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Evaluating temporal trends and variability of rainfall in Bundelkhand region of Madhya Pradesh using Mann-Kendall test

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Abstract

This study evaluates the trends and variability of annual rainfall across six key districts of the Bundelkhand region in Madhya Pradesh, Chhatarpur, Damoh, Datia, Panna, Sagar, and Tikamgarh, over the period 2008 to 2022. Using time series analysis, autocorrelation functions (ACF), and the non-parametric Mann-Kendall trend test supplemented by Sen's slope estimation, the research documents pronounced inter-annual variability in precipitation but finds no statistically significant long-term trends in rainfall for any district. Slight positive or negative tendencies observed in some districts were not significant at the 95% confidence level. The ACF analysis also revealed no strong year-to-year autocorrelation, indicating rainfall values are largely independent and influenced primarily by natural climatic fluctuations. These findings highlight the predominance of variability over persistent trend in the region's rainfall patterns, underscoring the need for adaptive water resource management and agricultural planning in the face of an uncertain and variable climate.

Keywords: Bundelkhand, Madhya Pradesh, M-K test, ACF.

Introduction

The Bundelkhand region of central India, encompassing key districts in Madhya Pradesh such as Chhatarpur, Tikamgarh, Damoh, Sagar, Datia, and Panna, is historically known for its unique geographical and climatic characteristics. Situated on a semi-arid plateau, this region experiences highly variable annual rainfall patterns, predominantly influenced by the monsoon season (Fanai *et al.*, 2022) ^[2]. The economy of Bundelkhand remains heavily dependent on rain-fed agriculture, making the availability and distribution of precipitation critical for the livelihoods of its predominantly rural population.

Multiple studies indicate that Bundelkhand receives mean annual rainfall ranging from about 650mm in the north to over 1,200mm in the southern districts, with approximately 85-90% of precipitation concentrated in the Southwest Monsoon season (June-September) (Singh, *et al.*, 2023) ^[7]. However, rainfall across the region is marked by considerable year-to-year variability, frequent droughts, and occasional floods, all of which collectively threaten agricultural productivity and water resource security (Yadav *et al.*, 2025; Jatav, 2024) ^[9, 4]. This variability is reflected in significant spatial gradients as well: southern districts such as Sagar, Damoh, and Panna tend to receive more rainfall and show greater variability compared to more drought-prone northern districts like Datia and Tikamgarh (Singh, *et al.*, 2023) ^[7].

Trend analyses employing nonparametric methods such as the Mann-Kendall test and Sen's slope estimations consistently reveal either declining or stagnant rainfall trends over multi-decadal periods, though these changes are typically not statistically significant at conventional confidence levels for most districts (Kumar *et al.*, 2023; Fanai *et al.*, 2022) ^[5, 2]. Some locations, notably Sagar, show weak positive tendencies, but overall, there is little robust evidence for systematic increases or decreases in annual rainfall. Moreover, tests for autocorrelation suggest rainfall events in the region are largely random and independent from year to year, illuminating the stochastic nature of precipitation in Bundelkhand (Fanai *et al.*, 2022; Yadav *et al.*, 2025) ^[2, 9]. The region's agriculture is therefore intricately tied to this climatic unpredictability and faces increasing challenges in adapting to both current

variability and projected climate changes (Jatav, 2024; Vishwakarma *et al.*, 2024) [4, 8].

Given the critical challenges posed by rainfall variability and its profound impact on agriculture and water resources in Bundelkhand, this study undertakes a rigorous analysis of annual precipitation patterns across the major districts of Madhya Pradesh from 2008 to 2022. Employing robust statistical methods such as the Mann-Kendall trend test and autocorrelation function (ACF) analysis, the study aims to detect any significant trends or persistent patterns in rainfall. The primary objective is to determine whether the rainfall regime in Bundelkhand exhibits definitive long-term changes or is predominantly governed by natural inter-annual variability. The insights gained will provide valuable evidence to inform sustainable agricultural planning, effective water resource management, and targeted climate adaptation strategies, thereby supporting policymakers and stakeholders in enhancing the region's resilience against climatic uncertainties.

2. Methodology

This study employed non-parametric statistical techniques to analyze the temporal trends in rainfall data, focusing on detecting the presence, direction, and magnitude of trends over the study period.

Trend analysis will be done by using non-parametric Mann-Kendall test. This is a statistical method which is being used for studying the spatial variation and temporal trends of rainfall.

2.1 Mann-Kendall Test: The Mann-Kendall statistic S is given as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

Each of the data point x_i is taken as a reference point which is compared with the rest of the data point's x_j so that,

$$\text{Sgn}(x_j - x_i) = \begin{cases} +1, & x_j > x_i \\ 0, & x_j = x_i \\ -1, & x_j < x_i \end{cases}$$

It has been documented that when $n \geq 8$, the statistic S is approximately normally distributed with the mean.

$$E(S) = 0$$

The variance statistic is given as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(i-1)(2i+5)}{18}$$

Where t_i is considered as the number of ties up to sample i . The test statistics Z_c is computed as

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases}$$

Z_c here follows a standard normal distribution. A positive (negative) value of Z signifies an upward (downward) trend. A significance level α is also utilised for testing either an upward or downward monotone trend (a two-tailed test). If Z_c appears greater than $Z_{\alpha/2}$ where α depicts the significance level, then the trend is considered as significant.

2.2 Sen's Slope Estimator Test

The magnitude of trend is predicted by the Sen's estimator. Here, the slope (T_i) of all data pairs is computed as (Sen, 1968)

$$T_i = \frac{x_j - x_k}{j - k}$$

For $i = 1, 2, \dots, N$

Where x_j and x_k are considered as data values at time j and k ($j > k$) correspondingly. The median of these N values of T_i is represented as Sen's estimator of slope which is given as:

$$Q_{med} = \frac{T(n+1)}{2}$$

If n appears odd, and it is considered as $Q_{med} = [T_{N/2} + T_{(N+2)/2}]/2$ if N appears even. Positive value of Q_i indicates an upward or increasing trend and a negative value of Q_i gives a downward or decreasing trend in the time series.

3. Results and discussion

The Bundelkhand region is a historically and geographically important area in central India, spanning primarily across northern Madhya Pradesh and lower Uttar Pradesh. The larger part of Bundelkhand lies within Madhya Pradesh, specifically covering key districts such as Chhatarpur, Tikamgarh, Damoh, Sagar, Datia, and Panna (Jain, 2002) [1]. This region forms a distinct plateau, recognized for its semi-arid climate, characterized by low to moderate rainfall, hot summers, and dry conditions outside the monsoon period (Scott and Divakar, 2024).

Geographically, Bundelkhand sits between the fertile Gangetic plains to the north and the rugged Vindhyan highlands to the south, making it a transitional zone between two significant landscapes. It is roughly positioned between 23°20'N to 26°20'N latitude and 78°20'E to 81°40'E longitude, reinforcing its identity as a bridge between plains and uplands.

Agriculture dominates the regional economy, but farming is mostly rain-fed, making communities highly vulnerable to erratic monsoon rains and recurring droughts. As a result, crop failures are a persistent challenge affecting rural livelihoods.

Despite climatic and economic challenges, Bundelkhand boasts several major rivers: Sindh, Betwa, Ken, Bagahin, Tons, Pahuj, Dhasan, and Chambal. These rivers are crucial lifelines, supporting drinking water supplies, irrigation, and domestic needs not only for Bundelkhand but also for neighboring areas in Uttar Pradesh.

Overall, Bundelkhand's landscape, water resources, and economic dependence on rain-fed agriculture play a pivotal role in shaping the lives and environment of its population. The base map of the study area is shown in Figure 1.

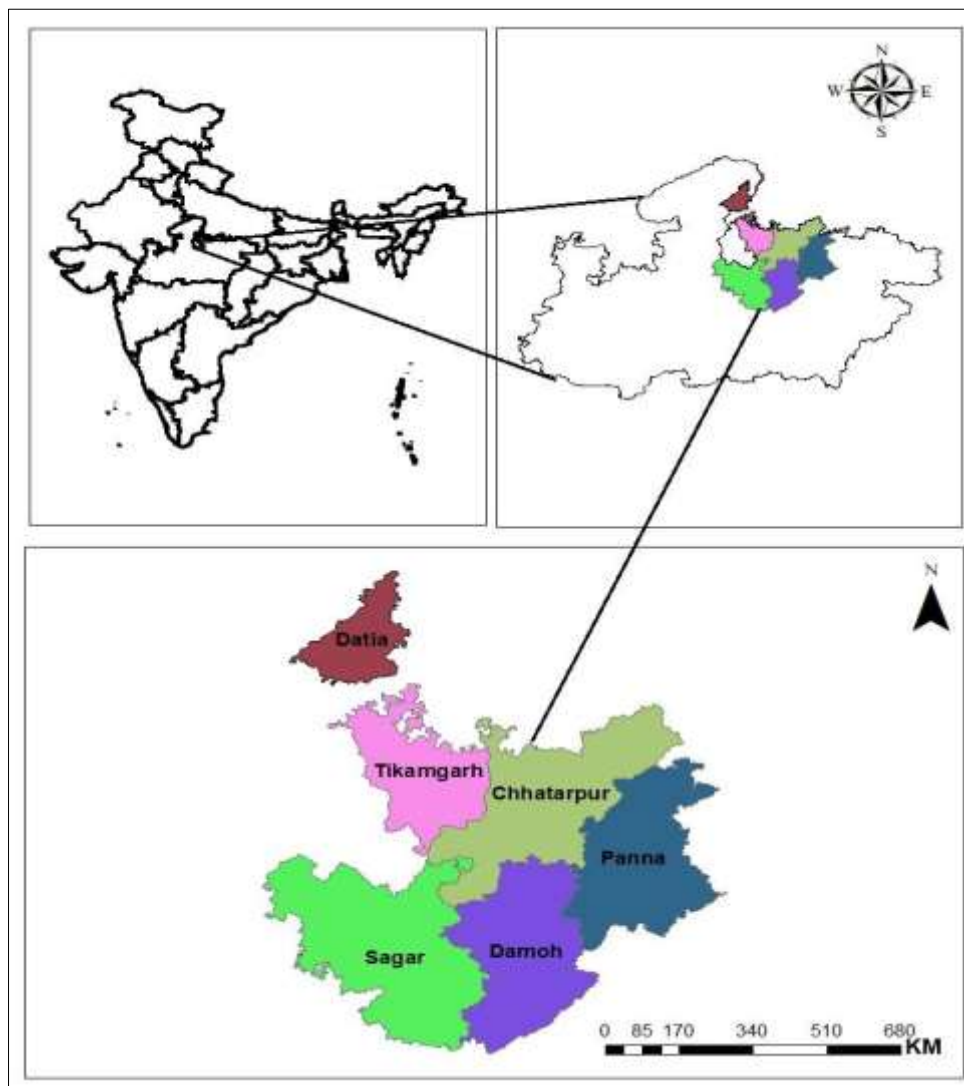


Fig 1: Map of the Study Area

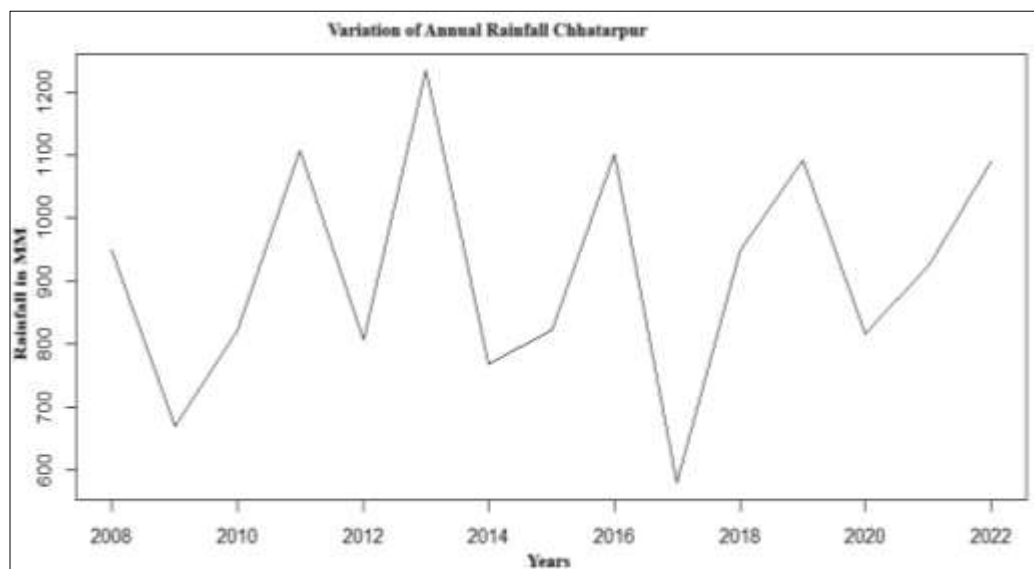


Fig 2: Annual Rainfall in Chhatarpur Region of 15 Years

Figure 2, The annual rainfall in Chhatarpur displays high inter-annual variability, with no clear upward or downward trend. Rainfall fluctuated considerably over the years, ranging approximately between 600 mm and 1250 mm. Peaks in rainfall occurred in 2013, 2016, and 2019, while notable lows were observed in 2009, 2011, and especially in 2017, which had the lowest rainfall during the period. Although there are

periods of increasing rainfall (e.g., 2017 to 2019 and 2020 to 2022), these are not sustained, which aligns with the Mann-Kendall test findings showing no statistically significant trend. This indicates that rainfall in Chhatarpur is influenced by year-to-year climatic variability, rather than a consistent long-term change.

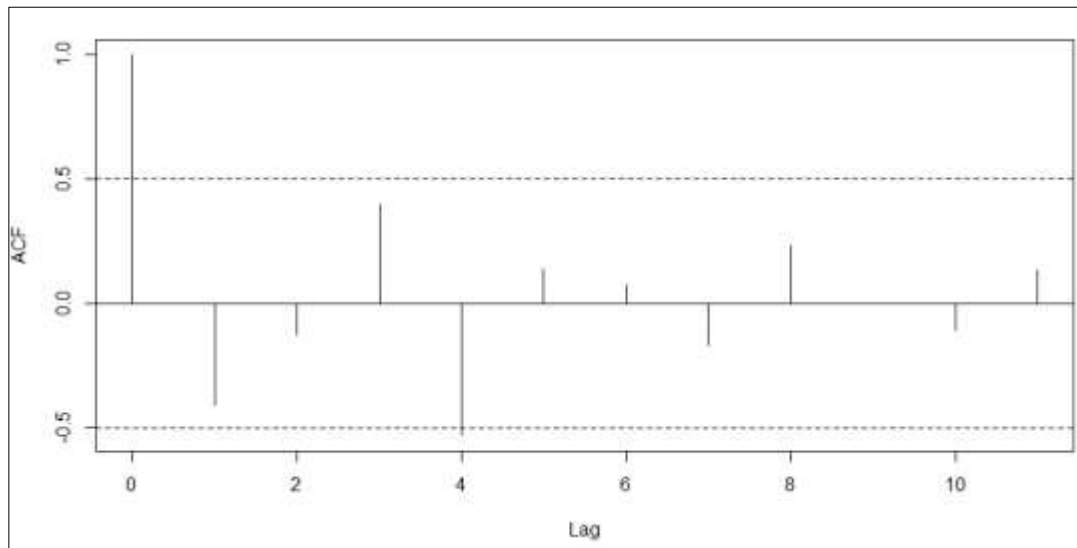


Fig 3: ACF at the Lag = 10 for Rainfall of Chhatarpur Region (2008-2022)

Figure 3, the ACF plot for rainfall in Chhatarpur from 2008 to 2022 indicates that there is no significant autocorrelation in the data up to lag 10, as most values fall within the 95% confidence interval. This suggests that annual rainfall values are largely independent from year to year, with no strong or

consistent pattern over time. The weak correlations observed at certain lags are not statistically meaningful, reinforcing the conclusion that rainfall in Chhatarpur varies randomly and lacks a predictable temporal structure.

Table 1: The findings of the Mann-Kendall test for rainfall in Chhatarpur Region

Best parameters	Mann-Kendall test
z	0.297
tau	0.067
Sen's slope	7.910
p-value	0.766

Above Table 1, the Mann-Kendall test results show no statistically significant trend in rainfall for Chhatarpur during the period from 2008 to 2022. The z-value (0.297) is close to zero, and the p-value (0.766) is considerably higher than the

typical significance threshold of 0.05, indicating that any trend is not statistically significant. Although the tau value (0.067) and Sen's slope (7.910) suggest a slight increasing trend, this change is not meaningful in a statistical sense.

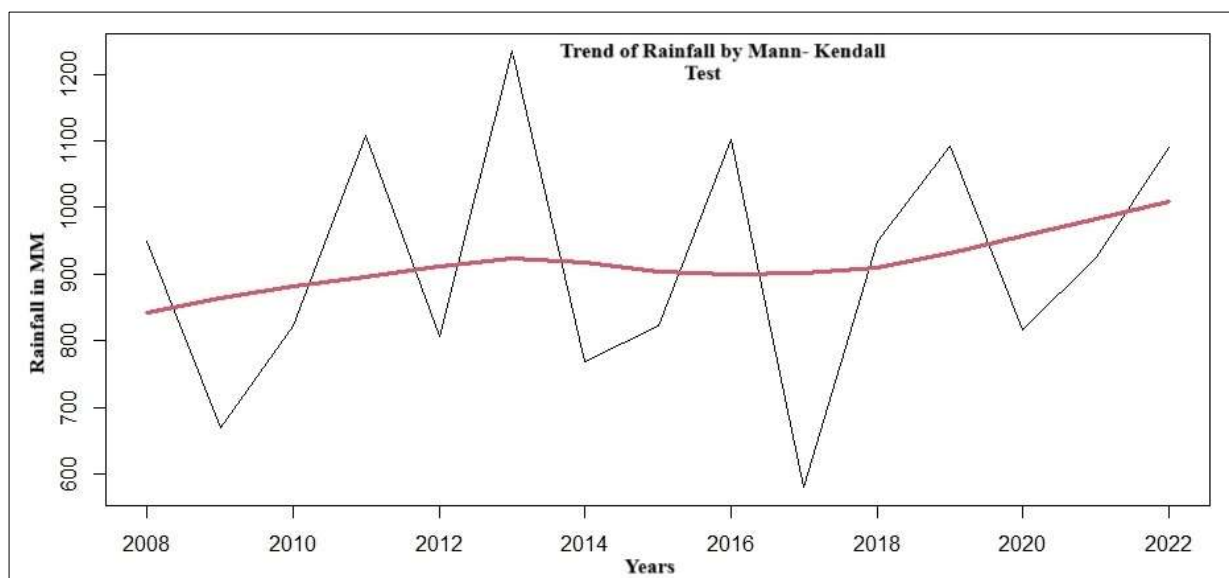


Fig 4: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Chhatarpur Region

Figure 4, the Mann-Kendall trend analysis of annual rainfall in Chhatarpur over the period 2008-2022 reveals a slight upward trend in rainfall, as shown by the smooth red line superimposed on the yearly fluctuations. Despite noticeable inter-annual variability such as peaks around 2013 and 2016, and a sharp dip in 2017 the overall direction of the trend line

suggests a gradual increase in rainfall over time. However, statistical results from the Mann-Kendall test (with a high p-value of 0.766) confirm that this apparent increase is not statistically significant, meaning the trend could be due to natural variability rather than a consistent long-term change.

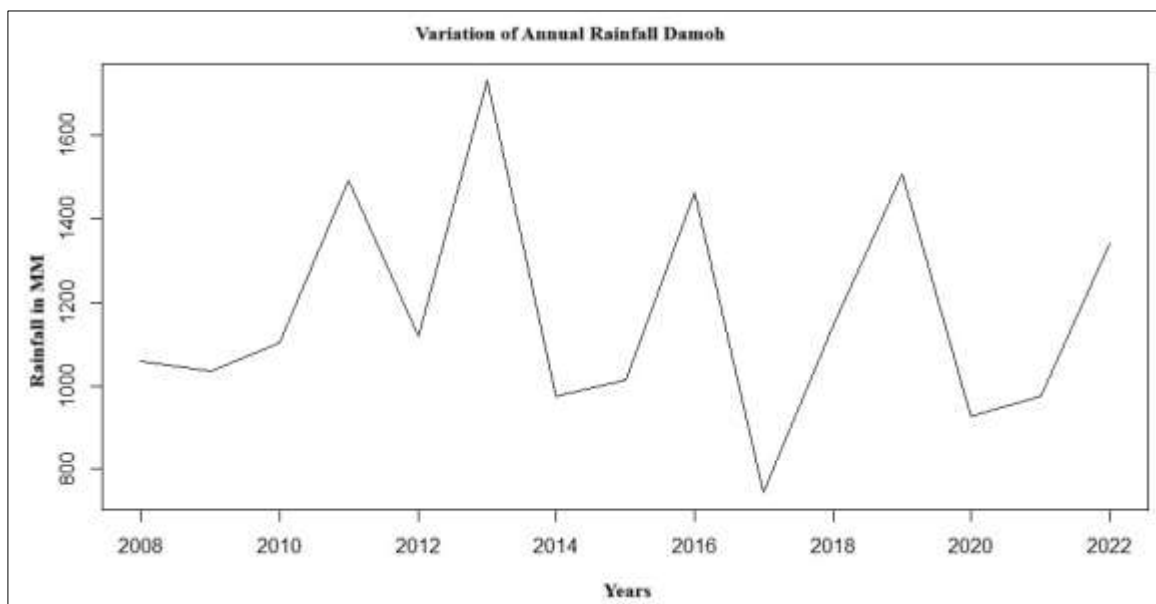


Fig 5: Annual Rainfall in Damoh Region of 15 Years

Figure 5, the annual rainfall pattern in Damoh district from 2008 to 2022 is highly variable, without a clear upward or downward trend. While there are years of both extreme high and low rainfall, the absence of a consistent increase or

decrease indicates no definite long-term trend in rainfall during this period. This suggests the influence of natural climatic variability, rather than a persistent change in rainfall behavior.

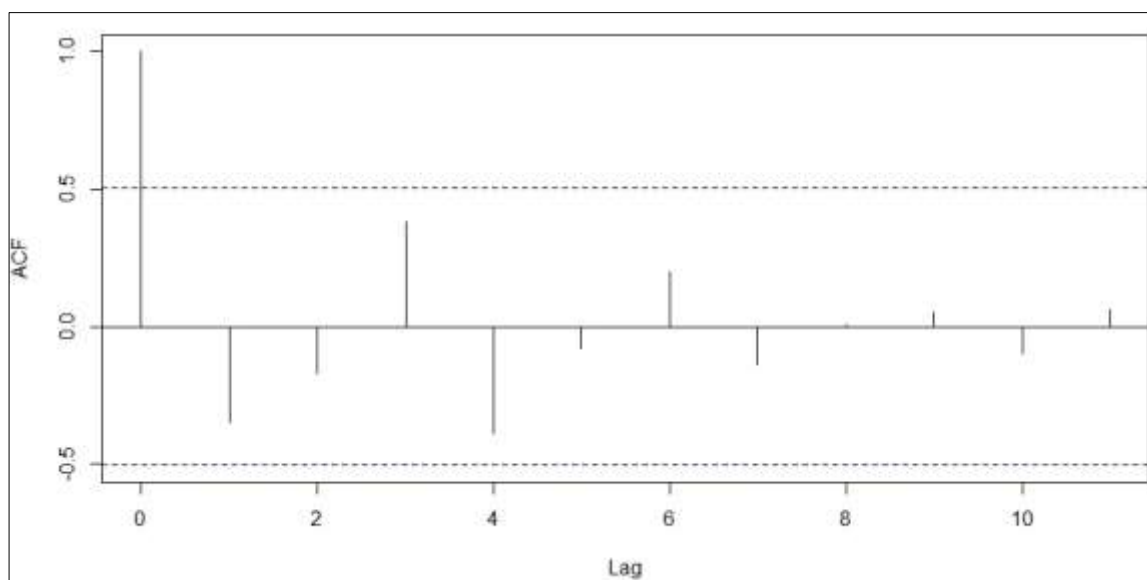


Fig 6: ACF at the Lag = 10 for Rainfall of Damoh Region (2008-2022)

Figure 6, The annual rainfall in Damoh district over the 2008-2022 period exhibits random year-to-year fluctuations with weak short-term dependency. There is no strong evidence of a persistent or cyclic pattern, indicating that rainfall values are

largely independent across years. This supports the conclusion that rainfall behavior in Damoh is primarily driven by natural variability rather than predictable trends or autocorrelated processes.

Table 2: The findings of the Mann-Kendall test for rainfall in Damoh Region

Best parameters	Mann-Kendall test
z	-0.19795
tau	-0.04761905
Sen's slope	-4.9325
p-value	0.8431

Above Table 2, the Mann-Kendall test indicates no significant trend in rainfall for Damoh from 2008 to 2022. The z-value (-0.19795) is close to zero, and the p-value (0.8431) is well above the typical significance level (e.g., 0.05), showing that

any observed trend is not statistically significant. The negative tau (-0.0476) and Sen's slope (-4.9325) suggest a very weak decreasing trend in rainfall over time, but this trend is not statistically meaningful due to the high p-value.

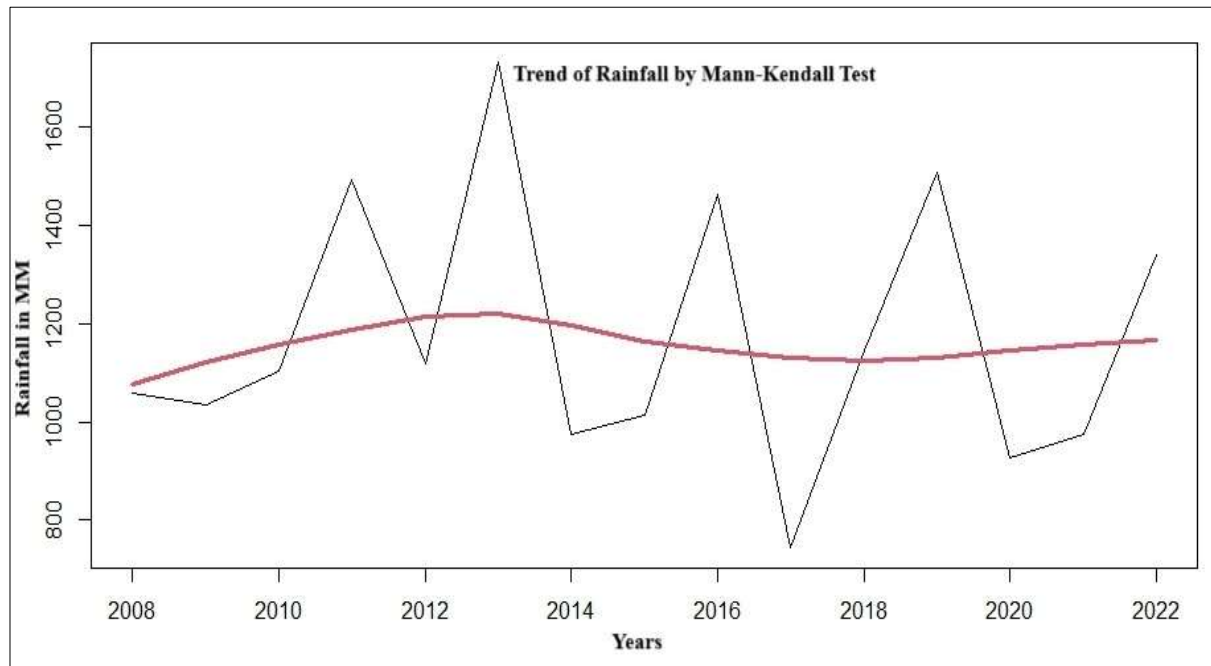


Fig 7: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Damoh Region

Figure 7, the Mann-Kendall trend analysis for annual rainfall in Damoh from 2008 to 2022 shows high inter-annual variability, with pronounced peaks and troughs throughout the 15-year period. The smooth red trend line suggests a slight downward pattern around the middle years (2013-2018), followed by a gentle recovery toward the end. However, the

overall trend is relatively flat and inconsistent, and statistical results (p -value = 0.8431) indicate that this apparent trend is not statistically significant. This means the changes in rainfall are more likely due to natural fluctuations rather than any persistent or meaningful long-term trend.

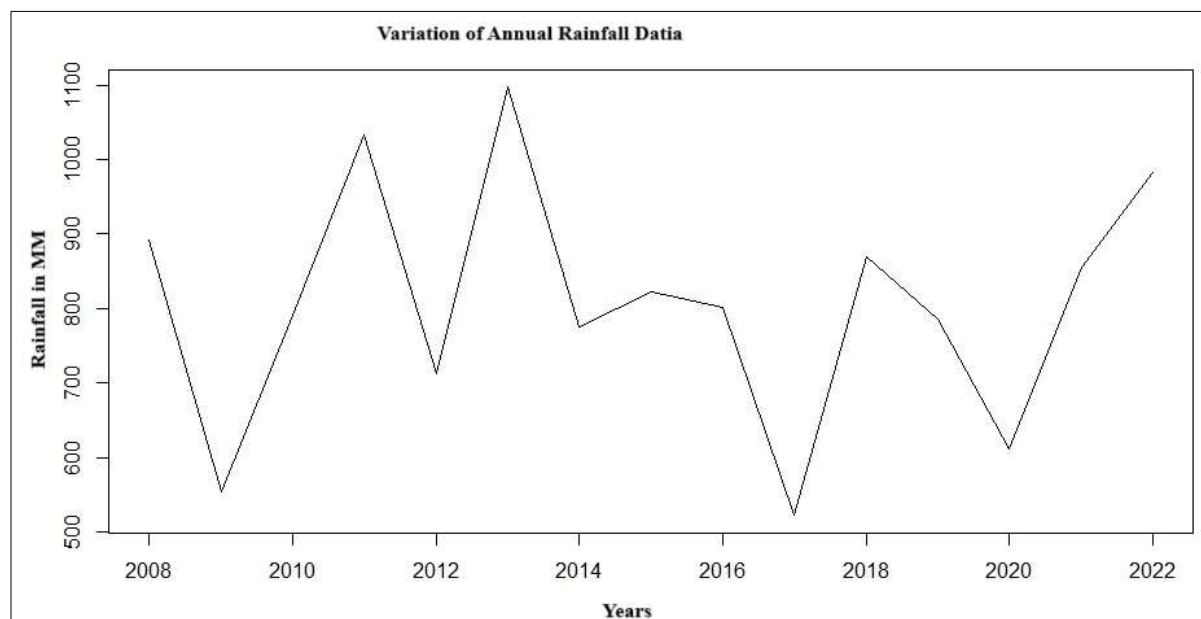


Fig 8: Annual Rainfall in Datia Region of 15 Years

Figure 8, the graph depicting annual rainfall in Datia from 2008 to 2022 shows considerable year-to-year variability, with rainfall values ranging from just above 500 mm to over 1000 mm. Sharp fluctuations are evident throughout the 15-year period, such as noticeable lows in 2009, 2017, and 2020, and peaks in 2011 and 2013. Despite a slight upward

movement in the final years, there is no clear or consistent long-term trend, aligning with the Mann-Kendall test results that indicate no statistically significant trend in rainfall. This pattern suggests that rainfall in Datia is influenced more by short-term climate variability than by any persistent change.

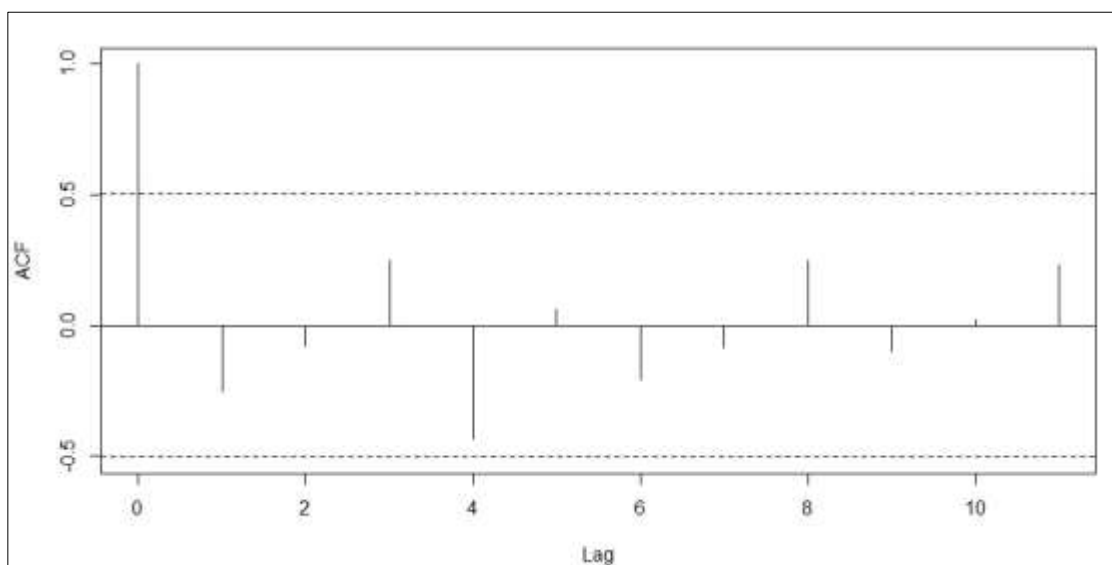


Fig 9: ACF at the Lag = 10 for Rainfall of Datia Region (2008-2022)

Figure 9, the ACF plot for rainfall in Datia from 2008 to 2022 shows that, aside from lag 0, most autocorrelation values fall within the 95% confidence limits, indicating they are not statistically significant. This suggests that the rainfall data lacks strong autocorrelation, meaning there is little to no

predictable pattern or dependency between rainfall values over time. Such a pattern is typical of natural processes like rainfall, which often behave randomly. Therefore, the rainfall in Datia appears to follow a weakly correlated or near-random pattern, with limited influence from previous time periods.

Table 3: The findings of the Mann-Kendall test for rainfall in Datia Region

Best parameters	Mann-Kendall test
z	0.098974
tau	0.02857143
Sen's slope	2.108
p-value	0.9212

Above Table 3, the Mann-Kendall test results indicate no significant trend in the rainfall data for Datia between 2008 and 2022. The z-value (0.098974) is close to zero, and the p-value (0.9212) is much greater than the typical significance level (e.g., 0.05), suggesting that the observed trend is not

statistically significant. The tau value (0.0286) is very low, indicating a very weak positive association, while the Sen's slope (2.108) implies a small increasing trend in rainfall over time. However, due to the high p-value, this trend is not considered statistically meaningful.

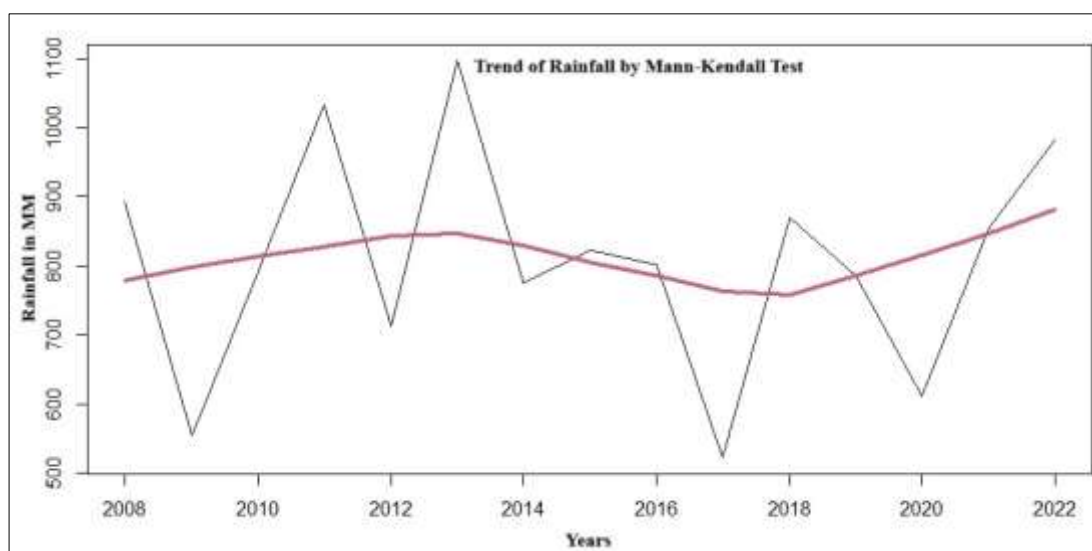


Fig 10: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Datia Region

Figure 10, The Mann-Kendall trend analysis of annual rainfall in Datia from 2008 to 2022 illustrates noticeable fluctuations in rainfall, with sharp dips and peaks across the years. The red trend line suggests a slight upward trend toward the later part of the period, particularly after 2020. However, the increase is

not statistically significant, as supported by the Mann-Kendall test results ($z = 0.098974$, $p\text{-value} = 0.9212$). This indicates that the observed variations are likely due to natural climate variability, and there is no conclusive evidence of a consistent long-term trend in rainfall over the 15-year period.

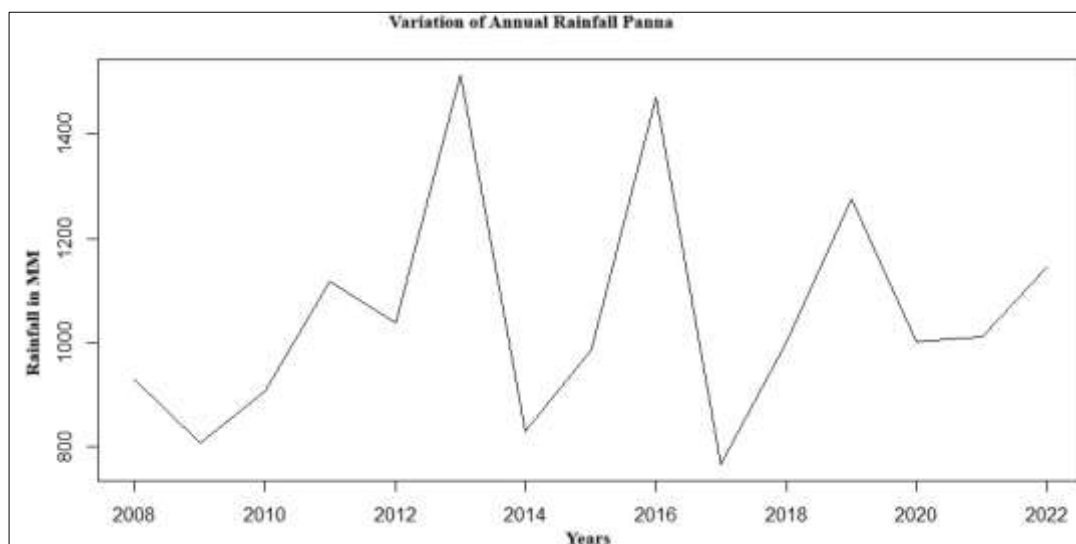


Fig 11: Annual Rainfall in Panna Region of 15 Years

Figure 11, the graph showing the annual rainfall in Panna over 15 years indicates significant fluctuations in rainfall amounts from year to year. The rainfall varies widely, with some years experiencing high rainfall peaks, such as around

2013 and 2016, while other years, like 2017, see considerably lower rainfall. Overall, there is no clear consistent upward or downward trend, but the variability suggests that Panna experiences irregular rainfall patterns throughout this period.

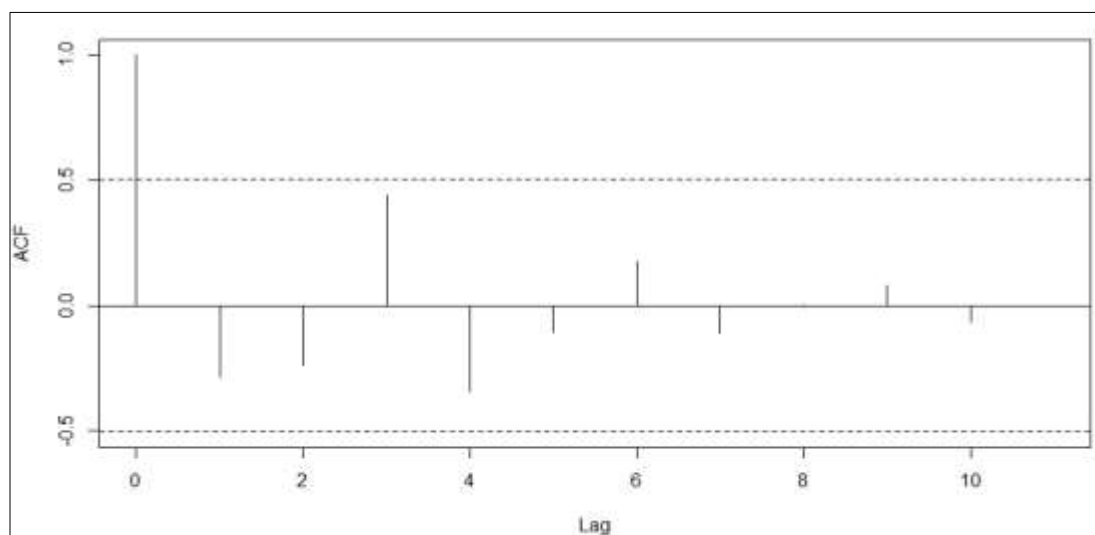


Fig 12: ACF at the Lag = 10 for Rainfall of Panna Region (2008-2022)

Figure 12, the ACF plot for Panna's rainfall from 2008 to 2022 shows that the autocorrelation is strongest at lag 0 (which is always 1 by definition). At lag 1, the autocorrelation is negative, indicating a slight inverse relationship with the previous year's rainfall. For other lags up to 10, the autocorrelation values fluctuate around zero and mostly fall

within the confidence bounds (dashed lines), suggesting no significant autocorrelation at these lags. Overall, this indicates that the annual rainfall in Panna does not show strong persistence or repeating patterns over these time lags and behaves somewhat randomly from year to year.

Table 4: The findings of the Mann-Kendall test for rainfall in Panna Region

Best parameters	Mann-Kendall test
z	1.1396
tau	0.2296677
Sen's slope	9.366364
p-value	0.2545

Above Table 4, the Mann-Kendall test results for rainfall in Panna indicate a slight upward trend, as shown by the positive z-value (1.1396) and Kendall's tau (0.2297), with an estimated increase of about 9.37 mm per year according to Sen's slope. However, the p-value of 0.2545 suggests that this increasing trend is not statistically significant, meaning there

is insufficient evidence to confidently conclude that rainfall has been changing over the 15-year period. Overall, while rainfall appears to be gradually increasing, the observed variations could be due to natural fluctuations rather than a clear long-term trend.

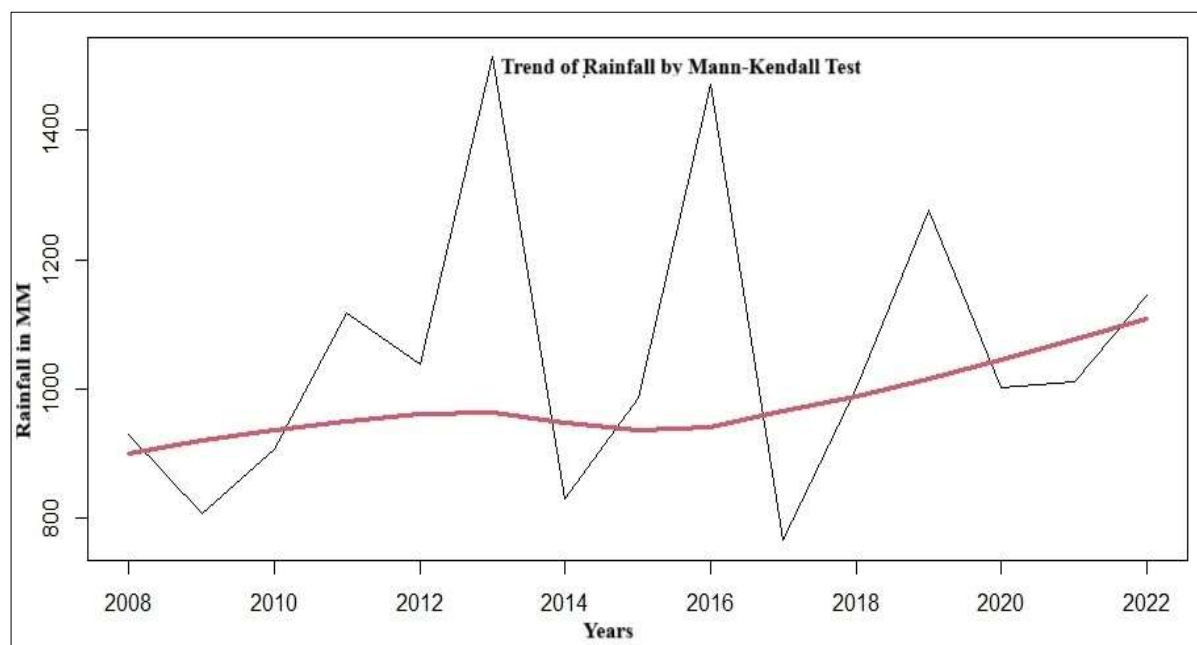


Fig 13: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Panna Region

Figure 13, the Mann-Kendall test analysis of annual rainfall trends in the Panna region over 15 years shows a generally increasing trend in rainfall. The black line represents the observed annual rainfall data, which fluctuates year to year, while the red line shows the smoothed trend identified by the

test. Despite the variability, the overall trend suggests a gradual increase in rainfall from around 900 mm in 2008 to approximately 1100 mm by 2022. This indicates that, on average, the Panna region has experienced a slight rise in annual rainfall over the studied period.

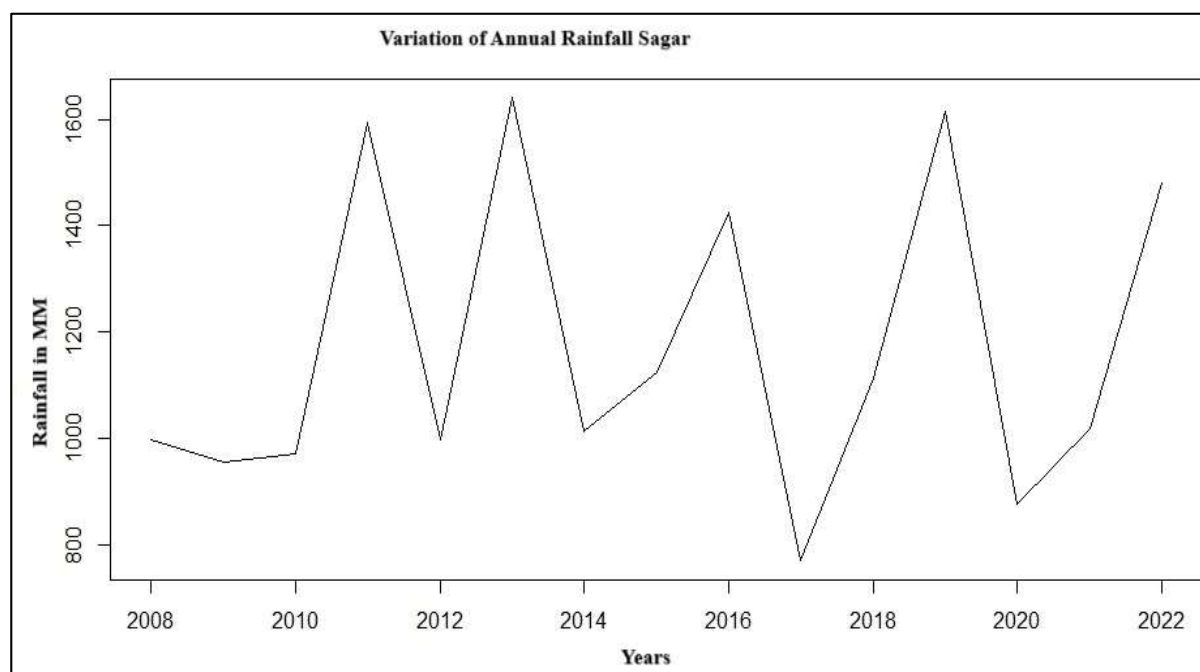


Fig 14: Annual Rainfall in Sagar Region of 15 Years

Figure 14, The annual rainfall data for Sagar from 2008 to 2022 shows high variability with pronounced peaks and troughs, ranging approximately from 850 mm to over 1650 mm. Significant spikes in rainfall are observed in 2011, 2013, 2016, and 2019, while sharp declines occurred in 2012, 2017, and especially in 2020. Despite these fluctuations, there is no

consistent increasing or decreasing trend visible over the 15-year period. This pattern suggests that Sagar's rainfall is primarily driven by inter-annual climatic variability, and without statistical analysis like the Mann-Kendall test, no conclusive long-term trend can be determined.

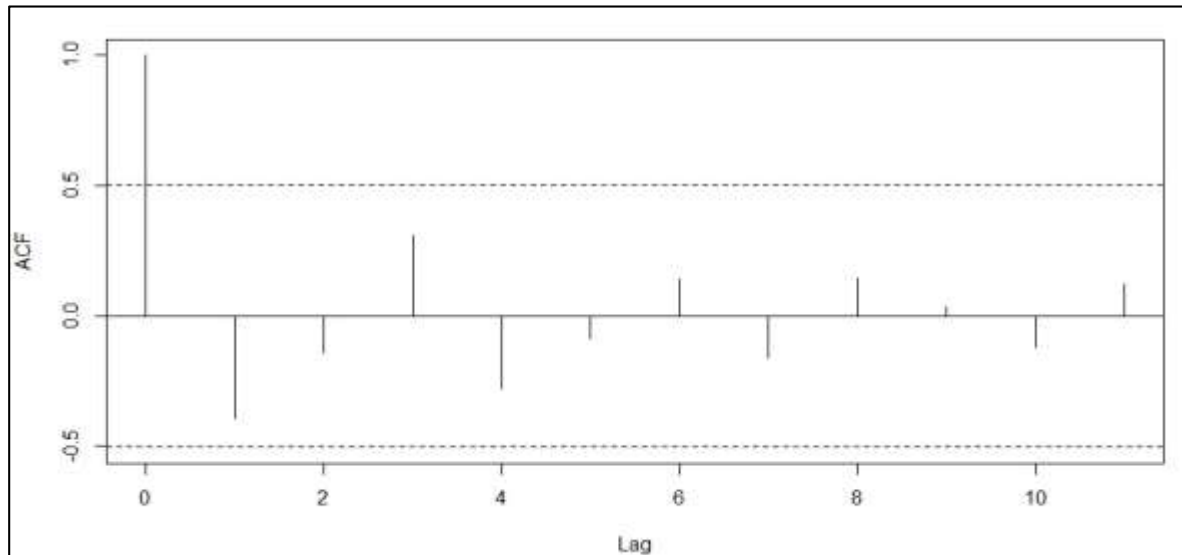


Fig 15: ACF at the Lag = 10 for Rainfall of Sagar Region (2008-2022)

Figure 15, The ACF (Autocorrelation Function) plot for Sagar's rainfall data from 2008 to 2022 shows that the autocorrelation at lag 0 is 1, which is expected as it's perfectly correlated with itself. At other lags up to 10, the autocorrelation values fluctuate around zero and mostly lie within the significance bounds (dashed lines at approximately

± 0.5), indicating that there is no strong or statistically significant autocorrelation in the rainfall data at these lags. This suggests that the annual rainfall in Sagar during this period is largely randomly distributed over time, with no clear pattern of dependence or persistence from one year to the next.

Table 5: The findings of the Mann-Kendall test for rainfall in Sagar Region

Best parameters	Mann-Kendall test
z	0.84231
tau	0.1722508
Sen's slope	9.45
p-value	0.3996

Above Table 5, the Mann-Kendall trend test was conducted to evaluate the presence of a monotonic trend in annual rainfall over the study period. The test produced a Z-value of 0.8423, Kendall's Tau of 0.1723, and a p-value of 0.3996. The Sen's slope estimate indicated a positive trend of 9.45 mm per year.

Although the results suggest a weak increasing trend, the p-value exceeds the 0.05 threshold, indicating that the trend is not statistically significant. The Z-value also lies within the non-significant range (-1.96 to +1.96), reinforcing this conclusion.

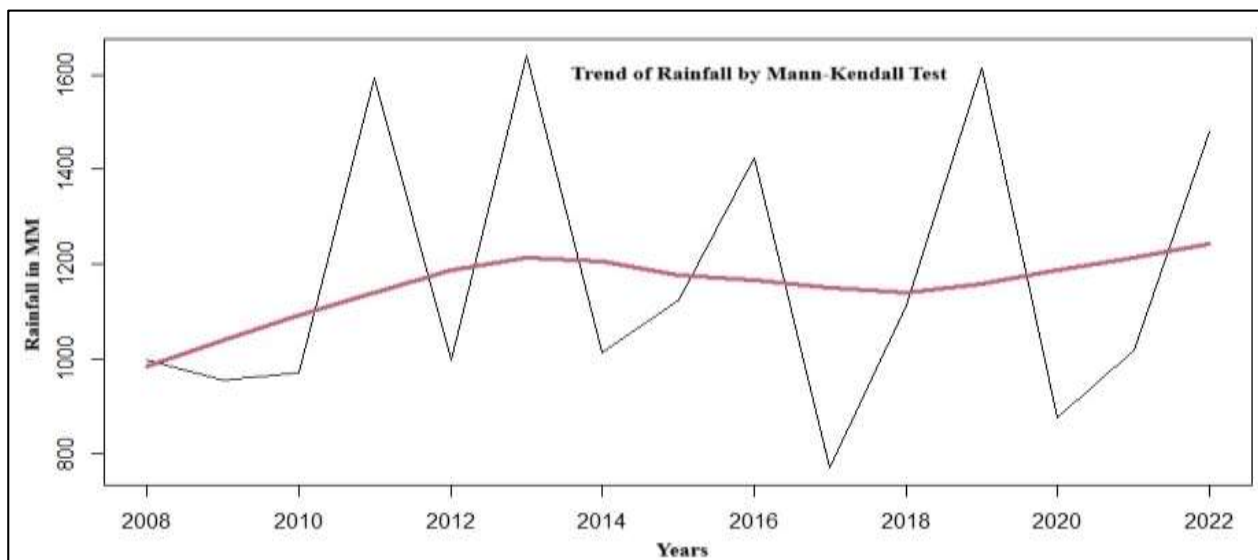


Fig 16: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Sagar Region

Figure 16, the Mann-Kendall test analysis of annual rainfall trends in Sagar over 15 years reveals a gentle upward trend in rainfall amounts. Although the yearly rainfall shows fluctuations with some years having significantly higher or

lower rainfall, the smooth trend line indicates a gradual increase in the overall rainfall over time. This suggests that despite year-to-year variability, there is a slight positive trend in rainfall in Sagar from 2008 to 2022.

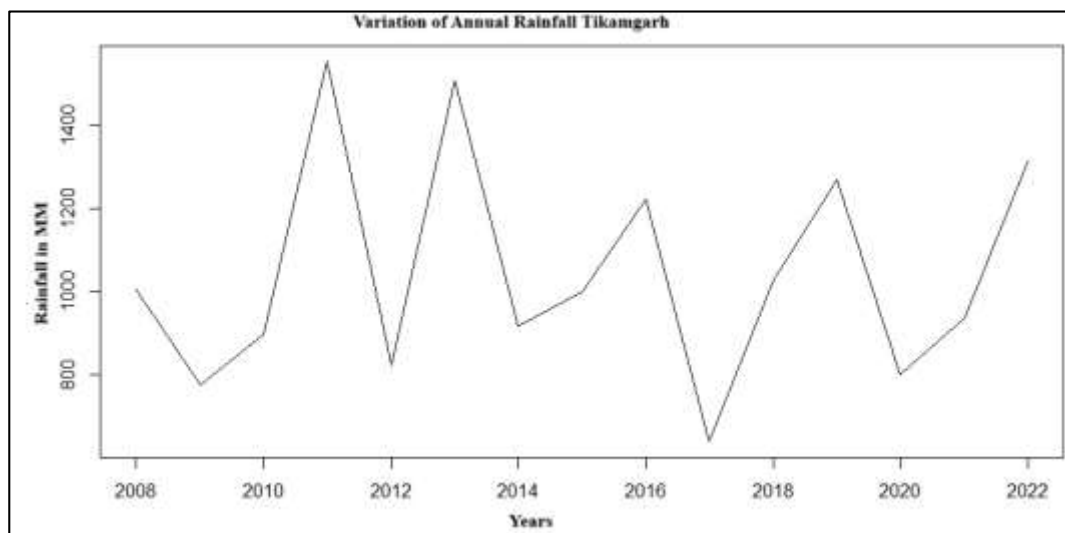


Fig 17: Annual Rainfall in Tikamgarh Region of 15 Years

Figure 17, shows the variation in annual rainfall in Tikamgarh over a 15-year period from 2008 to 2022. The data displays significant year-to-year fluctuations, with rainfall amounts ranging roughly from around 650 mm to nearly 1500 mm.

There is no clear consistent upward or downward trend, as some years exhibit high rainfall followed by sharp drops in the next years. This pattern suggests considerable variability in annual rainfall in Tikamgarh during this time frame.

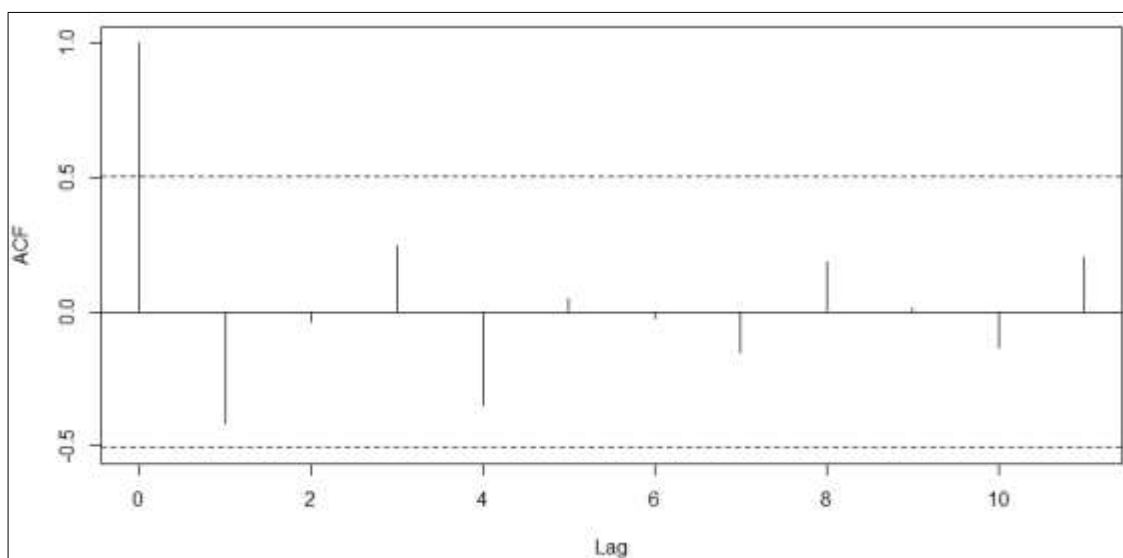


Fig 18: ACF at the Lag = 10 for Rainfall of Tikamgarh Region (2008-2022)

Figure 18, the Autocorrelation Function (ACF) plot for Tikamgarh rainfall data from 2008 to 2022 at lag 10 shows that the strongest correlation occurs at lag 0, as expected, with an autocorrelation of 1 (since any time series is perfectly correlated with itself at lag 0). Beyond lag 0, the autocorrelation values at other lags fluctuate around zero and

mostly fall within the confidence bounds (the dashed blue lines). This indicates that there is no significant autocorrelation in the rainfall data beyond the immediate year, suggesting that the annual rainfall values are largely independent over time and there is no strong seasonal or lagged relationship in the data up to lag 10.

Table 6: The findings of the Mann-Kendall test for rainfall in Tikamgarh

Best parameters	Mann-Kendall test
z	0.49487
tau	0.1047619
Sen's slope	8.79
p-value	0.6207

Above Table 6, the Mann-Kendall test results for rainfall in Tikamgarh indicate a positive but weak trend in annual rainfall over the study period. The test statistic $z=0.49487$ and Kendall's tau of 0.105 suggest a slight upward tendency in rainfall amounts. Sen's slope estimate of 8.79 mm per year quantifies this mild increasing trend. However, the p-value of

0.6207 is much higher than the typical significance level of 0.05, indicating that the observed trend is not statistically significant. Therefore, we conclude that there is no strong evidence of a meaningful change in rainfall patterns in Tikamgarh during this period.

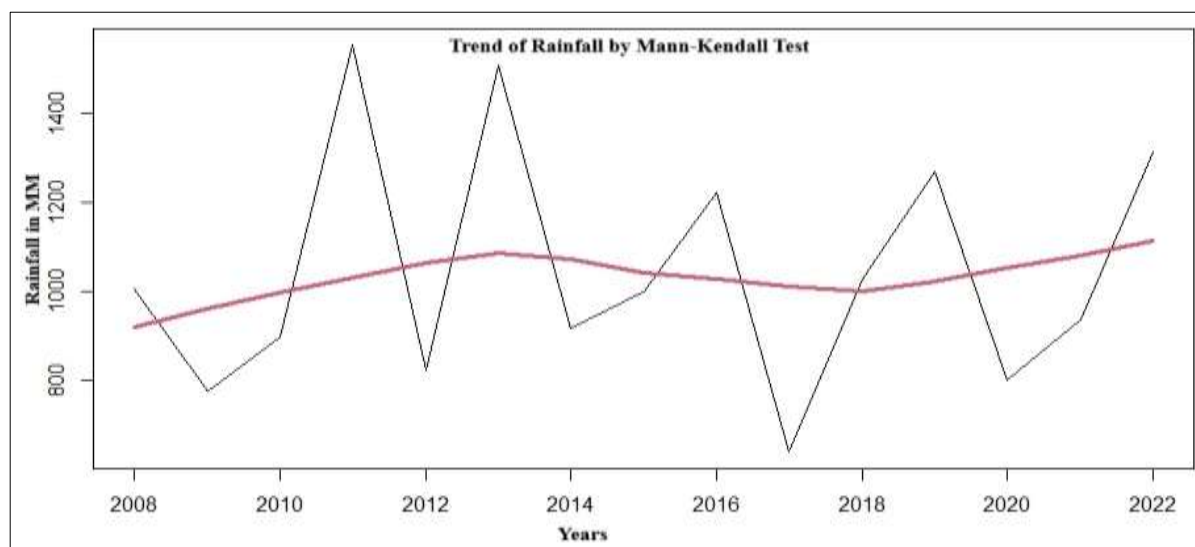


Fig 19: Mann-Kendall Test Analysis of Annual Rainfall Trends Over 15 Years in Tikamgarh Region

Figure 19, shows the annual rainfall trend in Tikamgarh over 15 years, analyzed using the Mann-Kendall test. The black line represents the actual yearly rainfall amounts, showing notable fluctuations throughout the period. The red smoothed line reflects the overall trend derived from the test, which indicates a slight increase in rainfall over time. However, as supported by the Mann-Kendall test statistics, this upward trend is mild and not statistically significant, suggesting that rainfall patterns in Tikamgarh have remained relatively stable with no strong evidence of a consistent increase or decrease over the years.

4. Conclusion

The comprehensive analysis of annual rainfall across the Bundelkhand region's districts-Chhatarpur, Damoh, Datia, Panna, Sagar, and Tikamgarh reveals substantial year-to-year fluctuations but no clear, statistically significant long-term trend between 2008 and 2022. The Mann-Kendall test and Sen's slope estimations consistently indicate only weak positive or negative trends in some districts, none of which are significant at the 95% confidence level. Autocorrelation function analyses further confirm the absence of persistent temporal patterns, demonstrating that rainfall in these districts behaves largely as a sequence of independent yearly events driven by natural variability. This variability dominates over any detectable signals of increasing or decreasing precipitation, suggesting that the region's climate has remained relatively stable in terms of annual rainfall over the study period. Consequently, water resource management and agricultural planning in Bundelkhand must continue to address the inherent unpredictability of rainfall rather than rely on expectations of consistent changes in precipitation. The findings emphasize the critical need for adaptive strategies to cope with climate variability and mitigate impacts on rural livelihoods dependent on rain-fed agriculture.

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