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Geospatial Analysis of Rainfall Variability in the Trans-Saryu Region in Uttar Pradesh, India

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ABSTRACT

This study investigates the spatial and temporal variability of rainfall in the Trans-Saryu Region of Eastern Uttar Pradesh, India, using satellite-derived rainfall data from the Centre for Hydrometeorology and Remote Sensing (CHRS) and the Inverse Distance Weighting (IDW) interpolation technique. The analysis reveals a pronounced west-to-east gradient in rainfall distribution, with western districts experiencing lower rainfall compared to eastern districts. The change detection analysis highlights a dual climatic challenge: progressive aridity in the west and rainfall intensification in the east. The findings emphasize the need for area-specific adaptation measures, such as groundwater recharge and drought-proofing in the west, flood management in the east, and integrated water resource management in the central belt.

Figures : 03 References : 12 Table : 01

KEY WORDS : CHRS data, IDW interpolation, Rainfall variability, Spatial analysis, Temporal analysis, Trans-Saryu region

Introduction

Rainfall plays a pivotal role in shaping hydrological processes and strongly influences water resource availability, agriculture, and disaster management. Its distribution, however, is far from uniform; it exhibits pronounced spatial and temporal variability, particularly in the tarai regions where diverse topographical features and climatic influences interact.[4] Understanding rainfall variability in such landscapes is essential not only for sustainable agricultural planning but also for effective water resource management and flood risk reduction[5,7,11]. The Trans-Saryu region, characterized by its relatively flat terrain yet subjected to varying climatic influences, presents a unique case for examining rainfall distribution patterns. A systematic analysis of rainfall variability in this region can provide valuable insights to support sustainable development and climate resilience initiatives.

The growing reliance on satellite-based precipitation products has transformed rainfall research, particularly in areas where ground-based monitoring networks are inconsistent[6]. The Centre for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (https:// chrsdata.eng.uci.edu/) provides high-resolution product, with a spatial resolution of 0.04° × 0.04° (approximately 4 km × 4 km), delivers near-real-time global precipitation estimates between the latitudes 60°S to 60°N. Such coverage makes it particularly advantageous for regions like the Trans-Saryu, where dense rain-gauge networks

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TABLE-1 : District-wise Change in Average Annual Rainfall (2004–2024)

District	Change in Rainfall (mm)	Category(Key Concern)
Bahraich	–310 to –221	Severe Decline(Increasing aridity, risk of drought)
Shrawasti	–310 to –221	Severe Decline(Sharp reduction in rainfall, risk of drought)
Gonda	–172 to –124	Moderate Decline(Declining rainfall, reduced soil moisture)
Balrampur	–124 to –81	Moderate Decline(Transition zone, drought risks emerging)
Basti	–40 to –3	Slight Decline(Near stable, vulnerable to seasonal variability)
Sant Kabir Nagar	–40 to –3	Slight Decline(Stable but sensitive to rainfall fluctuations)
Siddharth Nagar	–3 to +40	Slight Increase(Transitional zone, mixed drought/flood risks)
Maharajganj	–40 to +40	Stable(Minor changes)
Kushinagar	+122 to +214	Significant Increase(Intensified rainfall, inundation risk)
Gorakhpur	+122 to +214	Significant Increase(Sharp rise in rainfall, increased flood risks)
Deoria	+122 to +214	Significant Increase(Intensified rainfall, flood stress)

Source: Computed from satellite data of 2004-2024

are absent.

To translate the estimates into meaningful spatial patterns, interpolation techniques are often used in hydrology, climatology, and environmental sciences. These methods create continuous surfaces from discrete data points, allowing researchers to recognize heterogeneity and regional differences in rainfall. Among these, the Inverse Distance Weighting (IDW) technique has become a popular approach because of its simplicity and effectiveness.[7] Studies have indicated that the accuracy of IDW depends on parameters such as the radius of influence and the power value used in distance weighting. However, the performance of IDW is not universal; it is influenced by grid resolution and the underlying physiographic characteristics of the study area. In mountainous catchments, for instance, interpolation accuracy is more sensitive to power values than grid size.[3] Recent advancements, such as dual IDW methods, further refine its application by incorporating data-to-data correlations and locally varying parameters, thereby reducing error and better capturing localized rainfall dynamics.[8]

Considering these developments, assessing rainfall variability in the Trans-Saryu region using CHRS satellite data and the IDW interpolation method provides a solid framework for filling gaps in observational networks. This approach ensures accurate spatial rainfall mapping, supporting water management, agricultural decisions, and disaster preparedness in this climate-sensitive area[1].

Aim of the Study

The study aims to investigate the spatial and temporal variability of rainfall in the Trans-Saryu region to generate reliable rainfall distribution patterns, compare historical and recent trends, and provide insights for sustainable resource management and climate adaptation strategies.Despite the availability of rainfall studies in Uttar Pradesh, limited research focuses on the Trans-Saryu region using high-resolution satellite data. Ground station scarcity restricts spatial analysis. This study bridges the gap by employing CHRS data and IDW interpolation in ArcGIS to generate reliable rainfall variability patterns for regional planning.

Objectives of the Study

1. To analyse spatial and temporal variations in rainfall across the Trans-Saryu region using CHRS satellite-based datasets.
2. To generate averaged rainfall maps for the baseline period (2004–2009) and the recent period (2020–2024) to minimize annual variability and enable meaningful comparison.
3. To apply the Inverse Distance Weighting (IDW) interpolation technique in ArcGIS for developing continuous spatial surfaces of rainfall distribution.
4. To compare past and recent rainfall scenarios to identify significant trends, shifts, or anomalies in rainfall patterns.

Study Area -Trans-Saryu Region

The Trans-Saryu region mainly covers 11 districts of the Northern East Gangetic Plain. Its topography is very flat and low-lying, shaped by sediment from the Saryu, Ghaghara, and Ganges River systems over thousands of years. The elevation varies little, usually between 50 and 100 meters above sea level, creating a gentle slope toward the southeast[9]. The region's water system is dominated by the Saryu River and its network of tributaries and distributaries, making the area prone to flooding during the monsoon season. The river channels often change course over time, leaving behind old oxbow lakes and tals (seasonal wetlands), which are common features of the terrain[10].

The Trans-Saryu region experiences a monsoon-influenced humid subtropical climate. This region experiences considerable spatial variability in rainfall distribution, making it an ideal case study for understanding complex precipitation patterns. The annual rainfall averages between 900 mm to 1,200 mm, mostly received from the southwest monsoon. Rainfall is highly variable in its spatial distribution and temporal pattern, often occurring in heavy, intense downpours. This variability is a critical climatic feature, as both excessive rainfalls leading to floods and prolonged breaks leading to drought can occur within the same season. Agricultural practices in the area range from rain-fed cropping systems to irrigated agriculture, further emphasizing the importance of accurate rainfall information for making water management decisions

Methodology

The present study employed a geospatial approach to analyse rainfall variability in the Trans-Saryu region using satellite-based rainfall data and spatial interpolation techniques within the ArcGIS environment. The methodology involved three major steps: data acquisition and preprocessing, temporal aggregation of rainfall records, and geospatial interpolation for spatial pattern analysis.

Data Source and Temporal Framework

Rainfall data were obtained from the online portal of the Centre for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine. The CHRS Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) system provides high-resolution gridded rainfall datasets with a spatial resolution of 0.04° × 0.04° (approximately 4 km). This fine resolution makes it suitable for regional scale hydrological and climatological studies, particularly in data-scarce areas like the Trans-Saryu region.For this study, two distinct temporal windows were selected to enable comparative assessment. The first data set represented the baseline period of 2004–2009, while the second dataset corresponded to the recent period of 2020–2024.To minimize the influence of inter-annual fluctuations and extreme events, average annual rainfall values were computed for each period.

This temporal averaging enabled a more reliable comparison of long-term rainfall conditions, capturing broader climatic trends rather than short-term anomalies.

Data Pre-processing

The satellite-derived rainfall data were downloaded in TIFF format,which is compatible with ArcGIS. Spatial subsets corresponding to the administrative boundaries of the Trans-Saryu region were extracted using a mask layer. The data were then organized into annual and multi-year averages for the two chosen periods (2004–2009 and 2020–2024). This ensured uniformity in the data sets before applying spatial interpolation.

Interpolation Technique

Spatial interpolation was performed using the Inverse Distance Weighting (IDW) technique, which is available in ArcGIS. IDW assumes that the value at an unsampled location could be estimated as a weighted average of nearby sampled values, with closer points exerting greater influence. The method was chosen due to its demonstrated reliability in hydrological applications and its capacity to generate smooth, continuous rainfall surfaces. The interpolation was performed separately for the two temporal data sets, creating gridded rainfall distribution maps for both the baseline and recent periods.

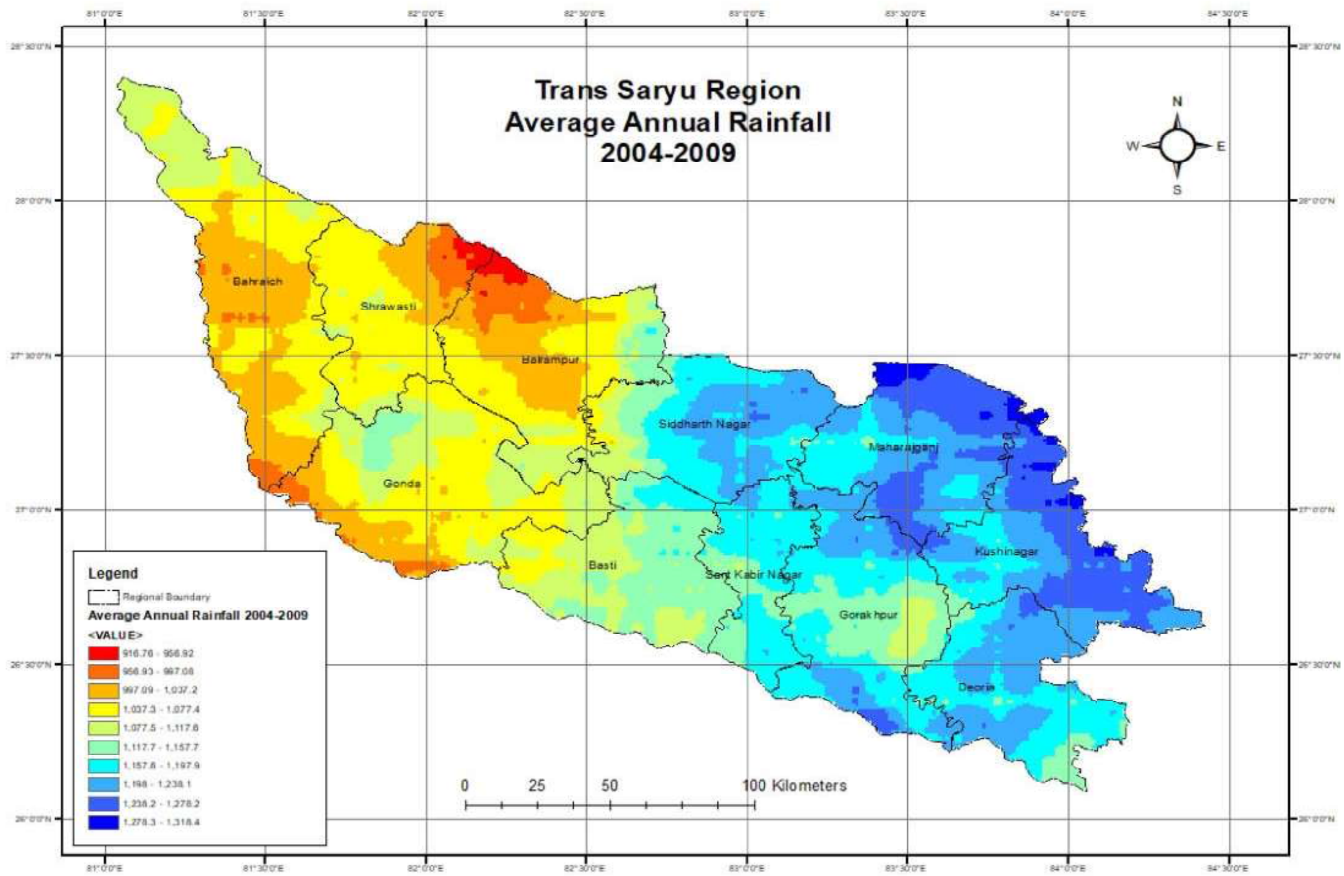

Fig. 1 : Source: Computed from (PERSIANN) Satellite-based Annual Rainfall Data

Comparative Analysis

The interpolated average annual rainfall maps were analysed to identify spatial heterogeneity and shifts in rainfall distribution between the two time frames. By comparing the baseline average (2004–2009) with the recent average (2020–2024), the study was able to highlight long-term changes in rainfall intensity and spatial variability across the Trans-Saryu region. This comparison was critical for assessing emerging rainfall trends and evaluating their implications for agriculture, water management, and climate adaptation strategies in the region.

Results and Discussion

Spatial Variation in Average Annual Rainfall during 2004–2009

The spatial variation of average annual rainfall in the Trans Saryu region during 2004–2009 highlights significant geographical differences across districts (Fig.1). The map depicts a clear west-to-east and northwest-to-southeast transition in rainfall distribution, with districts in the western and northwestern parts receiving comparatively lower rainfall, while the eastern and southeastern districts experience higher precipitation levels. This pattern provides valuable insights into the hydrological regime and agricultural potential of the region.

In the western zone, districts such as Bahraich, Shrawasti, and Gonda recorded relatively lower average annual rainfall. The average annual rainfall amount in these areas generally ranges between 916 mm and 1,037 mm, which places them in the lowest category of rainfall observed across the Trans Saryu region. The brown, orange, and yellow shades dominating these districts on the map confirm a semi-arid tendency when compared to the rest of the region. Such conditions likely create water stress for rainfed agriculture, particularly for crops like paddy that demand high water inputs. Farmers in these areas might have had to rely more heavily on irrigation infrastructure or adapt to less water-intensive crops.

Moving towards the central districts, including Balrampur, Basti, and Sant Kabir Nagar, there is a noticeable transition in rainfall intensity. Balrampur shows some of the highest rainfall concentrations in its northern zone, where the rainfall amount surpasses 1,198 mm annually. This contrasts sharply with its southern counterparts, where rainfall is more moderate. Similarly,

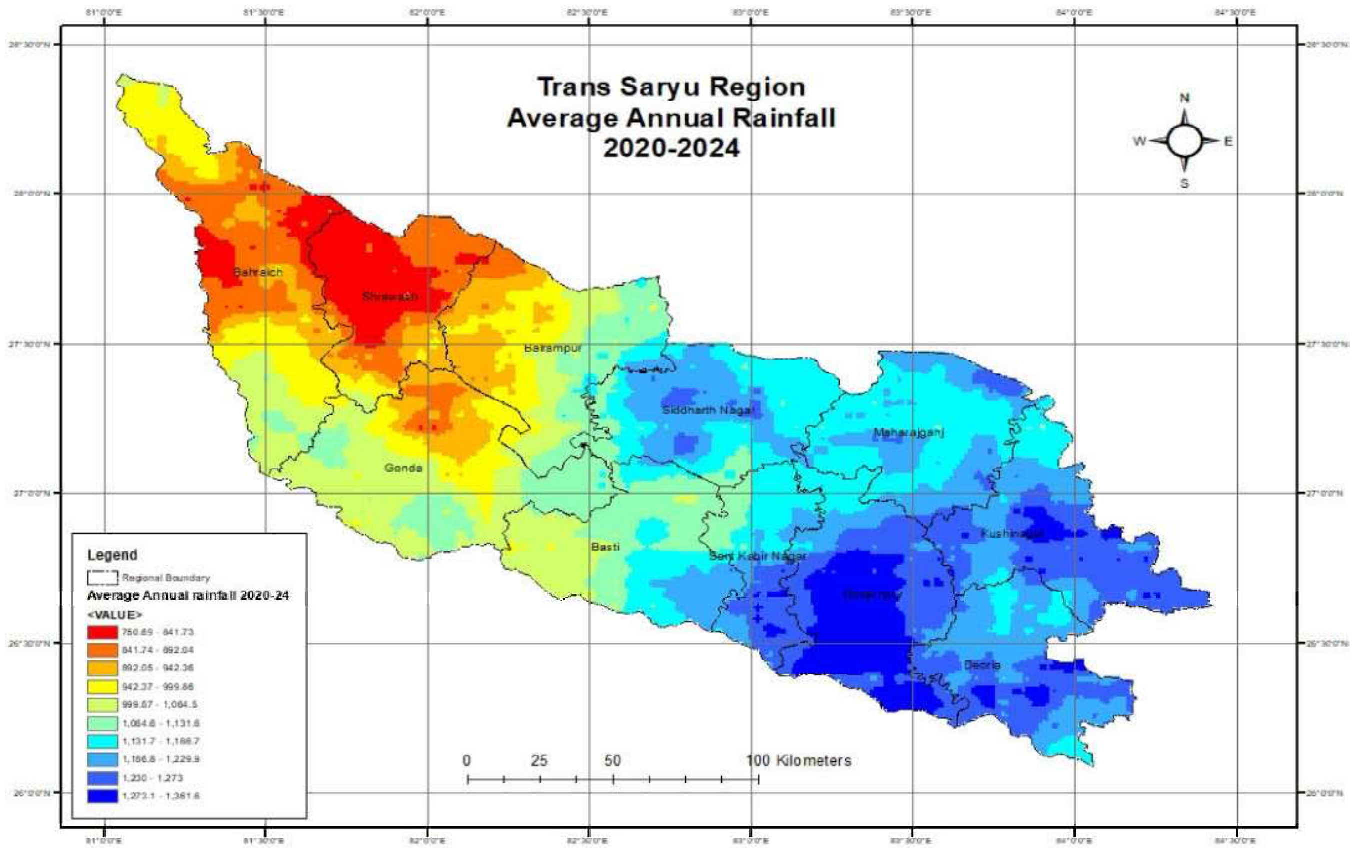

Fig. 2 : Source: Computed from (PERSIANN) Satellite-based Annual Rainfall Data

Basti and Sant Kabir Nagar exhibit moderate levels of rainfall, mostly between 1,077 mm and 1,198 mm. This intermediate rainfall zone acts as a climatic buffer between the drier western districts and the wetter eastern belt. The variation within Balrampur itself suggests localized influences of terrain and monsoon circulation, making it a district of contrasting rainfall patterns.The eastern sector of the Trans Saryu region, comprising Siddharth Nagar, Maharajganj, Kushinagar, Gorakhpur, and Deoria, experiences the highest rainfall during the period. These districts are shaded in light blue to dark blue tones, indicating average rainfall between 1,157 mm and 1,315 mm

Maharajganj and Kushinagar, in particular, stand out as high-rainfall zones, consistently crossing 1,200 mm annually. The abundance of rainfall in these districts supports water-intensive agricultural practices and contributes significantly to groundwater recharge. However, this also brings challenges, such as frequent waterlogging, floods, and soil erosion during heavy monsoon spells. Gorakhpur, located centrally in the eastern part, experiences slightly moderate rainfall compared to Maharajganj and Kushinagar, but still significantly higher than the western districts. Deoria, positioned in the southeast, also records high rainfall levels, reinforcing the eastward gradient of precipitation.

The spatial variation indicates a distinct west-to-east gradient, where rainfall increases progressively across the region. This gradient reflects the influence of the southwest monsoon winds, which weaken as they move westward after entering eastern Uttar Pradesh. The higher rainfall in the eastern districts could also be attributed to proximity to the Himalayan foothills and local climatic conditions that enhance precipitation. Such spatial disparities in rainfall distribution play a critical role in shaping cropping patterns, groundwater availability, and overall vulnerability to climatic risks across the region.

Spatial Variation of Average Annual Rainfall: 2020–2024

The spatial variation of average annual rainfall across the Trans Saryu region during 2020–2024 indicates significant heterogeneity, with a marked west-to-east gradient similar to the earlier period, but with notable shifts in magnitude and spatial concentration (Fig. 2). The figure shows that the western districts, particularly Bahraich, Shrawasti, and parts of Balrampur, experienced considerably lower rainfall levels compared to their eastern counterparts. The average annual rainfall

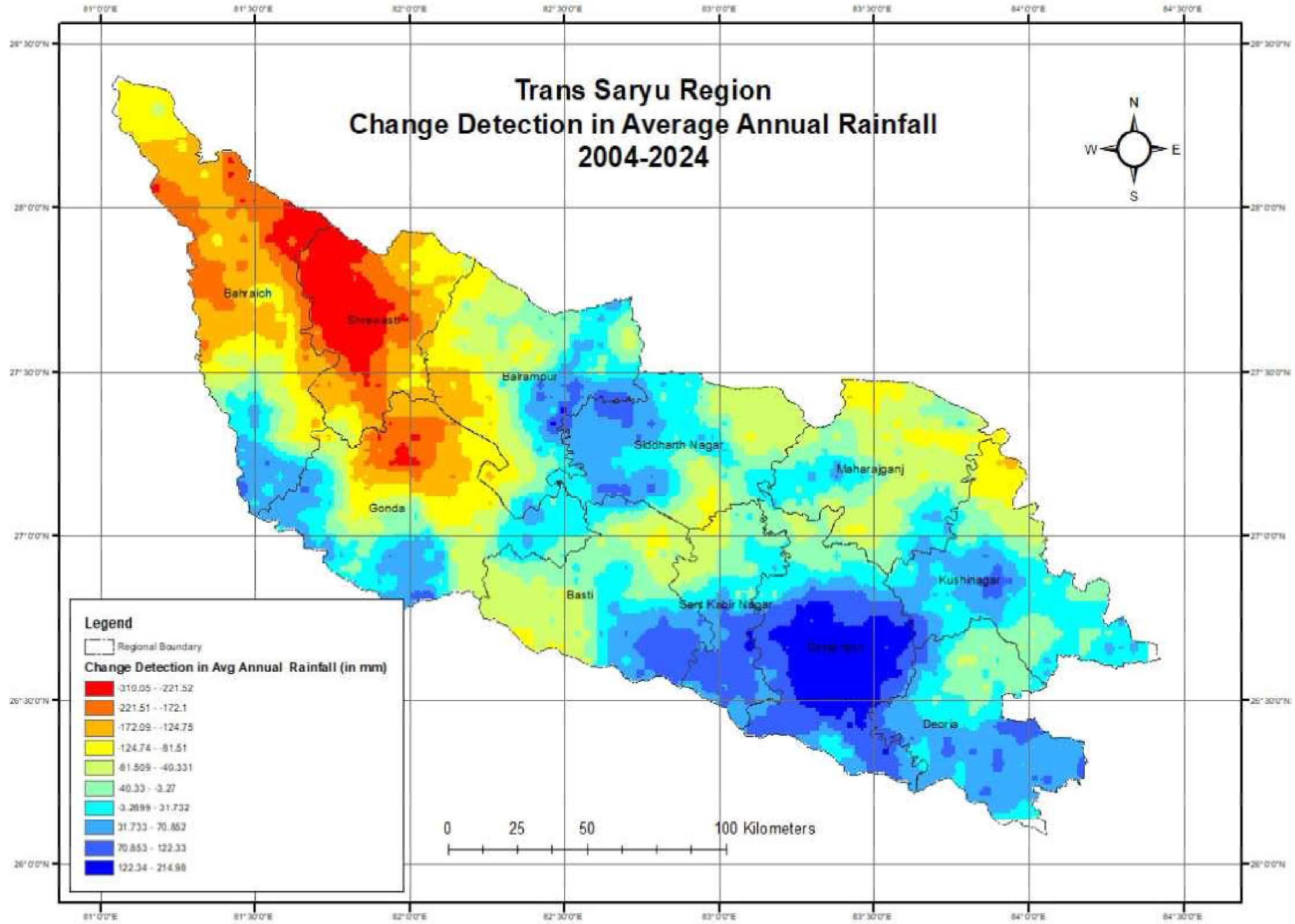

Fig. 3 : Source: Computed from (PERSIANN) Satellite-based Annual Rainfall Data

in these areas now falls within 750–950 mm, representing the lowest category in the region. The red and orange zones dominating this part of the map highlight a worrying trend of increasing dryness in western districts. This suggests a strengthening of the rainfall deficit that was already present in 2004–2009, when these same districts received around 916–1,037 mm of rainfall. The current reduction points toward a potential long-term drying trend in the western Trans Saryu, posing challenges for agriculture and water resource management.

In contrast, central districts such as Gonda, Balrampur, and Basti show intermediate rainfall levels, ranging between 950–1,150 mm. These rainfall amount, although moderate, represent a relative decline in rainfall compared to the earlier period (1,037–1,198 mm).

The yellow and light green shades indicate that these districts form a transitional belt between the low-rainfall western zone and the high-rainfall eastern zone. The overall rainfall decline in these central districts suggests increased vulnerability to rainfall variability, especially for farmers dependent on the kharif paddy crop. Balrampur is particularly notable, as it displayed higher rainfall patches in its northern part during 2004–2009, but in the recent period, these high-rainfall areas have contracted, indicating a shift in rainfall concentration.

The eastern districts, comprising Siddharth Nagar, Maharajganj, Kushinagar, Gorakhpur, and Deoria, continue to experience relatively high rainfall. The rainfall in these districts now ranges between 1,150–1,360 mm, as indicated by the green, blue, and deep blue shades. While this continues the historical trend of high rainfall in the east, a comparison with 2004–2009 reveals subtle changes.

Previously, districts like Maharajganj, Kushinagar, and Deoria consistently received 1,198–1,315 mm of rainfall. Now, rainfall values have expanded slightly upward to 1,273–1,361 mm in some pockets, especially in Deoria and southern Gorakhpur. This indicates localized intensification of rainfall events, which may be linked to stronger monsoon systems or climate variability. While beneficial for water availability and irrigation potential, such intensification increases the risks of flooding, waterlogging, and soil erosion.

Absolute Change Detection in Average Annual Rainfall

The spatial change detection of average annual rainfall in the Trans-Saryu region between 2004 and 2024 reveals striking patterns of variability, with distinct west–east contrasts. Figure 3 highlights areas of decline in rainfall in the western districts and increases in the eastern and southern districts, pointing to a shift in the hydrological regime that has significant implications for water management and agriculture

In the western districts such as Bahraich and Shrawasti, the figure shows the most severe negative change, with rainfall reductions ranging between –310 mm and –221 mm (Table-1). These areas fall under the high-decline category, signalling the onset of progressive aridity. Such a decline will likely intensify water stress, reduce soil moisture availability, and adversely affect rainfed agriculture. Similar but slightly lower declines are observed in Gonda, where reductions range from –172 mm to –124 mm, placing it in the moderate-decline zone. These trends confirm a westward shift toward drier conditions, requiring urgent adaptation measures such as drought-resistant cropping systems and irrigation expansion.

In contrast, the eastern districts present an opposite trend. Deoria, Gorakhpur, and Kushinagar show substantial positive changes, with increases of +122 mm to +214 mm. Gorakhpur, in particular, demonstrates significant intensification of rainfall, which could aggravate the district's existing flood and waterlogging risks.

Similarly, Deoria and Kushinagar, already known for their high rainfall, are becoming more vulnerable to seasonal flooding, drainage congestion, and associated crop damage. These districts represent zones of rainfall intensification, where adaptation will require robust flood-control infrastructure, improved drainage, and climate-resilient agricultural practices.

The central transitional belt, comprising Balrampur, Basti, Sant Kabir Nagar, and Siddharth Nagar, shows mixed patterns of both slight decline and marginal increases. For instance, parts of Balrampur register moderate declines (–124 mm to –81 mm), while Basti and Sant Kabir Nagar indicate smaller fluctuations close to stability (–40 mm to –3 mm). Siddharth Nagar displays minor increases in localized zones, highlighting its position as a transitional buffer between the arid west and flood-prone east. This belt remains particularly vulnerable as it faces both drought and flood risks, depending on seasonal variability. Integrated water management is therefore critical in this zone.

Interestingly, Maharajganj reflects a moderate to stable pattern, with changes ranging mostly between –40 mm and +40 mm. This relative stability compared to neighbouring districts suggeststhat rainfall variability here has been less pronounced, although its proximity to high-rainfall areas like Kushinagar and Deoria may still expose it to indirect flood impacts.

Hence, the spatial change detection for 2004–2024 underlines a dual climatic reality: While the west is becoming drier, the east and south are witnessing rainfall intensification. This divergence in rainfall dynamics poses contrasting challenges—aridity threatens agricultural productivity in the west, while excessive rainfall increases flood hazards in the east. The transitional districts in the centre face compounded risks and demand flexible strategies that address both extremes. The findings strongly call for district-specific adaptation measures: groundwater recharge and drought-proofing in the west, flood management in the east, and integrated resource management in the central belt. Without such targeted interventions, the changing rainfall regime could exacerbate vulnerabilities and undermine sustainable development in the Trans-Saryu region.

Conclusion and Recommendations

This study effectively examined the spatial heterogeneity and temporal variability of rainfall in the Trans-Saryu region with progressive aridity in the western districts and intensifying rainfall in the eastern districts, which requires district-specific policy interventions. In the West, priority should be given to strengthening irrigation infrastructure, adopting drought-tolerant cropping systems, and enhancing groundwater recharge mechanisms. Conversely, in the east, strategies must focus on flood control, drainage improvement, and the promotion of resilient agricultural practices. The central transitional belt, which faces exposure to both drought and flood risks, necessitates an integrated water management approach.

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