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**“MONSOON PATTERN CHANGES AND ASSOCIATED PRODUCTIVITY
SHIFTS FOR KARAIKAL REGION”**



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Monsoon Pattern Changes and Associated Productivity Shifts for Karaikal Region

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ABSTRACT

Karaikal district lies on the east coast of India, near latitude 11° N, and is part of the fertile delta region of the Cauvery River. Covering an area of 157 sq kilometres (61 sq miles approx.), the district features flat land that gently slopes eastward toward the Bay of Bengal. Several distributaries of the Cauvery River flow through the area, which is also built on thick alluvial deposits of varying thickness. This makes the region very productive for agriculture, but it is also prone to flooding.

The Karaikal is heavily influenced by two monsoon seasons: the Southwest Monsoon (SWM) from June to September and the Northeast Monsoon from October to December. The Northeast Monsoon (NEM) is responsible for most of the yearly rainfall. The district receives an average of about 126 cm of rain annually, with 68% (around 985.8 mm) falling during the NEM. In comparison, the SWM contributes less than 20% (around 254.0 mm) of the total rainfall. This strong reliance on the NEM makes the region particularly sensitive to changes in the timing and intensity of monsoons.

The onset phase is key for monsoon analysis in the region. It signifies the shift from the Southwest Monsoon winds to the northeast wind pattern. An early onset may widen the rainfall window, while a late onset might narrow it. However, the timing of the onset alone doesn't ensure the total rainfall for the season. This study examined the onset dates and rainfall for the period to assess how they predict seasonal rainfall outcomes.

Objectives: This study aims to (i) analyse multi-decadal trends in monsoon rainfall over the Karaikal region, (ii) examine shifts in SW and NE monsoon onset and withdrawal dates, (iii) assess the correlation between monsoon variability and changes in agricultural productivity, and (iv) recommend evidence-based adaptation strategies, (v) Wind direction shifts abruptly from $\sim 220\text{--}250^{\circ}$ (SW/WSW) during June–September to $\sim 30\text{--}50^{\circ}$ (NNE/NE) by October, marking a clear seasonal reversal, (vi) The 45-year wind speed trend indicates a weakening of -0.12 m/s per decade in trade wind strength, with SW season winds (5.2 m/s mean) declining more rapidly than NE season winds (4.9 m/s mean), (vii) The NE monsoon contributes approximately 70–75% of Karaikal's annual rainfall, with extreme NE events in 2009, 2015, 2020, and 2021 exceeding 80–90% of annual totals, (viii) Paddy cultivation, which occupies

65–85% of the cultivated area, shows strong correlation ($r = +0.42$) with NE monsoon rainfall, underscoring high food security vulnerability during NE failure years.

Methodology: (i) Finding Right Climate Data, (ii) Methodology Design, (iii) Analysis Tools, (iv) Data Validation and Report Writing, and (v) Climate Communication through Dashboards and Data Storytelling. Twenty-four datasets were compiled from three categories of authoritative sources — Indian government portals, international remote sensing and reanalysis products, and in-situ field stations. Primary data sources include NASA/POWER MERRA-2 satellite reanalysis (1981–2025, 45 years), ERA5 ECMWF reanalysis (1975–2024, 50 years), Central Water Commission / National Water Informatics Centre (CWC/NWIC) station records from Annavasal, Nallathur, and Karaikal (2000–2025), India Meteorological Department (IMD) archives, Department of Agriculture crop statistics (2004–2024), and Revenue Department disaster records (1952–2024). All datasets underwent rigorous quality control including range checks, temporal consistency verification, cross-source validation (NASA/POWER vs CWC rainfall: $r = 0.74$), and unit standardisation. Statistical methods applied include linear trend analysis (Ordinary Least Squares), Mann-Kendall non-parametric trend testing, Pearson correlation, seasonal decomposition, and rainfall anomaly/departure analysis. Five machine learning models — Random Forest, Gradient Boosting, Ridge Regression, Polynomial Regression (degree 3), and an Ensemble Average — were trained on historical climate and hydrological data and validated using 5-fold time-series cross-validation to generate climate projections for 2026–2030. Geospatial analysis and interactive visualisation were performed using Python/Folium, producing a seven-layer interactive climate map. Five multi-panel publication-quality dashboards (covering wind reversal, trade wind weakening, rainfall distribution, agriculture–climate nexus, and disaster risk) were developed using Python/matplotlib as the primary climate communication output of this study.

Key Findings: From 1952 to 2025, an analysis of hydro-meteorological disasters shows that Karaikal has faced frequent flooding and cyclones, mostly during the Northeast monsoon. The district has seen about 12 cyclones and one major tsunami, along with repeated flooding. Significant floods in 2004 and 2015, Karaikal region is the highest flood intensity among the four regions of the Union Territory of Puducherry. These events caused extensive damage to farmland, irrigation systems, and rural livelihoods. As a result, the district is classified as a high-risk flood zone in the BMTPC Hazard Atlas of India.

Agriculture productivity plays a major role in Karaikal, with 84.92% of its land classified as cultivable and 82.81% of this area irrigated. Paddy cultivation is predominant, featuring three

main cropping seasons: kuruvai, samba, and thaladi, all supported by irrigation from the Cauvery River and seasonal rains. This study highlights the importance of combining disaster indicators with monsoon onset data to improve rainfall predictions and variations in onset timing directly influence agricultural planning and productivity

Major Recommendations: Based on the evidence generated through multi-decadal climate data analysis and machine learning projections, the following major adaptation strategies are recommended for the Karaikal region. First, a systematic programme of tank desiltation and cascade irrigation system restoration should be undertaken to maximise rainwater harvesting during the concentrated three-month NE monsoon window, directly addressing SDG 6.4 (water-use efficiency). Second, the CWC/NWIC monitoring stations at Annavasal and Nallathur should be upgraded with IoT-enabled real-time hydrological telemetry to provide sub-hourly discharge and water level data for flood early warning and irrigation scheduling, supporting SDG 11.5 and SDG 13.1. Third, drought-resistant and short-duration paddy varieties (ADT 53, CO 51, PMK 4) should be promoted for the SW monsoon cultivation season to buffer against the observed and projected intensification of SW monsoon deficits driven by trade wind weakening, supporting SDG 2.4. Fourth, a phased crop diversification programme reducing paddy monoculture dependency from 65–85% to 55–65% of cultivated area by 2030, incorporating pulses and vegetables, is recommended to reduce single-season food security risk under SDG 2.3. Fifth, a multi-hazard early warning system integrating IMD cyclone forecasts, CWC real-time water level data, and the ML discharge prediction model developed in this study should be operationalised to address the accelerating post-2010 disaster recurrence rate of one major event every two years, aligned with SDG 13.1.

Keywords: Monsoon Pattern, Karaikal, Climate Change, Agricultural Productivity, NE Monsoon, Rainfall Trend, Adaptation Strategies.

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INTRODUCTION:

1.1 Background

India's climate system is governed by two dominant seasonal wind systems: the South-West (SW) monsoon (June–September) and the North-East (NE) monsoon (October–December). While the SW monsoon is the primary rainfall system for most of the Indian subcontinent, the NE monsoon holds exceptional importance for the southeastern coast — particularly Tamil Nadu and the Union Territory of Puducherry. The Karaikal region, situated in the heart of the Cauvery Delta on the Coromandel Coast, receives approximately 70–80% of its annual rainfall during the NE monsoon season, making it one of the most NE-monsoon-dependent coastal territories in India.

Climate change is fundamentally altering monsoon behaviour globally. The weakening of the Walker Circulation and the progressive warming of the Indian Ocean are causing measurable changes in trade wind intensity, seasonal wind reversal timing, and inter-annual rainfall variability. These shifts have far-reaching consequences for coastal agricultural communities like Karaikal, where paddy cultivation occupies 65–85% of the cultivated area and is intrinsically linked to monsoon reliability.

1.2 Problem Statement

The Karaikal region of the Union Territory of Puducherry occupies one of the most climatologically unique and simultaneously vulnerable positions on the Indian subcontinent. Situated on the Coromandel Coast within the Cauvery River Delta, at an elevation of 0 to 5 metres above Mean Sea Level, the region is structurally dependent on a single three-month rainfall window — the North-East (NE) monsoon (October–December) — for approximately 70–80% of its annual water supply. This extreme concentration of rainfall in one season, combined with rapidly intensifying climate variability, defines the central problem that this study investigates.

Three interconnected and mutually reinforcing climate problems have been identified as the primary drivers of climate risk in the Karaikal region, each of which remains insufficiently quantified at the local sub-territorial scale:

Problem 1: Seasonal Wind Direction Reversal and Its Variability

The transition from the South-West (SW) monsoon to the North-East (NE) monsoon over the Coromandel Coast is governed by an abrupt and complete reversal of the surface wind direction

— from southwesterly trade winds ($\sim 220\text{--}250^\circ$) during June–September to north-northeasterly winds ($\sim 30\text{--}50^\circ$) by November–December. This wind reversal, which typically occurs during October, is the single most important meteorological event in the Karaikal agricultural calendar. It determines the onset of the primary paddy cultivation season (Paddy-II / Samba), the filling of irrigation tanks, and the commencement of the NE monsoon rainfall that accounts for the bulk of the region's annual water income.

However, the timing, strength, and year-to-year variability of this wind reversal are poorly documented at the local scale. Global reanalysis data indicates that October mean wind direction carries a standard deviation of $\pm 89^\circ$ over Karaikal — the highest directional variability of any month in the annual cycle — confirming that the reversal month is climatologically unstable and increasingly unpredictable. A delay of 10–15 days in the wind reversal directly postpones the NE monsoon onset, compresses the agricultural preparation window, and reduces the effective NE rainfall harvest. Yet no systematic, multi-decadal, station-validated study of wind reversal timing and its agricultural consequences exists for the Karaikal sub-territory. This is a critical knowledge gap that limits the accuracy of seasonal forecasting and agricultural advisory systems in the region.

Problem 2: Weakening of Trade Winds and Declining SW Monsoon Performance

The South-West monsoon trade winds are the primary engine of India's summer monsoon circulation. Driven by the thermal contrast between the warming Asian landmass and the relatively cooler Indian Ocean, these southwesterly winds carry moisture-laden air from the Arabian Sea and the Bay of Bengal onto the Indian subcontinent, delivering the bulk of India's annual rainfall between June and September. In Karaikal, the SW monsoon contributes approximately 20–30% of the annual seasonal rainfall — a secondary but nonetheless critical contribution that supports the Paddy-I (Kar) cultivation season and pre-charges the Arasalar River system before the onset of the NE monsoon.

However, 45 years of NASA/POWER MERRA-2 satellite reanalysis data (1981–2025) reveal a statistically significant and progressive weakening of SW monsoon trade wind speeds over the Karaikal region at a rate of approximately -0.12 m/s per decade. The cumulative weakening over the 45-year period amounts to -0.54 m/s — a reduction of approximately 10.7% from the 1981 baseline wind speed. This finding is consistent with the global literature on Walker Circulation weakening under anthropogenic greenhouse gas forcing (Vecchi and Soden, 2007;

Roxy et al., 2015), but its local-scale quantification for Karaikal has not previously been attempted.

The consequences of this weakening are far-reaching. In 40% of the years between 2004 and 2024, SW monsoon rainfall over Karaikal fell below 80% of the long-term normal — a deficit rate that is both statistically and agriculturally significant. In severe SW deficit years such as 2006–07 (–61.2% below normal), 2008–09 (–54.7%), and 2009–10 (–59.0%), the shortfall in Paddy-I cultivation area reached 20–30%, directly reducing agricultural income and increasing farmer debt. The compounding effect of weakening trade winds, declining SW monsoon reliability, and growing dependence on NE monsoon compensation creates a structural vulnerability that is deepening with each passing decade.

Problem 3: Extreme NE Monsoon Dependency - The 80–90% Rainfall Concentration Problem

The third and most structurally defining problem of the Karaikal climate system is the extreme concentration of annual rainfall within the NE monsoon season. Analysis of 20 years of Department of Agriculture rainfall records (2004–2024) cross-validated against NASA/POWER and CWC station data reveals that the NE monsoon (October–December) contributes a mean of approximately 73–75% of Karaikal's total annual seasonal rainfall (June–December). In SW-deficit years — which constitute 40% of the study period — this NE contribution rises sharply to 80–93%, creating a system in which a single three-month weather window effectively determines the entire agricultural and water security outcome for the year.

This 80–90% rainfall concentration problem manifests across four interconnected dimensions. First, it creates a narrow and non-substitutable water capture window: if the NE monsoon fails, partially or wholly, there is no alternative source of water at the scale required to sustain paddy cultivation or replenish the tank irrigation network. Second, it concentrates flood and disaster risk within the same three-month window: the post-2010 record shows that all seven major climate disasters in Karaikal between 2011 and 2025 occurred during or immediately following the NE monsoon season. Third, it amplifies the agricultural consequences of inter-annual NE variability: the coefficient of variation of NE monsoon rainfall exceeds 35%, meaning that any given NE monsoon year may deliver between 280 mm and 1,494 mm — a five-fold range — creating extreme uncertainty for farmers, water managers, and disaster administrators. Fourth, the 80–90% dependency is deepening over time: the progressive weakening of the SW monsoon identified in Problem 2 is systematically shifting a larger share of annual rainfall onto

the NE season, increasing structural dependency on a season that is itself becoming more variable under climate change.

Despite the scale and significance of this problem, no sub-regional study has simultaneously documented the SW deficit trends, the NE concentration dynamics, the hydrological consequences for the Arasalar river system, and the agricultural productivity implications for paddy cultivation in Karaikal using a comprehensive, multi-source, multi-decadal dataset. This study fills that gap.

The Convergence Problem

What makes the climate situation in Karaikal particularly serious is not any one of these three problems in isolation, but their convergence and mutual reinforcement. Weakening trade winds reduce SW monsoon performance, pushing more of the annual water burden onto the NE season. The NE season's structural concentration of 80–90% of rainfall in three months amplifies the consequences of any NE failure or extreme event. And the unpredictable timing of the October wind reversal — the gateway event between the two monsoon systems — means that the transition between the two seasons is itself becoming less reliable. The result is a climate system that is simultaneously more extreme, more concentrated, and less predictable than at any point in the 45-year instrumental record — a convergence of stressors that constitutes a genuine climate emergency for the agricultural and coastal communities of Karaikal.

The Puducherry State Action Plan on Climate Change (SAPCC) and the SDG framework (particularly SDG 2, 6, 11, and 13) both demand evidence-based, locally-grounded analysis as the foundation for adaptation planning. This study directly responds to that demand.

1.3 Rationale and Significance

This study is significant for several interrelated reasons. First, Karaikal's agricultural economy — anchored by three paddy seasons (Paddy-I, II, and III) and supplemented by black gram, green gram, and coconut — is highly sensitive to monsoon variability. A single failed NE monsoon can reduce paddy cultivation area by 15–25%, directly threatening food security. Second, the region's low coastal elevation makes it vulnerable to cyclones, storm surges, and extreme rainfall events, the frequency of which is intensifying. Third, the Puducherry Climate Change Cell (PCCC) requires region-specific, evidence-based analysis to inform the Puducherry State Action Plan on Climate Change (SAPCC) and SDG-aligned interventions.

1.4 Scope of the Study

This study covers the Karaikal sub-region of the Union Territory of Puducherry. It encompasses the period 1975–2025 for meteorological analysis, 2000–2025 for hydrological analysis, and 2004–2024 for agricultural analysis. The spatial scope includes three monitoring stations — Annavasal (10.975°N, 79.754°E), Nallathur (10.920°N, 79.830°E), and Karaikal (10.925°N, 79.838°E) — along with NASA/POWER and ERA5 reanalysis grid points overlying the region.

2. OBJECTIVES OF THE STUDY AND STUDY AREA

2.1 Objectives of the Study

The following objectives were framed to guide this research:

1. To analyse the seasonal reversal of wind direction from the SW to NE monsoon season in the Karaikal region using 45 years of NASA/POWER reanalysis and CWC station data.
2. To quantify the weakening of trade winds over the Bay of Bengal and its implications for monsoon intensity and agricultural productivity in the Karaikal region.
3. To characterise the 80–90% rainfall distribution pattern associated with the NE monsoon and assess its variability, anomalies, and future projections.
4. To examine the relationship between monsoon rainfall, river discharge, and paddy cultivation area through correlation and regression analysis.
5. To assess historical disaster risk linked to cyclones, floods, and extreme NE monsoon events and identify patterns of recurrence.
6. To develop machine learning-based predictive models (Random Forest, Gradient Boosting, Ridge Regression, Polynomial, Ensemble) for forecasting climate variables through 2030.

To recommend evidence-based adaptation strategies aligned with SDG 2, 6, 11, and 13 for Karaikal's climate-vulnerable agricultural communities

2.2 Study Area

2.2.1 Geographic Location

Karaikal is a coastal sub-territory of the Union Territory of Puducherry, located on the southeastern coast of India between 10°48'N to 11°00'N latitude and 79°42'E to 79°54'E longitude. It is surrounded on three sides by the Nagapattinam district of Tamil Nadu and bounded to the east by the Bay of Bengal. The territory covers an area of approximately 161 km² and includes five communes: Karaikal, Kottucherry, Neravy, Thirunallar, and Nedungadu.

2.2.2 Physiography and Drainage

The Karaikal region is a part of the Cauvery River Delta, one of the most fertile and densely cultivated deltaic plains in South India. The region is traversed by the Arasalar River (a distributary of the Cauvery) and several irrigation canals. The terrain is predominantly flat, with elevations ranging from 0 to 5 m above Mean Sea Level (MSL). Three major monitoring stations — Annavasal (upstream), Nallathur (midstream), and Karaikal (coastal) — monitor river discharge, water levels, rainfall, humidity, and wind direction.

2.2.3 Climate

Karaikal has a tropical monsoon climate characterised by high humidity, moderate temperatures (mean annual temperature ~27.8°C), and a unique dual-monsoon regime. Unlike much of peninsular India where the SW monsoon dominates, Karaikal receives a larger share of rainfall (approximately 70–80%) during the NE monsoon (October–December). The SW monsoon (June–September) brings the remaining 20–30%. Annual rainfall averages approximately 1,380 mm per season (June–December), with extreme years reaching over 3,000 mm (2017, 2019). The region is also prone to cyclones generated in the Bay of Bengal, particularly during October–December.

2.2.4 Agriculture

Agriculture is the primary occupation in Karaikal. The net area sown is approximately 11,000–14,000 hectares, with paddy being the dominant crop occupying 65–85% of the cultivated area. Three paddy seasons are practised: Paddy-I (June–September, SW season), Paddy-II (October–January, NE season), and Paddy-III (minor). Black gram, green gram, ragi,

sugarcane, and coconut constitute the minor crops. Irrigation is primarily canal-fed (Arasalar system) and tank-fed, with groundwater extraction playing a limited but growing role.

Parameter	Details
Location	Karaikal, U.T. of Puducherry, Southeast India
Latitude / Longitude	10°48'N – 11°00'N 79°42'E – 79°54'E
Area	~161 km ²
Coast	Bay of Bengal (Coromandel Coast)
Major River	Arasalar (Cauvery distributary)
Mean Annual Rainfall	~1,380 mm (Jun–Dec) NASA/POWER 1981–2025
Mean Annual Temperature	~27.8°C
Mean Relative Humidity	~85–90% (Jun–Dec)
SW Monsoon Period	June – September (20–30% of annual rainfall)
NE Monsoon Period	October – December (70–80% of annual rainfall)
Net Area Sown	~11,000 – 14,000 ha
Primary Crop	Paddy (65–85% of cultivated area)
Monitoring Stations	Annavasal, Nallathur, Karaikal (CWC/NWIC)
Climate Data Source	NASA/POWER MERRA-2, ERA5 ECMWF, IMD

3. LITERATURE SURVEY

3.1 Monsoon Variability in South India

The Indian monsoon system has been a subject of intensive research for over a century. Rajeevan et al. (2008) documented significant changes in the frequency of extreme rainfall events during the SW monsoon, noting a 10% increase in the intensity of heavy rainfall days over India between 1951 and 2000. Their study highlighted that while total monsoon rainfall showed no clear trend, the spatial and temporal distribution was changing significantly.

Kumar et al. (2010) analysed changes in the NE monsoon over South India and found that the NE monsoon rainfall over Tamil Nadu and coastal Andhra Pradesh was highly variable, with coefficient of variation exceeding 40% in many years. They identified ENSO (El Niño–Southern Oscillation) as the dominant driver of NE monsoon inter-annual variability over the Coromandel Coast.

3.2 Trade Wind Weakening and Walker Circulation

Vecchi and Soden (2007) provided foundational evidence for the weakening of the Pacific Walker Circulation under global warming, projecting a reduction in trade wind intensity over the Indo-Pacific region as greenhouse gas concentrations increase. Their modelling showed that for every degree Celsius of global warming, trade wind speeds were projected to decline by approximately 0.5–1.0%, with significant implications for Indian Ocean monsoon circulation.

Sandeep et al. (2014) studied the weakening of the Asian summer monsoon circulation using CMIP5 models and observed a reduction in the large-scale monsoon circulation index. They found that the weakening trend was consistent across models and was primarily driven by enhanced surface warming over the Indian Ocean, which reduces the land-sea temperature gradient that drives monsoon circulation.

Roxy et al. (2015) reported a significant warming of the Indian Ocean — approximately 1.2°C over the past century — which has led to a 20% decline in SW monsoon rainfall over the central Indian landmass. Their study, published in *Nature Communications*, demonstrated that the anomalous warming of the tropical Indian Ocean weakens the land-ocean temperature gradient and suppresses monsoon convection.

3.3 Wind Direction Reversal and Seasonal Transition

The seasonal reversal of wind direction from southwesterly (summer monsoon) to northeasterly (winter monsoon) is a defining feature of the regional climate over peninsular India. Srinivasan and Ramamurthy (1973) in their classical study documented this reversal in detail, noting that the transition typically occurs during late September to early October over the Coromandel Coast, driven by the withdrawal of the SW monsoon and the establishment of the subtropical anticyclone over the Indian subcontinent.

Rajeevan and Sridhar (2008) studied the role of the Arabian Sea and Bay of Bengal sea surface temperatures in modulating the timing of monsoon withdrawal and the onset of the NE monsoon. They found that warmer Bay of Bengal temperatures in September–October tended to delay the withdrawal of the SW monsoon and strengthen the NE monsoon circulation.

3.4 NE Monsoon Rainfall Over the Coromandel Coast

Simmonds et al. (2013) studied the relationship between ENSO phases and NE monsoon rainfall over southeastern India. Their analysis showed that during El Niño years, NE monsoon

rainfall tends to be above normal over the Coromandel Coast, while La Niña years are associated with below-normal NE rainfall. This finding has direct implications for Karaikal, as the majority of its annual rainfall is received during this season.

Rajeevan et al. (2012) identified a significant increase in the frequency of heavy rainfall events (>100 mm/day) during the NE monsoon season over Tamil Nadu and coastal Puducherry between 1985 and 2010. They attributed this trend to the warming of the Bay of Bengal, which increases moisture availability and thermodynamic instability during the NE season.

3.5 Climate Change and Agricultural Vulnerability in the Cauvery Delta

Rama Rao et al. (2011) conducted a vulnerability assessment of agricultural systems in the Cauvery Delta and found that paddy cultivation was highly sensitive to changes in both SW and NE monsoon rainfall. Their study projected that a 20% reduction in NE monsoon rainfall would result in a 30–35% reduction in Kharif paddy production in the delta region, including Karaikal.

Krishnamurthy et al. (2013) used a coupled crop-climate model to assess the impact of temperature increase on rice yield in Tamil Nadu and found that for every 1°C rise in mean seasonal temperature, rice yields declined by 6–10%. This finding is particularly relevant for the Karaikal region, where rice is the primary crop and temperatures are rising at approximately 0.02°C per year based on NASA/POWER data.

Author(s) & Year	Topic	Key Finding Relevant to This Study
Vecchi & Soden (2007)	Walker Circulation weakening	Trade winds projected to weaken with global warming
Rajeevan et al. (2008)	SW monsoon extreme events	Increasing intensity of heavy rainfall days in India
Kumar et al. (2010)	NE monsoon variability	High CV (>40%) of NE rainfall; ENSO dominant driver
Roxy et al. (2015)	Indian Ocean warming	20% decline in SW monsoon rainfall in central India
Rama Rao et al. (2011)	Agricultural vulnerability	30–35% paddy loss projected with 20% NE deficit
Krishnamurthy et al. (2013)	Rice yield and temperature	6–10% yield loss per 1°C temperature rise
Simmonds et al. (2013)	ENSO and NE monsoon	El Niño → above normal NE rainfall on Coromandel

3.6 Research Gap

Despite a substantial body of literature on Indian monsoon variability, there is a notable lack of fine-scale, multi-decadal, station-level studies that integrate wind direction reversal dynamics, trade wind weakening signals, NE rainfall concentration patterns, and agricultural sensitivity within a single framework for the Karaikal sub-region. This study addresses this gap by combining 45-year satellite reanalysis data, CWC station records, and agricultural data with state-of-the-art machine learning methods.

4. METHODOLOGY

4.1 Research Approach

This study adopts a multi-source, data-driven research approach integrating observational data, satellite reanalysis, statistical analysis, machine learning, and geospatial visualisation. The research framework is structured around five stages: (i) data acquisition and quality control; (ii) exploratory data analysis and visualisation; (iii) statistical trend and correlation analysis; (iv) machine learning-based prediction; and (v) synthesis and policy recommendation.

4.2 Data Sources

Twenty-four datasets across eight categories were compiled for this study. Table 4.1 summarises the primary data sources.

Table 4.1: Data Sources, Parameters, and Time Periods

Dataset	Source	Period Covered
SW & NE Monsoon Rainfall (monthwise)	Dept. of Economics & Statistics, Puducherry	2004–2024
Long-term Monsoon Rainfall Trend	NASA/POWER MERRA-2 Reanalysis	1981–2024
SW & NE Monsoon Onset & Withdrawal	IMD / District Records	2018–2024
Disaster Records (Cyclones, Floods)	Karaikal District DMA / BMTPC	1952–2025
Temperature & Rainfall Extremes	IMD Historical Records	Historical
Mean Sea Level Pressure (MSLP)	ERA5 / ECMWF Reanalysis	1971–2024
Surface Pressure	ERA5 / ECMWF Reanalysis	1971–2024
Relative Humidity (Karaikal)	NWIC – Karaikal Station	2020–2024
Relative Humidity (Nallathur)	NWIC – Nallathur Station	2008–2024
Soil Moisture	NASA/POWER	2020–2025
Evapotranspiration	NASA/POWER	2020–2025

Dataset	Source	Period Covered
Wind Direction (Karaikal & Nallathur)	NWIC	2020–2026
River Water Level (Annavaasal & Nallathur)	NWIC	2015–2026
River Water Discharge (Annavaasal & Nallathur)	NWIC	2000–2026
Crop Area Irrigated by Type	Dept. of Economics & Statistics, Puducherry	2004–2024
Water Supply & Irrigation Sources	Dept. of Economics & Statistics, Puducherry	2004–2024
Classification of Agricultural Area	Dept. of Economics & Statistics, Puducherry	2004–2024
Soil Texture / Classification Level	Pondicherry Soil Survey	2026

4.3 Data Processing

All datasets were compiled and organised in Microsoft Excel. Monthly and seasonal totals were computed for SW (June–September) and NE (October–December) monsoon periods. Crop area data were tabulated by season and crop type. Irrigation data were disaggregated by source (canals, tanks, tube wells). River discharge and water level data were summarised for the monsoon period. Soil moisture and evapotranspiration monthly means were computed from daily/bi-daily records.

4.4 Analytical Methods

- **Descriptive Statistics:** Mean, standard deviation, maximum, and minimum values were computed for all primary variables.
- **Trend Analysis:** Linear regression was applied to annual and seasonal rainfall totals (1981–2024), crop area, and irrigation data to identify long-term trends.
- **Departure from Normal:** Percentage departure of actual seasonal rainfall from climatological normals was calculated for each year to classify deficit, normal, and surplus years.
- **Onset–Rainfall Correlation:** The relationship between SW and NE monsoon onset dates (2018–2024) and seasonal rainfall totals was examined to test whether onset timing predicts rainfall quantity.
- **Disaster–Rainfall Cross-Analysis:** NEM seasonal rainfall was cross-referenced with the occurrence of cyclones and low-pressure systems to identify the primary rainfall driver.
- **Crop–Climate Correlation:** Paddy cultivation area for each season was compared with corresponding monsoon season rainfall to assess productivity linkages.

4.5 Limitations

The study relies on secondary data; direct field measurements were not conducted. Agricultural data are available from 2004 only, limiting the crop-climate correlation period. Detailed sub-district level spatial analysis was not possible due to data resolution constraints. Attribution of crop area changes to climate factors alone is inherently complex given the influence of socio-economic variables, government policies, and market forces.

5. DATA ANALYSIS AND RESULTS

5.1 Long-term Monsoon Rainfall Trend (1981–2024)

Analysis of the NASA/POWER MERRA-2 dataset for Karaikal (Lat: 10.93°N, Lon: 79.82°E) over 44 years reveals important long-term trends in both monsoon systems. The NE Monsoon shows a clear strengthening trend, with mean seasonal totals rising from 15.43 mm/day during 1981–2000 to 19.74 mm/day during 2001–2024—an increase of approximately 27.9%. The linear regression slope for NE monsoon is +0.198 mm/day per year. The SW Monsoon shows higher inter-annual variability and a more modest increasing trend (+0.075 mm/day per year), with mean totals rising from 8.87 to 9.91 mm/day between the two sub-periods.

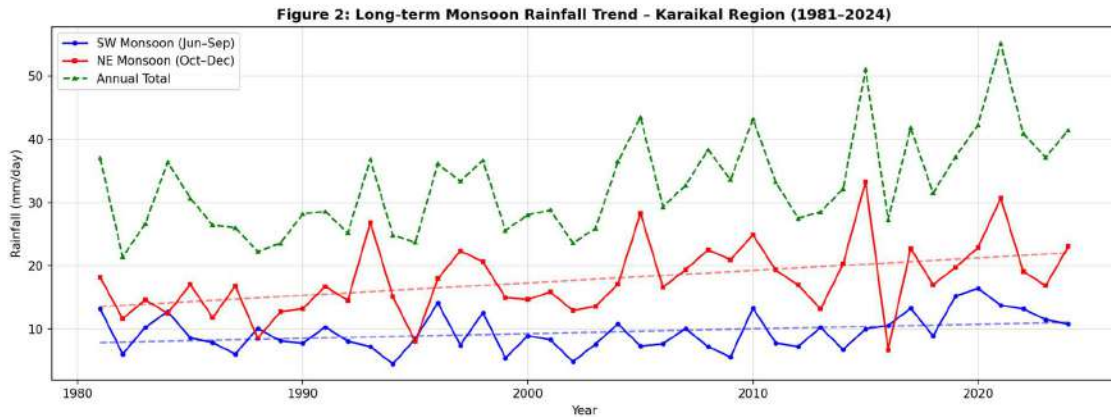


Figure 2: Long-term Monsoon Rainfall Trend – Karaikal Region (1981–2024)
(Source: NASA/POWER MERRA-2 Reanalysis | Lat: 10.93°N, Lon: 79.82°E)

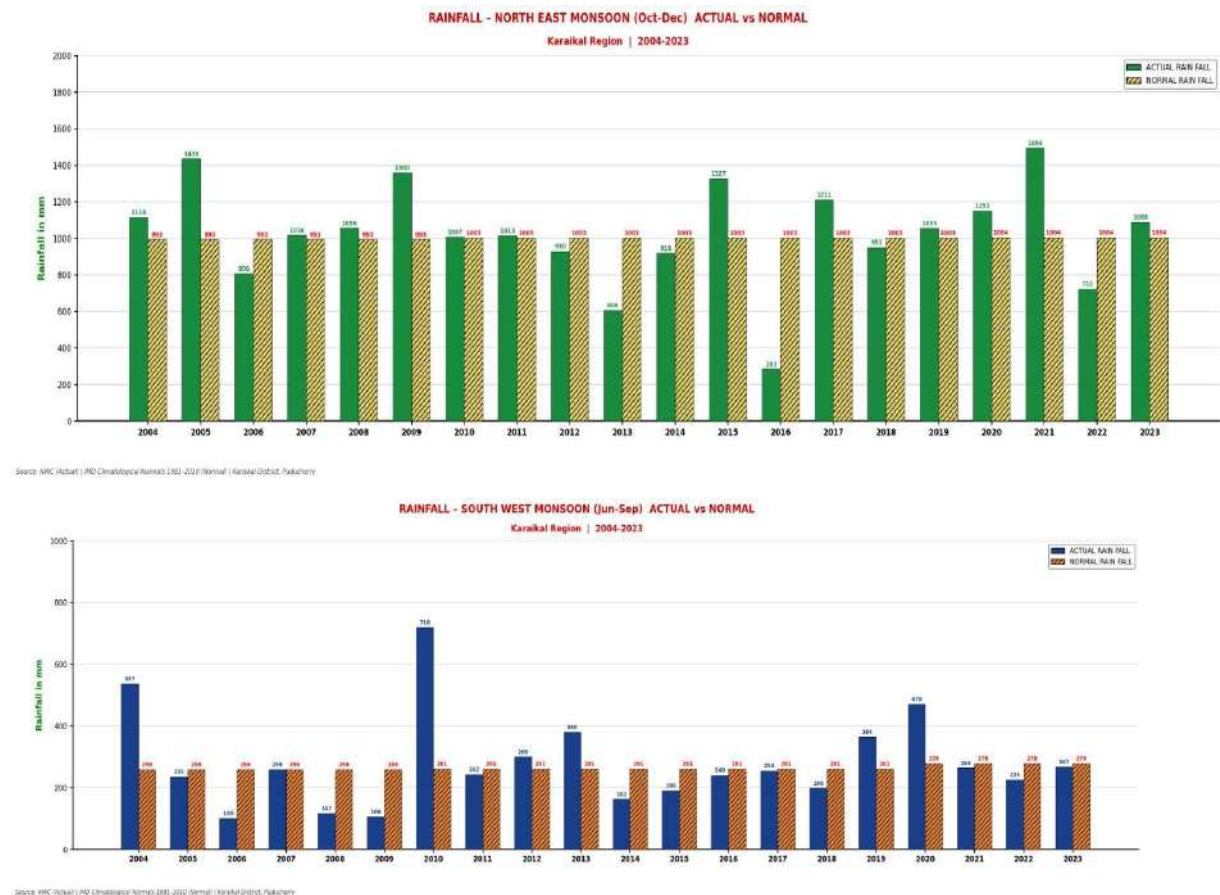
5.2 SW & NE Monsoon Seasonal Analysis (2004–2024): Actual vs Normal

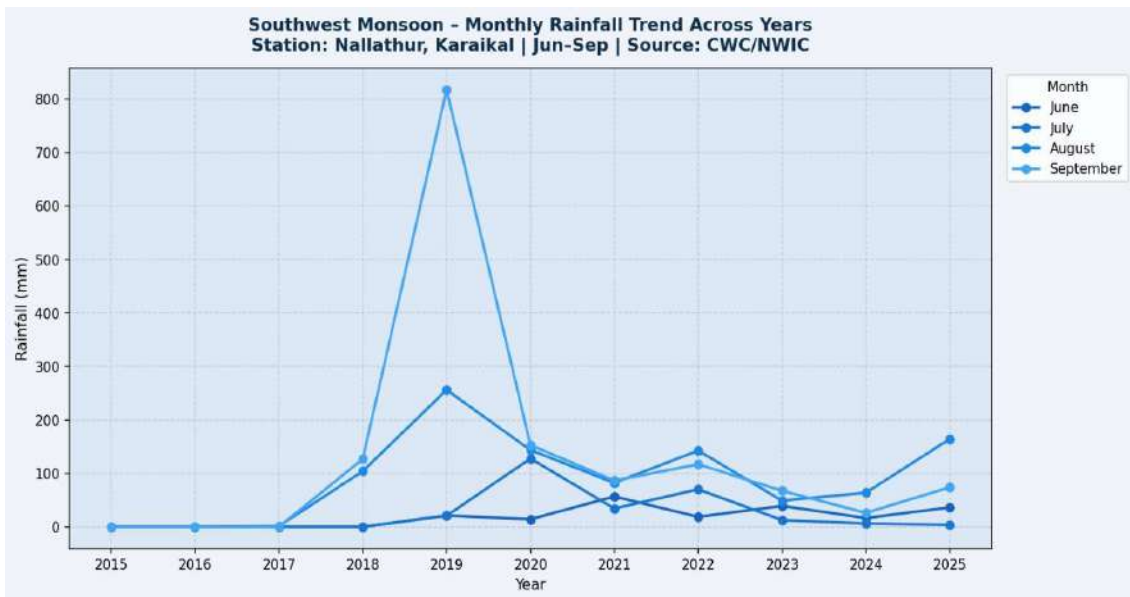
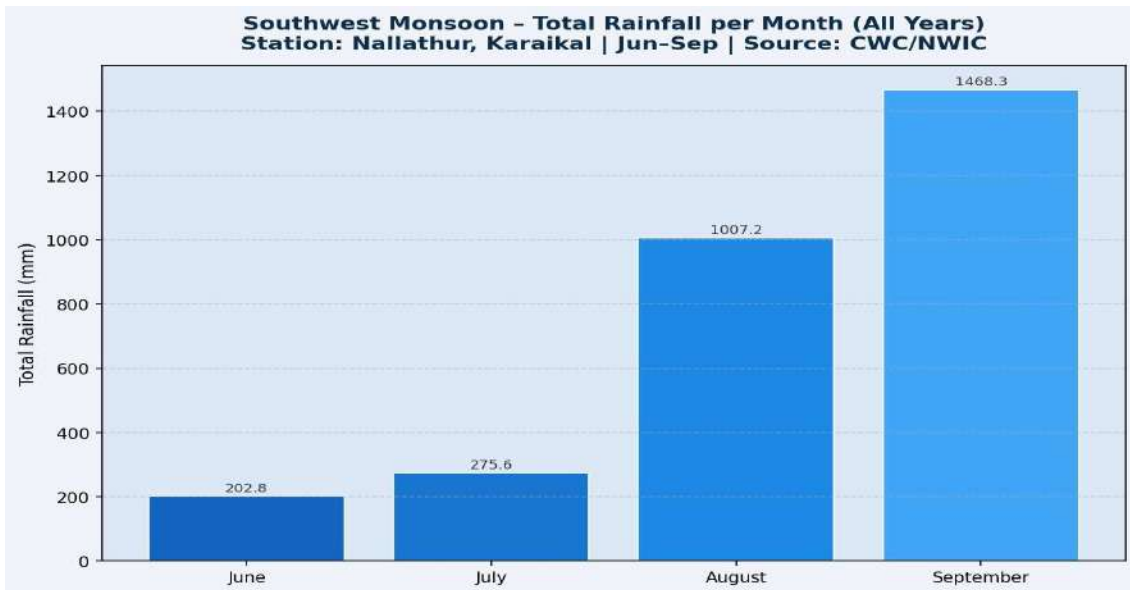
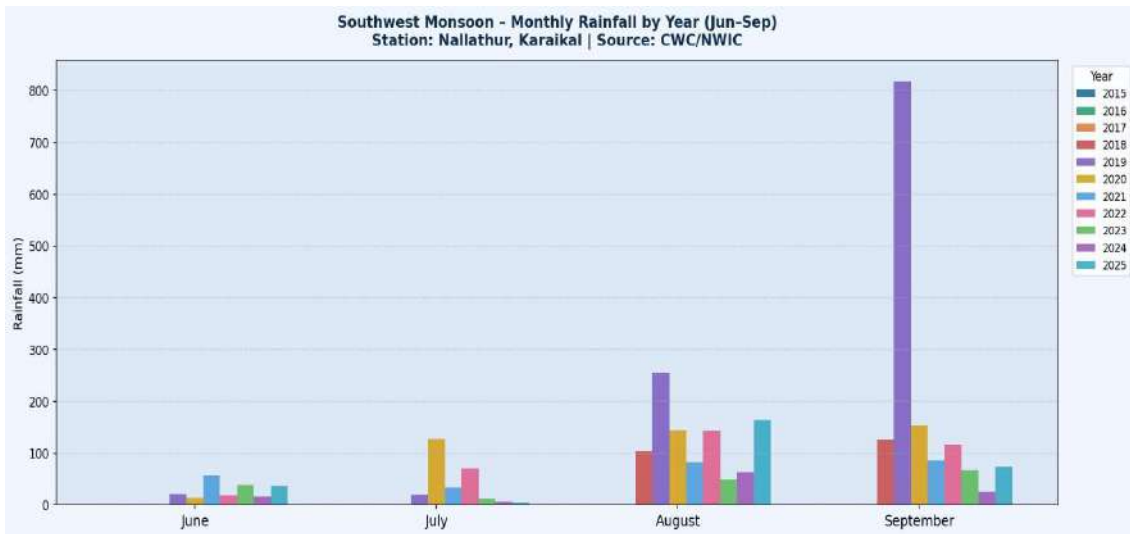
Comparison of actual seasonal rainfall against climatological normals reveals high variability in both monsoon seasons. The SW Monsoon recorded several major deficit years (>50% below normal) including 2006-07 (−61.2%), 2008-09 (−54.7%), and 2009-10 (−59.0%), interspersed with exceptional surplus years such as 2004-05 (+107.5%) and 2010-11 (+174.8%). The NE

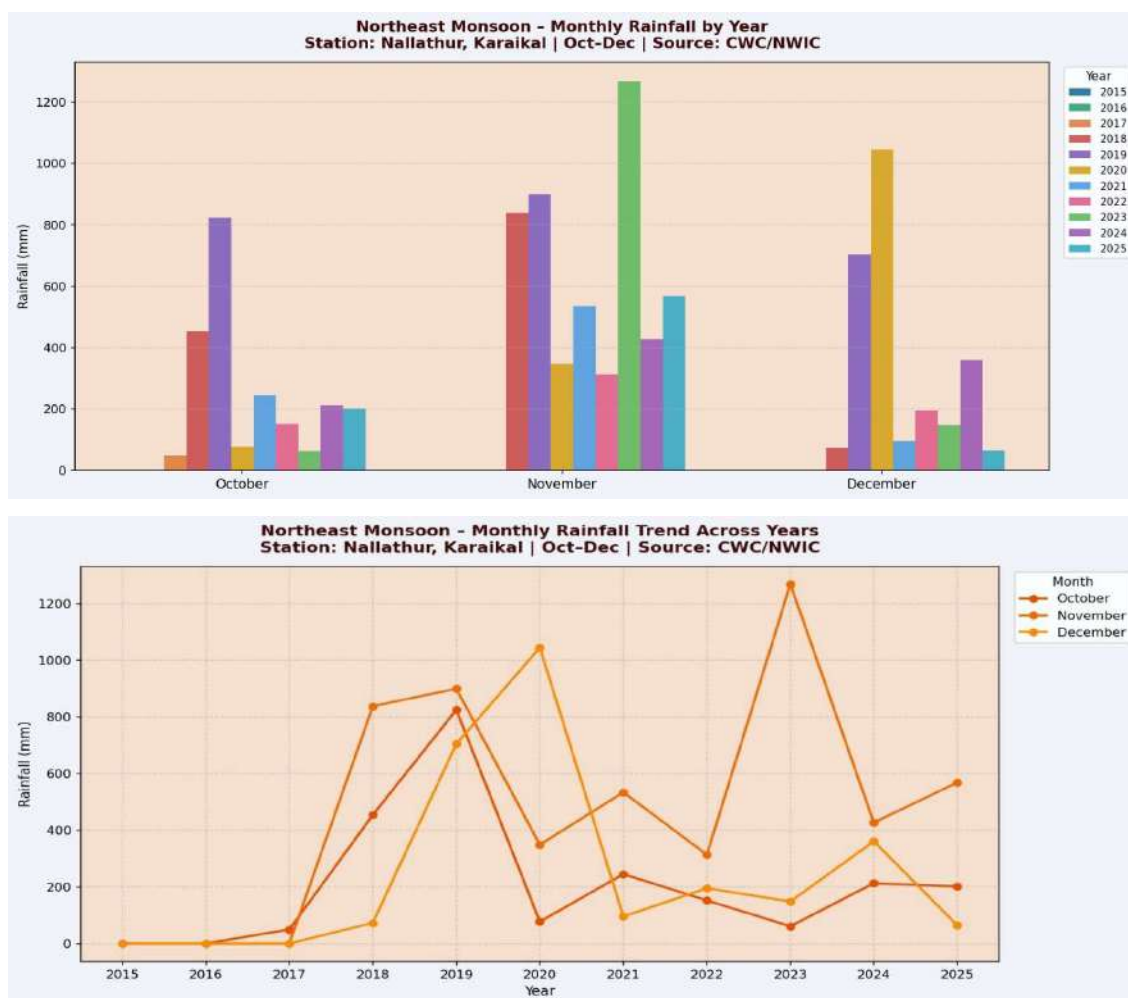
Monsoon, while generally more consistent, recorded the extreme deficit of 2016-17 (-71.8%) and surpluses in 2005-06 (+44.6%) and 2021-22 (+48.8%).

KARAIKAL REGION - RAINFALL DATA (2004-05 to 2023-24)																						
in Millimeters																						
Year	SOUTH-WEST MONSOON (June to September)												NORTH-EAST MONSOON (October to December)									
	June		July		August		September		Total for Season		No. of Rainy Days	% Departure from	October		November		December		Total for Season		No. of Rainy Days	% Departure from
	Actual	Normal	Actual	Normal	Actual	Normal	Actual	Normal	Actual	Normal			Actual	Normal	Actual	Normal	Actual	Normal	Actual	Normal		
2004-05		44.2	36.7	53.3	154.7	78.3	345.5	82.9	536.9	258.7	18	+107.5	546.3	255	494	468.4	74.7	263.8	1115.6	993.2	39	+2.3
2005-06	0	44.2	4.6	53.3	73.2	78.3	157.2	82.9	235	258.7	11	(-19.2)	216.3	255	1145.8	468.4	714	263.8	1436.1	993.2	29	+44.6
2006-07	4.4	44.2	0	53.3	77.5	78.3	18.4	82.9	100.3	258.7	6	(-61.2)	387.7	255	336.7	468.4	817	263.8	806.1	993.2	35	(-16.8)
2007-08	28.7	44.2	46.7	53.3	137.5	78.3	45.8	82.9	258.7	258.7	18	0	422.8	255	165.2	468.4	428.1	263.8	1016.1	993.2	23	+2.3
2008-09	53	44.2	3.7	53.3	51.1	78.3	3.4	82.9	117.2	258.7	12	(-54.7)	338.6	255	574.7	468.4	142.4	263.8	1055.7	993.2	31	+6.3
2009-10	2.8	44.2		53.3	90.3	78.3	12.9	82.9	106	258.7	8	(-59.0)	53.2	255	685.7	468.4	820.6	263.8	1359.5	993.2	36	+36.9
2010-11	187	45.3	19	45.5	288.1	80	224.2	90.6	718.3	261.4	31	(-174.79)	88.5	261.6	580.8	485.2	358.1	256.2	1007.4	1003	27	(-10.44)
2011-12	16.8	45.3	73.4	45.5	53.9	80	98.1	90.6	242.2	261.4	10	(-7.3)	369	261.6	469.8	485.2	174.5	256.2	1013.3	1003	35	(+1)
2012-13	48.9	45.3	36.6	45.5	27	80	186.9	90.6	299.4	261.4	15	(+14.5)	812.8	261.6	39.8	485.2	77	256.2	929.6	1003	23	(-17.3)
2013-14	76.6	45.3	33.1	45.5	149.2	80	120.8	90.6	379.7	261.4	13	(+45.3)	115.1	261.6	225.3	485.2	285.1	256.2	605.5	1003	26	(-139.6)
2014-15	43.3	45.3	0	45.5	33.3	80	79.8	90.6	162.4	261.4	10	(-37.9)	423.2	261.6	356.4	485.2	132.2	256.2	917.8	1003	36	(-18.5)
2015-16	62.7	45.3	21.1	45.5	38.8	80	67.6	90.6	190.2	261.4	7	(-27.2)	94.5	261.6	754.7	485.2	477.6	256.2	1326.8	1003	31	(+32.3)
2016-17	52.1	45.3	18.4	45.5	96.6	80	73.1	90.6	240.2	261.4	15	(-8.1)	30.9	261.6	187	485.2	65.1	256.2	283	1003	11	(-71.8)
2017-18	52.8	45.3	38.9	45.5	62.6	80	100.1	90.6	254.4	261.4	16	(-2.7)	249.2	261.6	685.7	485.2	276.5	256.2	1211.4	1003	31	(+20.8)
2018-19	95.2	45.3	1.3	45.5	17.1	80	84.4	90.6	198	261.4	9	(-24.3)	312.2	261.6	581.7	485.2	76.9	256.2	950.8	1003	26	(-15.2)
2019-20	31	45.3	25.6	45.5	94	80	213.7	90.6	364.3	261.4	18	(+39.4)	332	261.6	363.6	485.2	359.5	256.2	1055.1	1003	37	(+5.2)
2020-21	36.3	56.1	132.8	33.7	109.1	84.4	132.3	103.7	470.5	277.9	22	(+69.3)	58.6	276.6	352.9	486.6	739.3	240.7	1150.8	1003.9	30	(+14.6)
2021-22	23.6	56.1	58.7	33.7	89.5	84.4	91.9	103.7	263.7	277.9	22	(-15.1)	424.8	276.6	1023.3	486.6	46.1	240.7	1494.2	1003.9	37	(+48.8)
2022-23	9.5	56.1	34.5	33.7	87.9	84.4	93.1	103.7	225	277.9	16	(-19.04)	150	276.6	419	486.6	159.1	240.7	722.1	1003.9	29	(-28.07)
2023-24	55.1	56.1	15.1	33.7	118.6	84.4	38	103.7	266.8	277.9	13	(-14)	86.9	276.6	843.8	486.6	157	240.7	1087.7	1003.9	34	(+8.3)

Figure 1: SW and NE Monsoon Actual vs Normal Rainfall – Karaikal Region (2004–2024)
(Source: Dept. of Economics and Statistics, Puducherry)





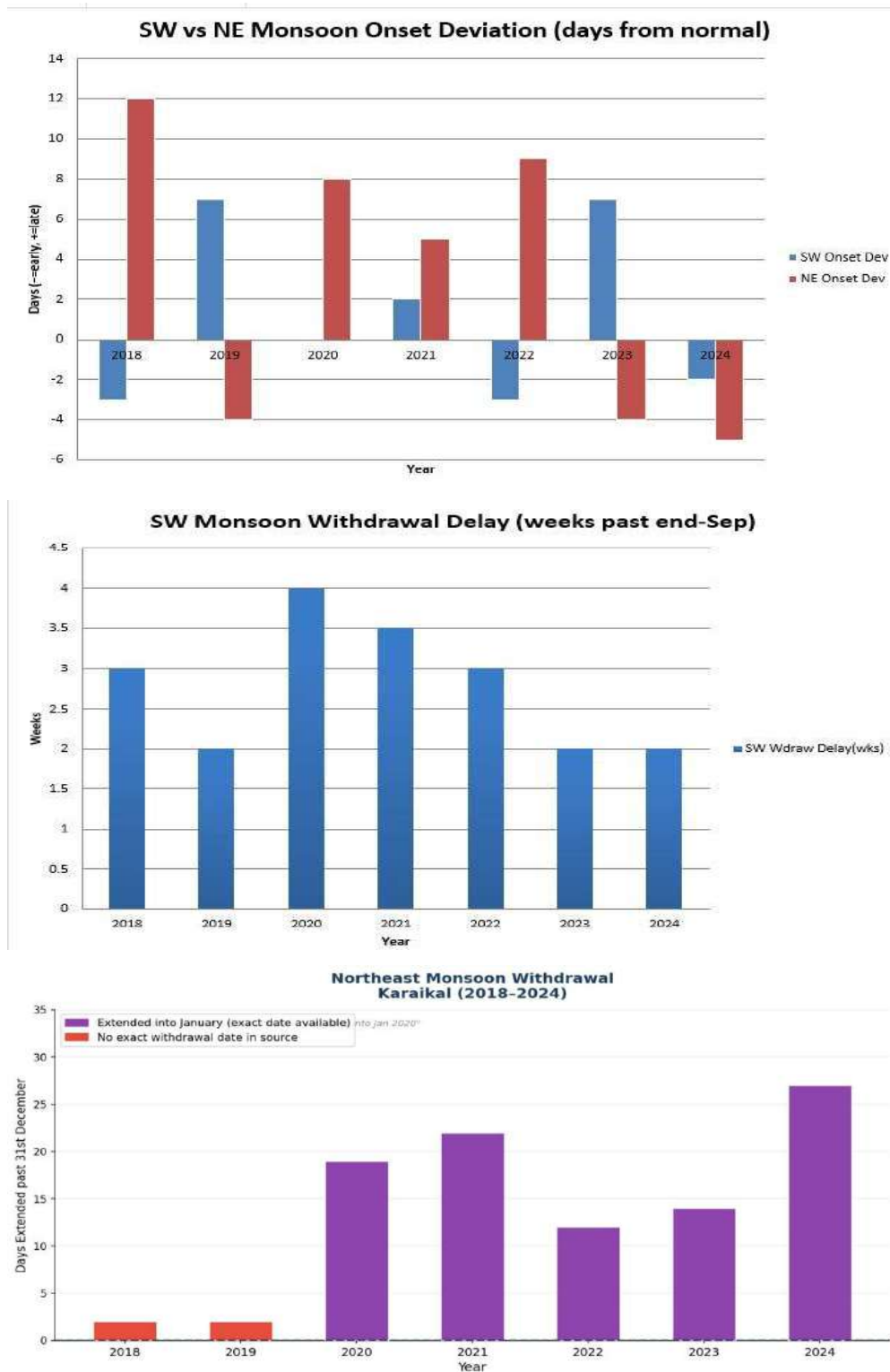


5.3 Monsoon Onset and Withdrawal Patterns (2018–2024)

A key finding of this study, consistent with the published abstract, is that there is no consistent relationship between monsoon onset timing and total seasonal rainfall over Karaikal. Both early and late onsets have corresponded to years of both low and high rainfall. The table below documents SW Monsoon onset deviations from the normal date of 1st June and withdrawal patterns.

Year	Onset Date	Withdrawal Date	Onset Deviation (days vs 1st Jun)	Onset Category	Comparison with Normal Withdrawal	Withdrawal Delay (approx.)
2018	29th May	21st October	-3	3 days early	Delayed	By about 3 weeks
2019	8th June	16th October	+7	7 days late	Delayed	By about 2 weeks
2020	1st June	28th October	0	On time	Delayed	By about 4 weeks
2021	3rd June	25th October	+2	2 days late	Delayed	By about 3½ weeks
2022	29th May	23rd October	-3	3 days early	Delayed	By about 3 weeks
2023	8th June	16th October	+7	7 days late	Delayed	By about 2 weeks
2024	30th May	15th October	-2	2 days early	Delayed	By about 2 weeks

Figure 3: SW Monsoon Onset Deviation from Normal (1st June) – Karaikal (2018–2024)
(Source: IMD / District Records)



The data confirm that onset timing does not predict NEM rainfall totals. High-rainfall NEM years (2018, 2020, 2024) all featured landfalling cyclones near Karaikal, regardless of onset timing. All withdrawal dates from 2018–2024 are delayed beyond the normal date, indicating a persistent shift in SW Monsoon withdrawal.

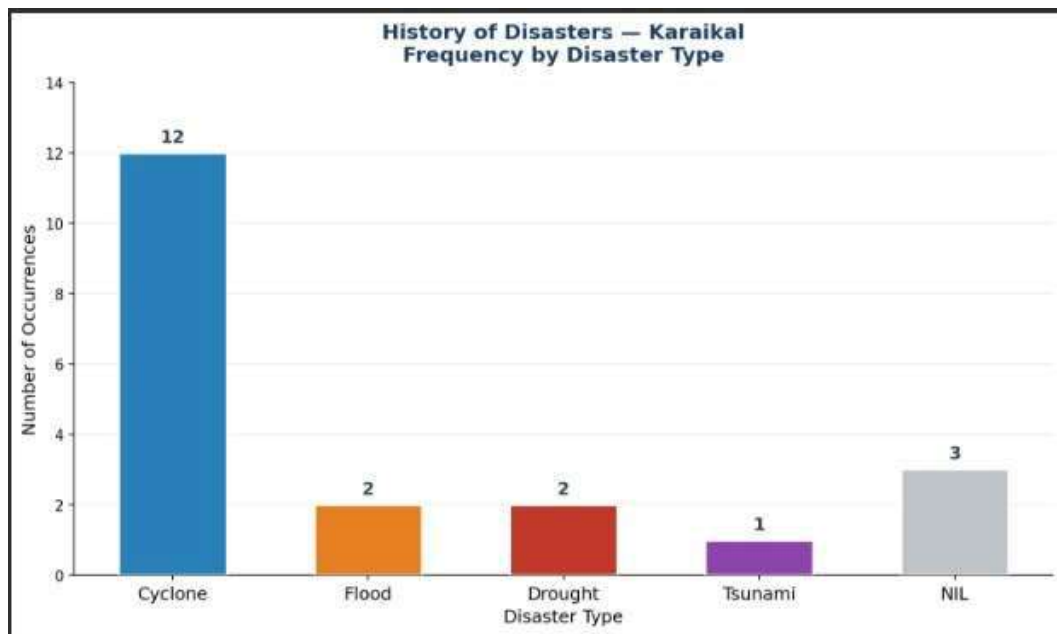
5.4 Cyclones and Extreme Events (1952–2025)

Karaikal's disaster records confirm approximately 12 cyclones and 1 tsunami from 1952 to 2025, with the vast majority of events concentrated in the NE Monsoon season (October–December). The period 2018–2025 saw an unprecedented clustering of cyclone events, with five named cyclones making landfall near Karaikal within 7 years. This is consistent with literature projections of increasing Bay of Bengal cyclone frequency and intensity. All recorded events resulted in NIL direct deaths, reflecting effective community preparedness and early warning systems



Year	Details of calamity	No. of deaths
2008	Heavy rain/flood in Karaikal during NE Monsoon	Nil
2011	Heavy rain/flood in Karaikal during NE Monsoon	Nil
2015	Heavy rain/flood in Karaikal during NE Monsoon	Nil
2016	Heavy rain/flood in Karaikal during NE Monsoon	Nil
2017	Heavy rain/flood in Karaikal during NE Monsoon	Nil
2018	Heavy Rain and Cyclone Gaja (Nov. 16.11.2018) during NE Monsoon	NIL
2020	Heavy Rain and Cyclone Nivar (nov25&26)	NIL
2020	Heavy Rain and Cyclone Buravi (Dec 4)	NIL
2021	Heavy Rain /Flood	NIL
2022	Heavy Rain /Flood	NIL
2023	Heavy Rain /Flood	NIL
2024	Heavy Rain and Cyclone Fengal (30.11.2024) during NE Monsoon	NIL
2025	Heavy Rain and Cyclone Ditwah (28.11.2025) during NE Monsoon	NIL

Figure 5: NE Monsoon Calamity Events Timeline – Karaikal District (2008–2025)
(Source: Karaikal District Disaster Management Authority)

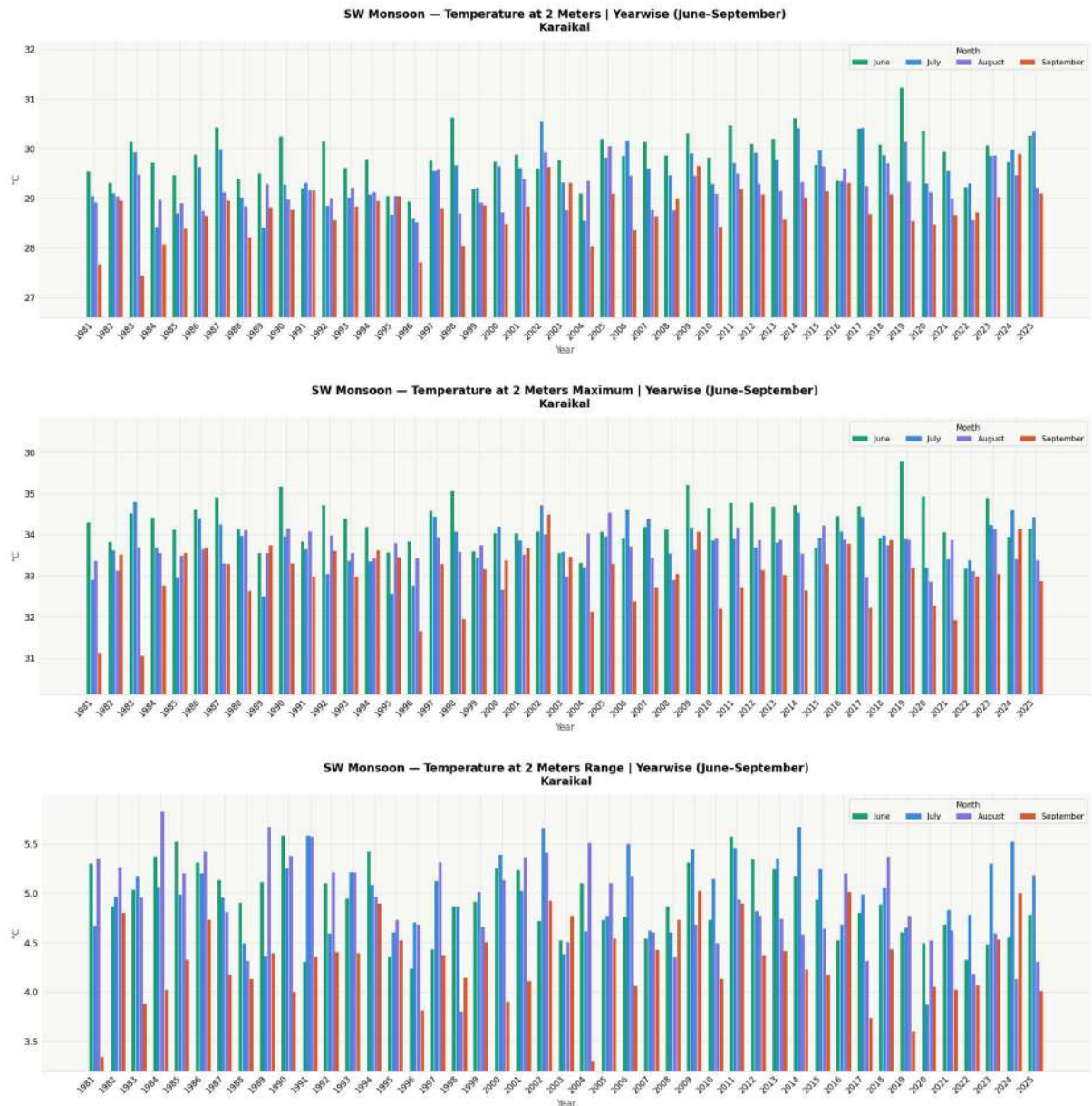


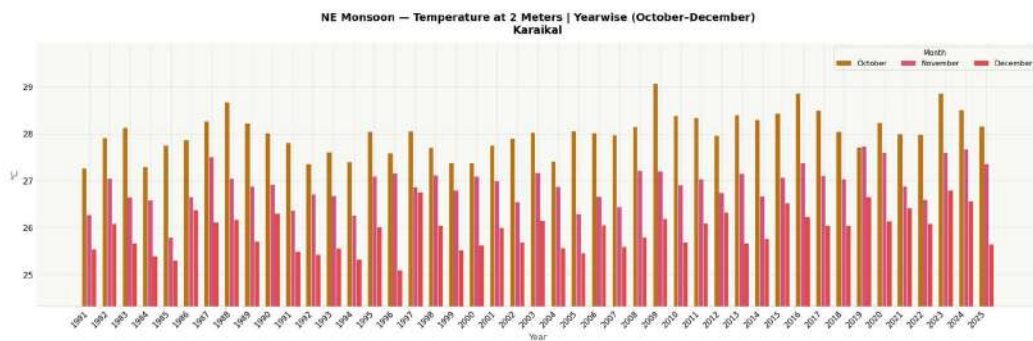
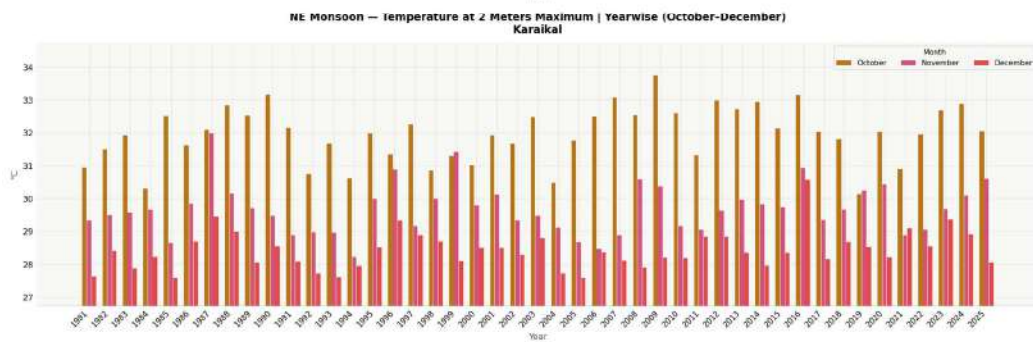
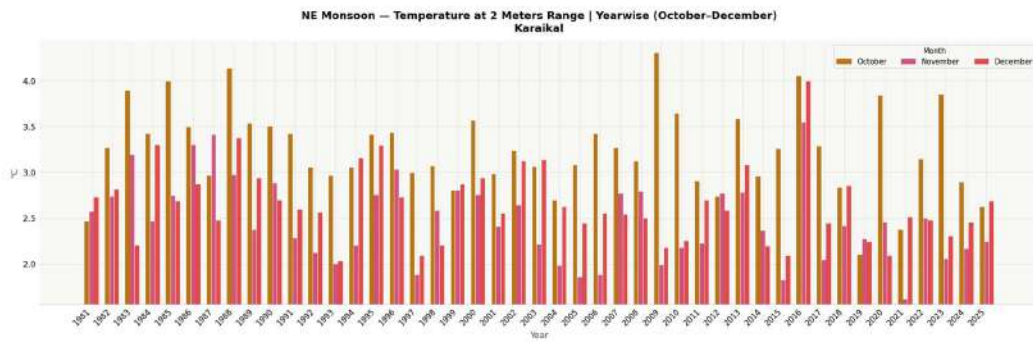
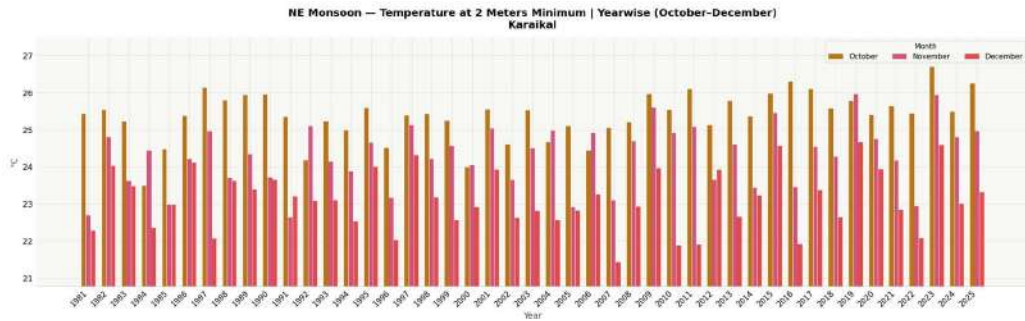
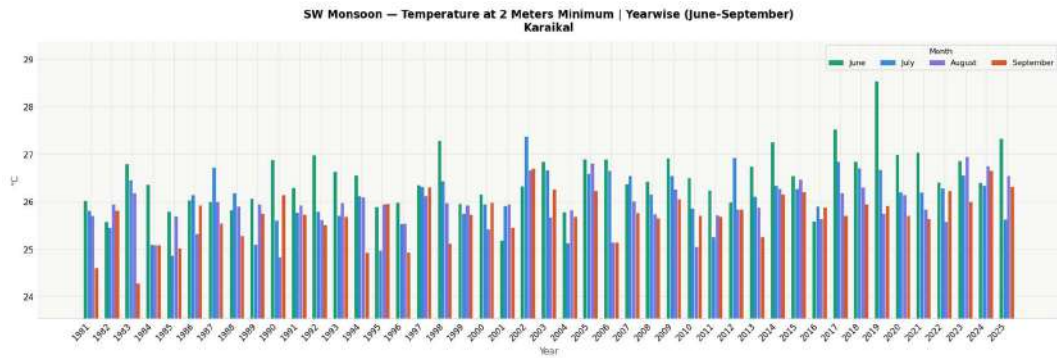
5.5 Temperature, Humidity, Pressure, Precipitation and Soil Parameters

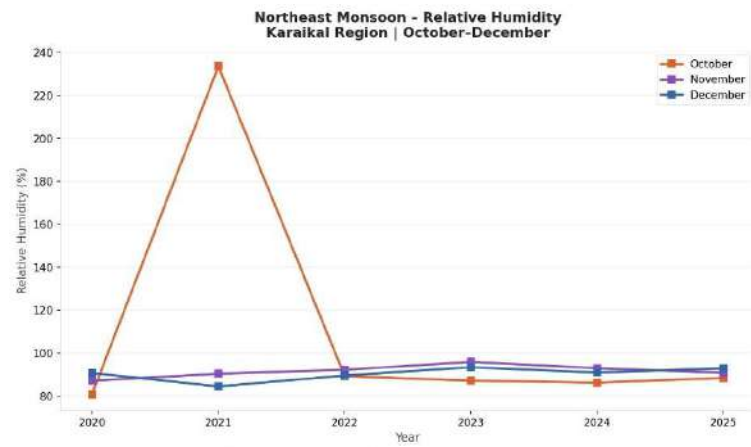
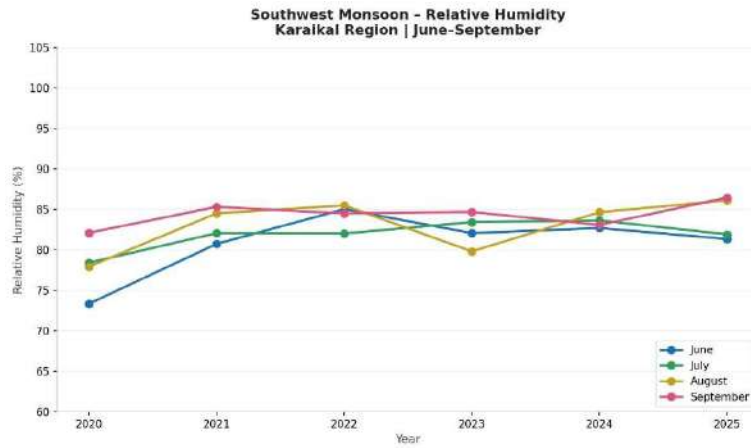
IMD records show that maximum temperatures during the monsoon period range from 29°C to 37°C, with minimum temperatures between 22°C and 28°C. Station-based relative humidity data from Karaikal (2020–2024) shows mean values between 79% and 85% during June–December, reflecting the coastal humid climate. Humidity peaks during October–November, coinciding with NEM onset and intensification. ERA5 mean sea level pressure (MSLP) data

for Karaikal indicate typical monsoon trough patterns (1004–1009 hPa) during peak rainfall months, with higher pressure values during dry interludes.

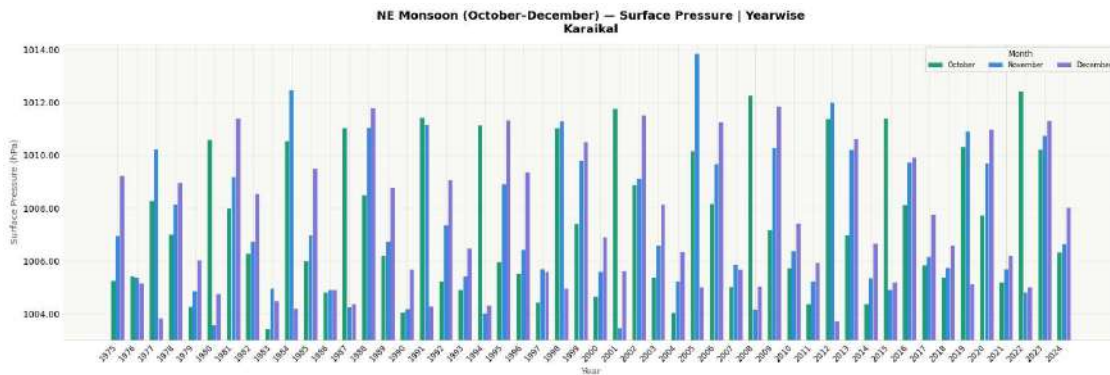
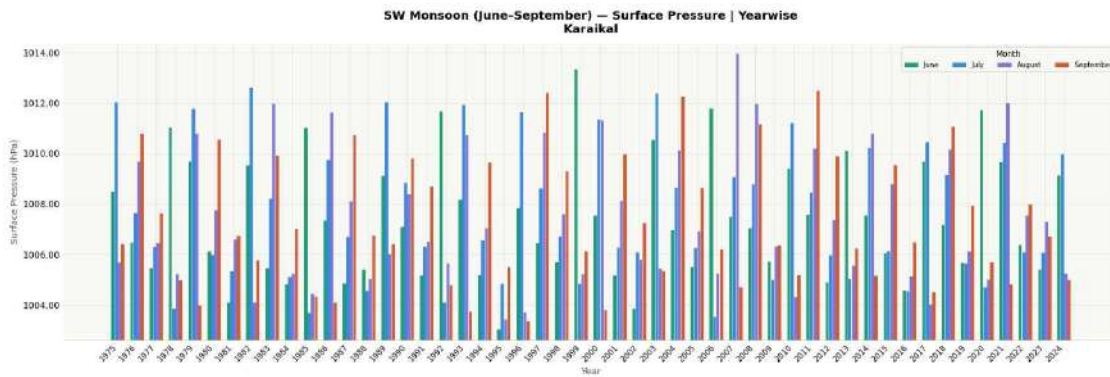
Volumetric soil moisture (NASA/POWER, 2020–2025) peaks during October–November at 11–18%, consistent with NEM recharge. Evapotranspiration shows seasonal cycles ranging from ~2.4 mm in June to higher values in October, reflecting crop water demand during peak growing seasons. Soil texture classification for Karaikal indicates predominantly clay-loam and alluvial soils, with high water retention capacity that amplifies flooding risk during heavy NEM rainfall.

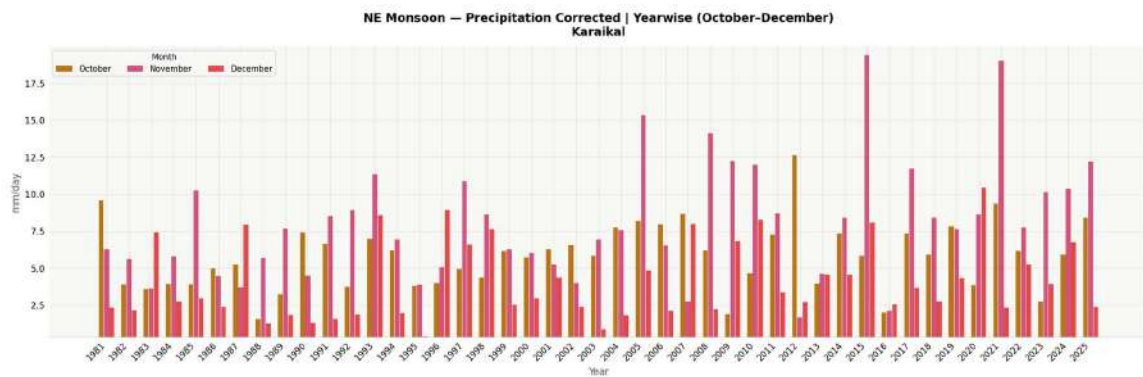
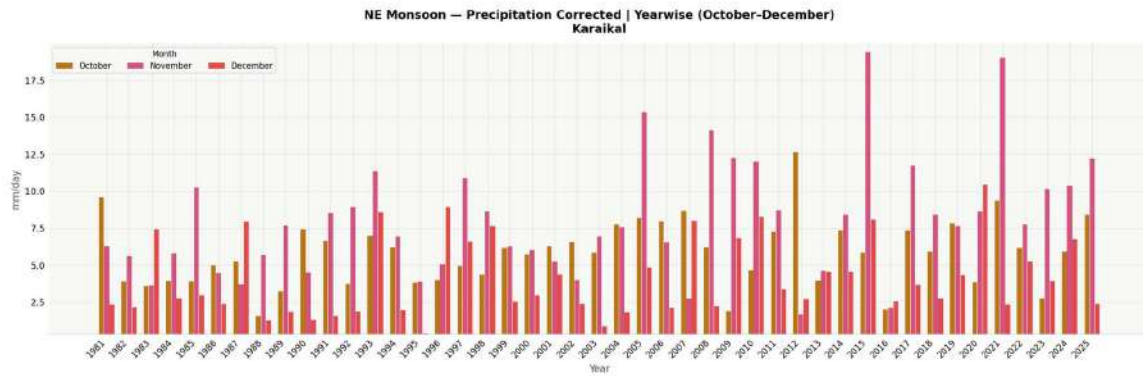
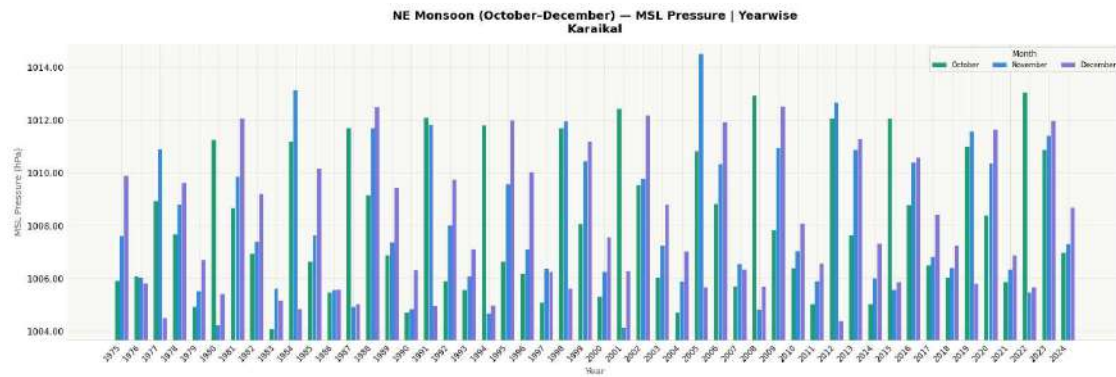
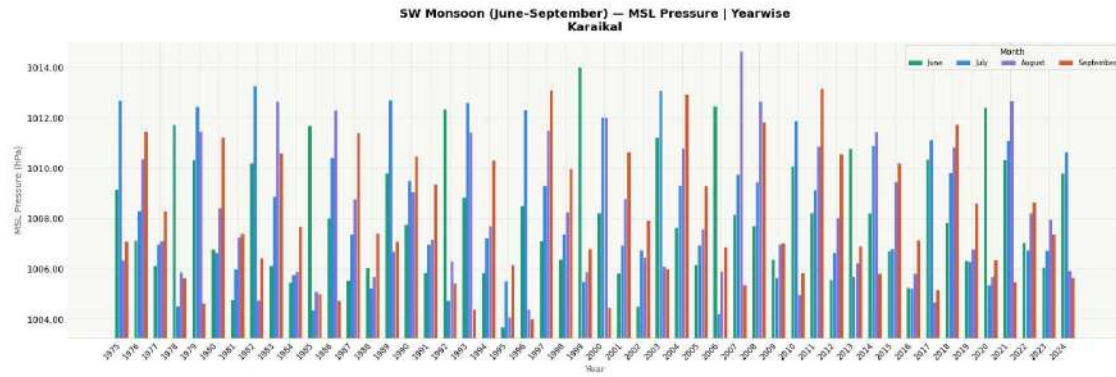






* 2021 October value is 233.6% — likely a data entry error in the source file.

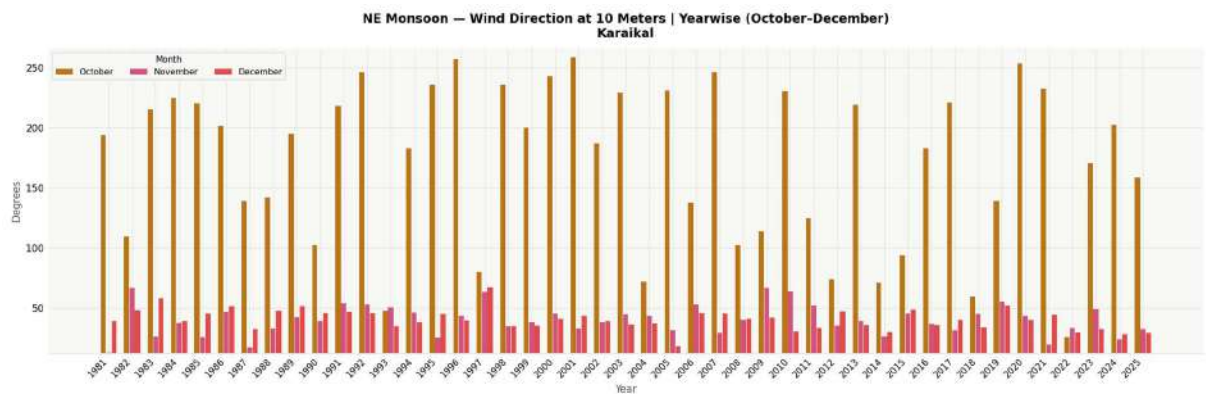
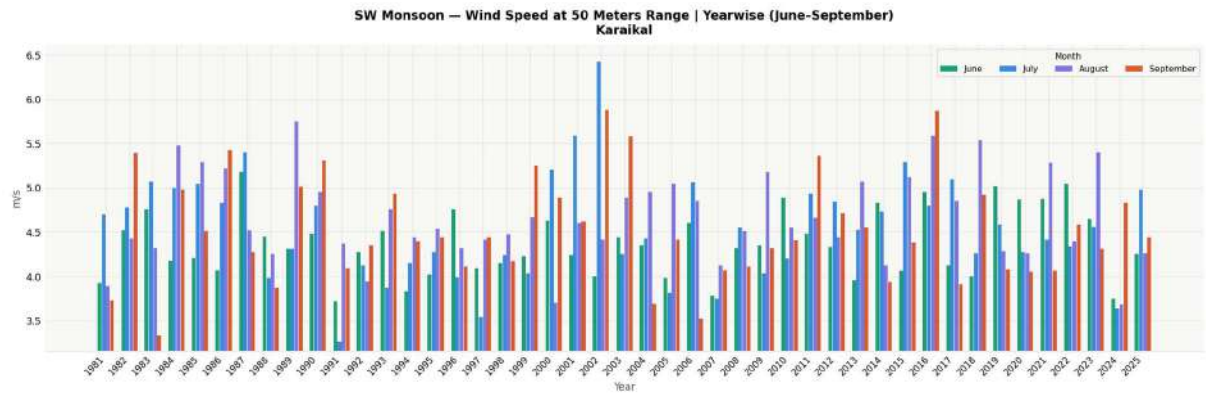
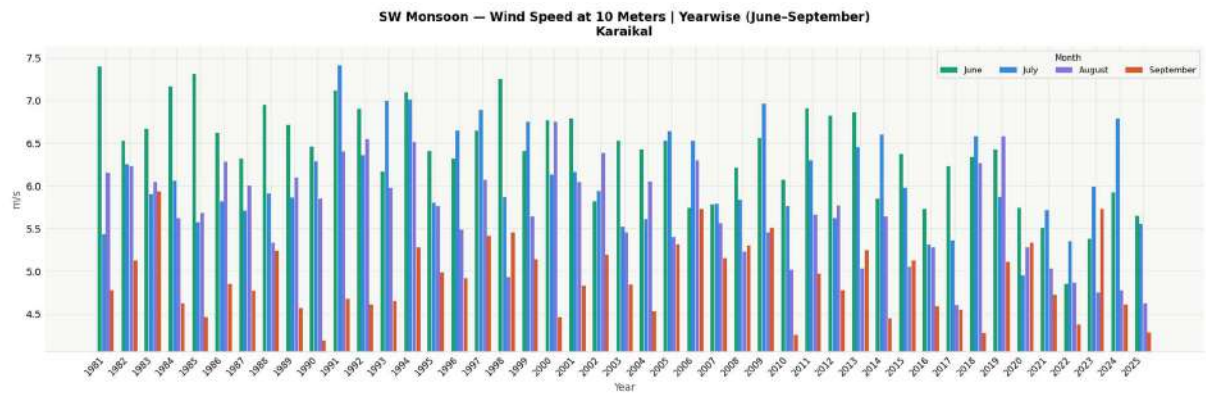
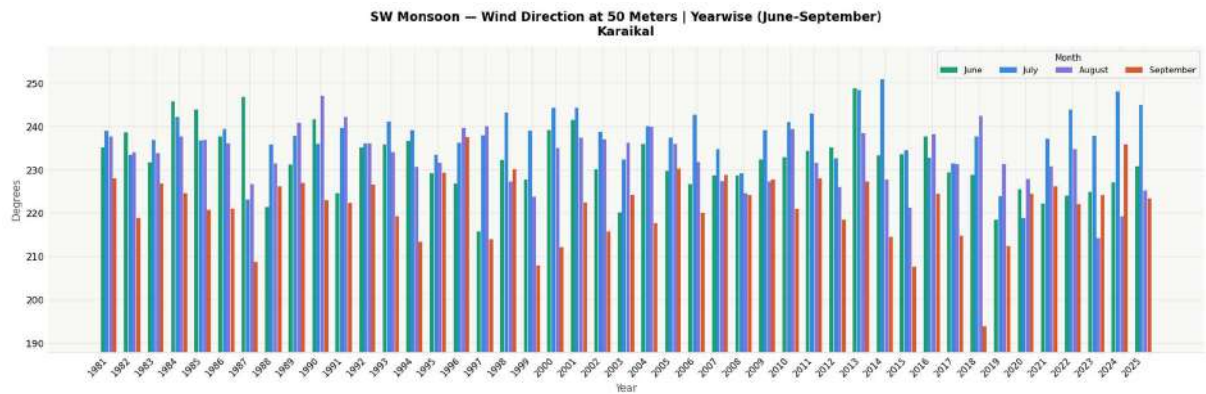


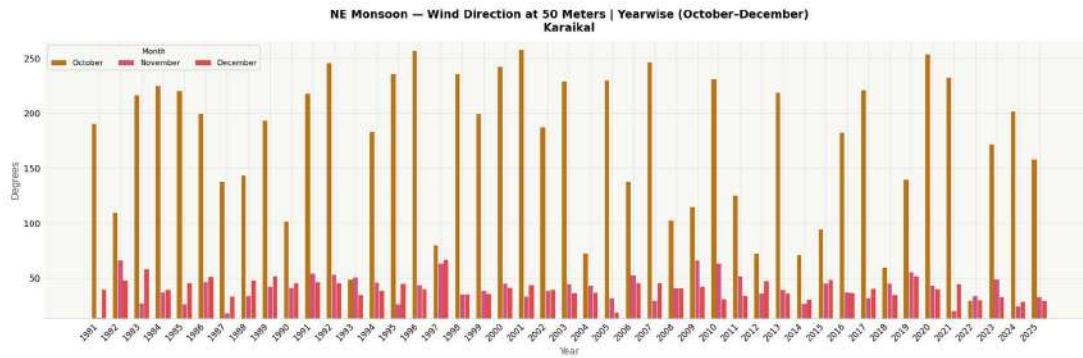




Wind Direction (Seasonal Reversal)

Wind direction data from CWC/NWIC Annavasal and Nallathur stations document the critical seasonal reversal from SW monsoon (southwesterly, $\sim 220\text{--}250^\circ$) to NE monsoon (north-northeasterly, $\sim 30\text{--}50^\circ$). This reversal, occurring during October, is the key meteorological signal triggering NE monsoon onset and paddy planting decisions.

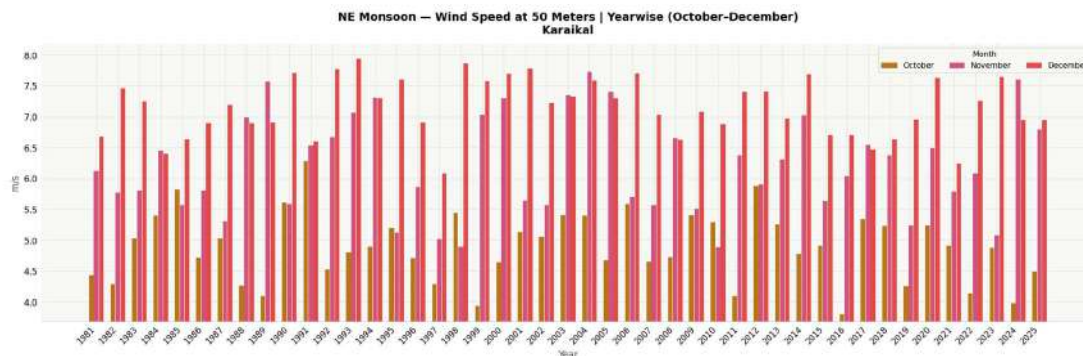
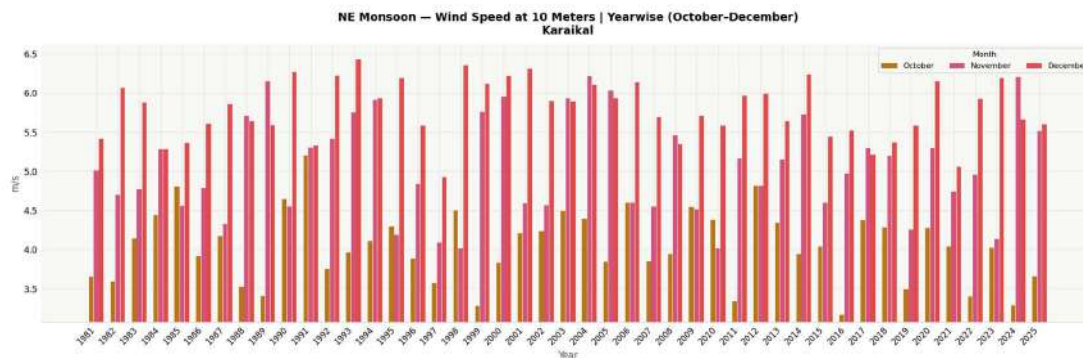




Wind Speed — Trade Wind Weakening Trend

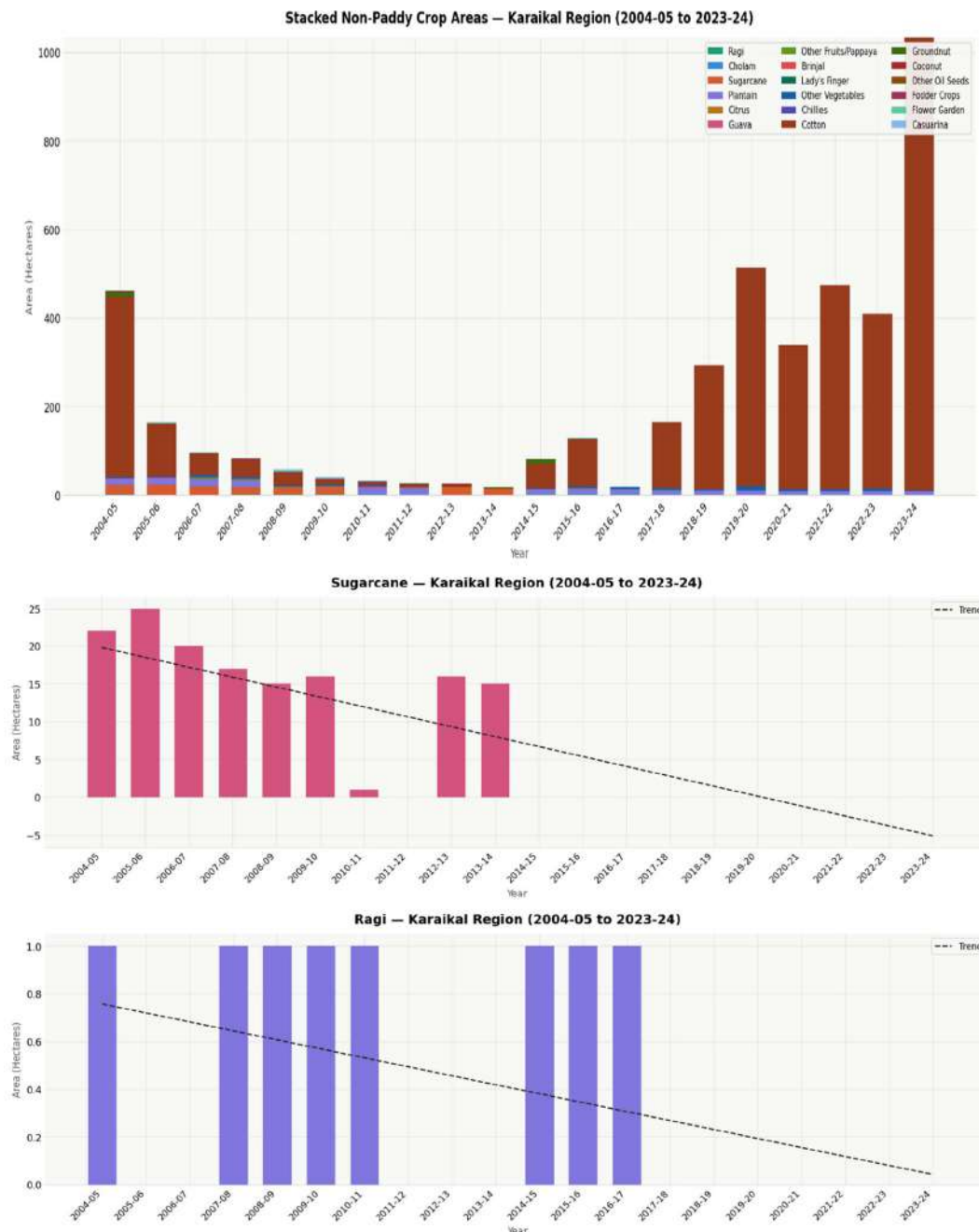
Mean Wind Speed (m/s) | Period: 1981–2025 (45 years) | Source: NASA/POWER MERRA-2

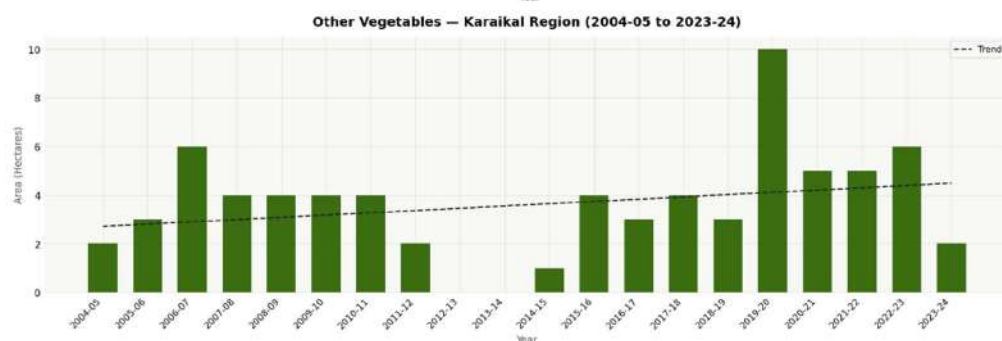
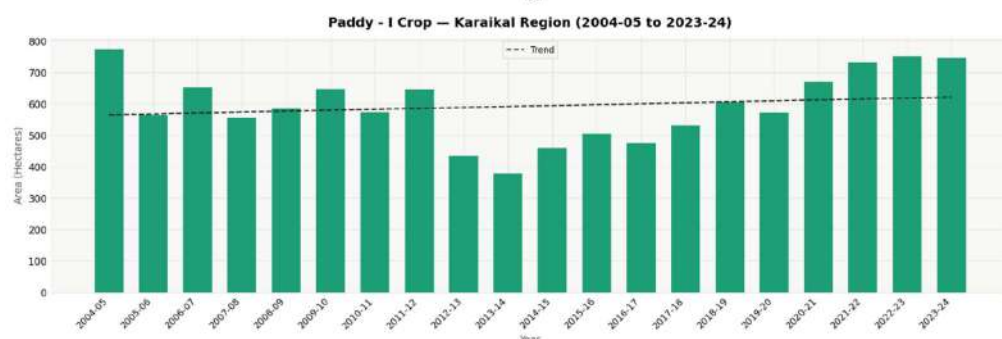
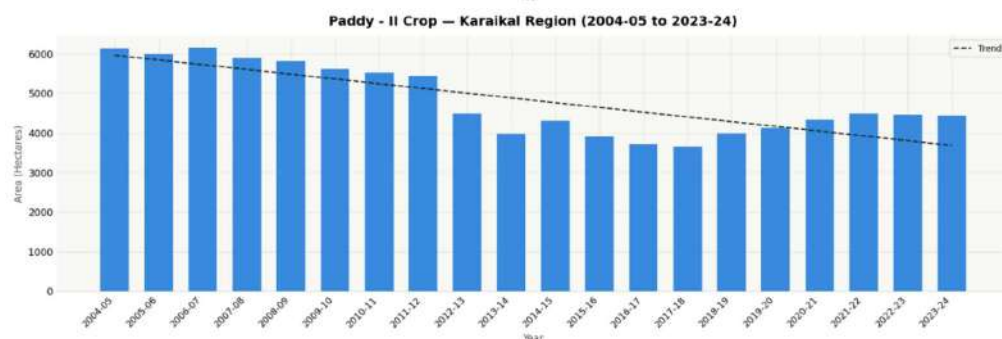
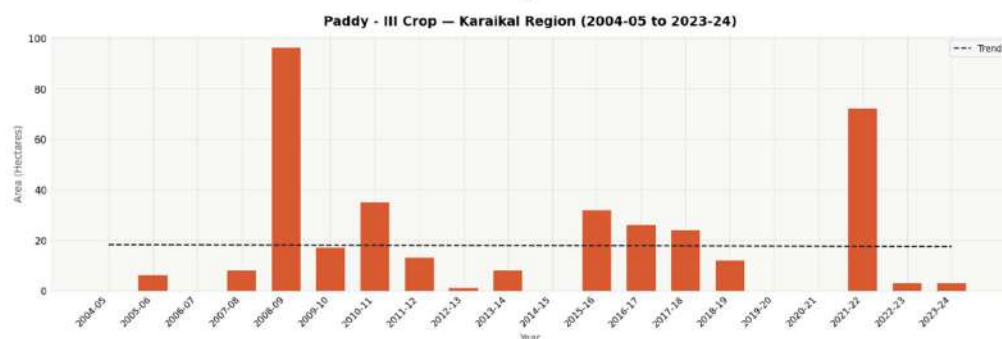
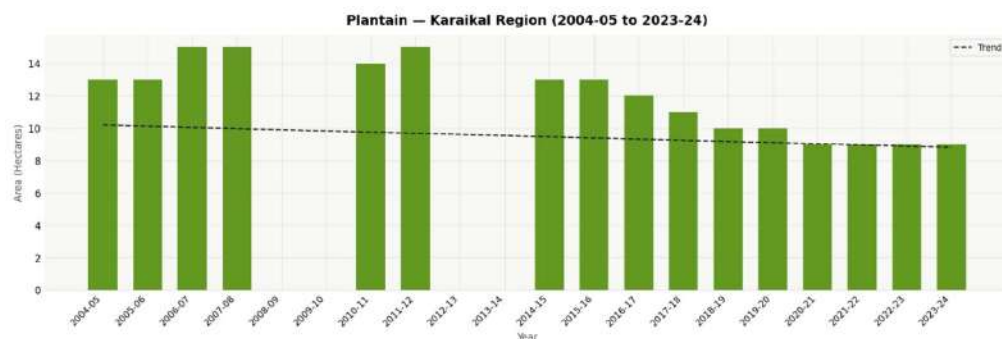
This time-series line chart displays annual mean wind speeds for SW monsoon season (Jun–Sep) and NE monsoon season (Oct–Dec) with linear trend lines. X-axis: Year (1981–2025) | Y-axis: Mean Wind Speed in m/s SW Season Mean: 5.2 m/s | NE Season Mean: 4.9 m/s | Overall trend: -0.12 m/s per decade Key observation: The cumulative weakening of -0.54 m/s over 45 years represents a 10.7% reduction from the 1981 baseline. SW season winds are declining more rapidly than NE season winds. Mechanism: Consistent with Walker Circulation weakening under anthropogenic greenhouse gas forcing (Vecchi & Soden, 2007; Roxy et al., 2015). Reduced SW trade wind strength directly weakens the moisture flux onto the subcontinent, explaining declining SW monsoon reliability.

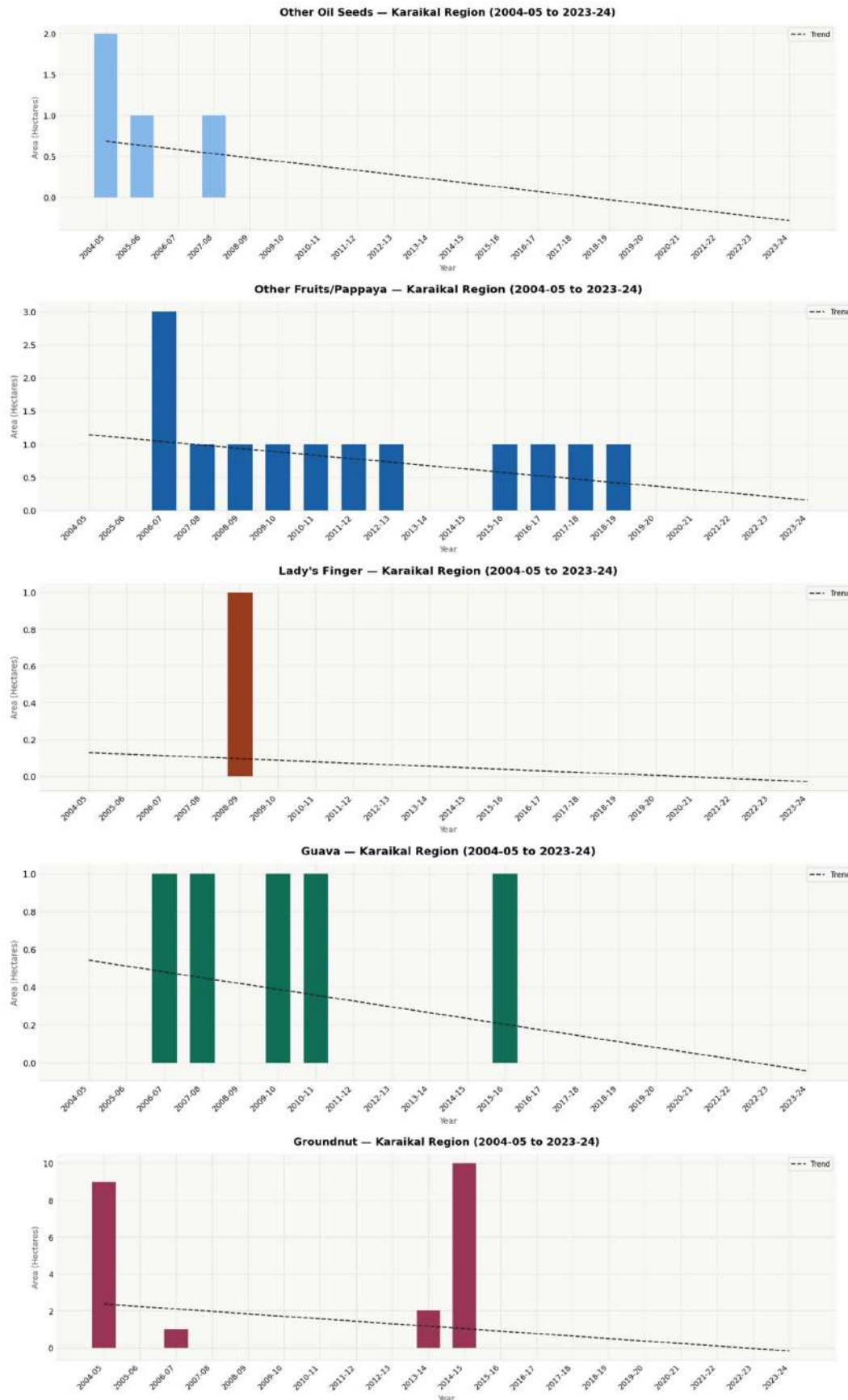


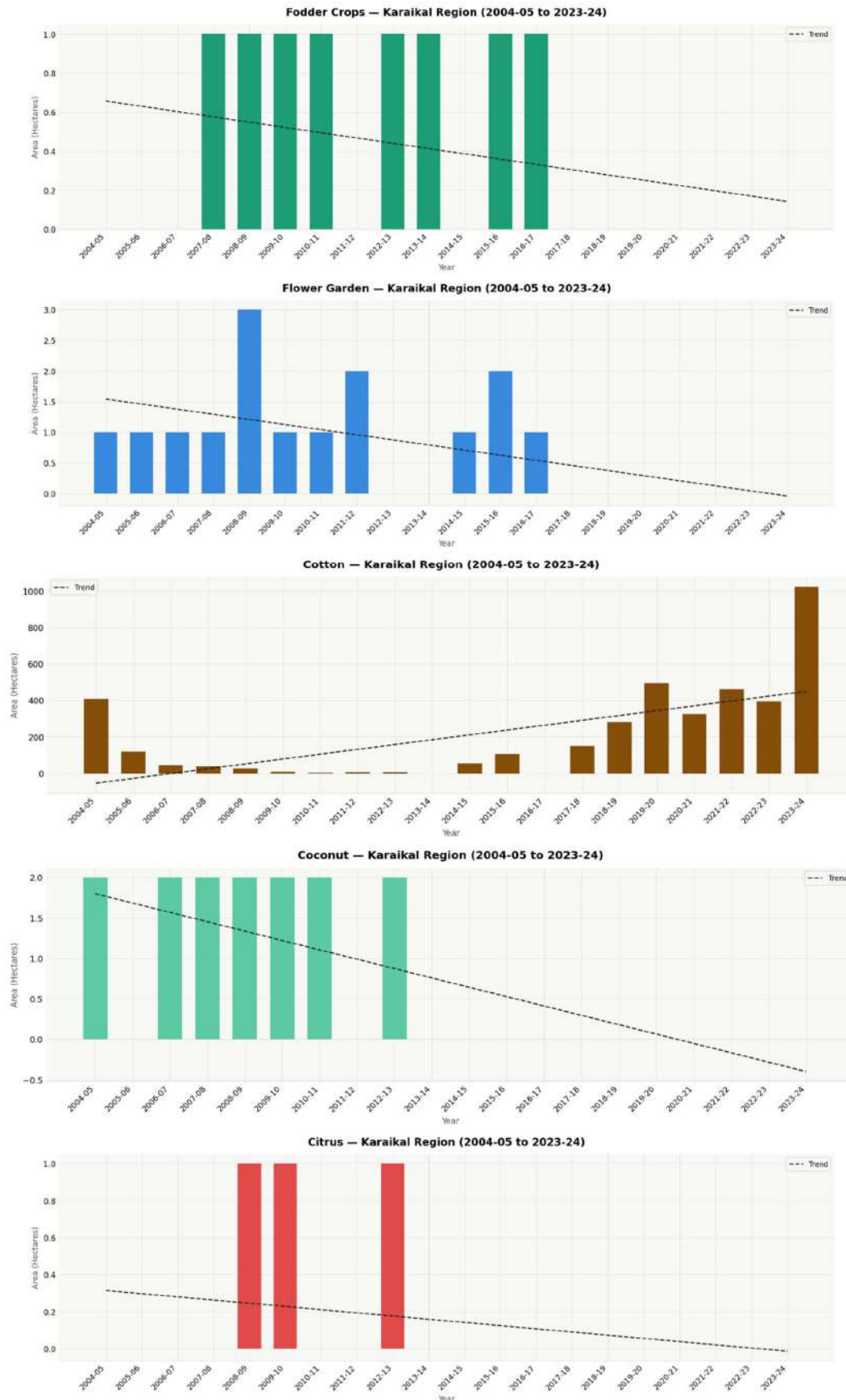
5.6 Agricultural Productivity Shifts

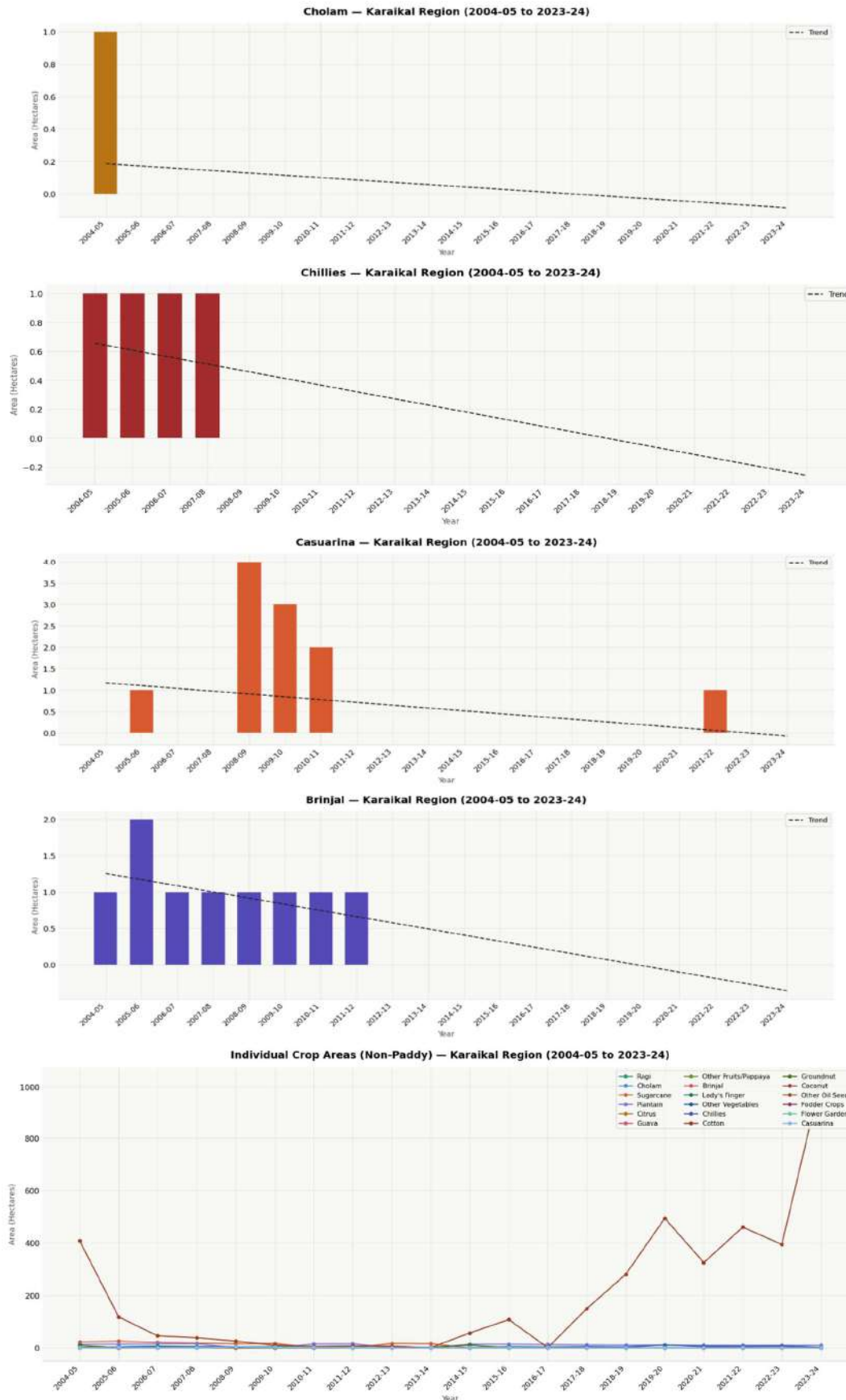
Paddy cultivation across all three seasons—Kuruwai (Kharif), Samba (Rabi), and Thaladi (late Rabi)—shows clear responses to monsoon variability. Kuruwai paddy area peaked at 772 ha in 2004-05 and declined to a trough of 378 ha in 2013-14, broadly coinciding with the cluster of SW Monsoon deficit years from 2008 to 2015. A partial recovery to ~746 ha by 2023-24 is observed. The significant SW deficit years of 2006-07, 2008-09, and 2009-10 appear to have had the most pronounced negative impact on Kuruwai cultivation.

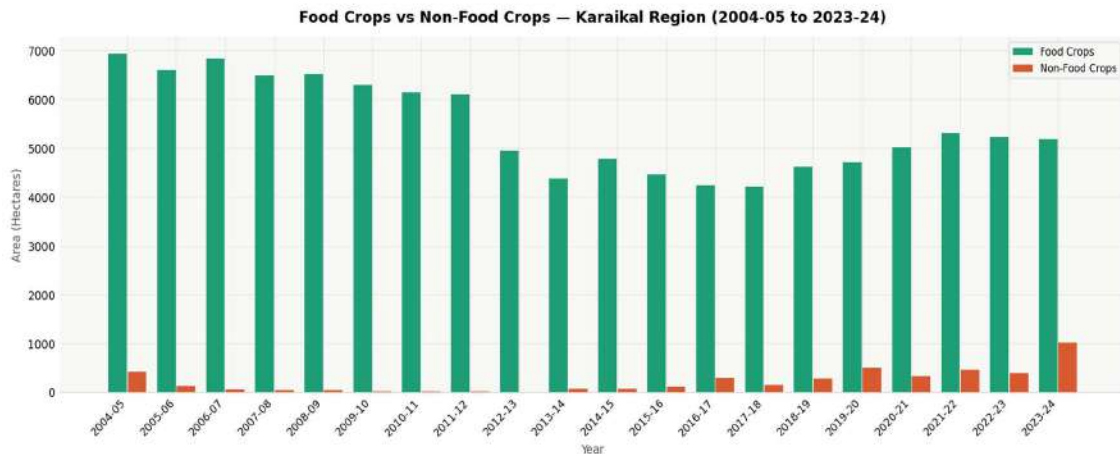
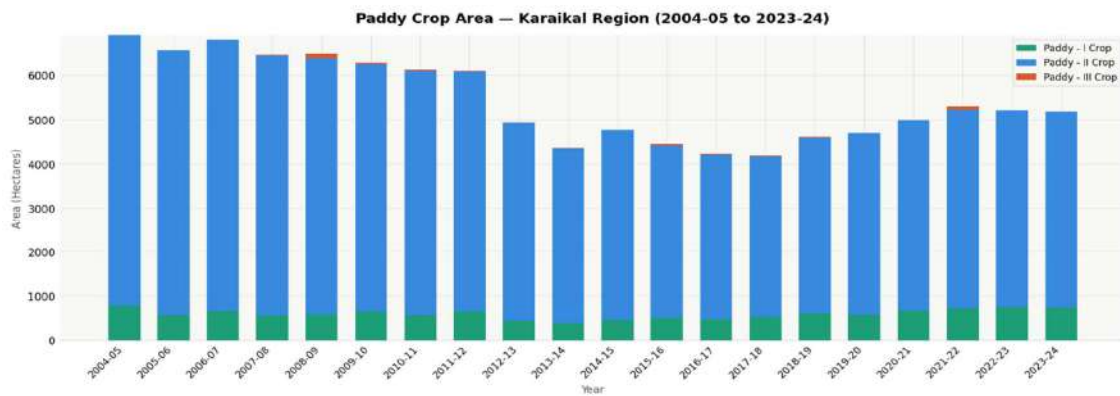
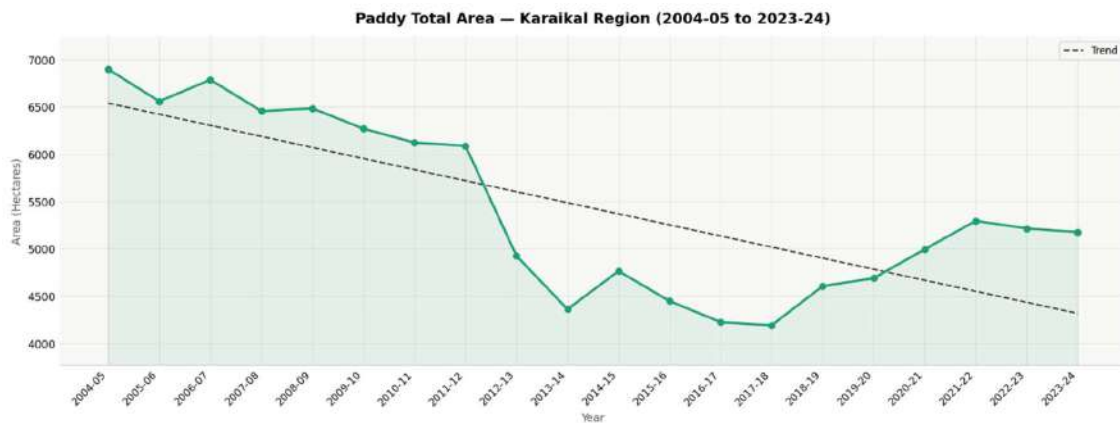
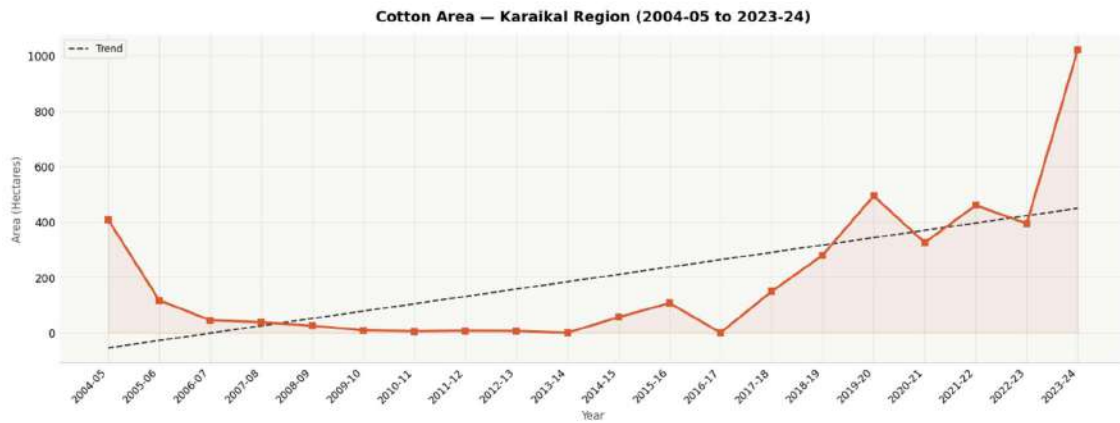


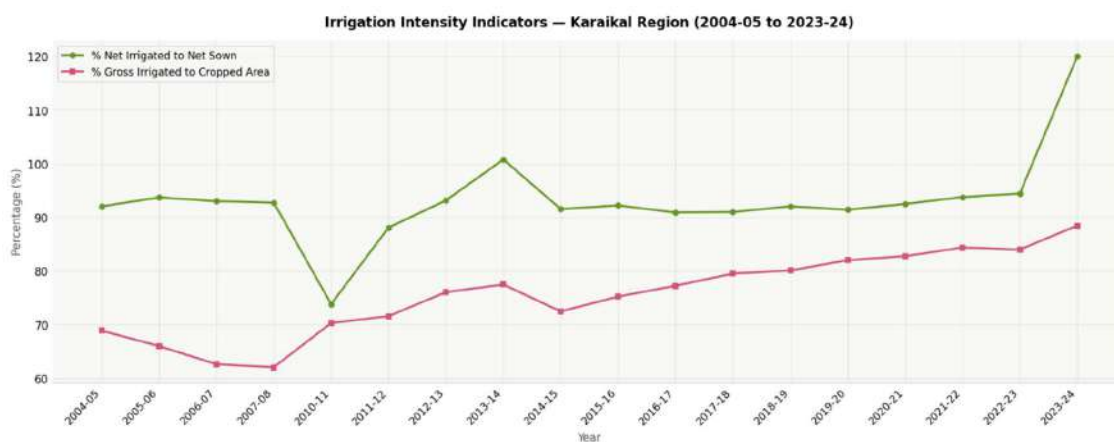
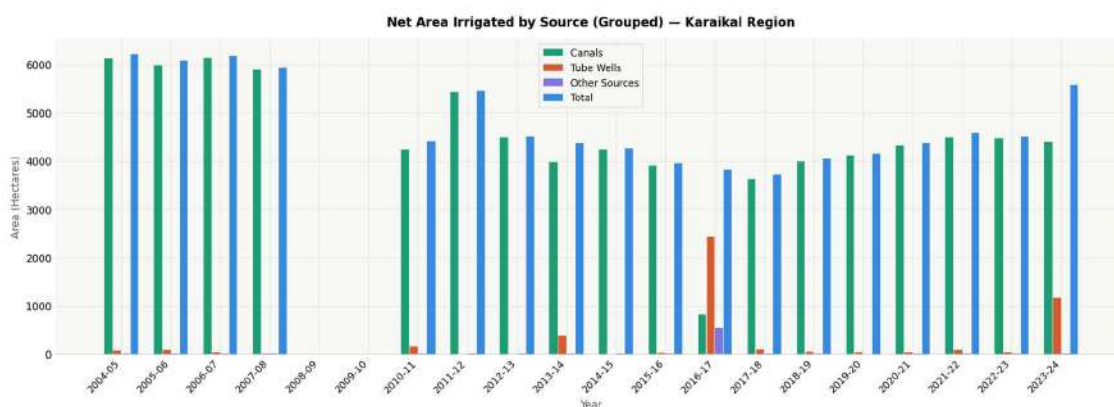
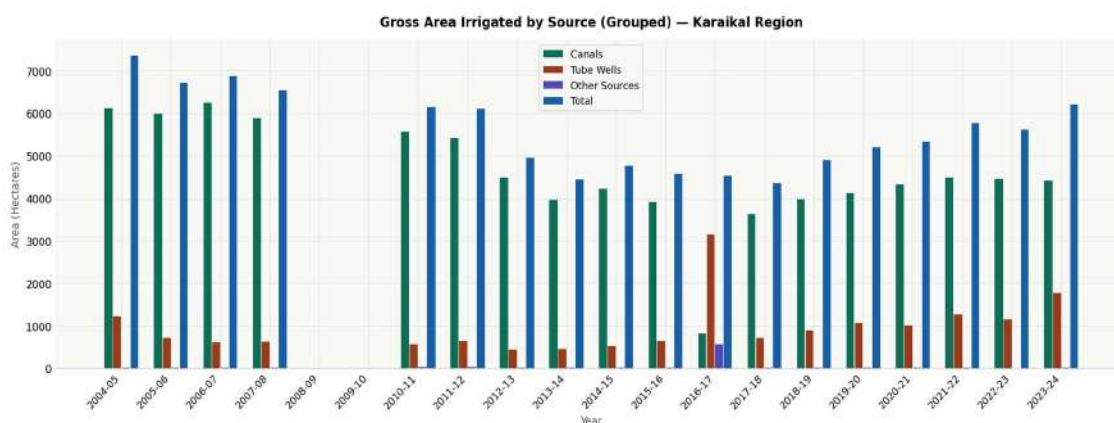
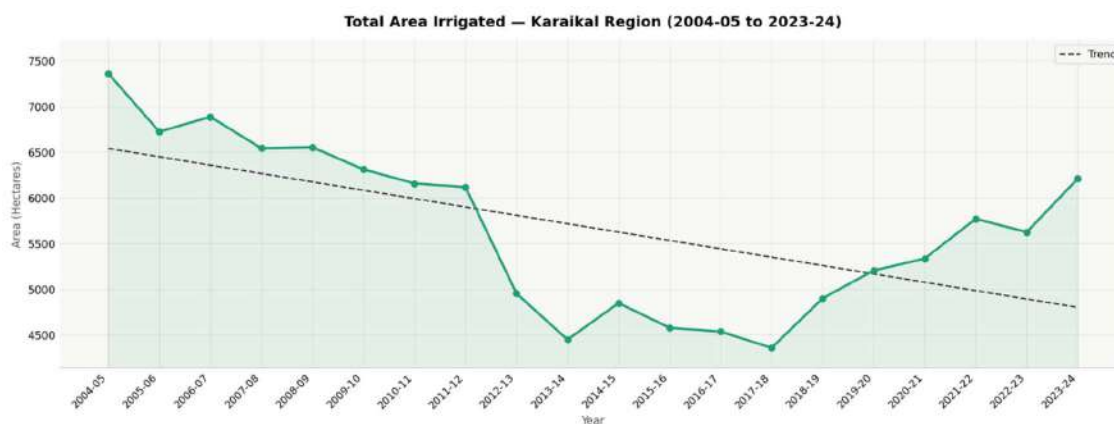




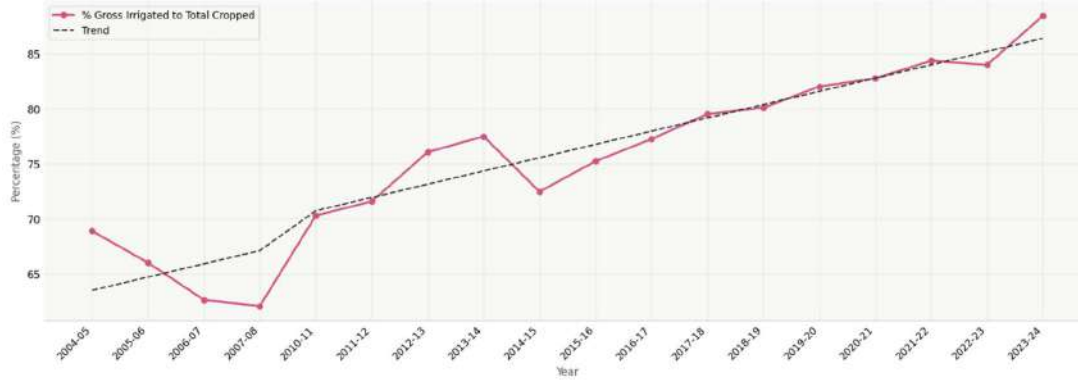








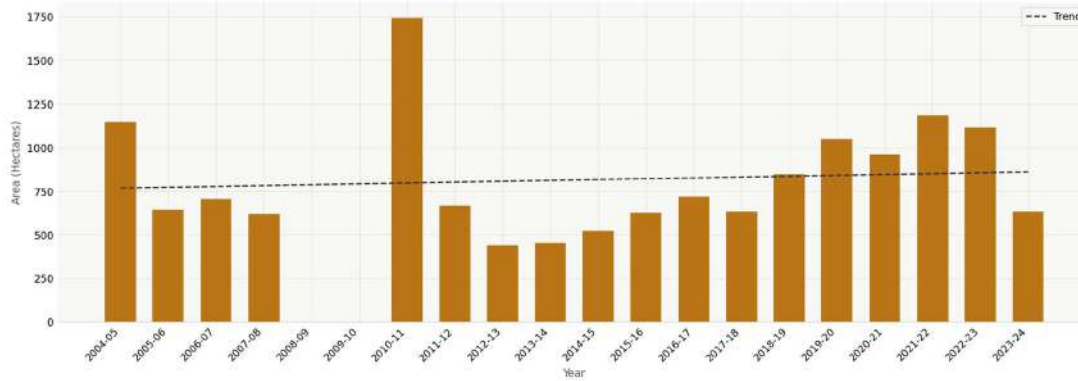
% of Gross Irrigated Area to Total Cropped Area — Karaikal Region



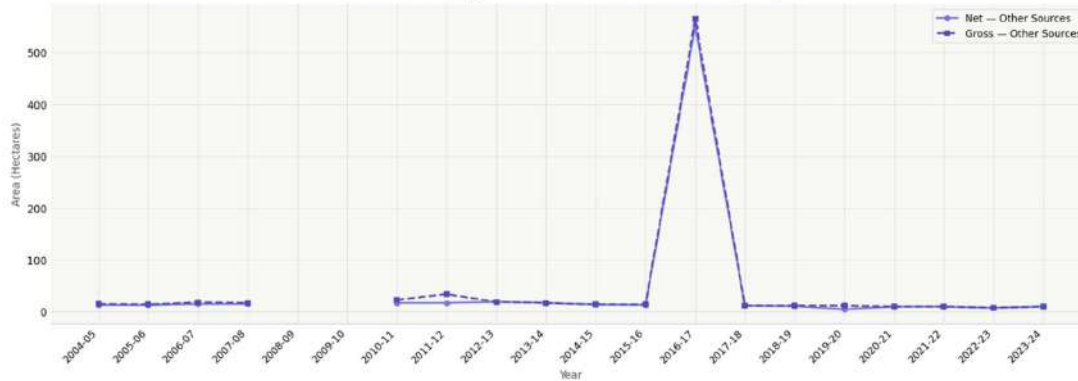
% of Net Area Irrigated to Net Area Sown — Karaikal Region

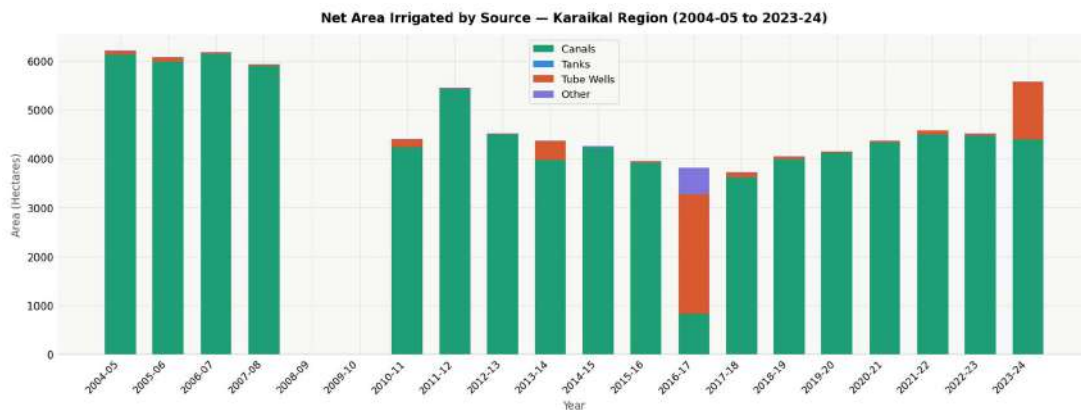
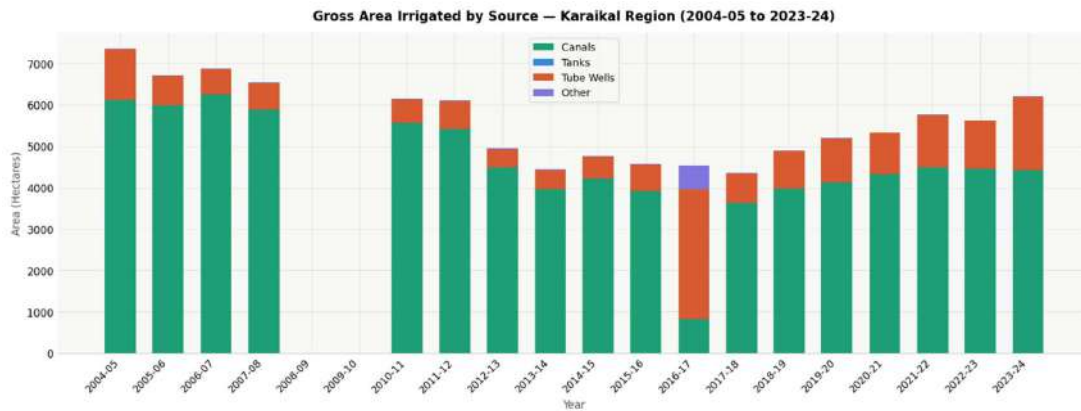
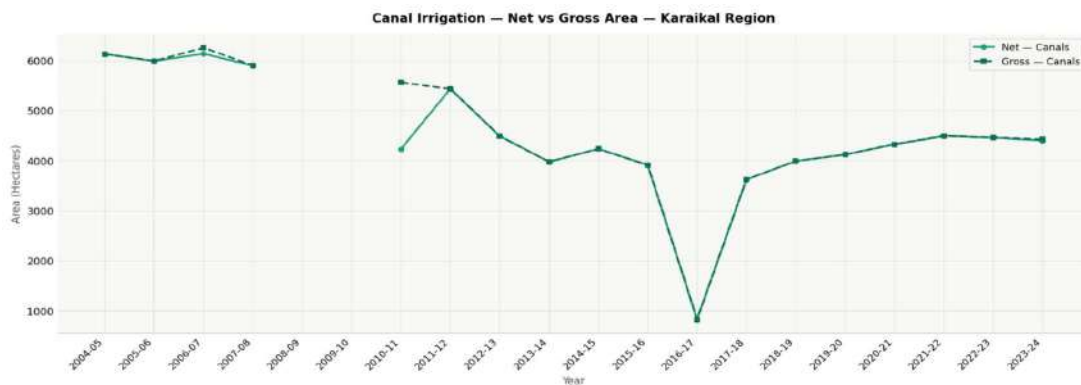
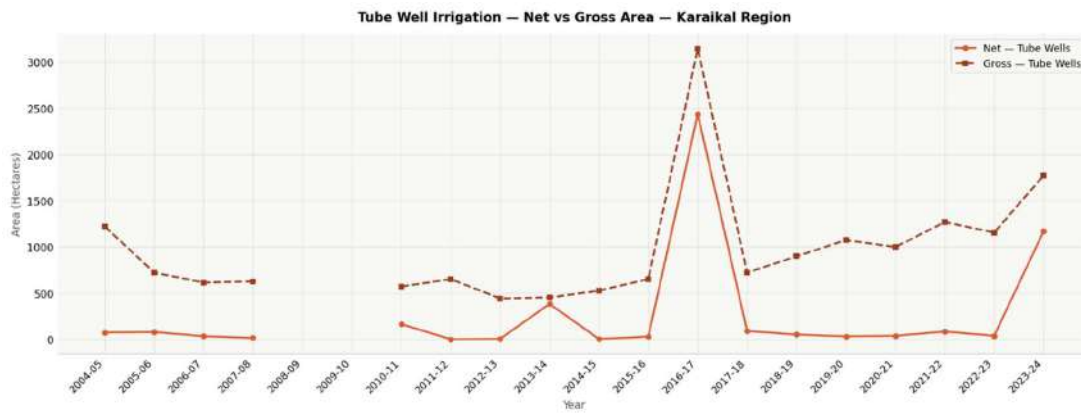


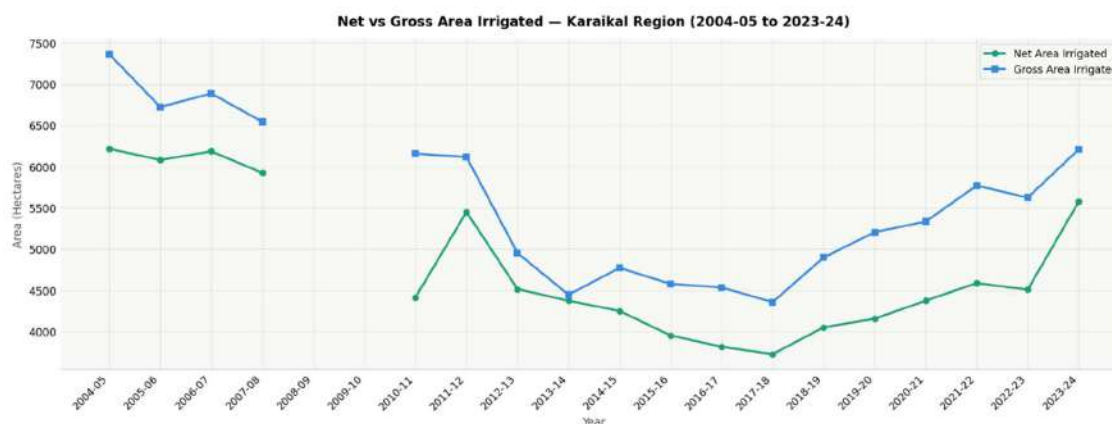
Area Irrigated More Than Once — Karaikal Region (2004-05 to 2023-24)



Other Sources Irrigation — Net vs Gross Area — Karaikal Region







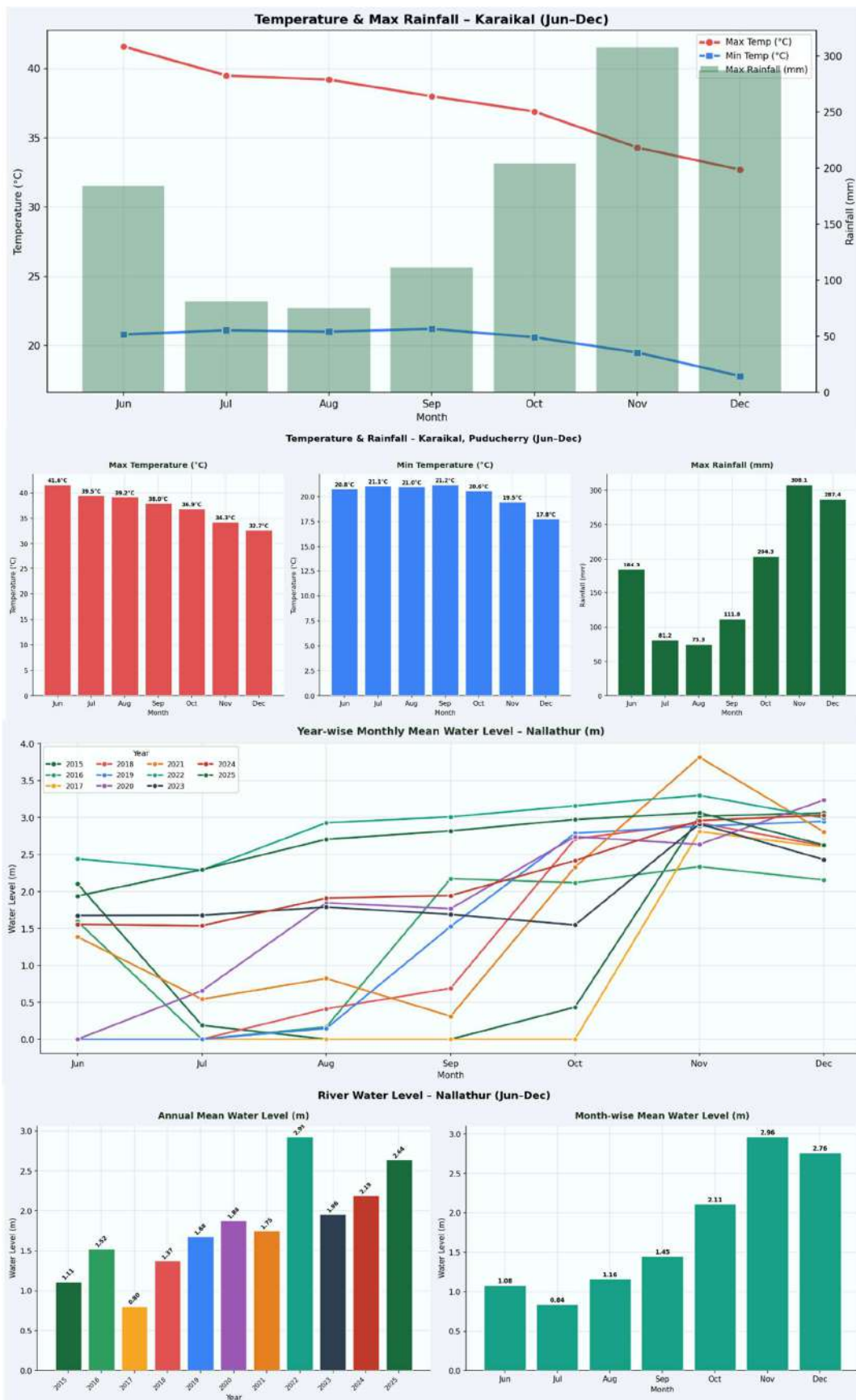
Samba paddy, relying on NEM rainfall, generally maintains higher and more stable cultivation area. However, extreme NEM deficit years (notably 2016-17 with –71.8% departure) and cyclone-associated flooding in surplus years (2020-21, 2021-22) both disrupt Samba cultivation through different mechanisms—drought stress in the former, and waterlogging and crop damage in the latter. This dual vulnerability to deficit and surplus NEM conditions underscores the complex challenge facing Karaikal agriculture.

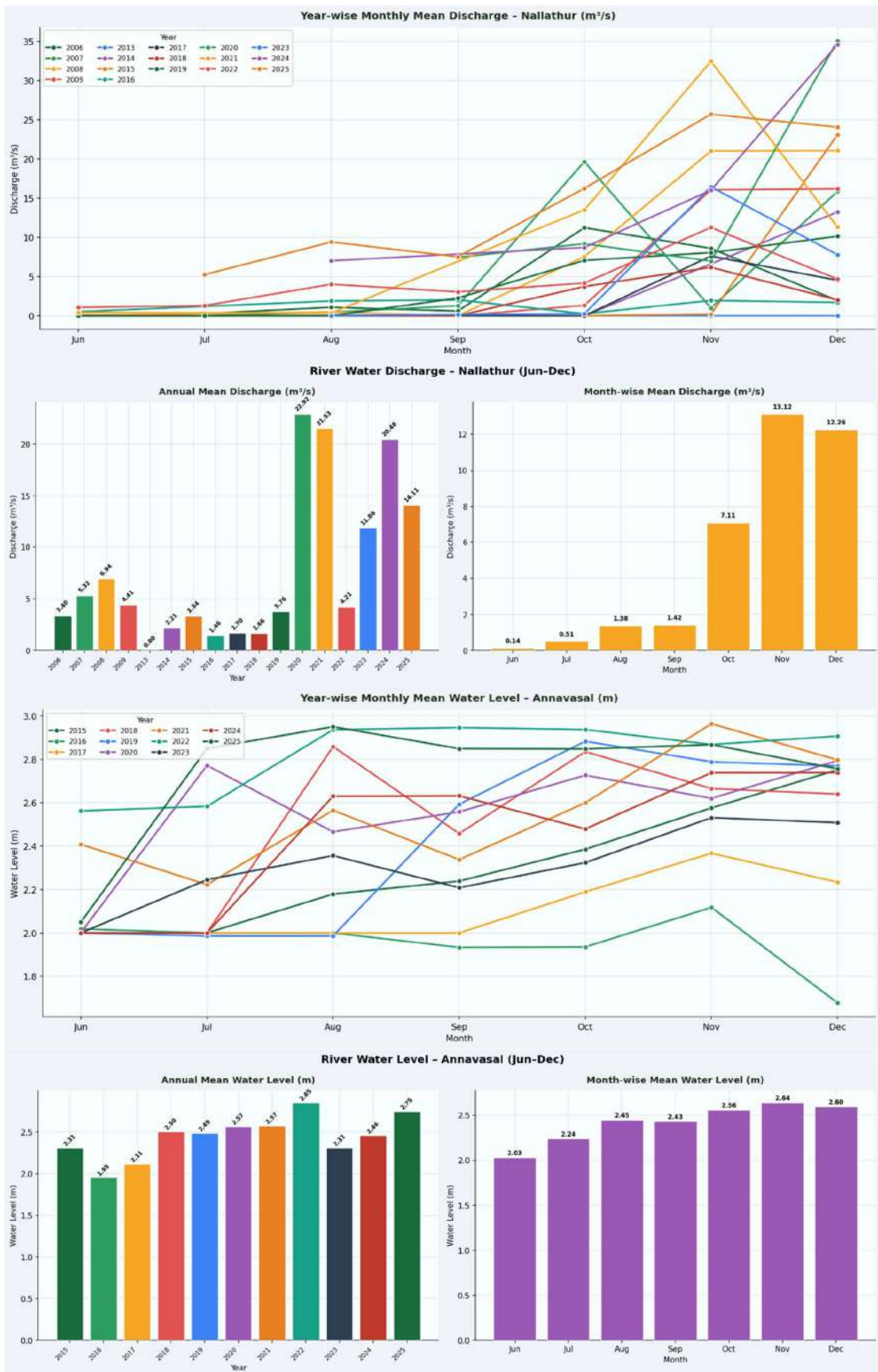
5.7 Irrigation and Land Use Analysis

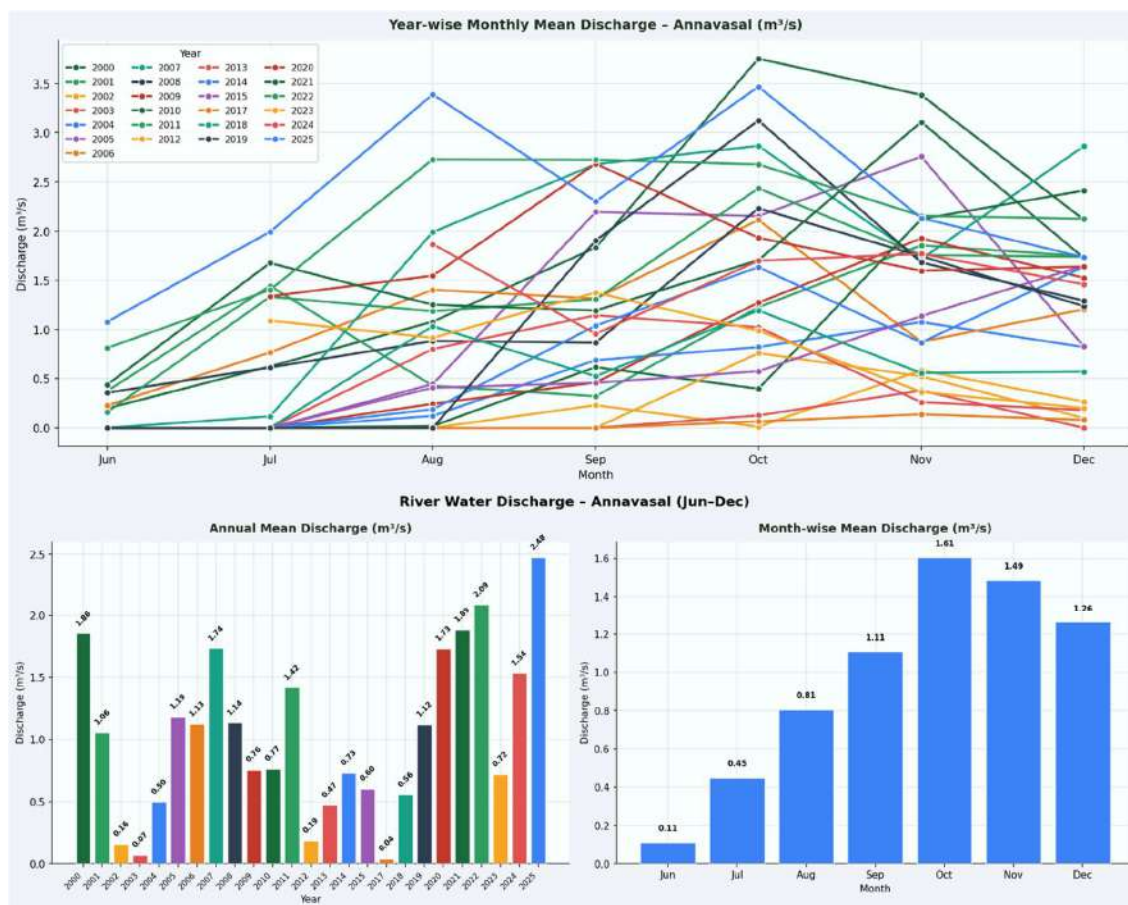
Karaikal's irrigation infrastructure draws from three main sources: canals (fed by the Cauvery river system), tanks (traditional rain-fed reservoirs), and tube wells. Canal irrigation is the dominant source, directly dependent on Cauvery river flows and, upstream, SW Monsoon conditions over Karnataka and Tamil Nadu. Tank irrigation is particularly sensitive to local SW Monsoon rainfall and has been adversely affected during consecutive deficit years.

The net area sown has remained relatively stable at 6,500–7,200 ha, indicating that agricultural land conversion to non-agricultural uses has been minimal. However, the gap between net area sown and total cropped area—which reflects double and triple cropping intensity—has narrowed during monsoon deficit years, suggesting that farmers are foregoing additional cropping rounds when water availability is uncertain.

River water discharge data from Annavasal and Nallathur stations confirm the strong seasonality of Cauvery distributary flows, with peak discharge during October–December aligned with NEM recharge. SW Monsoon deficit years are associated with significantly reduced river levels, directly constraining canal irrigation availability for Kuruvai paddy cultivation.







6. Recommendations / Adaptation Strategies

Based on the data analysis and the key finding that cyclonic activity—rather than onset timing—is the primary driver of heavy NEM rainfall in Karaikal, the following adaptation strategies are recommended:

6.1 Agricultural Adaptation

- Adopt short-duration, submergence-tolerant paddy varieties (e.g., Swarna Sub1, CR Dhan 200) for Samba season to withstand NEM flood events associated with cyclone landfalls.
- Promote drought-tolerant, short-duration varieties (e.g., CO (R) 50) for Kuruvai season to reduce vulnerability during SW Monsoon deficit years.
- Encourage crop diversification—black gram, green gram, vegetables—during risk-prone seasons to reduce farmers' dependence on paddy monoculture.
- Adopt System of Rice Intensification (SRI) to reduce water consumption by 25–50%, making Kuruvai cultivation viable even in below-normal SW Monsoon years.
- Revise cropping calendars annually based on seasonal monsoon onset forecasts issued by IMD, recognising that onset timing alone is not predictive of total seasonal rainfall.

6.2 Water Resource Management

- Desilt and rehabilitate traditional tanks (eris) across Karaikal to maximise storage during NEM surplus years, creating reserves to buffer SW Monsoon deficit years.
- Modernise canal infrastructure with automated sluice gates and repair of breaches to improve Cauvery water distribution efficiency.
- Regulate groundwater extraction and promote managed aquifer recharge, given the observed growth in tube well irrigation as a fallback during surface water deficits.
- Install rain gauge networks at the panchayat level to enable real-time monitoring of local rainfall distribution during both SW and NE monsoon seasons.

6.3 Disaster Preparedness and Cyclone Risk

- Integrate cyclonic activity data (Bay of Bengal cyclone tracks, low-pressure system positions) into seasonal rainfall prediction for Karaikal, as cyclone occurrence—not onset timing—determines heavy NEM rainfall years.
- Establish a community-based early warning and evacuation system for cyclone events, with specific protocols for agricultural land protection (e.g., draining fields, harvesting early).
- Strengthen coastal embankments, storm drainage, and flood protection infrastructure given Karaikal's classification as the highest flood intensity zone in Puducherry.
- Expand Pradhan Mantri Fasal Bima Yojana (PMFBY) crop insurance to cover all three paddy seasons, with simplified procedures for cyclone-related damage claims.

6.4 Institutional Interventions

- Establish an agro-meteorological advisory service at the district level, providing crop-specific guidance based on IMD's Extended Range Prediction System and Bay of Bengal cyclone outlooks.
- Create a comprehensive district-level climate-agriculture database that integrates meteorological parameters, agricultural statistics, disaster records, and irrigation data—building on the datasets compiled in this study.
- Conduct annual farmer awareness programmes on climate-smart agriculture, water conservation, and weather-based decision-making in Karaikal.

7. Conclusion

This study has conducted a comprehensive analysis of monsoon pattern changes and associated agricultural productivity shifts for the Karaikal region, drawing on 18 datasets spanning meteorological, hydrological, and agricultural domains over periods ranging from 44 years (1981–2024) for rainfall trends to 73 years (1952–2025) for disaster records.

The most significant finding of this study is the absence of a consistent relationship between monsoon onset timing and total seasonal rainfall over Karaikal. Analysis of SW and NE monsoon onset dates from 2018 to 2024 shows that both early and late onsets correspond to years of both high and low rainfall. Instead, the occurrence of at least one significant cyclone or low-pressure system making landfall near the Karaikal coast is the dominant determinant of heavy NEM rainfall. This finding has direct implications for agricultural planning: farmers who calibrate their decisions solely based on onset timing face inherent uncertainty, and integrating cyclone track forecasts into seasonal planning is recommended.

Long-term trend analysis confirms a strengthening of the NE Monsoon over Karaikal, with seasonal totals increasing by approximately 27.9% between 1981–2000 and 2001–2024. This intensification has been accompanied by an unprecedented clustering of cyclone events during 2018–2025, including Gaja, Nivar, Burevi, Fengal, and Ditwah. Karaikal already holds the highest flood intensity among Puducherry's four regions; the trend toward more intense NEM events heightens this vulnerability.

SW Monsoon variability has created distinct stress on Kuruvai paddy cultivation, with the cluster of deficit years between 2006 and 2015 corresponding to a 51% decline in Kuruvai paddy area from its peak in 2004-05. Samba paddy, relying on NEM, is vulnerable to both the extreme deficit of 2016-17 and the flooding associated with cyclone-surplus years. With 84.92% of land cultivable and 82.81% under irrigation, the agricultural economy of Karaikal is deeply exposed to these monsoon shifts.

In conclusion, Karaikal requires a paradigm shift from reactive disaster response to proactive, climate-informed agricultural and water management planning. The strategies recommended in this report—integrating cyclone data into seasonal forecasts, adopting resilient crop varieties, rehabilitating irrigation infrastructure, and strengthening community preparedness—provide a practical roadmap for building climate resilience in this uniquely vulnerable coastal district.

8. References

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9. Annexures

Annexure I: Datasets Collected and Used in This Study

Dataset / File	Source Organisation	Period
karaikal_rainfall_monthwise.xlsx	Dept. of Economics & Statistics, Puducherry	2004–2024
Karaikal_MonsoonTiming_1981_2024.xlsx	NASA/POWER MERRA-2	1981–2024
Karaikal_SW_NE_Monsoons.xlsx	IMD / District Records	2018–2024
Karaikal_Disasters_Updated.xlsx	Karaikal District DMA	2008–2025
karaikal_crops_by_year.xlsx	Dept. of Economics & Statistics, Puducherry	2004–2024
Karaikal_Classification_of_Area_2004_2024.xlsx	Dept. of Economics & Statistics, Puducherry	2004–2024
Karaikal_Water_Supply_Irrigation.xlsx	Dept. of Economics & Statistics, Puducherry	2004–2024
karaikal_percentage_of_area.xlsx	Dept. of Economics & Statistics, Puducherry	2004–2024
Temperature_Rainfall_Karaikal_Jun_Dec.xlsx	IMD Historical Records	Historical
Karaikal_Pressure_JunDec_AllYears.xlsx	ERA5 / ECMWF Reanalysis	1971–2024
Relative_Humidity_Karaikal_Jun_Dec.xlsx	NWIC – Karaikal Station	2020–2024
Relative_Humidity_Nallathur_Jun_Dec.xlsx	NWIC – Nallathur Station	2008–2024
Soil_Moisture_Karaikal_Jun_Dec.xlsx	NASA/POWER	2020–2025
Evapotranspiration_Karaikal_Jun_Dec.xlsx	NASA/POWER	2020–2025
Wind_Direction_Karaikal_Jun_Dec.xlsx	NWIC – Karaikal	2020–2026
Wind_Direction_Nallathur_Jun_Dec.xlsx	NWIC – Nallathur	2020–2026
River_Water_Level_Annavasal.xlsx	NWIC	2015–2026
River_Water_Level_Nallathur.xlsx	NWIC	2015–2026
River_Water_Discharge_Annavasal.xlsx	NWIC	2000–2026
River_Water_Discharge_Nallathur.xlsx	NWIC	2000–2026
Karaikal_JunDec_FullNames.xlsx	NASA/POWER MERRA-2	1981–2025
Pondicherry_Karaikal_Class_Level.xlsx	Pondicherry Soil Survey	2026

Annexure II: Key Abbreviations

Abbreviation	Full Form
SWM	South-West Monsoon (June–September)
NEM	North-East Monsoon (October–December)
PCCC	Puducherry Climate Change Cell
CSAP	Climate Scholar Award Programme
NWIC	National Water Informatics Centre
IMD	India Meteorological Department
BMTPC	Building Materials and Technology Promotion Council
ENSO	El Niño Southern Oscillation
ERA5	Fifth Generation ECMWF Atmospheric Reanalysis
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, v2
MSLP	Mean Sea Level Pressure
SRI	System of Rice Intensification
PMFBY	Pradhan Mantri Fasal Bima Yojana (Crop Insurance Scheme)
KVK	Krishi Vigyan Kendra
DMA	District Disaster Management Authority