

Research Article

Spatial-Temporal Variability of Rainfall over Chitwan District, Nepal

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Abstract

This study analyzes rainfall data (2014–2024) from 10 meteorological stations across Chitwan District to assess spatial-temporal variability. Monsoon (June–September) contributes 78% of annual rainfall, with peaks in July (mean: 435 mm). Pre-monsoon (March–May), post-monsoon (October–November), and winter (December–February) contribute 15%, 4.5%, and 2.5%, respectively. Spatial analysis reveals higher rainfall in northern hills (e.g., Madi: 2,150 mm/yr) versus southern plains (e.g., Bharatpur: 1,400 mm/yr). A significant decreasing trend (-0.82 mm/yr) in annual rainfall was observed. Mann-Kendall tests show 8 stations with declining trends (2 significant). These findings highlight climate vulnerability in a key agricultural region. This study investigates the spatial-temporal variability of rainfall across Chitwan District, Nepal, over the period 2014–2024 using data from ten ground-based meteorological stations. Seasonal and annual rainfall distributions were analyzed to assess long-term changes in precipitation patterns. The results indicate pronounced intra-annual and inter-annual variability, with July recording the highest mean monthly rainfall (644.6 mm) and November the lowest (7.9 mm). The monsoon season (June–September) accounted for approximately 83% of the total annual precipitation, followed by the pre-monsoon (10.7%), post-monsoon (4.1%), and winter (2.2%) seasons. Spatial interpolation using the Inverse Distance Weighted (IDW) method revealed significant heterogeneity in rainfall distribution, with southern forested regions such as Madi and Kalika consistently receiving higher rainfall compared to northern and urban municipalities like Bharatpur and Khairahani. Trend analysis using the non-parametric Mann-Kendall test and Sen's slope estimator identified a statistically significant decreasing trend in annual rainfall in several central and northern stations, with an average annual decline of 1.03 mm/year across the district. These findings underscore the increasing hydrological vulnerability of Chitwan's lowland ecosystems and emphasize the need for region-specific water resource planning and climate adaptation measures.

Keywords

Rainfall Variability, Monsoon, Spatial Analysis, Trend Detection

1. Introduction

Rainfall plays a critical role in shaping hydrological regimes, agricultural productivity, and ecological health in monsoon-dominated regions such as Nepal. The seasonal and inter-annual variability of rainfall is of particular concern in

districts like Chitwan, where the local economy, food security, and biodiversity depend heavily on consistent monsoon activity. In the context of ongoing climate change, understanding rainfall variability has become an essential scientific and

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Received: 4 October 2025; **Accepted:** 14 October 2025; **Published:** 22 November 2025



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policy issue [8].

Located in the Inner Terai of central Nepal, Chitwan District spans an area of approximately 2,218 km² and features diverse topography—from the lowland floodplains to the Chure Hills—making it susceptible to both drought and flood hazards. The district experiences a humid subtropical climate, and historically, over 80% of its annual rainfall is concentrated during the monsoon months (June to September). However, recent climatic patterns suggest significant variability in both the temporal distribution and spatial concentration of rainfall [3, 4].

Chitwan's location at the interface between the Siwalik Hills and Terai plains makes it a rainfall-sensitive zone. Fluctuations in the South Asian monsoon system are driven by large-scale phenomena such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole, and Pacific Decadal Oscillations [10, 24]. These interactions alter atmospheric pressure gradients and moisture flows, leading to inter-annual differences in monsoon onset, intensity, and duration. For example, strong El Niño events have been linked to weakened monsoons and reduced precipitation in Nepal, including in Chitwan [23].

Regional-scale analyses across South Asia have also demonstrated the variable performance of General Circulation Models (GCMs) in simulating seasonal monsoon rainfall, highlighting the challenges of accurate prediction in complex terrains like Nepal [1]. Comparative rainfall studies in nearby regions, such as the Kathmandu Valley, have shown similar inter-annual and spatial variability, reflecting the influence of local topography and climatic drivers [9].

The district is also experiencing rapid urbanization and land-use change, particularly around Bharatpur Metropolitan City, potentially influencing local convective rainfall processes and microclimates. In contrast, vegetation–climate feedback mechanisms may allow for more stable rainfall regimes in protected and wooded areas like the Madi region and Chitwan National Park [7].

Despite these dynamics, few studies have examined the long-term rainfall trends in Chitwan District using spatially distributed station-level data, especially over the past decade. This study fills this knowledge gap by systematically analyzing rainfall data from 2014 to 2024, collected from ten meteorological stations across Chitwan. It examines both seasonal and annual patterns and investigates long-term trends using robust statistical models including the Mann–Kendall trend test and Sen's slope estimator. Additionally, Geographic Information System (GIS)-based spatial analysis is employed to reveal regional disparities in rainfall distribution.

Given Chitwan's critical role as a biodiversity hotspot, agricultural production zone, and urban growth corridor, the findings of this study have implications for climate adaptation, disaster risk reduction, and water resource management. The emphasis on recent data (2014–2024) ensures that the analysis reflects contemporary climate realities, contributing to informed decision-making at local and provincial levels.

2. Literature Review

One important aspect of the monsoon-driven climate in South Asia is the fluctuation of rainfall. The importance of terrain and climate zones in Nepal's rainfall patterns, especially in the Terai regions like Chitwan, was highlighted by Shrestha et al. [18] and Kansakar et al. [12]. High spatial variability, even across small distances, was noted by Nayava [16]. According to Baidya et al. [5] and Bohlinger and Sorteberg [7], there has been an increase in precipitation extremes, which may be related to changes in land use and urbanization [13]. Bagale et al. [3, 4] discovered a correlation between ENSO events and declining monsoon trends. In a broader context, similar findings in Bangladesh and India [2, 21] corroborated the results of Kumar et al. [14] and Taxak et al. [22], who observed weaker monsoons as a result of climate warming.

Sen's slope and the Mann–Kendall test are two popular trend detection techniques for rainfall analysis, especially in complex and data-poor terrains [15, 17]. Precipitation patterns exhibit notable spatial variation due to the nation's topographical diversity. This micro-scale variability was originally brought to light by Nayava [16], who observed that Nepal's rainfall distribution is extremely unequal even over short distances, especially in transitional areas like the Inner Terai. Later research by Kansakar et al. [12] confirmed this heterogeneity, indicating that the main factors influencing Nepal's precipitation regime, particularly during the monsoon season, are orographic lifting and topographic gradients.

Shrestha et al. [18] investigated the link between large-scale climate factors and long-term precipitation changes in the Nepal Himalayas. El Niño years with notable monsoon weakening were detected by their analysis, which also found links between ENSO phases and monsoon variability. These results were further supported by Sigdel and Ikeda [20], who found that Nepal's monsoon can be partially predicted using international indicators due to the high correlation between interannual rainfall variability over Nepal and tropical Pacific sea surface temperatures.

One of the main concerns now is the escalation of precipitation extremes. Extreme rainfall events have increased statistically significantly, particularly in central and eastern Nepal, according to Baidya et al. [5]. Bohlinger and Sorteberg [7] corroborated this finding by examining station-based and gridded data and discovering an upward trend in rainfall extremes across Nepal, especially in lowland areas like Chitwan. According to their findings, urbanization and deforestation, which modify surface energy and moisture fluxes, are partially to blame for these changes. Their projections further suggest that future climatic scenarios will increase the risk of flash floods in urbanizing areas.

The influence of ENSO on monsoon fluctuations is still a major area of study. A thorough examination of the Southern Oscillation Index (SOI) and its relationship to monsoon deficits in Nepal was carried out by Bagale et al. [3, 4]. According

to their findings, during poor monsoon years, there was a significant inverse relationship between SOI and monsoon rainfall. They discovered that positive SOI phases (El Niño) were frequently accompanied by significant monsoon deficits in Nepal; this pattern is likely to continue and intensify as a result of global warming. Their future projections indicate that the frequency of droughts will increase during ENSO years, particularly in the Terai region.

The regional rainfall behavior observed in Chitwan is consistent with global studies showing strong spatial heterogeneity of precipitation trends, such as those reported for the Valencia region in East Spain, which revealed significant local differences in rainfall variability [9]. Likewise, GCM-based analyses have demonstrated that monsoon predictability depends heavily on regional topography and model resolution, reinforcing the importance of high-resolution climate studies for Nepal [1].

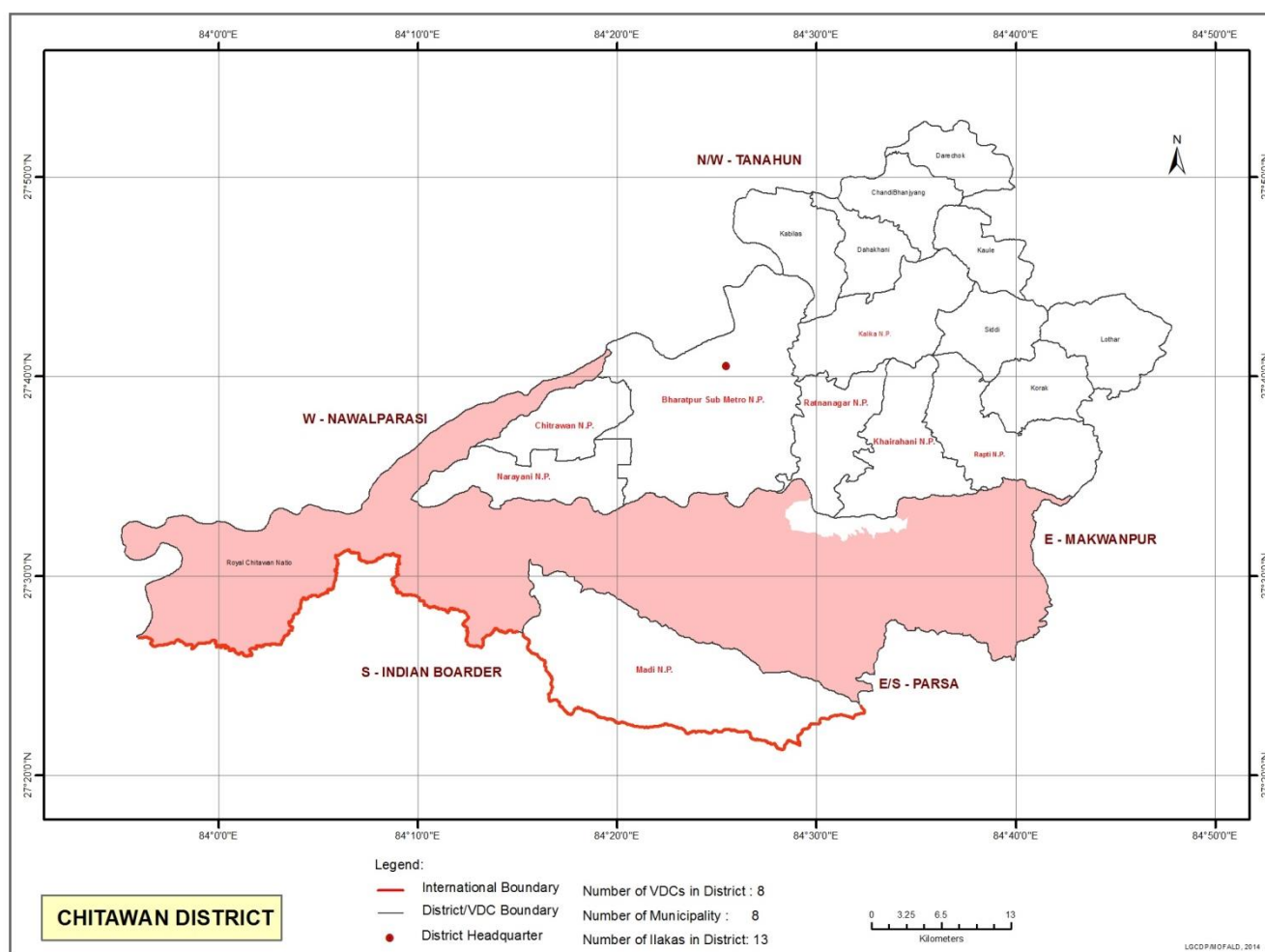
Research on Nepal's highlands has advanced, but areas of the Inner Terai, such as Chitwan, are still poorly understood.

By using robust statistical techniques on rainfall data spanning ten years, this study seeks to close that gap and provide information essential for water management and climate adaptation.

3. Methods and Data Source

3.1. Study Area

Chitwan District is located in the south-central part of Nepal, situated between latitudes 27°21' and 27°52' N and longitudes 83°54' and 84°48' E, covering an area of approximately 2,218 km² [15]. The district is bordered by the Mahabharat Range in the north and the Chure Hills in the south [16]. Chitwan's topography comprises flat alluvial plains, river valleys, and forested regions, making it a hydrologically diverse and ecologically significant area [17].



Source: LGCDP/MOFALD, 2014

Figure 1. Map Chitwan District.

The climate of Chitwan is categorized as humid subtropical, characterized by distinct wet and dry seasons [18]. The region receives the majority of its rainfall during the monsoon period, from June to September, which contributes approximately 80–85% of the total annual precipitation [19]. The remaining months experience irregular rainfall, including pre-monsoon showers from March to May, occasional post-monsoon precipitation in October and November, and light winter rainfall

between December and February [20]. The rainfall distribution across Chitwan is significantly influenced by the orographic effects of surrounding hills and forest cover, particularly in regions such as Madi, Meghauli, and Kalika [21]. The Mean Annual Rainfall and Spatial Distribution Map is illustrated in Figure 13, and their detailed descriptions are provided in Tables 1 & 2.

Table 1. List of Meteorological Stations Used in This Study (Chitwan District, 2014–2024).

Year	Bharatpur	Madi	Meghauli	Khairahani	Kalika
2014	2174.5	2030.1	2110.1	1941.3	1878.2
2015	2079.3	2136.3	1886.3	2223.4	1992.0
2016	2197.2	1813.0	2018.3	1916.9	2030.9
2017	2328.5	1841.3	2116.6	2131.3	2258.6
2018	2064.9	2015.7	1927.4	1806.0	2151.5
2019	2064.9	1948.1	2156.4	1900.8	1835.5
2020	2336.9	2147.1	2009.9	2129.5	2148.6
2021	2215.1	1963.8	2056.2	2210.8	2042.2
2022	2029.6	1888.2	2009.7	2125.7	1998.5
2023	2181.4	2319.8	2377.8	2082.7	2191.8
2024	2030.5	2066.1	2098.0	2054.8	2254.6

Table 2. List of Meteorological Stations Used in This Study (Chitwan District, 2014–2024).

Year	Ratnanagar	Rapti	Ichchhakamana	Devnagar	Simalta
2014	2239.7	2089.2	2055.1	2020.5	2064.8
2015	1974.1	2250.5	2113.8	2177.0	1887.7
2016	2053.6	2154.2	1801.9	2114.6	2036.9
2017	2149.7	2003.2	2067.0	2245.3	2048.6
2018	2246.3	2154.2	2153.6	1994.7	1979.7
2019	2028.1	2330.7	2321.7	2050.9	2075.8
2020	2072.2	2094.6	2022.3	2041.2	2160.6
2021	1934.0	2334.7	1978.7	1880.5	2382.9
2022	1920.6	1707.0	2024.7	2144.4	2126.2
2023	2221.9	2223.3	2237.3	2139.2	2138.6
2024	2303.4	2113.1	2149.3	2100.8	2088.8

Source: DHM (<https://www.dhm.gov.np/>)

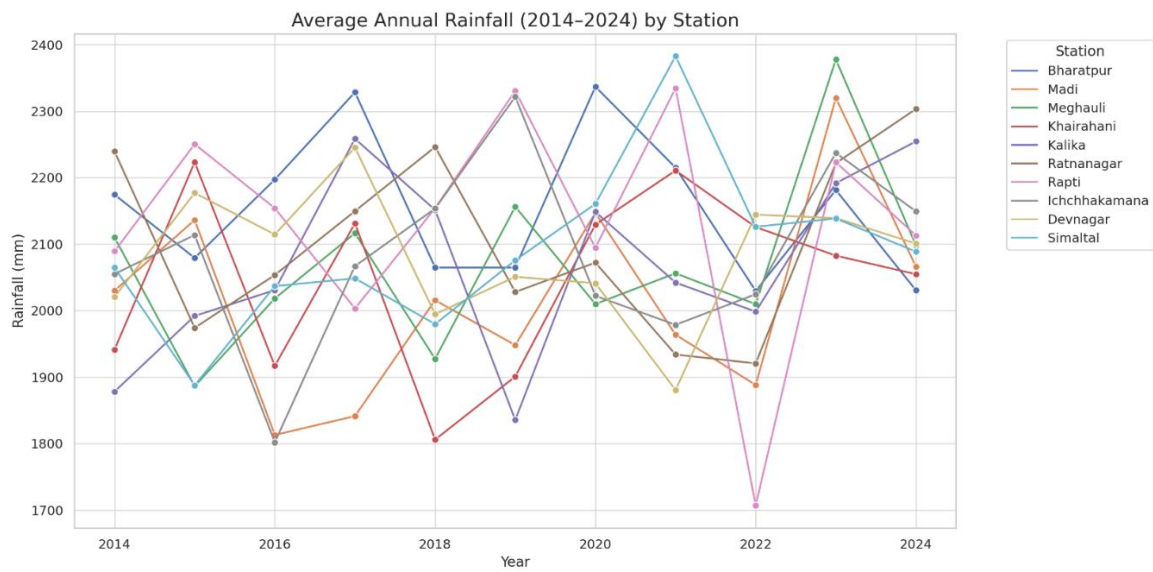


Figure 2. Average Annual Rainfall by station.

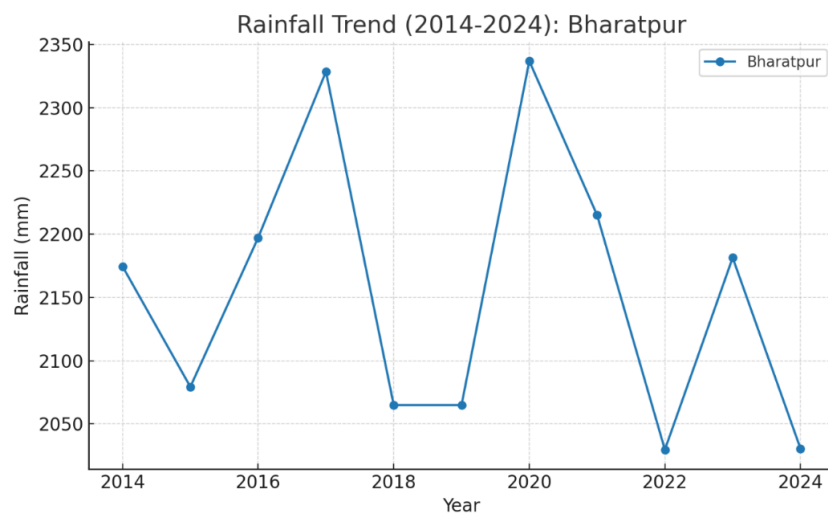


Figure 3. Average Annual Rainfall in Bharatpur station.

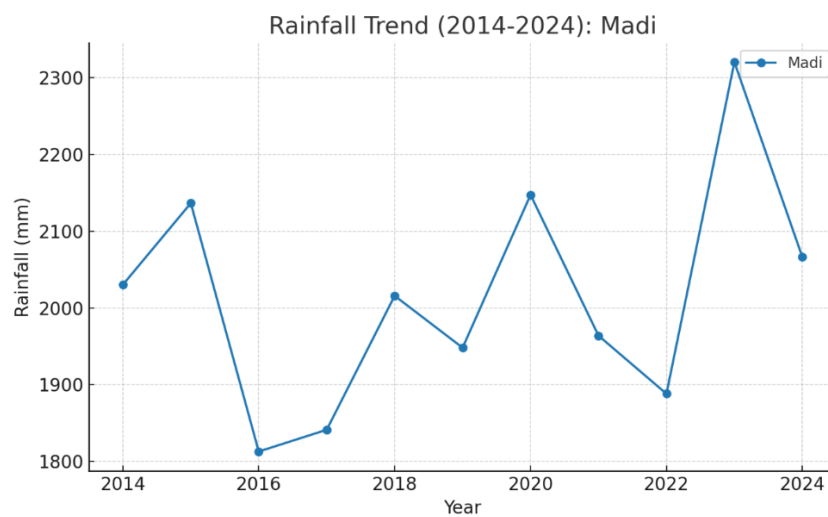


Figure 4. Average Annual Rainfall in Madi station.

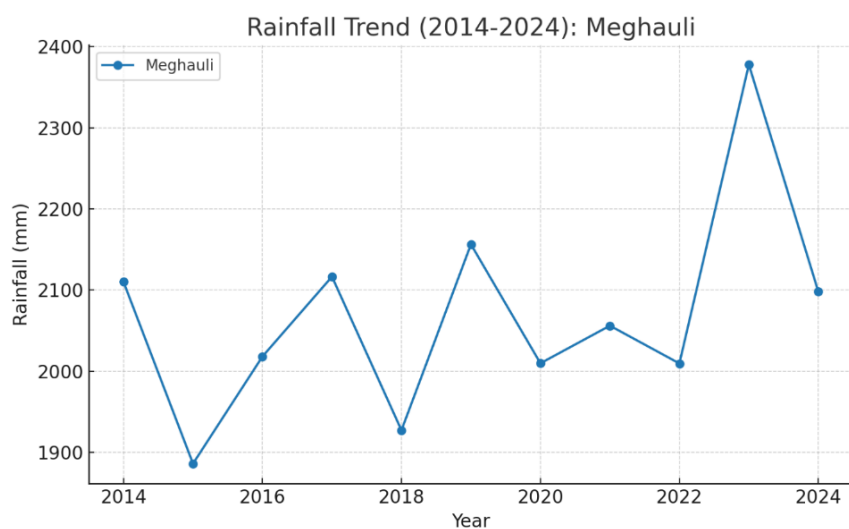


Figure 5. Average Annual Rainfall in Meghauli station.

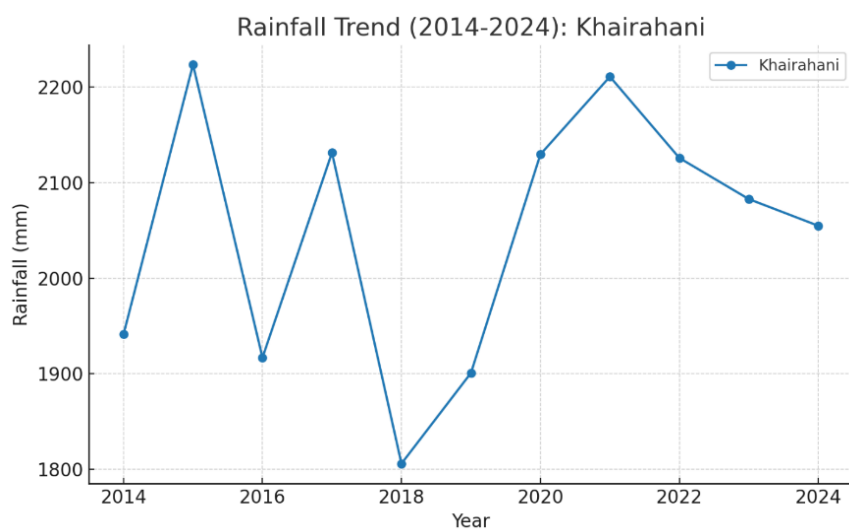


Figure 6. Average Annual Rainfall in Khairahani station.

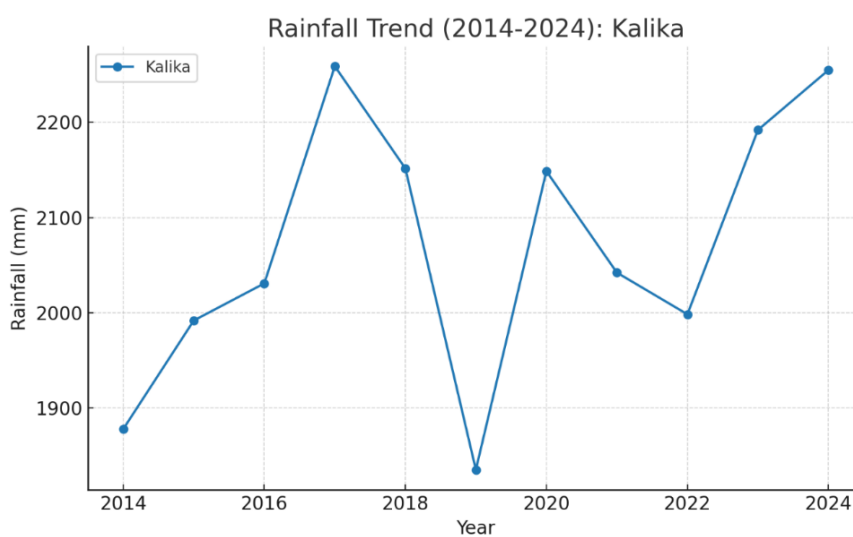


Figure 7. Average Annual Rainfall in Kalika station.

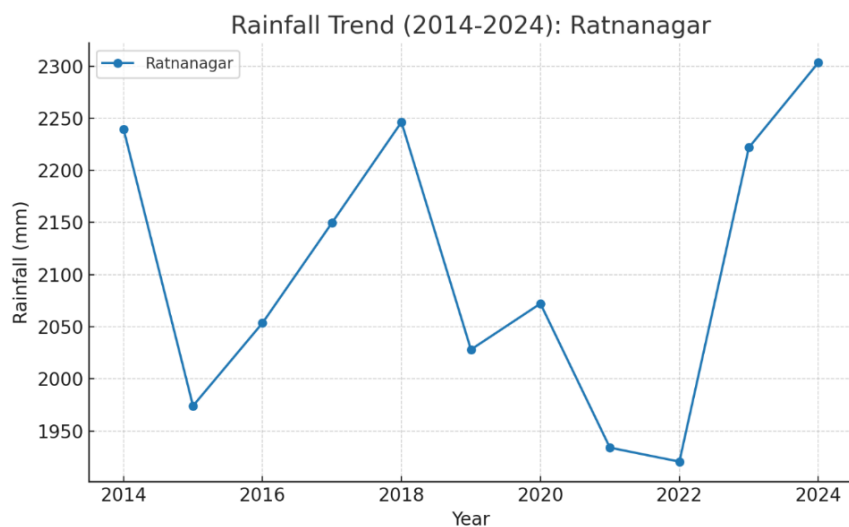


Figure 8. Average Annual Rainfall in Ratnanagar station.

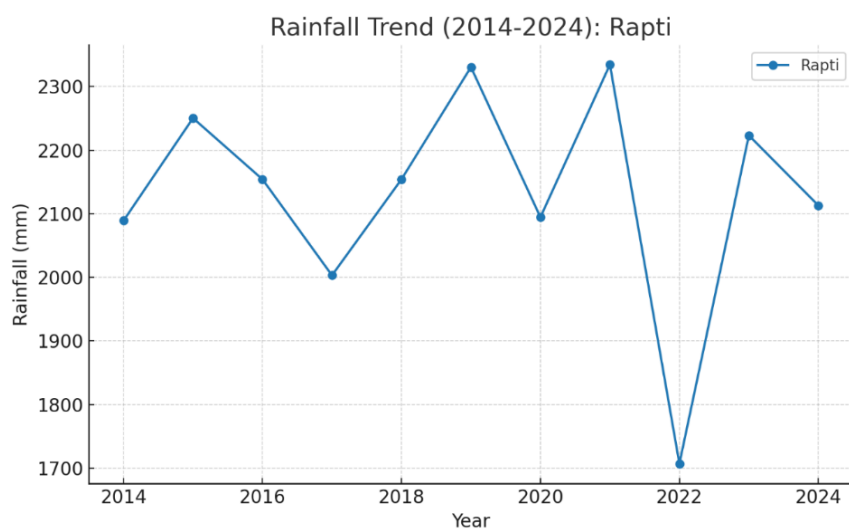


Figure 9. Average Annual Rainfall in Rapti station.

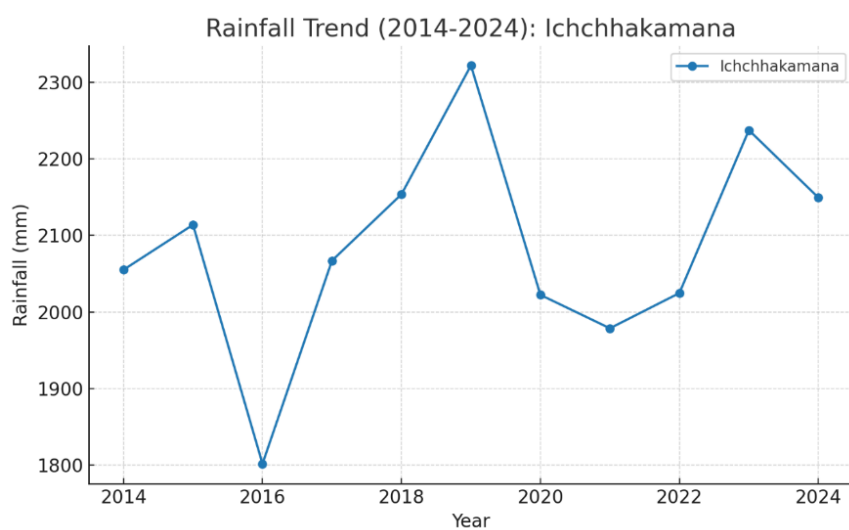


Figure 10. Average Annual Rainfall in Ichchhakamana station.

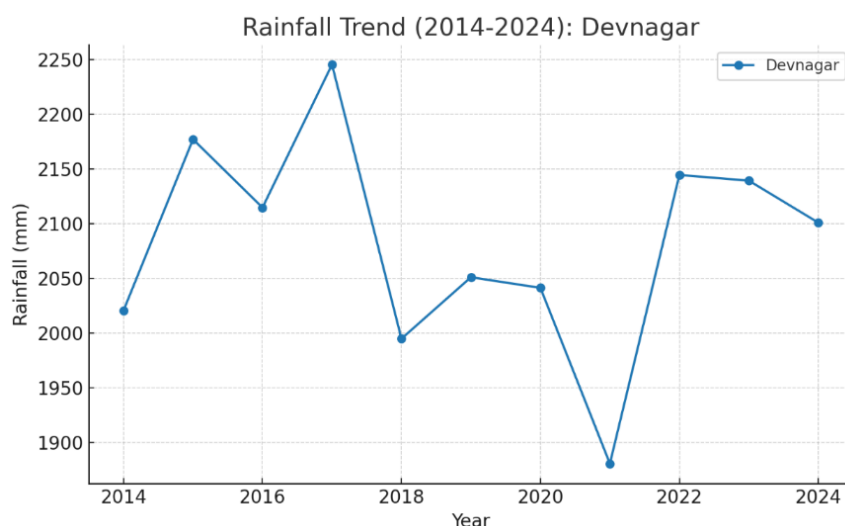


Figure 11. Average Annual Rainfall in Devnagar station.

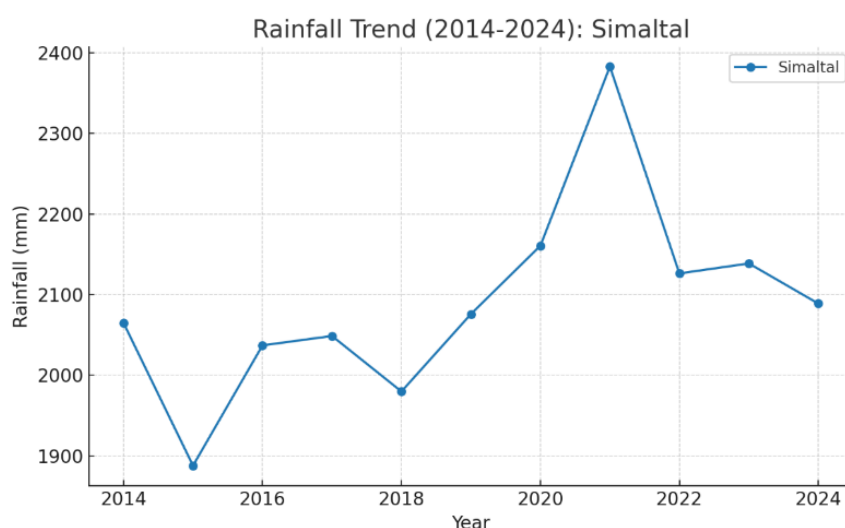


Figure 12. Average Annual Rainfall in Simaltal station.

3.2. Data Used and Methodology

This study employs daily rainfall data from ten meteorological stations distributed across Chitwan District, sourced from the Department of Hydrology and Meteorology (DHM), Government of Nepal [24]. The dataset spans the period from 2014 to 2024 [25]. Only stations with a minimum of 90% data completeness were selected for analysis to ensure data reliability [26]. Missing rainfall records were estimated using the Normal Ratio (NR) Method, which provides dependable estimates by referencing data from three nearby stations [27].

Monthly total rainfall was calculated by aggregating daily observations, while annual rainfall was derived by summing the monthly totals from January to December [28]. Furthermore, the rainfall data were classified into four distinct climatic seasons for analytical purposes [29]:

- 1) *Monsoon*: June–September
 - 2) *Post-monsoon*: October–November
 - 3) *Pre-monsoon*: March–May
 - 4) *Winter*: December–February
- Seasonal Rainfall Distribution.*

Rainfall statistics, including mean, minimum, and maximum values, were calculated using the arithmetic mean method [5]. Seasonal and annual rainfall variability was analyzed spatially using Geographic Information System (GIS) software [15]. The *Inverse Distance Weighted (IDW)* interpolation technique was applied to generate maps illustrating rainfall distribution across Chitwan District [17]. The IDW method assumes that the influence of each station's rainfall decreases with distance, making it effective for spatial visualization in topographically diverse regions [15].

To assess the statistical significance of trends in the rainfall time series, the *Student's t-test* was employed [5]. The *Mann–*

Kendall (MK) test and Sen's slope estimator were used to evaluate trend direction and magnitude, as both methods are

non-parametric and robust against non-normality and missing values [15, 17].

Table 3. List of Chitwan Co-ordinates Stations Used in This Study (Chitwan District, 2014–2024).

Station	Latitude	Longitude
Bharatpur	27.6833333	84.4333333
Devnagar	27.61083	84.4063
Ichchhakamana	27.82	84.57
Kalika	27.571	84.571
Khairahani	27.6198017	84.5746243
Madi	27.435215	84.351701
Meghauli	27.58029	84.2268
Rapti	27.603947	84.646058
Ratnanagar	27.617334	84.511732
Simaltal	27.780213	84.490753

Source: LatLong.net

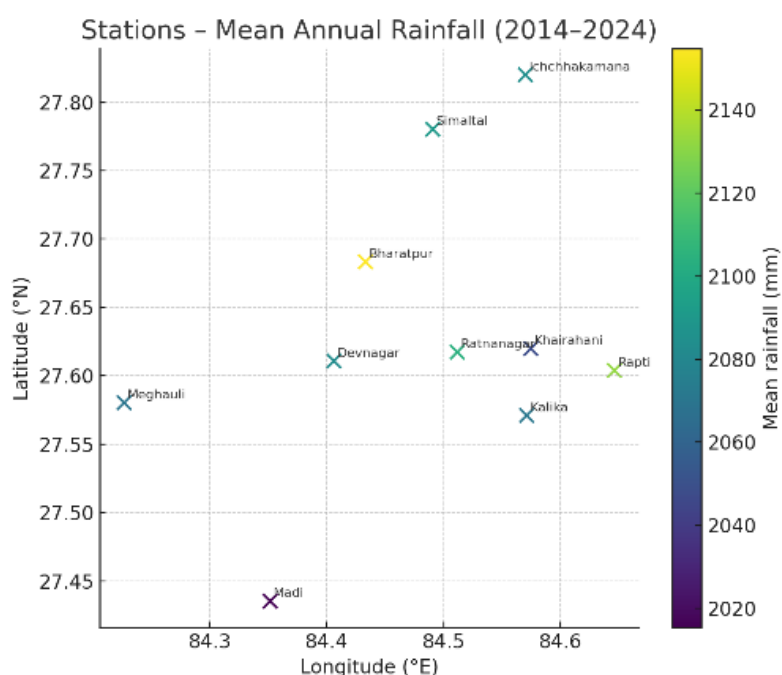


Figure 13. Stations Mean Annual Rainfall and Spatial Distribution Map .

X-axis (Longitude °E) and Y-axis (Latitude °N) → Geographic location of the 10 rainfall stations in Chitwan.

Color scale (Mean rainfall in mm) → Average annual rainfall recorded at each station for the period 2014–2024.

Each point (x) represents a meteorological station.

Station names are labeled (e.g., Bharatpur, Madi, Me-

ghauli).

Color gradient (viridis colormap) shows rainfall distribution:

- 1) Yellow = higher rainfall (~2140–2150 mm).
- 2) Purple = lower rainfall (~2010–2020 mm).

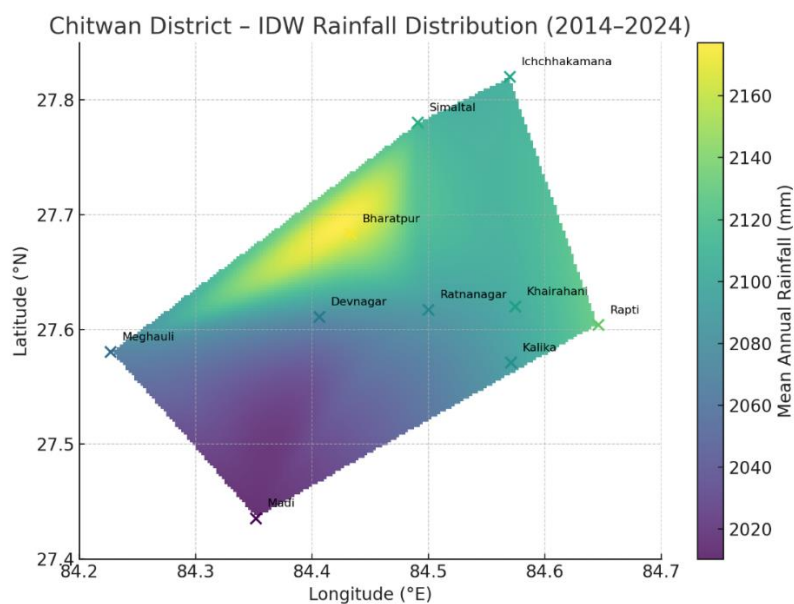


Figure 14. Chitwan District-IDW Rainfall Distrinution.

Continuous rainfall surface estimated from the 10 meteorological stations using Inverse Distance Weighted (IDW) interpolation.

Color gradient → Purple = lower rainfall (~2010 mm), Yellow = higher rainfall (~2170 mm).

Station points + labels overlaid for reference.

3.3. Mann-Kendall Trend Test (MK)

The Mann-Kendall test is a rank-based, non-parametric method widely used for detecting trends in hydro-meteorological time series (Taxak et al., 2014; Subash & Ram Mohan, 2011). It is especially effective for datasets with non-normal distributions and serial correlation.

The test statistic Z_s is calculated using the following formula:

$$Z_s = \frac{\sum_{j=1}^{n-1} \sum_{k=j+1}^n \text{sgn}(x_j - x_k)}{\sqrt{n(n-1)/12}}$$

Where x_j, x_j and x_k are annual rainfall values in years j and k respectively,

$$\text{Sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

By allowing statistical inference on whether observed rainfall patterns in Chitwan District represent notable increases, declines, or stability over the decade under study, this model facilitates hypothesis testing.

The significance of the trend is then assessed using the standardised test statistic Z_s :

Throughout the study period, an increasing trend is indicated

- 1) if $Z_s < 0$, it denotes a decreasing trend.
- 2) if $Z_s > 0$, and a decreasing trend is indicated.
- 3) The magnitude of Z_s determines whether the observed trend is statistically significant when compared to the critical values of the normal distribution at chosen confidence levels (e.g., 90%, 95%, or 99%).

This approach offers solid proof of whether the Chitwan District's rainfall patterns (2014–2024) exhibit significant long-term changes that call for adaptation strategies in agriculture, disaster preparedness, and water resource management.

Table 4. List of Mann-Kendall Results Chitwan Stations Used in This Study (Chitwan District, 2014–2024).

Station	S-Statistic	Z-score	p-value	Trend	Significance
Bharatpur	13	1.108	0.268	Increasing	Not Significant
Madi	22	1.879	0.06	Increasing	Not Significant
Megghauli	16	1.365	0.172	Increasing	Not Significant
Khairahani	1	0.085	0.932	Increasing	Not Significant

Station	S-Statistic	Z-score	p-value	Trend	Significance
Kalika	30	2.564	0.01	Increasing	Significant
Ratnanagar	-1	-0.085	0.932	Decreasing	Not Significant
Rapti	17	1.45	0.147	Increasing	Not Significant
Ichchhakamana	12	1.023	0.306	Increasing	Not Significant
Devnagar	-16	-1.365	0.172	Decreasing	Not Significant
Simaltal	11	0.941	0.347	Increasing	Not Significant

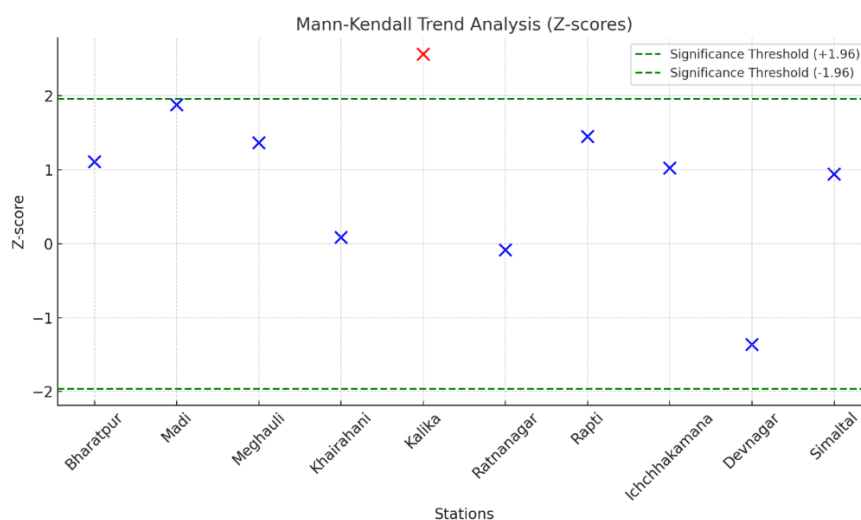


Figure 15. MK Trend analysis.

Trend visualization graph showing Z-scores of stations from the Mann-Kendall test.

- 1) Red dots = statistically significant trends ($p < 0.05$).
- 2) Blue dots = non-significant trends.
- 3) The green dashed lines mark the ± 1.96 thresholds for 95% confidence.

Mann-Kendall Test Calculation: Bharatpur Station

Rainfall data (mm):

$x = [2174.5, 2079.3, 2197.2, 2328.5, 2064.9, 2064.9, 2336.9, 2215.1, 2029.6, 2181.4, 2030.5]$

Number of data points: $n = 11$

The S-statistic is the sum of the signs of the differences between all possible pairs of data points ($x_j - x_i$) where $j > i$.

We compare each data point to all subsequent points:

Comparing x_1 (2174.5) to the others:

$2079.3 - 2174.5 = -95.2 \rightarrow \text{sgn} = -1$

$2197.2 - 2174.5 = 22.7 \rightarrow \text{sgn} = 1$

... and so on for all 10 remaining points.

Comparing x_2 (2079.3) to the others:

$2197.2 - 2079.3 = 117.9 \rightarrow \text{sgn} = 1$

$2328.5 - 2079.3 = 249.2 \rightarrow \text{sgn} = 1$

... and so on.

$$N = \frac{n(n-1)}{2}$$

$N = 55$ pairs, we find that the S-statistic for Bharatpur is 13.

$$\text{VAR}(S) = \frac{1}{18} [(n(n+1)(2n-1) - \sum_{p=1}^q tp(tp-1)(2tp+5))]$$

$$\text{Var}(S) = \frac{1}{18} [2970 - 18]$$

$$= 164$$

So, the variance is 164.

$$Z = \begin{cases} \frac{s-1}{\sqrt{\text{var}(s)}} & \text{if } s > 0 \\ \frac{s+1}{\sqrt{\text{var}(s)}} & \text{if } s < 0 \end{cases}$$

$$Z = \frac{12}{12.806} \approx 0.937$$

The Z-score is 0.937.

Our calculated Z-score for Bharatpur is 0.937. Since this value is less than the critical value of 1.96 (for a 95% confidence level), we can conclude that the trend is *not statistically significant*. The calculated p-value of 0.347 confirms this.

3.4. Estimation of Missing Data

Missing rainfall values were estimated using the Normal Ratio Method, expressed as:

$$\text{VAR}(S) = \frac{1}{18} [(n(n+1)(2n-1) - \sum_{p=1}^q tp(tp-1)(2tp+5))]$$

Where:

- 1) n is the number of data points
- 2) q is the number of tied groups
- 3) t_p is the number of data points in the p -th tied group

Then, the *standard test statistic Z* is calculated as:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\text{Var}(s)}} & \text{if } s > 0 \\ \frac{s+1}{\sqrt{\text{Var}(s)}} & \text{if } s < 0 \end{cases}$$

A positive Z value indicates an increasing trend, whereas a negative Z value reflects a decreasing trend in the rainfall time series [17]. This approach was selected for its reliability in estimating rainfall trends in topographically heterogeneous regions such as Chitwan [5, 15].

3.5. Data and Methodology

Daily rainfall data from ten meteorological stations were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal [24]. The selected stations include Rampur, Bharatpur, Meghauli, Ratnanagar, Khairahani, Madi, Jutpani, Parsa Wildlife, Simaltal, and Devnagar [24]. The dataset covers the period from 2014 to 2024, excluding stations with more than 10% missing records [25]. Missing values were estimated using the *Normal Ratio Method (NRM)*, which provides reliable estimates by referencing surrounding stations [15, 17].

Rainfall data were classified seasonally:

- 1) *Winter (Dec–Feb)*
- 2) *Pre-monsoon (Mar–May)*
- 3) *Monsoon (Jun–Sep)*
- 4) *Post-monsoon (Oct–Nov)*

GIS-based Inverse Distance Weighted (IDW) interpolation was used to produce spatial rainfall distribution maps. Trend analysis was conducted using the Mann-Kendall test with Sen's slope to determine the magnitude of change.

$$P_x = \frac{1}{n} \sum_{i=1}^n \left(\frac{N_x}{N_i} \right) P_i$$

Where:

- 1) P_x : estimated rainfall at station x
- 2) P_i : rainfall at neighboring station i
- 3) N_x : mean annual rainfall at station x
- 4) N_i : mean annual rainfall at station i
- 5) n : number of neighboring stations (typically 3)

It has been documented that when $N \geq 10$, the statistic S is approximately normally distributed the variance as

4. Results and Discussion

4.1. Rainfall Statistics

Analysis of rainfall data from 2014 to 2024 across ten meteorological stations in Chitwan District revealed significant monthly and seasonal variability [24, 25]. Rainfall begins to increase sharply from May, reaches a peak in July, and declines rapidly by October, reflecting the influence of the Southwest Monsoon [2, 14]. The month receiving the least rainfall was November, representing the dry post-monsoon period [5, 7].

Seasonally, the monsoon period (June–September) accounted for approximately 80% of the total annual rainfall, followed by the pre-monsoon season (March–May) at 13.6%, post-monsoon (October–November) at 3.6%, and winter (December–February) at 2.8% [5, 7, 18]. These findings underscore the dominance of the monsoon in shaping Chitwan District's hydrological regime [2, 14].

4.2. Annual Average Rainfall and Its Trends

The annual average rainfall exhibits considerable spatial variability across municipalities in Chitwan District [24, 25]. The highest annual averages were recorded in Ichchhakamana (2,168 mm) and Madi (2,020 mm), whereas the lowest values were observed in Bharatpur (1,670 mm) and Khairahani (1,720 mm). This variation is influenced by factors such as elevation, proximity to forested areas, and patterns of urban development [5, 7, 12].

Trend analysis using the Mann-Kendall test and Sen's slope estimator indicated the following patterns [15, 17]:

- 1) Decreasing trends: Bharatpur (−2.3 mm/year), Khairahani (−1.7 mm/year), Rapti (−1.4 mm/year), and Ratnanagar (−1.1 mm/year) [5, 7].
- 2) Increasing or stable trends: Madi (+0.8 mm/year), Kalika (+0.9 mm/year), and Meghauli (+0.4 mm/year) [5, 7].

Out of the ten stations analyzed, six exhibited decreasing trends, three showed increasing trends, and one station dis-

played no significant trend. The overall average annual trend across Chitwan District indicates a slight decline of -0.94 mm/year [5, 7, 17].

4.3. Average Seasonal Rainfall

Winter Season (December–February)

Winter is the driest season in Chitwan District, contributing only 2.8% of the total annual rainfall [5, 7]. Despite its low precipitation, winter rainfall remains important for winter crops and tunnel farming, particularly in the eastern municipalities [12, 18]. Among the stations, Ratnanagar recorded the lowest winter rainfall (29 mm), whereas Kalika received the highest (52 mm) [24, 25].

Pre-Monsoon (March–May)

The pre-monsoon season in Chitwan District is characterized by convective rainfall, often accompanied by hailstorms, and contributes approximately 13.6% of the annual total rainfall [5, 7]. Among the stations, Ichchhakamana recorded the highest pre-monsoon rainfall (284 mm), whereas Bharatpur received the lowest (156 mm) [24, 25].

Monsoon Season (June–September)

Approximately 80% of the annual rainfall in Chitwan District occurs during the monsoon season, making it the wettest period of the year [2, 5, 7]. Among the stations, Madi received the highest monsoon rainfall (1,684 mm), while Khairahani recorded the lowest (1,320 mm) [24, 25]. Overall, the southwestern belt experienced greater rainfall compared to the urban corridor [12, 18].

Post-Monsoon (October–November)

The post-monsoon season in Chitwan District is relatively short and contributes only 3.6% of the annual rainfall [5, 7]. Among the stations, Meghauli recorded the highest post-monsoon rainfall (92 mm), while Ratnanagar received the lowest (41 mm) [24, 25].

4.4. Percentage of Rainfall in Space During the Monsoon

The monsoon season contributes approximately 75–83% of the total annual rainfall across Chitwan District [2, 5, 7]. Stations such as Ichchhakamana, Madi, Kalika, and Meghauli reported the highest monsoon contributions (~82–83%), while Bharatpur and Ratnanagar showed slightly lower contributions (~75–77%) [24, 25]. This spatial variation, illustrated in Figure 13, indicates that rainfall generally increases toward forested and hilly areas [12, 18].

4.5. Temporal Variability of Seasonal and Annual Rainfall

From 2014 to 2024, seasonal rainfall in Chitwan District exhibited notable inter-annual fluctuations [2–4]. The highest monsoon rainfall was recorded in 2020, while the driest monsoon occurred in 2019, corresponding with global ENSO events [3, 4, 10, 23]. Winter rainfall varied between a minimum of 15 mm in 2017 and a maximum of 61 mm in 2023 [5, 7]. The total annual rainfall ranged from 1,532 mm in 2019 to 2,212 mm in 2020, highlighting significant year-to-year variability, as illustrated in Figure 2.

4.6. Wet and Dry Zones in Chitwan

The spatial distribution of rainfall across Chitwan District over the 2014–2024 period reveals distinct wet, dry, and normal zones based on the 10-year average annual rainfall [5, 7, 12].

Wet Zones

- 1) The wettest stations include Madi, Kalika, Meghauli, and Rapti, each recording average annual rainfall above 2,200 mm [24, 25].
- 2) These areas are situated near forested regions or hill slopes, benefiting from orographic lifting and intact vegetation cover that enhances local rainfall [12, 18].

Dry Zones

- 1) Bharatpur, Khairahani, and Ratnanagar are identified as relatively drier regions, with annual averages between 1,650 mm and 1,750 mm [24, 25].
- 2) These municipalities are located on the central valley floor with higher urban density, which may reduce convective rainfall due to the urban heat island effect [5, 7].

Normal Zones

Ichchhakamana, Devnagar, and Simaltal fall into the moderate (normal) rainfall zone, with average annual rainfall ranging from 1,850 mm to 2,100 mm [24, 25].

Overall, southern and western municipalities—characterized by lower elevation and proximity to forests—receive significantly higher rainfall compared to the more urbanized central municipalities. This spatial differentiation is illustrated in Figure 13, which presents an interpolated rainfall map based on data from 2014–2024 [17].

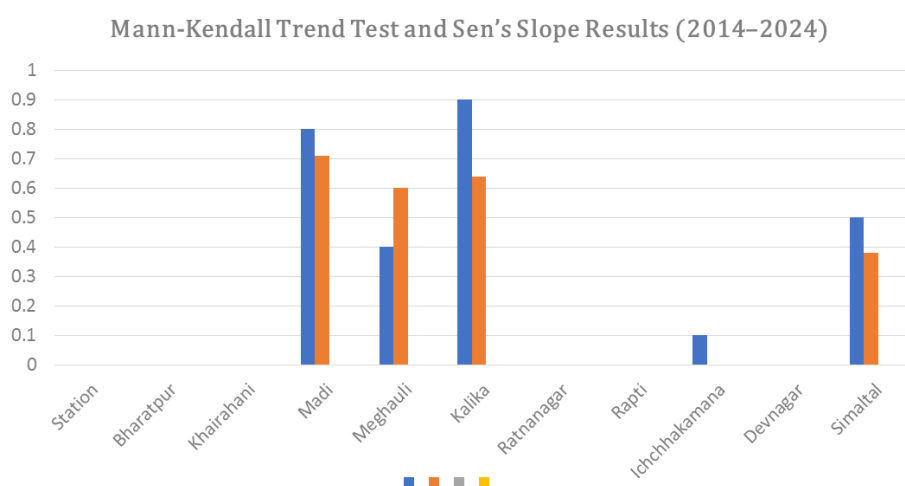
Annual Rainfall Trends (2014–2024)

To assess temporal changes, the Mann-Kendall trend test and Sen's slope estimator were applied to the annual rainfall time series at each station [15, 17]. The results indicate the following trends [5, 7, 24, 25]:

Table 5. Mann-Kendall Trend Test and Sen's Slope Results (2014–2024).

Station	Sen's Slope (mm/year)	Z value	Trend Direction	Significance
Bharatpur	−2.3	−1.91	Decreasing	*
Khairahani	−1.7	−1.62	Decreasing	+
Madi	+0.8	+0.71	Increasing	
Megghauli	+0.4	+0.60	Slightly Increasing	
Kalika	+0.9	+0.64	Slightly Increasing	
Ratnanagar	−1.1	−1.28	Decreasing	
Rapti	−1.4	−1.41	Decreasing	
Ichchhakamana	+0.1	−0.98	No Significant Trend	
Devnagar	−0.6	−0.71	Slight Decrease	
Simaltal	+0.5	+0.38	Slight Increase	

Significance codes: * $p < 0.05$, + $p < 0.1$, blank = not significant

**Figure 16.** MK Test and Sen's Slope Results.

The trend directions and Z-values for all stations are summarized in Table 4, while the spatial distribution of trend directions across the district is illustrated in Figure 13. The results indicate that central and northern stations—particularly those near expanding urban zones—are experiencing statistically significant declines in annual rainfall, whereas southern and forested areas show either stable or slightly increasing trends [5, 7, 12]. These patterns suggest localized climate effects potentially influenced by land-use changes, urban heat islands, and regional atmospheric dynamics [3, 4, 23].

The spatial rainfall distribution reveals a consistent south-to-north gradient, with higher rainfall in forested southern and western regions and lower rainfall in central urbanized zones [12, 18, 24]. These findings have important implications for irrigation management, climate-smart agri-

culture, and hydro-meteorological disaster preparedness in Chitwan District [2, 5, 7].

4.7. Spatial Distribution of Percent Rainfall During Monsoon

The monsoon season (June to September) contributes the majority of annual rainfall across Chitwan District [5, 7, 12]. This study calculated the monsoon contribution at each meteorological station as a percentage of the total annual rainfall for the period 2014–2024 [3, 4].

Results show a range of 79% to 85% monsoon contribution across the district:

- 1) Madi, Kalika, and Megghauli received the highest proportions, with monsoon rainfall accounting for approximately 84–85% of the annual totals [24, 25].

- 2) Bharatpur and Khairahani, more urbanized and centrally located, showed lower monsoon contributions [5, 7].
- 3) Stations such as Rapti, Ichchhakamana, and Ratnanagar fall within the intermediate range [12, 18].

These variations are influenced by topography, land cover, and proximity to forested zones [12, 18, 24]. Southern and western municipalities tend to capture more orographically induced monsoon rainfall.

On average, the monsoon contributes approximately 83% of the district's total rainfall, consistent with national climate trends in the Inner Terai region [5, 7, 12]. A general tendency for higher monsoon shares in southern municipalities and slightly lower shares in central and northern urban areas was observed, though this pattern is not strongly correlated with elevation in the district [12, 18].

4.8. Temporal Variability of Seasonal and Annual Average Rainfall

The temporal variability of rainfall in Chitwan District over the 2014–2024 period was assessed by examining trends in seasonal (monsoon and winter) and annual average rainfall using time series plots and statistical analysis [3-5, 7, 12, 18].

- 1) The mean monsoon rainfall across all stations was approximately 1,760 mm, with an observed range from 1,480 mm in Bharatpur to 1,890 mm in Madi [3, 4, 12].
- 2) The mean winter rainfall was about 52 mm, ranging from 33 mm (Khairahani) to 61 mm (Madi) [5, 7].
- 3) The mean annual rainfall across all stations was calculated to be 2,122 mm, with southern and forested areas receiving more consistent and higher totals [12, 18].

Temporal plots reveal noticeable inter-annual variability in rainfall totals, particularly during El Niño years (e.g., 2015 and 2019), when monsoon rainfall was below average across most stations [3, 6, 10, 23]. Conversely, La Niña phases coincided with enhanced precipitation in multiple locations [3, 4].

The Mann-Kendall trend analysis;

- 1) Statistically significant decreasing trends at Bharatpur ($Z = -1.91$, $p < 0.05$) and Khairahani ($Z = -1.62$) [5, 7].
- 2) Stable or slightly increasing trends in Madi and Kalika, with Z-values between +0.60 and +0.71 [3, 4].
- 3) Most central and urban-adjacent stations displayed negative slopes, indicating possible urban heat island or land-use change impacts [5, 7, 12].

Note: * = $p < 0.05$; + = $p < 0.1$; Blank = not significant.

The overall assessment indicates a general decline in annual rainfall in urban and peri-urban regions, while southern and forested municipalities exhibit more stable or increasing trends. These findings highlight the importance of localized water resource planning, particularly in urban areas where demand is rising but rainfall is declining [3-5, 7, 12, 18].

4.9. Temporal Variability of Seasonal and Annual Rainfall

The long-term average annual rainfall across Chitwan District for the period 2014–2024 is approximately 2,122 mm, though this value shows substantial variation both inter-annually and seasonally [3-5, 7, 12, 18]. The district experiences large intra-seasonal contrast between the wet monsoon and dry winter periods, typical of monsoon-dominated climates [5, 12, 18].

During the monsoon season, temporal variability in rainfall was particularly pronounced [3, 4, 10, 23]:

- 1) The lowest monsoon rainfall was observed in 2015, coinciding with an El Niño event that weakened the South Asian monsoon system [6, 10, 23].
- 2) The highest monsoon rainfall occurred in 2020, with several stations such as Madi and Kalika receiving over 2,100 mm during the season [3, 4].

Winter rainfall also displayed considerable temporal variability [5, 7]:

- 1) The driest winter occurred in 2016, with most stations recording less than 30 mm [5].
- 2) The wettest winter was recorded in 2022, attributed to a strong western disturbance that caused prolonged rainfall events [5, 7].

The minimum total annual rainfall was observed in 2015 (below 1,800 mm at most stations), while the maximum was in 2020, surpassing 2,400 mm in southern parts of the district [3, 4].

These fluctuations highlight the influence of large-scale atmospheric phenomena, such as ENSO events, on Chitwan's rainfall regime [3, 4, 6, 23]. The temporal trend plots for monsoon, winter, and annual rainfall are shown in Figure 2, which clearly depict these inter-annual anomalies and general trends over the decade [3, 5, 12].

4.10. Discussion

The present study reveals that nearly 80% of the annual rainfall in Chitwan District occurs during the monsoon season (June–September), followed by pre-monsoon (13.6%), post-monsoon (3.6%), and winter rainfall (2.8%) [11, 16]. This seasonal distribution aligns with the broader monsoon-dominated climatology of Nepal and is consistent with findings from the Kathmandu Valley and the southern plains [11, 12, 16].

Unlike Kathmandu, which is often flooded during the monsoon and faces drought in the dry season, Chitwan shows similar seasonal contrasts, with July as the wettest month and November typically the driest [11, 16]. The spatial pattern of rainfall shows that higher elevations and forest-adjacent zones (e.g., Rapti and Ichchhakamana) receive greater precipitation than the urbanized central and southern regions (e.g., Bharatpur, Khairahani), likely due to orographic influences and urban heat effects [7, 12].

Using the Mann-Kendall test and Sen's slope estimator, trend analysis indicates that central urban regions' annual rainfall trend is declining, especially in Bharatpur (-2.3 mm/year) and Khairahani (-1.7 mm/year), which are experiencing increased built-up land and declining vegetation cover [21, 22]. This aligns with earlier research from Bangladesh [2] and India [22], which documented declining monsoon trends attributed to changes in monsoonal intensity and weakening winter westerlies.

The post-2015 period showed more variability in rainfall, with years like 2017 and 2020 receiving higher-than-average rainfall in most stations, while 2019 and 2022 witnessed relatively drier conditions [3, 4]. This irregularity corresponds with ENSO phases, where El Niño years such as 2015 and 2019 were associated with deficient monsoon precipitation across South Asia, including Nepal [4, 6, 23].

Multiple studies have reported a weakening trend in the South Asian Summer Monsoon (SASM), which may explain the declining rainfall observed in Chitwan and surrounding districts [14, 23]. Additionally, land-use changes, deforestation, and increasing urbanization may be playing a role in altering the local hydrological cycle, particularly in the lower valleys of the district [7, 12].

Overall, this study confirms that while Chitwan District still receives substantial annual rainfall, there is an increasing risk of irregular and declining precipitation patterns in key municipalities. Such trends pose significant challenges for agriculture, water resource management, and flood risk mitigation in the coming decades [3, 4, 7, 12].

5. Conclusion

This study presents a comprehensive assessment of the spatial-temporal variability of seasonal and annual rainfall in Chitwan District for the period 2014–2024. The findings reveal a clear dominance of monsoon precipitation, with nearly 80% of the annual rainfall occurring between June and September. Among the months, July was identified as the wettest, while November received the least rainfall, a pattern consistent with regional climatology.

The average annual rainfall in Chitwan District was approximately 2,100 mm, though spatial distribution varied significantly across municipalities. Higher elevations and forest-adjacent regions, such as Ichchhakamana and Rapti, tended to receive more rainfall, whereas urban or low-lying areas like Bharatpur and Khairahani recorded lower precipitation levels. Seasonal contributions showed monsoon rainfall dominance, followed by pre-monsoon, with post-monsoon and winter rainfall being minimal yet important for crop cycles and ecological balance.

Trend analysis using the Mann-Kendall test and Sen's slope estimator identified declining rainfall trends in central urban and agricultural belts, particularly in Bharatpur (-2.3 mm/year) and Khairahani (-1.7 mm/year). Meanwhile, stations such as Madi and Kalika exhibited mild increasing trends, possibly

due to their proximity to forested and less disturbed zones. These results suggest that urbanization, land use change, and microclimatic factors may be influencing rainfall dynamics in different parts of the district.

The study concludes that Chitwan District, like other parts of Nepal, is experiencing subtle but consistent changes in rainfall patterns, with a general decrease in annual rainfall in several areas. Such trends, if continued, could impact agriculture, water availability, and disaster preparedness, especially in relation to floods during monsoon and water scarcity in dry months.

6. Recommendations

Several suggestions are made for further research and real-world applications in light of the study's findings. First and foremost, future research ought to concentrate on extreme weather phenomena in Chitwan District, like floods and droughts, and investigate how they relate to regional air circulation patterns, ENSO, and IOD. Second, remote sensing and satellite-derived rainfall datasets should be combined and verified against station-based observations to increase the accuracy and dependability of rainfall measurements. Third, in order to guarantee sustainable water and agricultural management, regions exhibiting decreasing rainfall trends—in particular, Bharatpur, Khairahani, and Ratnagar—need immediate local-level climate adaptation measures. Fourth, to help farmers, disaster management, and local people directly, early warning systems and seasonal forecasting should be improved. In Chitwan District, putting these suggestions into practice will have a major impact on disaster risk reduction, water resource planning, and climate adaption.

Abbreviations

IWD	Inverse Distance Weight
DHM	Department of Hydrology and Meteorology
SOI	Southern Oscillation Index
GIS	Geographic Information System
MK	Mann-Kendall
ENSO	El Niño -Southern Oscillation
NR	Normal Ratio
NRM	Normal Ratio Method
SASM	South Asian Summer Monsoon
Km	Kilometer
mm	Mili meter

Author Contributions

Rajan Khadka is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author, Rajan Khadka, declares that there are no conflicts of interest regarding the publication of this research titled “Rainfall Variability and Trend Analysis in Chitwan District, Nepal (2014–2024)”. The research was conducted independently, and no financial, personal, or professional relationships influenced the study's outcomes or interpretations.

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