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Rainfall distribution patterns during the monsoon seasons in Vellore district, Tamil Nadu

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Abstract
Rainfall is the most critical weather parameter determining agricultural productivity in the semi-arid regions of Tamil Nadu, where the socioeconomic stability of rural communities is intrinsically linked to monsoon behaviour. This study presents a monsoon onset dynamics, temporal distribution, and rainfall intensity over the Vellore district, Tamil Nadu from 2018 to 2024. The results of onset dates reveal the Northeast Monsoon exhibits high synchronization with state-level onset, whereas the Southwest Monsoon shows greater interannual variability and occasional significant delays. Despite these delays, Southwest Monsoon rainfall remained consistently above the normal value (475.3 mm) throughout the study period. In contrast, the Northeast Monsoon displayed extreme fluctuations, ranging from a 22.3% deficit to a 70.3% surplus in 2021, underscoring its dominant yet erratic influence on the region's hydrology. Weekly and monthly distributions revealed that while light to moderate events predominate both seasons, the northeast monsoon is characterized by high intensity, episodic rainfall, particularly during November (44 to 48th Standard Meteorological Week). Significant extreme events, such as the 244.2 mm recorded in July 2020 and 179.1 mm in November 2020, highlight a shift toward rainfall extremes post-2020. These findings highlight the Southwest Monsoon provides a stable baseline, the NEM's high variability, driven by Bay of Bengal cyclonic activity dictates the district's agricultural and water resource success. This temporal rainfall distribution pattern results emphasize the urgent need for adaptive water management and climate-resilient agricultural planning to mitigate the risks posed by increasing rainfall intensity and shifting monsoon behaviour.

Keywords*: Rainfall distribution; South West Monsoon; North East Monsoon; Vellore district*

Introduction

Rainfall is the most critical climatic factor determining agricultural productivity in the semi-arid regions of Tamil Nadu, where the socio-economic stability of rural communities is intrinsically linked to monsoon behaviour. In the Vellore district, agriculture is predominantly rain-fed, making it highly sensitive to the onset, duration, and intensity of the two major monsoon systems: the Southwest Monsoon (SWM) and the Northeast Monsoon (NEM). While the SWM provides a steady baseline of precipitation from June to September, the NEM, occurring from October to December, is the primary contributor to the annual rainfall budget, often characterized by high-intensity episodic events driven by cyclonic disturbances in the Bay of Bengal (Prasanna, 2014; Sivasuriyan *et al.,* 2025). The temporal and spatial distribution of this rainfall dictates the cropping patterns and yields of major regional crops such as groundnut, paddy and pulses. Recent climatic shifts have affecting rainfall distribution, hydrological cycles, agricultural sustainability (IPCC, 2021; Mall *et al.,* 2006) and erratic dry spells during critical growth stages such as flowering and grain filling lead to substantial yield gaps. Rainfall variability not only affects the yield it also affects the groundwater re-

EQA 75 (2026): 53 - 61

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sources (Subbah Rao, 2021). Over recent decades, the country has experienced significant alterations in rainfall patterns, including shifts in monsoon onset, intensity, and distribution, leading to increased frequency of extreme weather events such as floods and droughts (Maharana *et al.,* 2021). Understanding these rainfall distribution patterns is essential for developing adaptive agricultural strategies, optimizing irrigation scheduling and ensuring water security in the district to face of changing monsoon dynamics.

Materials and Methods

Study **area**

Vellore district is geographically situated in the north eastern zone of Tamil Nadu and lies between 12° 15' to13° 15' N latitude and 78° 20' to 79° 50' E longitude (Fig. 1).. The region exhibits a semi-arid to tropical climate, where agricultural success is heavily dependent on the variability of both the Southwest Monsoon (SWM) and more significantly, the Northeast Monsoon

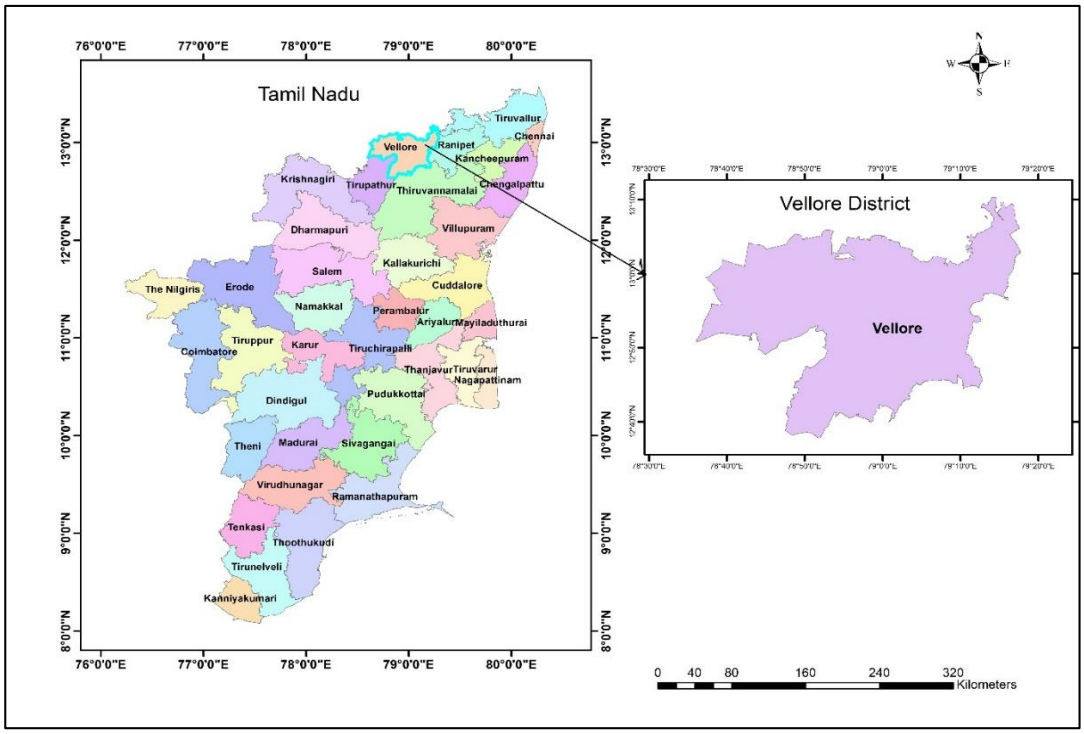

Figure 1
Study Area

(NEM). It is bounded on north by Chittoor District of Andhra Pradesh, on the South by Thiruvannamalai District and on the East by Kancheepuram District. Its geography is marked by a mix of plains and hills, particularly the Jawadhu and Yelagiri Hills, which modulate the districts rainfall through orographic effects.

Data collection

Rainfall daily data were observed and collected from ICAR-Krishi Vigyan Kendra, Vellore District, Tamil Nadu during the period 2018-2024 through the District Agro-Met Unit (DAMU) established at the centre to assess temporal rainfall distribution patterns. All datasets were carefully examined to ensure continuity and reliability. The rainfall data, recorded in mil-limeters (mm), were systematically compiled and organized into weekly, monthly and seasonal datasets using structured spreadsheets to facilitate compre-hensive analysis.

Data categorization

For an accurate assessment of multi-temporal rainfall distribution patterns, rainfall data for Vellore District were categorized into weekly, monthly, and seasonal segments in accordance with the standards of the India Meteorological Department. Additionally, as per IMD guidelines, rainfall recorded over a 24-hour period (ending at 08:30 IST) is classified into specific intensity categories (Table 1). Further, year-wise actual onset and

Table 1
Rainfall category according IMD

Category rainfall	Rainfall (mm)/day
Very light	Trace-2.4
Light	2.5-15.5
Moderate	15.6-64.4
Heavy	64.5-115.5
Very heavy	115.6-204.4
Extremely heavy	>204.4

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

Year	Southwest monsoon		Northeast monsoon	
	Onset Date	Withdrawal Date	Onset Date	Withdrawal Date
2018	29 May	6 October	2 November	2 January
2019	8 June	16 October	20 October	10 January
2020	1 June	28 October	13 November	19 January
2021	3 June	25 October	25 October	22 January
2022	29 May	23 October	29 October	12 January
2023	8 June	15 October	21 October	Not specified
2024	30 May	15 October	15 October	Late December

Table 2
Year-wise actual onset and withdrawal dates of southwest and northeast monsoon over Tamil Nadu (2018–2024)

withdrawal dates of the Southwest and Northeast Monsoon over Tamil Nadu (2018-2024) were incurporated to support seasonal analysis and interpretation of rainfall variability (Table 2).

Results and Discussion

Onset Dynamics of Monsoon Seasons

The analysis of monsoon onset over Vellore district, in comparison with Tamil Nadu onset dates, reveals notable interannual variability (Table 3). The Southwest Monsoon (SWM) onset in Vellore generally follows the state onset with slight variation; however, a significant delay was observed in 2019 and moderate delay in 2022. In most other years (2018, 2020, 2021, 2023, and 2024) the southwest monsoon onset occurred either on the same day or within a few days of the Tamil Nadu onset, indicating relatively consistent inland progresssion of monsoon currents. In contrast, the Northeast Monsoon (NEM) onset over Vellore shows a high degree of synchronization with Tamil Nadu, with onset dates either coinciding exactly or occurring one day earlier in most years. Slight early onset was observed in 2018, 2020, 2021, 2024 and exact coincidence was noted in 2019, 2022 and 2023. Overall, the results indicate that while the Northeast Monsoon exhibits consistent and synchronous onset behaviour in Vellore district, the Southwest Monsoon shows comparatively higher variability, with occasional significant delays, highlighting the dominant influence of the Northeast Monsoon on the district's rainfall regime.

Year	Southwest monsoon		Northeast monsoon	
	Onset Date (TN)	Onset Date (Vellore)	Onset Date (TN)	Onset Date (Vellore)
2018	29 May	30 May	2 November	1 November
2019	8 June	22 June	20 October	20 October
2020	1 June	2 June	13 November	12 November
2021	3 June	5 June	25 October	24 October
2022	29 May	5 June	29 October	29 October
2023	8 June	9 June	21 October	21 October
2024	30 May	30 May	15 October	14 October

Table 3
Onset dynamics of monsoon seasons in Vellore district

Temporal distribution of weekly rainfall across monsoon seasons

The Standard Meteorological Week (SMW) rainfall data for the period 2018–2024 (Figure 2) revealed a highly variable distribution of rainfall across both the Southwest Monsoon (23 to 39 SMW) and Northeast monsoon (40 to 52 SMW) seasons. During the SWM period, rainfall onset typically began in early June (SMW 23–24), with peak activity observed in July (28 to 31 SMW). Notably, an extreme rainfall event of 244.2 mm was recorded during 28th SMW in 2020, which indicated episodic high-intensity rainfall. However, several weeks also experienced zero and negligible rainfall, particularly in 2019 and parts of 2024; this highlighted the erratic and discontinuous nature of SWM precipitation. In contrast, the NEM season exhibited comparatively higher rainfall intensity, especially during November (44 to 48 SMW). Significant rainfall events, such as 179.1 mm (48th SMW, 2020) and 134.9 mm (47th SMW, 2021), emphasized the dominance of dura-

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

tion, high-intensity rainfall during this season. Overall, the dataset indicated that the NEM contributed more effectively to total annual rainfall than the SWM. The observed rainfall variability aligned with findings reported in previous studies. For instance, Rajeevan et al. (2006) highlighted the significant intra-seasonal variability and occurrence of extreme rainfall events over India, particularly during monsoon periods. Similarly, Prasanna (2014) reported that Northeast Monsoon rainfall over Tamil Nadu was largely influenced by cyclonic disturbances and low-pressure systems over the Bay of Bengal, which led to intense rainfall events within short durations. The present analysis corroborated these findings, as evidenced by the frequent high rainfall peaks during SMW 44–48. Furthermore, the increasing occurrence of extreme rainfall events after 2020 suggested a possible shift in rainfall patterns, which may have been associated with climate variability and warming trends, as also discussed by Goswami et al. (2006). These results underlined the need for improved water management and adaptive agricultural planning in response to changing monsoon behaviour.

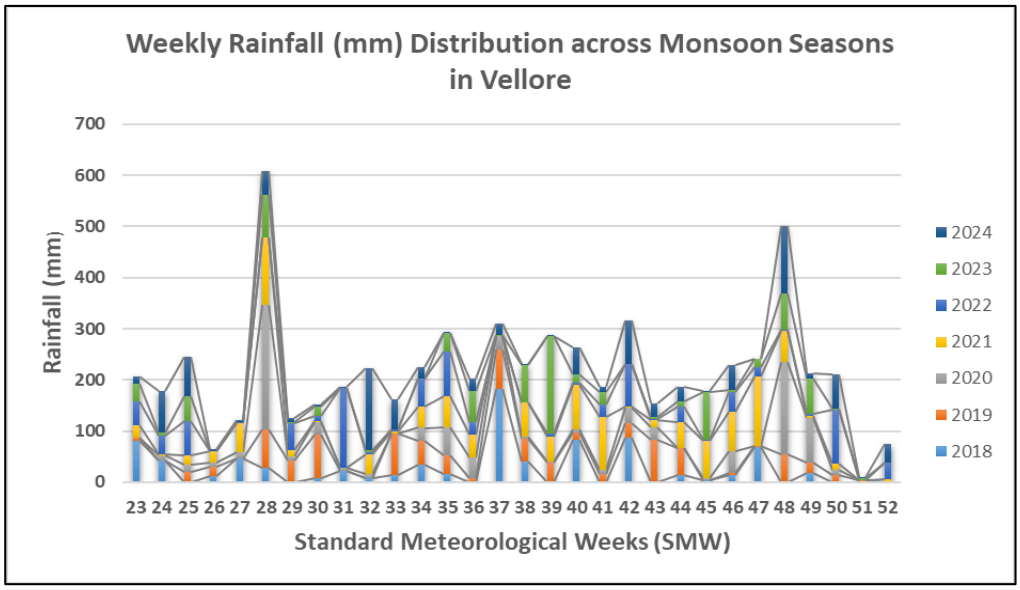

Figure 2
Temporal distribution of weekly rainfall (mm) across monsoon seasons in Vellore

Rainfall characteristics of southwest and northeast monsoon

The analysis of seasonal rainfall over Vellore district (Fig. 3 and Table 4) indicates clear differences in the behaviour of the Southwest Monsoon (SWM) and Northeast Monsoon (NEM). The SWM rainfall remained consistently above the normal value (475.3 mm throughout the study period, with positive deviations ranging from 8.0% to 24.9%. Higher surplus rainfall was recorded in 2019 and 2021, suggesting stronger monsoon circulation during these years. This relatively stable and above-normal trend indicates that the SWMcontributes moderately but reliably to the district's rainfall regime.

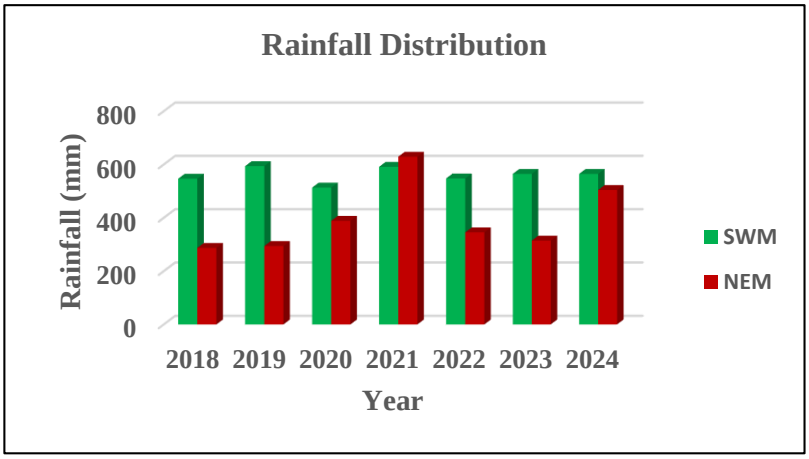

Figure 3
Rainfall distribution in monsoon seasons in Vellore

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

Table 4. *Rainfall characteristics of southwest and northeast monsoon in Vellore district (2018-2024)*

Year	Southwest monsoon			Northeast monsoon		
	Actual rainfall (mm)	Normal rainfall (mm)	Deviation (%)	Actual rainfall (mm)	Normal rainfall (mm)	Deviation (%)
2018	546.4	475.3	15.0	287	369.3	-22.3
2019	593.8	475.3	24.9	294	369.3	-20.4
2020	513.4	475.3	8.0	388.5	369.3	5.2
2021	591.2	475.3	24.4	629	369.3	70.3
2022	547.6	475.3	15.2	345.3	369.3	-6.5
2023	564.7	475.3	18.8	314.3	369.3	-14.9
2024	564.6	475.3	18.8	504.2	369.3	36.5

In contrast, the NEM rainfall exhibited significant interannual variability, with both deficit and excess conditions observed. Deficit years such as 2018, 2019, 2022, and 2023 showed negative deviations ranging from -6.5% to -22.3%, whereas excess rainfall was recorded in 2020, 2021, and 2024, with a notably high deviation of 70.3% in 2021 indicating an extreme wet year. This variability highlights the dominant role of the Northeast Monsoon in influencing annual rainfall fluctuations in Vellore district. Similar studies across Tamil Nadu have reported that the Northeast monsoon contributes the major share of annual rainfall and exhibits high variability influenced by large-scale ocean–atmosphere interactions and extreme weather events (Sivasuriyan *et.al.,* 2025). Recent research also indicates increasing frequency of rainfall extremes and interannual fluctuations in monsoon patterns over Tamil Nadu districts (Gowtham and Rama-chandran, 2025). Overall, the findings confirm that while the Southwest Monsoon provides relatively stable rainfall, the Northeast Monsoon is highly variable and plays a crucial role in determining the hydrological and agricultural conditions of the region.

Monthly Rainfall Distribution

Monthly rainfall distribution during southwest monsoon (2018–2024). The month-wise analysis of Southwest Monsoon rainfall over Vellore district during 2018 to 2024 reveals considerable variability in both total rainfall and extreme daily events (Table 5). June rainfall showed notable variation, with the highest in 2024 (204.7 mm) followed by 2022 (150.1 mm) and 2018 (140.0 mm), while lower rainfall occurred in 2019 (61.6 mm), 2020 (53.8 mm) and 2021 (58.4 mm); intense daily events included 80.0 mm (07.06.2018) and 74.4 mm (17.06.2024). July recorded very high rainfall in 2020 (292.0 mm) with an extreme of 140.0 mm (10.07.2020), while other years like 2021 (224.9 mm) and 2019 (202.6 mm) also showed substantial rainfall, compared to lower totals in 2018 (86.2 mm), 2022 (63.9 mm), 2023 (102.6 mm) and 2024 (64.8 mm). August rainfall was highly variable, peaking in 2022 (285.5 mm) and 2024 (245.6 mm), with intense daily events such as 100.2 mm (02.08.2022) and 65.6 mm (06.08.2024), while 2023 recorded the lowest (38.8 mm). September also showed wide variation, with the highest rainfall in 2023 (329.0 mm) followed by 2018 (240.2 mm) whereas lower values were seen in 2022 (48.1 mm) and 2024 (49.5 mm); notable extremes included 83.0 mm (16.09.2018) and 62.8 mm (25.09.2023). Overall, the Southwest Monsoon rainfall in Vellore district is highly variable, with no consistent pattern and extreme rainfall events, particularly in July and August play a major role in seasonal rainfall contribution.

Monthly rainfall distribution during northeast monsoon (2018–2024). The monthly rainfall distribution during the Northeast Monsoon (NEM) in Vellore district from 2018 to 2024 shows high variability across years (Table 6). October rainfall was moderate, with higher values in 2021 (213.0 mm) and 2024 (181.7 mm), while 2023 recorded the lowest (50.4 mm). November contributed the highest rainfall in most years, especially in 2021 (387.0 mm) and 2020 (226.3 mm), indicating it as the most important month of the season, whereas 2019 recorded very low rainfall (22.8 mm). December rainfall also varied widely, with very high rainfall in 2024 (243.1 mm) and 2022 (144.0 mm), but low in years like 2018 (19.0 mm) and 2021 (29.0 mm). Several heavy rainfall events were observed, particularly in November and December such as 90.0 mm (27 November 2020) and 81.2 mm (1 December 2024), indicating the influence of cyclonic systems. Overall, the Northeast Monsoon rainfall pattern in Vel-

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

Table 5. *Month wise highest rainfall recorded during southwest monsoon 2018 to 2024*

Year	June		July		August		September	
	Total (mm)	Highest daily mm (Date)	Total (mm)	Highest daily mm (Date)	Total (mm)	Highest daily mm (Date)	Total (mm)	Highest daily mm (Date)
2018	140.0	80.0 07.06.2018	86.2	30.0 03.07.2018	80.0	35.0 26.08.2018	240.2	83.0 16.09.2018
2019	61.6	17.0 03.06.2019	202.6	60.0 26.07.2019	164.0	59.0 17.08.2019	165.6	46.0 13.09.2019
2020	53.8	22.0 02.06.2020	292.0	140.0 10.07.2020	90.4	39.2 31.08.2020	77.2	30.0 03.09.2020
2021	58.4	22.9 06.06.2021	224.9	55.6 10.07.2021	142.5	33.8 28.08.2021	165.4	44.6 26.09.2021
2022	150.1	33.0 15.06.2022	63.9	26.5 21.07.2022	285.5	100.2 02.08.2022	48.1	15.0 02.09.2022
2023	94.3	36.0 10.06.2023	102.6	61.2 13.07.2023	38.8	26.8 27.08.2023	329.0	62.8 25.09.2023
2024	204.7	74.4 17.06.2024	64.8	34.8 13.07.2023	245.6	65.6 06.08.2024	49.5	22.5 08.09.2024

Table 6. *Month wise highest rainfall recorded during northeast monsoon 2018 to 2024*

Year	October		November		December	
	Total (mm)	Highest daily mm (Date)	Total (mm)	Highest daily mm (Date)	Total (mm)	Highest daily mm (Date)
2018	170.0	88.0 18.10.2018	98.0	33.0 21.11.2018	19.0	15.0 05.12.2018
2019	196.0	59.0 24.10.2019	22.8	8.0 29.11.2019	75.2	36.0 01.12.2019
2020	63.3	28.4 17.10.2020	226.3	90.0 27.11.2020	98.9	40.3 08.12.2020
2021	213.0	71.8 06.10.2021	387.0	82.5 19.11.2021	29.0	6.8 01.12.2021
2022	116.9	73.6 16.10.2022	84.4	21.4 13.11.2022	144.0	39.8 13.12.2022
2023	50.4	21.0 11.10.2023	185.9	48.2 05.11.2023	78.0	47.4 03.12.2023
2024	181.7	37.6 05.10.2024	79.4	25.0 15.11.2024	243.1	81.2 01.12.2024

lore is irregular, with November playing a major role in seasonal rainfall contribution.

Rainfall intensity distribution during SWM and NEM

The analysis of rainfall intensity during the Southwest Monsoon (SWM) in Vellore district from 2018 to 2024 indicates that light and moderate rainfall events were predominant, while heavy and very heavy rainfall events were rare (Figure 4). Light rainfall events were recorded frequently across all months, for instance in September 2022 (8 days) and June 2024 (7 days), followed by moderate rainfall events such as September 2023 (8 days) and June 2022 (5 days). Very light rainfall events were also observed in several cases, particularly during June 2023 (6 days) and July 2024 (5 days), indicating weak monsoon phases. Heavy rainfall events were limited, occurring occasionally (e.g., June 2018, August 2022 and August 2024 with 1 day each), while very heavy rainfall was recorded only once in July 2020 (1 day), and no extremely heavy rainfall events were observed. This suggests that the Southwest Monsoon in Vellore is mainly characterized by frequent low to moderate intensity rainfall with very few extreme events, contributing steadily to seasonal rainfall totals. These findings agree with earlier and recent studies

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

which report that low to moderate rainfall events dominate the Indian monsoon regime, while extreme rainfall events are episodic in nature (Anonymous, 2023; Roxy *et al.*, 2017; Krishnan *et al.*, 2020). In contrast, the Northeast Monsoon (NEM) also showed dominance of light and moderate rainfall events, but with slightly higher variability and occasional heavy rainfall occurrences (Fig. 5). Light rainfall was frequent during months such as October 2024 (8 days) and November 2020 and 2021 (8 days each), while moderate rainfall was significant in October 2019 (6 days) and November 2021 (10 days). Very light rainfall events were observed in years like October 2020 and 2022 (5 days each), reflecting intermittent weak rainfall spells. Heavy rainfall events occurred sporadically, such as in November 2020 (2 days), October 2018 and 2021 (1 day each), and December 2024 (1 day), but no very heavy or extremely heavy rainfall events were recorded. Overall, the Northeast Monsoon exhibits a similar dominance of low to moderate intensity rainfall but with relatively higher variability and occasional intense events, largely influenced by cyclonic systems over the Bay of Bengal. Similar observations have been reported in recent studies highlighting the variability and synoptic control of Northeast Monsoon rainfall over Tamil Nadu (Anonymous, 2024; Singh *et al.*, 2023; Rajeevan *et al.*, 2012).

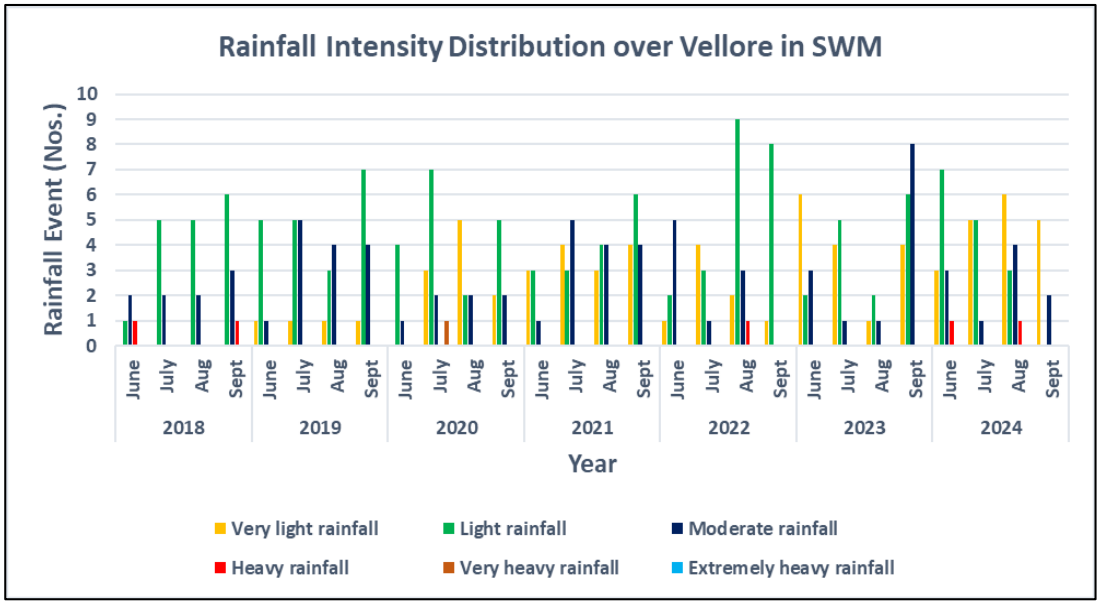

Figure 4
Monthly rainfall intensity distribution over Vellore in SWM 2018-2024

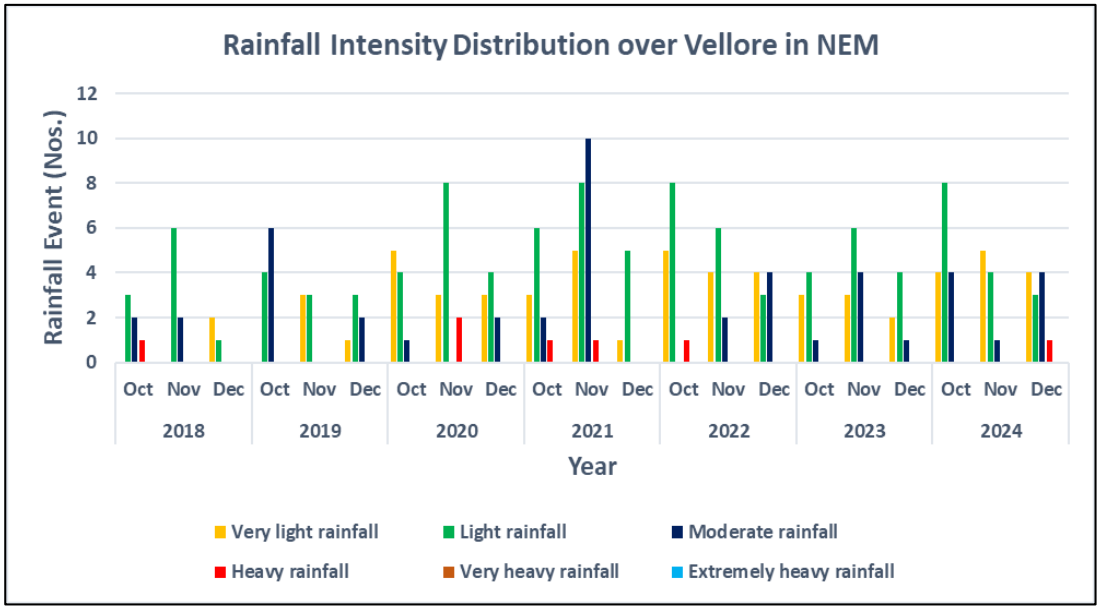

Figure 5
Monthly rainfall intensity distribution over Vellore in NEM 2018-2024

EQA 75 (2026): 53 - 61

DOI: 10.60923/issn.2281-4485/26036

Impact on crop production

Crops yields are highly sensitive to seasonal rainfall and its intra-seasonal distribution (Bowdan *et al.*, 2023; Manivasagam and Nagarajan, 2018).). These periods of water shortage or excess rainfall during critical crop stages like flowering, tillering and crown root initiation can reduce yield substantially (Gupta *et al.*, 2022). Machine learning models confirm that both yield anomalies and harvested area were strongly connected to monsoon variability including onset timing and season duration (Bowdan *et al.*, 2023).

Conclusions

The study concludes that while the Southwest Monsoon offers stable, above-normal rainfall, the Northeast Monsoon remains the primary yet highly volatile driver of Vellore's hydrological regime. A clear trend toward episodic, high-intensity rainfall events post-2020 suggests an increasing influence of climate variability on local precipitation patterns. November emerges as the most critical month for seasonal totals, though it is frequently subject to extreme fluctuations and cyclonic disturbances. The predominance of light-to-moderate rainfall across both seasons highlights the necessity of efficient water-harvesting systems to capture frequent but low-intensity runoff. Ultimately, these shifting dynamics necessitate a transition toward climate-smart agricultural practices to manage the dual challenges of monsoon delays and extreme wet years.

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Ethics statement

This study was conducted using recorded dataset sources. It did not involve human participants, animals or any form of personal data. Therefore, ethical approval was not required.

Originality and plagiarism

The authors confirm that this manuscript is an original work and has not been published previously, nor is it under consideration for publication elsewhere. All sources of data, concepts and previously published material have been properly cited and acknowledged. The manuscript has been prepared in accordance with ethical academic standards and plagiarism in any form has been strictly avoided.

Consent for publication

All authors have read and approved the final version of the manuscript and consent to its submission and publication in the journal.

Competing interests

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this manuscript.

Data availability

The data supporting the findings of this study were observed from ICAR-KVK Vellore, Distric Agro-Met Unit from surface observatory. Processed datasets and graphical rainfall summaries generated during the study are available from the corresponding author upon reasonable request.

Author contributions

Rathika K: Conceptualization, methodology development, drafting the initial manuscript and overall coordination of the research work; data interpretation and review. Sasikumar K: Data processing, statistical analysis and support in result interpretation. Ankit Kumar Meena: Data curation, analysis, visualization, and preparation of figures and tables. Akshaya S: Overall supervision, review and editing of the manuscript.

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