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Rainfall Variability and Its Implications for Agriculture and Water Resources in Meerut District, Uttar Pradesh (2005–2024)

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Abstract

Rainfall variability has significant implications for agricultural productivity, water-resource management, and sustainable regional development in monsoon-dependent regions. The present study investigated the temporal and seasonal variability of rainfall in Meerut District, Uttar Pradesh, for the period 2005–2024. The study aimed to analyse the long-term variability and trends in annual and seasonal rainfall and to assess the implications of rainfall variability on agriculture, water resources, and regional development under changing climatic conditions. Monthly precipitation data were obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database for the geographical coordinates of Meerut (28.9845° N, 77.7064° E). The corrected precipitation dataset (PRECTOTCORR) was converted from average daily precipitation (mm day^{-1}) to monthly rainfall totals (mm), and annual and seasonal rainfall were subsequently derived following the India Meteorological Department (IMD) seasonal classification. Descriptive statistical techniques and comparative analyses were employed to examine rainfall variability and seasonal distribution. The analysis revealed considerable interannual variability in rainfall during the study period. Annual rainfall ranged from approximately 640 mm to 1,280 mm, indicating substantial fluctuations between wet and dry years. The Southwest Monsoon (June–September) remained the dominant rainfall season, contributing nearly 80–90% of the total annual rainfall, while the Winter and Post-monsoon seasons accounted for only a small proportion. Years such as 2010, 2013, and 2021 experienced comparatively higher rainfall, whereas 2014, 2016, 2017, and 2019 recorded relatively lower rainfall totals. These variations influenced agricultural activities by affecting crop establishment, irrigation requirements, and groundwater recharge, while intense rainfall events increased the risk of waterlogging and localized urban flooding. The study concluded that rainfall variability in Meerut District exhibited a highly irregular temporal pattern with significant implications for agriculture and water-resource sustainability. The findings emphasized the need for climate-resilient agricultural practices, improved rainwater harvesting, groundwater recharge, efficient irrigation management, and adaptive planning to strengthen resilience against future climatic variability. The study provides valuable scientific evidence to support sustainable resource management and informed policy formulation in western Uttar Pradesh.

Keywords- Rainfall Variability, Seasonal Rainfall, Climate Change, Monsoon Rainfall, NASA POWER Dataset, Sustainable Water Management Meerut District, Uttar Pradesh

Introduction

Rainfall has remained one of the most influential climatic variables and the principal renewable source of freshwater supporting agricultural production, ecosystem sustainability, groundwater recharge, and socio-economic development. Its distribution has exhibited considerable spatial and temporal variability owing to atmospheric circulation, topographic conditions, land-use characteristics, and regional climatic processes. In India, the southwest monsoon has consistently supplied nearly three-fourths of the annual precipitation, making it the dominant hydrological event governing water availability, agricultural productivity, and food security. Recent assessments have further demonstrated that although the overall monsoon rainfall has remained relatively stable at the national scale, its spatial distribution and temporal behaviour have become increasingly erratic under a warming climate. Over the past two decades, climate change has substantially altered rainfall characteristics across many parts of India. Contemporary research has reported an increase in the frequency and intensity of extreme rainfall events, longer dry spells between rainfall episodes, irregular monsoon onset and withdrawal, and greater interannual variability in seasonal precipitation. These changes have increased hydrological uncertainty, thereby affecting agriculture, groundwater recharge, urban drainage systems, flood management, and water security. Recent climate model projections have further suggested that future monsoon precipitation may become more variable, with rainfall increasingly concentrated into short-duration, high-intensity events rather than being evenly distributed throughout the season. Long-term rainfall analysis has therefore become an essential approach for evaluating regional manifestations of climate change. Statistical examination of annual, seasonal, and monthly rainfall records has enabled researchers to identify trends, variability, shifts in rainfall distribution, and the occurrence of extreme hydro meteorological events. Recent studies have also highlighted the influence of large-scale climate drivers, including the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and atmospheric teleconnections, on the variability of the Indian summer monsoon. Improved understanding of these interactions has strengthened rainfall forecasting and climate adaptation planning at regional scales.

Study Area

Meerut district is located in the western part of Uttar Pradesh within the fertile Upper Ganga–Yamuna Doab, one of the most productive alluvial plains of northern India. Geographically, the district extends between 28°58′ N and 29°15′ N latitude and 77°42′ E and 78°07′ E longitude, with an average elevation of approximately 225 m above mean sea level. The district occupies an area of about 2,559 km² and forms an important part of the National Capital Region (NCR) owing to its strategic location and excellent transport connectivity. Meerut lies approximately 70 km northeast of New Delhi, the national capital, and about 450 km northwest of Kanpur, one of the major industrial cities of Uttar Pradesh. It is also situated nearly 453 km northwest of Lucknow, the state capital. Meerut experiences a subtropical monsoon climate, characterized by hot summers, a humid southwest monsoon season, and cool winters. The district receives the majority of its annual rainfall during the southwest monsoon (June–September), which contributes nearly 80–85% of the total annual precipitation. The long-term average annual rainfall ranges between 800 and 900 mm, although substantial interannual variability has been observed during recent decades, with increasing occurrences of intense rainfall events and prolonged dry spells. Such variability has significant implications for groundwater recharge, agricultural productivity, urban flooding, and water-resource management. According to the 2011 Census, Meerut District had a population of 3.44 million, while recent demographic projections estimate the population to have exceeded 4.0 million by 2025–2026. Rapid population growth, urban expansion, and its proximity to Delhi have accelerated land-use transformation and increased pressure on natural resources, particularly groundwater and urban infrastructure. The economy of Meerut is characterized by a mixed agricultural–industrial structure. Agriculture continues to employ a substantial proportion of the rural workforce, with sugarcane, wheat, rice, and horticultural crops forming the backbone of the primary sector. Simultaneously, the district has emerged as one of western Uttar Pradesh's major manufacturing and commercial centres.

Objective of the Study

- To analyse the long-term temporal variability and trends in annual, seasonal, and monthly rainfall in Meerut District using historical rainfall records, and to evaluate changes in monsoon characteristics under changing climatic conditions.

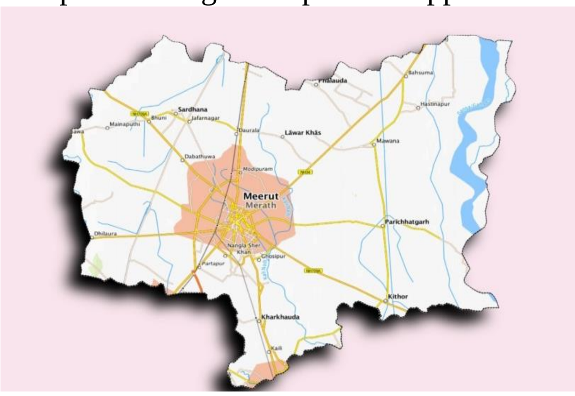
- To assess the implications of rainfall variability on agriculture, water resources, and regional development by comparing historical and recent rainfall patterns, thereby providing scientific inputs for climate-resilient planning and sustainable resource management.

Data Set and Methodology

The present study analysed the rainfall characteristics of Meerut District, Uttar Pradesh, using a 20-year monthly precipitation dataset (2005–2024) obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database. The dataset was extracted for the geographical coordinates of Meerut (28.9845° N, 77.7064° E), which represents the central location of the district. The NASA POWER dataset provides corrected precipitation estimates (PRECTOTCORR) expressed in millimetres per day (mm day^{-1}). Monthly precipitation values were converted into monthly rainfall totals (mm) by multiplying the average daily precipitation by the number of days in each month. Annual rainfall was then calculated by summing the monthly rainfall totals, while seasonal rainfall was derived according to the India Meteorological Department (IMD) classification: Winter (January–February), Pre-monsoon (March–May), Southwest Monsoon (June–September), and Post-monsoon (October–December).

The analysis employed descriptive and statistical techniques to evaluate rainfall variability and its implications for agriculture, water resources, and regional development. Basic descriptive statistics, including the mean, maximum, minimum, and annual rainfall totals, were computed to understand the overall rainfall characteristics of the study period. Seasonal rainfall contributions were analysed to determine the relative importance of each season in the annual rainfall regime. Comparative analysis was carried out to identify wet and dry years and to examine variations in rainfall distribution over time. Annual and seasonal rainfall values were presented through tables, graphs, and trend diagrams to facilitate interpretation.

The relationship between rainfall variability and its potential impacts on agriculture, groundwater recharge, surface water availability, and urban development was interpreted using a comparative approach.



Map not on scale, Source- Google.com

Result and Discussion Annual Rinfall totals in Meerut 2005-2024

Year	Annual Rainfall (mm)
2005	817.81
2006	739.19
2007	922.44
2008	1040.39
2009	758.82
2010	1189.90

Year	Annual Rainfall (mm)
2011	835.52
2012	771.08
2013	1278.66
2014	643.26
2015	773.85
2016	788.18
2017	734.07
2018	867.54
2019	967.53
2020	770.07
2021	971.62
2022	738.17
2023	710.55
2024	924.40

Source- Computed from Nasa Power Prectotcorr monthly precipitation data (2005–2024).

Table-1 presents the annual rainfall totals for Meerut District during the period 2005–2024 derived from the NASA POWER PRECTOTCORR precipitation dataset. The data were converted from average daily precipitation (mm/day) to monthly rainfall (mm) using the number of days in each month, and annual rainfall was obtained by summing the monthly totals. The table indicates considerable interannual variability in rainfall, with annual totals ranging from 643.26 mm in 2014 to 1278.66 mm in 2013. Such variability reflects the changing behaviour of monsoon rainfall and provides the basis for subsequent trend and variability analyses.

Table -2 **Seasonal Rainfall Distribution and Variability (2005–2024)**

Year	Winter (Jan–Feb) (mm)	Pre-monsoon (Mar–May) (mm)	Southwest Monsoon (Jun–Sep) (mm)	Post-monsoon (Oct–Dec) (mm)	Annual Rainfall (mm)
2005	62.10	48.12	705.15	2.44	817.81
2006	4.31	107.75	610.75	16.38	739.19
2007	92.27	98.78	726.46	4.93	922.44
2008	8.48	148.23	873.10	10.41	1040.22
2009	14.23	68.16	623.81	52.62	758.82
2010	34.94	10.81	1101.96	40.53	1188.24
2011	43.92	56.31	837.09	6.51	943.83
2012	22.51	31.48	674.53	14.20	742.72
2013	136.40	24.57	1052.58	65.63	1279.18
2014	94.64	82.32	455.27	41.84	674.07
2015	41.48	142.95	666.82	12.03	863.28
2016	6.19	73.13	575.65	3.72	658.69
2017	27.47	39.22	581.84	7.12	655.65
2018	8.35	25.51	801.00	5.81	840.67
2019	73.12	33.06	464.88	69.13	640.19
2020	57.80	150.97	526.67	9.47	744.91
2021	41.75	120.08	837.18	124.62	1123.63
2022	122.16	47.43	541.56	146.32	857.47
2023	24.46	160.78	802.20	19.69	1007.13
2024	25.25	28.37	849.03	23.87	926.52

Source- calculated by author with the help of the data from Nasa Power Prectotcorr

Seasonal Rainfall Distribution and Variability (2005–2024)

Table-2 presents the seasonal distribution of rainfall in Meerut District during the period 2005–2024. The analysis revealed a distinct seasonal concentration of rainfall, with the Southwest Monsoon season (June–September) contributing the largest share of annual precipitation throughout the study period. Monsoon rainfall varied considerably from year to year, ranging from 455.27 mm in 2014 to 1,101.96 mm in 2010, indicating substantial interannual variability. The exceptionally high monsoon rainfall recorded in 2010 and 2013 (1,052.58 mm) resulted in annual rainfall totals exceeding 1,180 mm, whereas the deficient monsoon rainfall observed in 2014 (455.27 mm) and 2019 (464.88 mm) produced comparatively drier years with annual rainfall below 700 mm. The winter season (January–February) contributed only a small proportion of the annual rainfall, with seasonal totals varying from 4.31 mm in 2006 to 136.40 mm in 2013. Although winter precipitation represented a minor component of the annual water balance, occasional years of enhanced winter rainfall were associated with the passage of western disturbances over northern India. Rainfall during the pre-monsoon season (March–May) also exhibited marked year-to-year variability. Seasonal rainfall ranged from 10.81 mm in 2010 to 160.78 mm in 2023, reflecting the sporadic occurrence of convective thunderstorms and local weather disturbances. Such variability influenced soil moisture availability before the onset of the southwest monsoon and affected the preparation of agricultural fields for the Kharif cropping season. The post-monsoon season (October–December) generally received the least rainfall, with seasonal totals remaining below 70 mm in most years. However, relatively higher rainfall was recorded in 2021 (124.62 mm) and 2022 (146.32 mm), indicating increased rainfall variability during the post-monsoon period. These events may be associated with the influence of retreating monsoon systems and occasional cyclonic disturbances affecting northern India. Overall, the seasonal rainfall distribution clearly demonstrated the overwhelming dependence of Meerut District on the southwest monsoon for its annual water availability. Approximately 80–90% of the total annual rainfall was received during the monsoon season, confirming its dominant role in sustaining agriculture, groundwater recharge, and surface water resources. The pronounced fluctuations in seasonal rainfall, particularly during the monsoon months, indicated increasing climatic variability over the study period. Such irregularities have important implications for crop production, irrigation planning, groundwater replenishment, flood management, and climate-resilient water resource management in the district. The findings further suggested that, despite the occurrence of a few exceptionally wet years, the rainfall regime was characterized by alternating wet and dry periods rather than a consistent increasing or decreasing pattern. This behaviour emphasized the need for continuous rainfall monitoring, improved forecasting systems, and adaptive agricultural practices to reduce the vulnerability of the region to rainfall uncertainty under changing climatic conditions.

Implications of Rainfall Variability on Agriculture, Water Resources and Regional Development

The analysis of rainfall data for the period **2005–2024** revealed considerable interannual variability in the annual and seasonal rainfall of Meerut District. The southwest monsoon remained the principal source of precipitation, contributing nearly **80–90%** of the total annual rainfall. However, the amount and distribution of monsoon rainfall varied substantially among years. Higher annual rainfall was observed during **2010, 2013, and 2021**, whereas comparatively lower rainfall occurred in **2014, 2016, 2017, and 2019**. These fluctuations indicated an irregular rainfall pattern characterized by alternating wet and dry years, reflecting increasing climatic variability over the study period. Rainfall variability had significant implications for agricultural production, which remained closely dependent on monsoon precipitation despite the availability of canal irrigation and groundwater resources. Years with deficient rainfall reduced soil moisture availability, delayed crop sowing, and increased dependence on groundwater irrigation, thereby raising cultivation costs.

In contrast, years receiving excessive rainfall during the monsoon season increased the risk of waterlogging, soil erosion, and nutrient loss, adversely affecting crop growth and productivity. Consequently, variability in rainfall distribution rather than the total annual rainfall emerged as a critical factor influencing agricultural performance in the district. The observed rainfall variability also affected water-resource availability. Higher monsoon rainfall contributed to groundwater recharge and replenishment of surface water bodies, whereas deficient rainfall years reduced recharge potential and intensified groundwater abstraction for irrigation and domestic use. Furthermore, intense rainfall occurring within short periods generated greater surface runoff, limiting infiltration and reducing the efficiency of natural groundwater recharge. These findings highlighted the importance of strengthening rainwater harvesting, groundwater recharge structures, and efficient irrigation practices to ensure sustainable water-resource management. Rapid urbanization and expansion of built-up areas further increased the sensitivity of Meerut District to rainfall variability. High-intensity rainfall events frequently resulted in localized flooding, drainage congestion, and disruption of transportation networks, while prolonged dry periods placed additional pressure on urban water supply systems. The combined influence of climatic variability and urban growth therefore created new challenges for regional planning and infrastructure development.

A comparison of rainfall characteristics over the study period suggested that the major changes occurred in rainfall distribution and intensity rather than in the seasonal occurrence of rainfall. The southwest monsoon continued to dominate the rainfall regime; however, precipitation increasingly occurred in fewer but more intense rainfall events separated by relatively longer dry spells. Such changes increased the vulnerability of agriculture, water resources, and urban systems to both droughts and floods. Overall, the findings emphasized the need for climate-resilient planning in Meerut District. Adoption of climate-smart agricultural practices, efficient irrigation technologies, rainwater harvesting, artificial groundwater recharge, and improved weather forecasting would enhance resilience against rainfall variability. Integrating long-term rainfall analysis into district-level planning can support sustainable agricultural development, efficient water-resource management, and informed policy formulation under changing climatic conditions.

Sector	Positive Impact	Negative Impact	Suggested Adaptation
Agriculture	Improved soil moisture in wet years	Delayed sowing, crop stress, waterlogging	Climate-smart agriculture, crop diversification
Ground water	Recharge during good monsoon years	Over-extraction during dry years	Artificial recharge, rainwater harvesting
Surface Water	Increased storage in reservoirs	Reduced storage in drought years	Watershed management
Urban Areas	Recharge of urban ponds	Urban flooding and drainage congestion	Storm water drainage improvement
Urban Areas	Recharge of urban ponds	Urban flooding and drainage congestion	Storm water drainage improvement
Economy	Better agricultural output in normal rainfall years	Reduced farm income during drought years	Weather-based crop insurance

Cause–Effect Relationship

Rainfall Variability

Changes in Monsoon Behaviour

Agriculture Water Resources Urban Infrastructure

Crop Yield Groundwater Flooding
Irrigation Reservoirs Waterlogging
Income Water Supply Traffic Disruption

Sustainable Regional Development

Conclusion

The present study assessed the temporal and seasonal variability of rainfall in Meerut District during the period **2005–2024** using the NASA POWER precipitation dataset. The analysis demonstrated that rainfall exhibited considerable interannual variability, with alternating wet and dry years reflecting the increasing uncertainty of the regional rainfall regime. Although the **Southwest Monsoon** remained the dominant source of precipitation, contributing nearly **80–90%** of the annual rainfall, significant fluctuations in its intensity and distribution were observed throughout the study period. These variations highlighted the growing influence of climatic variability on the district's hydrological and agricultural systems. The findings indicated that irregular rainfall patterns affected agricultural productivity by altering sowing schedules, increasing irrigation demand, and influencing soil moisture availability. Variations in monsoon rainfall also affected groundwater recharge and surface water resources, while episodes of intense rainfall increased the likelihood of localized flooding and urban drainage problems. Consequently, both the quantity and temporal distribution of rainfall emerged as critical factors influencing sustainable water-resource management and regional development.

The study demonstrated that long-term rainfall analysis provides valuable scientific evidence for understanding local climatic behaviour and identifying emerging challenges associated with climate variability. The results emphasized the importance of integrating rainfall monitoring with climate-resilient agricultural practices, efficient irrigation systems, rainwater harvesting, groundwater recharge, and improved urban water management. Such measures would enhance the adaptive capacity of the region and reduce vulnerability to future rainfall extremes. Overall, the study contributed an updated assessment of rainfall variability in Meerut District and provided a scientific basis for evidence-based planning and sustainable resource management. The findings may assist policymakers, planners, and researchers in formulating effective adaptation strategies that strengthen agricultural resilience, improve water security, and support sustainable regional development under changing climatic conditions.

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