	0.24	0.21	0.01
Virudhunagar	0.24	0.29	0.26	0.01

Overall, the results indicate that the Western Ghats and high-rainfall districts maintained higher and more reliable soil moisture levels, whereas the coastal dryland and southeastern districts experienced lower soil moisture availability and greater vulnerability to drought conditions.

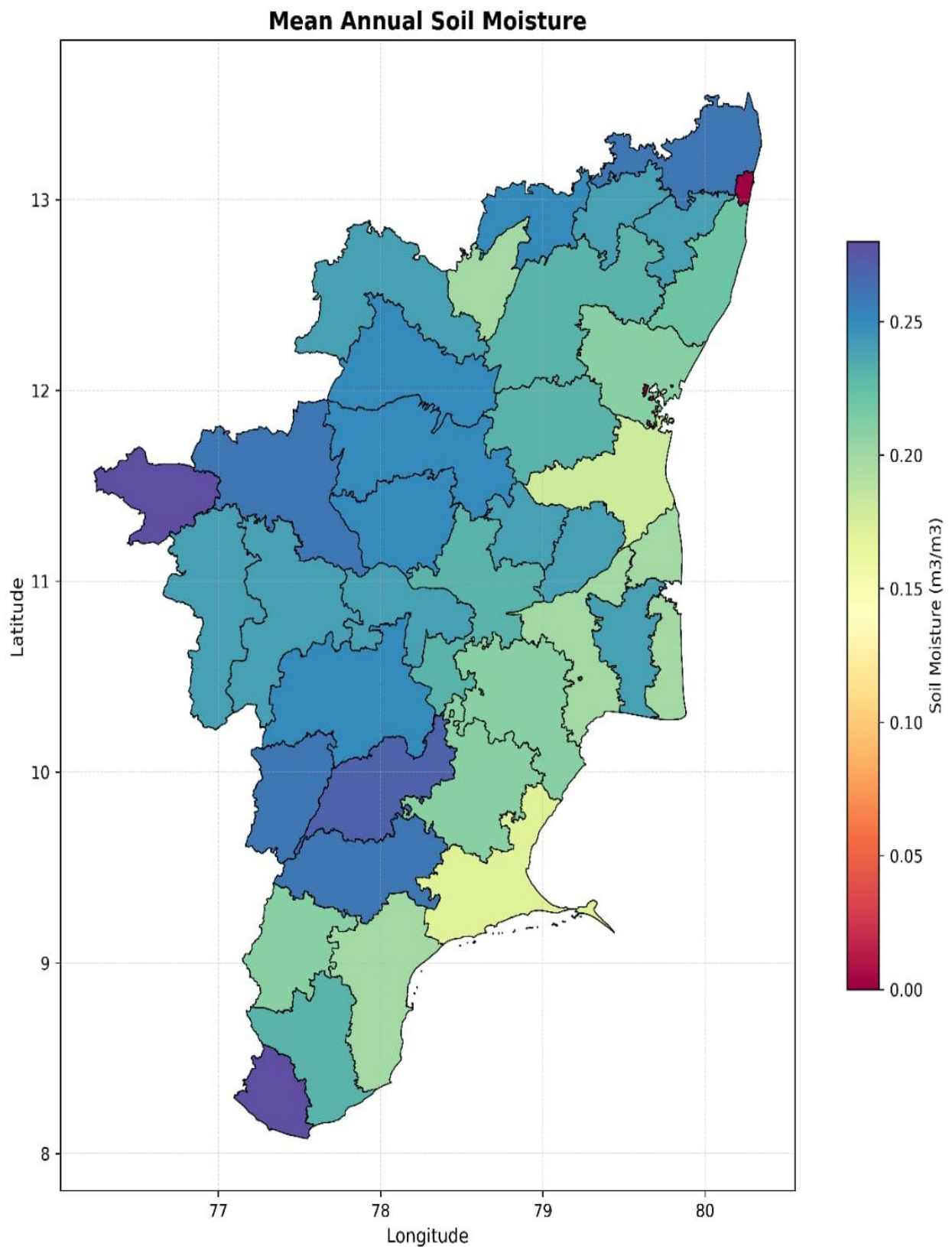


Figure 2. Annual Soil Moisture

3.7. Soil Moisture Persistence across Tamil Nadu

Soil moisture persistence was assessed using the autocorrelation function (ACF) of monthly soil moisture anomalies. The month-to-month memory of soil moisture was quantified by the lag-1 autocorrelation coefficient, while persistence duration was defined as the time it took for the autocorrelation to decay below the e-folding threshold ($1/e \approx 0.368$). Significant spatial variability in soil moisture persistence was observed across districts of Tamil Nadu (Fig. 3). Lag-1 autocorrelation coefficients ranged from 0.338 to 0.650, with an average of

approximately 0.506. All districts showed positive lag-1 autocorrelation, indicating that soil moisture anomalies generally carried over from one month to the next. However, the strength of this month-to-month memory varied considerably by district.

The highest lag-1 autocorrelation coefficients were found in Tirunelveli ($r = 0.650$), Chengalpattu (0.637), Thiruvallur (0.629), Ranipet (0.620), Kanchipuram (0.620), Ramanathapuram (0.615), and Viluppuram (0.608). These high coefficients suggest strong continuity in soil moisture anomalies from one month to the next. In these districts, unusually wet or dry conditions in a given month were more likely to influence soil moisture in the subsequent month.

Conversely, weaker lag-1 autocorrelation was observed in The Nilgiris (0.338), Ariyalur (0.385), Tiruppur (0.390), Virudhunagar (0.399), and Thoothukkudi (0.416). The Nilgiris recorded the lowest lag-1 autocorrelation, indicating a relatively rapid loss of soil moisture memory. Nevertheless, the positive lag-1 autocorrelation across all districts confirms that previous month soil moisture conditions influence subsequent monthly soil moisture across the Tamil Nadu.

3.8. Persistence Duration

The estimated duration of soil moisture persistence in Tamil Nadu ranged from one to four months. Most districts exhibited persistence durations of two or three months.

The longest persistence duration of four months was observed in the districts of Chengalpattu, Thiruvallur, Tirunelveli, and Vellore. These districts therefore retained the influence of previous soil moisture anomalies for a comparatively longer period. Tirunelveli was particularly notable, displaying both the highest lag-1 autocorrelation (0.650) and a four-month persistence duration. Chengalpattu and Thiruvallur similarly combined high lag-1 autocorrelation coefficients with extended persistence, demonstrating robust soil moisture memory.

A three-month persistence duration was found in 17 districts, representing 47.2% of those analyzed. Another 14 districts (38.9%) showed two-month persistence. In contrast, The Nilgiris was the only district with a one-month persistence duration, while only four districts exhibited four-month persistence.

Thus, 86% districts had a soil moisture persistence duration of two to three month. Four-month and one-month persistence accounted for only 11.1% and 2.8% of the districts, respectively. The prevalence of two- to three-month persistence indicates that this timescale characterizes the typical soil moisture memory across much of Tamil Nadu.

3.9. Temporal Decay of Soil Moisture Memory

The autocorrelation functions revealed a notable decline in soil moisture memory as the monthly lag increased. It sharply decreased during the initial monthly lags. The extent and rate of this decline varied among districts, leading to the observed differences in persistence duration (Fig. 1).

In districts with relatively short persistence, autocorrelation dropped below the e-folding threshold within one or two months. Conversely, districts with stronger soil moisture memory-maintained autocorrelation for a longer period before crossing this threshold. Most districts reached the persistence threshold within approximately two to three months, while only a few retained significant memory for four months.

At longer lags, autocorrelation coefficients generally remained substantially lower than those observed at shorter lags. This pattern indicates that soil moisture memory in Tamil Nadu is primarily a short- to intermediate-term process, rather than a long-term persistence spanning the entire year.

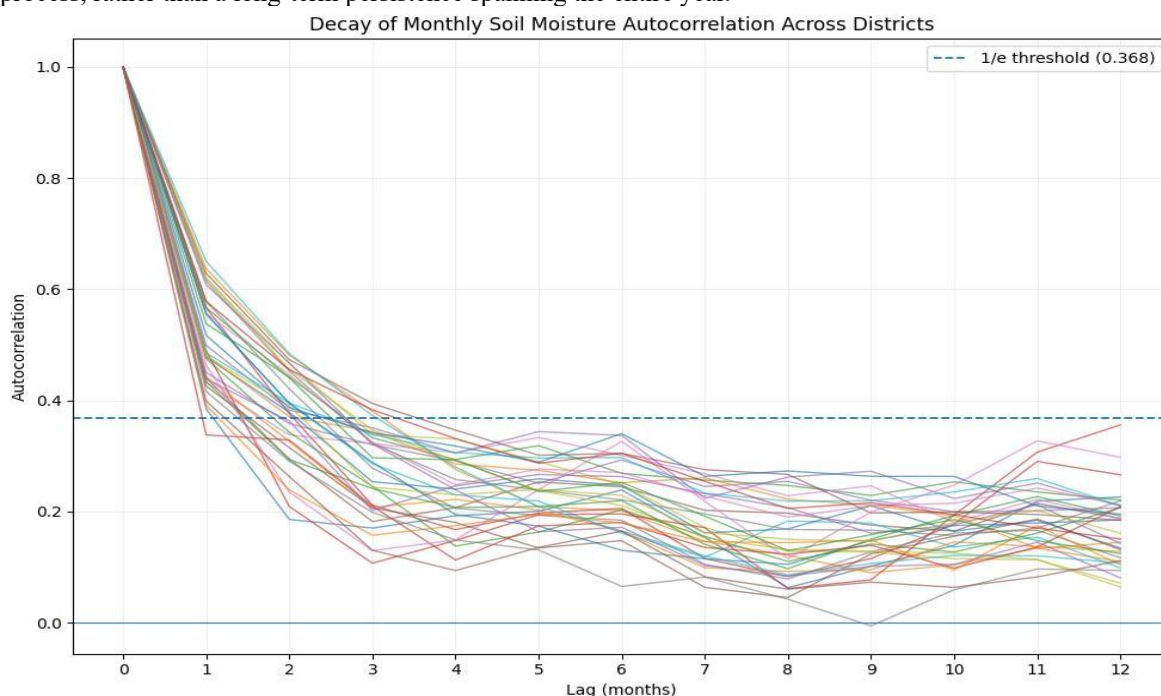


Figure 3. Temporal Decay of Soil Moisture Memory

3.10. Relationship between Rainfall and Soil Moisture

The relationship between rainfall (RF) and soil moisture (SM) was assessed using Pearson's correlation analysis. The analysis indicated a **weak positive correlation** between rainfall and soil moisture, with a Pearson correlation coefficient of $r = 0.144$. This suggests that soil moisture showed only a slight tendency to increase with increasing rainfall during the study period.

The relationship was **not statistically significant** at the 5% significance level ($p = 0.394$; $p > 0.05$). Therefore, the observed linear association between rainfall and soil moisture was weak, and the analysis does not provide sufficient evidence of a significant contemporaneous linear relationship between the two variables.

The low correlation may reflect the fact that soil moisture is influenced not only by rainfall but also by antecedent rainfall, evapotranspiration, soil properties, vegetation, infiltration, runoff and drainage. In addition, the response of soil moisture to rainfall may involve a **time lag**, meaning that rainfall occurring during an earlier period can influence soil moisture observed subsequently. Thus, the weak simultaneous RF–SM correlation does not necessarily imply that rainfall has little influence on soil moisture; rather, it indicates that the relationship is not well represented by a simple same-period linear correlation.

Overall, the results demonstrate a **weak and statistically non-significant positive association between rainfall and soil moisture** ($r = 0.144$, $p = 0.394$).

3.11. Correlation

Lagged correlation analysis was performed to examine the temporal relationship between rainfall and soil moisture at lags ranging from 0 to 12. At lag 0, rainfall showed a weak positive correlation with soil moisture ($r = 0.144$), which was statistically non-significant ($p = 0.394$). A similarly weak positive relationship was observed at lag 1 ($r = 0.156$, $p = 0.363$).

The correlation coefficients subsequently fluctuated between weak positive and negative values across lags 2–10. Negative correlations were observed at lags 2, 3, 4, 5, 7 and 9, with the strongest negative association occurring at lag 9 ($r = -0.276$, $p = 0.156$). None of these relationships was statistically significant ($p > 0.05$).

A notable increase in the correlation was observed at **lag 11**, where rainfall and soil moisture exhibited the **strongest positive correlation** ($r = 0.407$). This relationship was statistically significant at the 5% level ($p = 0.039$). The correlation subsequently decreased at lag 12 ($r = 0.162$, $p = 0.440$).

Overall, the lag analysis showed that the contemporaneous and short-lag relationships between rainfall and soil moisture were generally weak and statistically non-significant. The significant positive correlation at lag 11 indicates a temporal association between rainfall and soil moisture at this lag.

4. DISCUSSION

The present study examined the spatio-temporal characteristics of soil moisture and its persistence over Tamil Nadu with three objectives: (i) analyzing the spatial distribution and variability of rainfall and soil moisture, (ii) estimating soil moisture persistence, and (iii) examining the relationship between rainfall and soil moisture. The results obtained in Chapter IV are discussed below in relation to each objective.

4.1 Spatial distribution and variability of rainfall and soil moisture

Rainfall in Tamil Nadu is governed by two contrasting monsoon systems rather than a single wet season. The Northeast Monsoon was the principal contributor to annual rainfall (425.2 mm), benefiting coastal and delta districts such as Nagapattinam, Mayiladuthurai, Tiruvarur and Cuddalore, while the Southwest Monsoon (291.2 mm) was more consequential for Western Ghats-facing districts such as The Nilgiris, Kanniyakumari and Theni. The rain-shadow effect in Virudhunagar, Ramanathapuram and Karur further confirms the Ghats' topographic control on the state's rainfall regime. Mean annual rainfall (883.2 mm, CV 21.3%) masks considerable inter-district heterogeneity, from The Nilgiris (1277.6 mm) to Karur (595.0 mm), with coastal districts such as Tiruppur, Cuddalore and Villupuram showing higher inter-annual variability linked to erratic cyclonic and northeast monsoon rainfall — a compounded risk for districts like Tiruppur and Sivagangai that also have low mean rainfall. Soil moisture mirrored, but did not exactly replicate, the rainfall pattern: it reached an annual minimum in March (0.165 m³/m³) and February (0.179 m³/m³), and a maximum in November (0.309 m³/m³) and October (0.303 m³/m³), with recharge tracking the Northeast rather than Southwest Monsoon — a distinctive feature of Tamil Nadu's climatology and agronomically important for rabi-season moisture. Kanniyakumari and The Nilgiris showed direct rainfall-to-moisture translation, whereas Madurai and Erode recorded high soil moisture despite moderate rainfall, pointing to soil texture, irrigation and drainage as secondary controls. Ramanathapuram consistently recorded the lowest soil moisture despite not always being the driest district, indicating that its rain-shadow position is compounded by limited moisture-storage capacity. Together, these results confirm that soil moisture patterns in Tamil Nadu are shaped jointly by monsoon-driven rainfall and local land-surface controls.

4.2. Soil moisture persistence across Tamil Nadu

Autocorrelation analysis of monthly soil moisture anomalies gave lag-1 coefficients ranging from 0.338 to 0.650 (state average ≈ 0.506), positive in every district, confirming a consistent month-to-month memory relevant to short-range agricultural and hydrological forecasting. This persistence pattern did not mirror the rainfall/soil-moisture magnitude pattern: Tirunelveli, Chengalpattu, Thiruvallur, Ranipet and Kancheepuram showed the strongest memory and longest persistence (up to four months), whereas The Nilgiris, despite high rainfall and soil moisture, showed the weakest persistence ($r = 0.338$, one month) — explained by its hilly, well-drained terrain allowing rapid dissipation of moisture anomalies, versus the flatter, finer-textured plains of Tirunelveli and

Thiruvallur that retain moisture longer. This distinction between magnitude and persistence is a key insight, showing that a district can be simultaneously wet and hydrologically 'fast', or drier and 'slow'.

Since 86% of districts showed a persistence duration of two to three months, this timescale represents the characteristic soil moisture memory of Tamil Nadu, with autocorrelation decaying consistently across all districts, confirming that this memory is a short- to intermediate-term phenomenon rather than an inter-annual carryover. Given the Northeast Monsoon's role as the principal recharge season, this window implies that moisture accumulated during October-December meaningfully influences soil conditions into the early part of the following cropping season, with direct relevance for irrigation scheduling and rabi crop planning.

4.3. Relationship between rainfall and soil moisture

The simultaneous (lag-0) correlation between rainfall and soil moisture was weak and non-significant ($r = 0.144$, $p = 0.394$), indicating that same-period rainfall alone poorly predicts contemporaneous soil moisture — consistent with soil moisture integrating antecedent conditions, evapotranspiration, infiltration, runoff, drainage and soil properties rather than responding to a simple same-month linear relationship. Lagged correlations (lags 1-10) fluctuated between weak positive and negative values, including the strongest negative correlation at lag 9 ($r = -0.276$, $p = 0.156$), none significant. A significant positive correlation emerged only at lag 11 ($r = 0.407$, $p = 0.039$), weakening again at lag 12 — pointing to a delayed, near-annual recurrence linked to the strong seasonality of the state's rainfall regime, rather than a short-term causal response. This suggests the annual monsoon cycle, not month-to-month rainfall fluctuations, is the dominant organizing influence on the long-term rainfall-soil moisture relationship.

5. CONCLUSIONS:

Overall, the study originally intended to examine the influence of vegetation on this relationship; however, the results were confined to the rainfall-soil moisture linkage, and a vegetation-based analysis was not included. This component therefore remains for future analysis, which could help interpret the observed weak, lag-dependent relationship more completely, given the known mediating role of vegetation cover and canopy interception.

6. REFERENCES:

1. Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3–4), 125–161.
2. Gruber, A., Scanlon, T., van der Schalie, R., Wagner, W., & Dorigo, W. (2019). Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology. *Earth System Science Data*, 11, 717–739.
3. Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C. H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., & Yamada, T. (2004). Regions of strong coupling between soil moisture and precipitation. *Science*, 305, 1138–1140.
4. Orth, R., & Seneviratne, S. I. (2012). Analysis of soil moisture memory from observations in Europe. *Journal of Geophysical Research: Atmospheres*, 117, D15115.
5. Ghannam, K., Nakai, T., Paschalis, A., Oishi, A. C., Kotani, A., Igarashi, Y., Kumagai, T., & Katul, G. G. (2016). Persistence and memory timescales in root-zone soil moisture dynamics. *Water Resources Research*, 52, 1427–1445.
6. Rahmati, M., et al. (2024). Soil moisture memory: State-of-the-art and the way forward. *Reviews of Geophysics*.
7. Al-Wassai, F.A., & Kalyankar, N.V. (2013). Major limitations of satellite images. *arXiv preprint arXiv:1307.2434*.
8. Cai, J., Zhou, B., Chen, S., Wang, X., Yang, S., Cheng, Z., Wang, F., Mei, X., & Wu, D. (2024). Spatial and Temporal Variability of Soil Moisture and Its Driving Factors in the Northern Agricultural Regions of China. *Water*, 16(4), 556.
9. Dorigo, W. A., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., Chung, D., Ertl, M., Forkel, M., Gruber, A., Haas, E., Hamer, P. D., Hirschi, M., Ikonen, J., de Jeu, R., Kidd, R., Lahoz, W., Liu, Y. Y., Miralles, D., & Lecomte, P. (2017). ESA CCI Soil Moisture for improved Earth system understanding.
10. Chatterjee, S., Desai, A. R., Zhu, J., Townsend, P. A., & Huang, J. (2022). Soil moisture as an essential component for delineating and forecasting agricultural rather than meteorological drought. *Remote Sensing of Environment*, 269, 112833.
11. Myeni, L., Moeletsi, M. E., & Clulow, A. D. (2021). Development and analysis of a long-term soil moisture data set in three different agroclimatic zones of South Africa. *South African Journal of Science*, 117(5).
12. Dorigo, W. A., Gruber, A., De Jeu, R. A. M., Wagner, W., Stacke, T., Loew, A., ... & Kidd, R. (2015). Evaluation of the ESA CCI soil moisture product using ground-based observations. *Remote Sensing of Environment*, 162, 380–395.
13. Ghannam, K., Nakai, T., Paschalis, A., Oishi, C. A., Kotani, A., Igarashi, Y., Kumagai, T., & Katul, G. G. (2016). Persistence and memory timescales in root-zone soil moisture dynamics. *Water Resources Research*, 52(2), 1427–1445.