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Evaluation of Rainfall Tendency for the Twentieth Century over Indira Sagar Region in Central India

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Abstract

The study investigates long-term changes in annual and seasonal rainfall patterns in the Indira Sagar Region of Madhya Pradesh, India, from 1901 to 2010. Agriculture sustainability, food supply, natural resource development, and hydropower system reliability in the region rely heavily on monsoon rainfall. Monthly rainfall data from three stations (East Nimar, Barwani, and West Nimar) were analyzed. Initially, the pre-whitening method was applied to eliminate serial correlation effects from the rainfall data series. Subsequently, statistical trends in annual and seasonal rainfall were assessed using both parametric (student-t test) and non-parametric tests [Mann-Kendall, Sen's slope estimator, and Cumulative Sum (CUSUM)]. The magnitude of the rainfall trend was determined using Theil-Sen's slope estimator. Spatial analysis of the Mann-Kendall test on an annual basis revealed a statistically insignificant decreasing trend for Barwani and East Nimar and an increasing trend for West Nimar. On a seasonal basis, the monsoon season contributes a significant percentage (88.33%) to the total annual rainfall. The CUSUM test results indicated a shift change detection in annual rainfall data for Barwani in 1997, while shifts were observed in West and East Nimar stations in 1929. These findings offer valuable insights into regional rainfall behavior, aiding in the planning and management of water resources and ecological systems.

Keywords

Precipitation, Parametric, Non-Parametric Tests, Trend Analysis, Serial Correlations

1. Introduction

The climatology and water resources fields present an intriguing area for exploring the impact of climate change scenarios through trend detection. The increase in the absorption rate of greenhouse gases (GHGs) into the atmosphere has led to extensive climatic changes worldwide, posing a serious threat to climate change in an abrupt manner. According to the Intergovernmental Panel on Climate Change (IPCC) report of 2007 (IPCC, 2007), the rate of global warming was 0.74˚C ± 0.18˚C over a period of 100 years from 1906-2005, resulting in a significant decrease in the availability of freshwater in the future. Rainfall increased in lands between 30˚N to 85˚N latitude, but a notable decrease was observed in the past 30 - 40 years in the regions between 10˚S and 30˚N latitudes. In Southern Asia, a linear decrease in rainfall was observed from 1900 through 2005 at a rate of 7.5% per 100 years, which was statistically significant up to a level of 1%. Conversely, in northwestern India, an increase in rainfall at a rate of 20% per 100 years was observed during the same period (IPCC, 2013; Masson-Delmotte et al., 2018). According to the Central Water Commission (CWC, 2005), India receives approximately 4000 billion cubic meters (BCM) of annual average precipitation. Of this amount, 690 BCM is utilized as surface water, and 432 BCM is extracted from groundwater sources. However, the studies conducted by CWC revealed a decline in average annual precipitation. As a result, the availability of water may fluctuate significantly due to irregular rainfall patterns. Therefore, analyzing the trend of rainfall time series is crucial for designing hydraulic structures and managing local water resources efficiently (Mishra et al., 2013; Khare et al., 2014; Shukla et al., 2015). Several studies have been conducted to understand the effects of climate change on rainfall in various regions of the world (Kunkel et al., 1999; Osborn et al., 2000; Ventura et al., 2002; Xu et al., 2003; Partal & Kahya, 2006; Ampitiyawatta & Guo, 2009; Karpouzos et al., 2010; Tabari & Talaee et al., 2011; Shukla & Khare, 2013; Mishra et al., 2014; Meena et al., 2015; Mishra et al., 2016; Shukla et al., 2017: Preethi et al., 2017). Kunkel et al. (1999) utilized the non-parametric Mann-Kendall (MK) test to define the events associated with extreme precipitations of a certain duration and having a site-specific threshold and observed the linear trend in the frequency distribution of extreme rainfall events. Osborn et al. (2000) and Ventura et al. (2002) examined that the trend observed is a complex function of climate and environment.

India has a variable climatic scenario across the country, as one state of the country might be combating severe heat waves. In contrast, others may combat high floods due to this variability in climatic conditions. Local and regional analyses are the prime concerns for the evaluation of extreme events. Studies conducted by Kothyari & Singh (1996) and Kothyari et al. (1997) showed a decreasing trend in precipitation over the Gangetic Basin, beginning in the latter half of the 1960s. Singh & Sontakke (2002) also observed an increasing trend over Western Gangetic plains and a significant decrease over Central India. Singh et al. (2005) observed an increase in the trend of precipitation over the basins of the Indus, Ganga, Brahmaputra, Krishna, and Cauvery rivers. Goswami et al. (2006) observed increases in the frequency and magnitude of extreme precipitation events. Mishra et al. (2016) detected the mean annual rainfall shows an insignificant decreasing trend over the Tawa Canal command area, in central India There is a need for an extensive and in-depth study of the spatial and temporal variations in rainfall over a regional scale indicated by Shukla & Khare (2019).

Therefore, this research aims to examine the long-term rainfall patterns at three stations located in the Indira Sagar Project region of Madhya Pradesh, India. The study utilizes both parametric (Student-t) and non-parametric (Mann-Kendall) methods to analyze the monotonic trends in annual and seasonal rainfall series spanning 110 years (1901-2010). To enhance the accuracy of the analysis, a pre-whitening approach is employed to mitigate the influence of significant serial correlation coefficients in the long-term datasets. Additionally, the research incorporates the distribution-free cumulative sum test to identify any shift or change in the annual and seasonal rainfall series.

2. Methodology

2.1. Study Area

The Indira Sagar Region (ISR) is situated within three districts of Madhya Pradesh: Barwani, East Nimar (Khandwa), and West Nimar (Khargone) (**Figure 1**). In the Indira Sagar Region, construction of the canal (Indira Sagar Pariyojana) began in April 2002. The low seasonal rainfall due to the geographic location and climate characteristics of the ISR and the lack of an adequate quantity of rainwater for irrigation purposes have led to the construction of a canal in this region. Hence, a lined canal was created to remove water from the reservoirthrough the Punasa tunnel. The study area is located between 74˚46' to 76˚29' East longitude and 21˚46' to 22˚19' North latitude and covers an area of approximately 3550 km^2. The elevation of the study area varies from 84 to 320 m above mean sea level. However, due to the construction of the Indira Sagar dam about

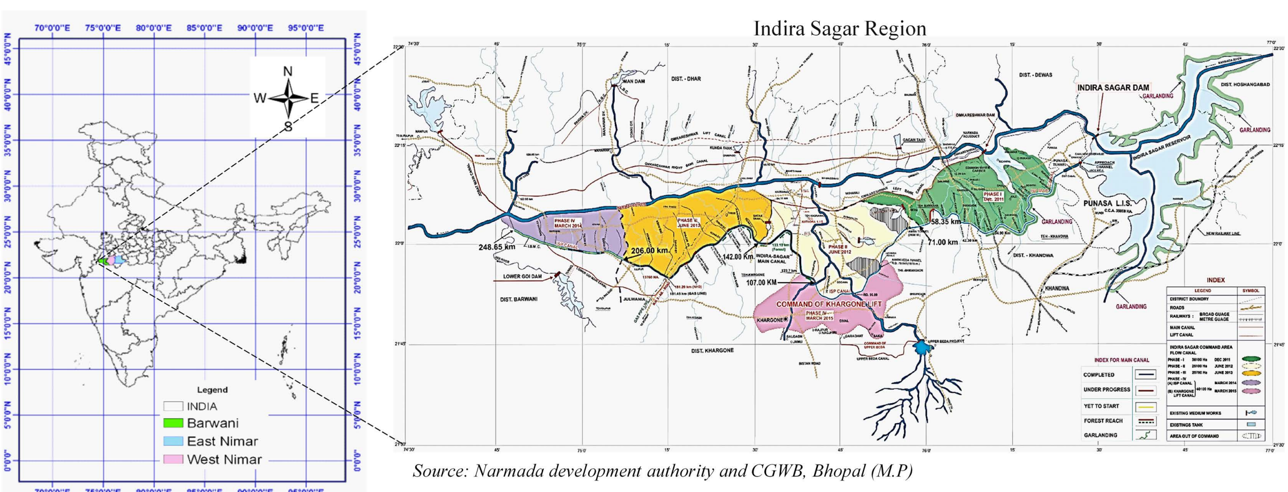

Figure 1. Location of Indira Sagar Region with canal command area.

91,348 ha (land including 41,111 ha of forest) was submerged under water which contains 248 villages and one town (Harsud) and about 80,572 people in total 30,739 families (Desai et al., 2007).

2.2. Data Collection and Trend Analysis Techniques

As per the World Meteorological Organization (WMO, 1986), a minimum record length of 30 years is deemed sufficient for the statistical validity of trends in climate change research, a sentiment echoed by Kahya & Kalayci (2004), Rudra et al. (2023) and Shukla et al. (2023). In this study, monthly rainfall data of 3 stations covering a period of 110 years (1901-2010) were downloaded from the Indian Meteorological Department (IMD), site of India water portal website, (https://www.indiawaterportal.org/articles/district-wise-monthly-rainfall-data-list-raingauge-stations-india-meteorological) and (https://www.indiawaterportal.org/met_data) and location of meteorological stations is presented in spatial **Figure 1** & **Figure 8**. The spatial representation in **Figure 8** indicates the locations of meteorological stations through the use of red arrows and also depicts both upward and downward trends in annual and seasonal rainfall. Data quality control is a necessary step; however, non-parametric tests are robust against outliers. On the other hand, outliers play a key role in parametric tests and in assessing the magnitude of the possible changes by computing means (moments) and linear regression. However, rainfall in all series for the period of 110 years was complete, and no gap-filling method was used in this study. By contrast, parametric tests are susceptible to outliers, impacting the assessment of potential changes through mean and linear regression computations (Duhan & Pandey, 2013; Mishra et al., 2013). The seasonal rainfall was computed by averaging monthly values for the following seasons: winter (December, January, and February), pre-monsoon (March, April, and May), monsoon (June, July, August, and September), and post-monsoon (October and November). For this study, rainfall data covering 110 years were analyzed for three stations in Madhya Pradesh. The analysis encompassed monthly, seasonal, and annual perspectives for rainfall. **Figure 2** illustrates the data collection and trend analysis framework.

In this study, the investigation into spatial and temporal annual and seasonal trends in rainfall series involved the application of both parametric (Student-t) and non-parametric (Mann-Kendall and Sen's slope estimator) methods. To mitigate the impact of serial correlation (autocorrelation), pre-whitening was initially applied, following the approach suggested by Von Storch & Navarra (1995). Despite initial assertions by Lettenmaier et al. (1994) that serial correlation effects on trend tests could be considered negligible, concerns about potential impacts on trend analysis have gained momentum in the recent years. Yue & Hashino (2003) noted that persistent positive serial correlation in time series could elevate the risk of rejecting the null hypothesis, even if it is true that the time series has no trend.

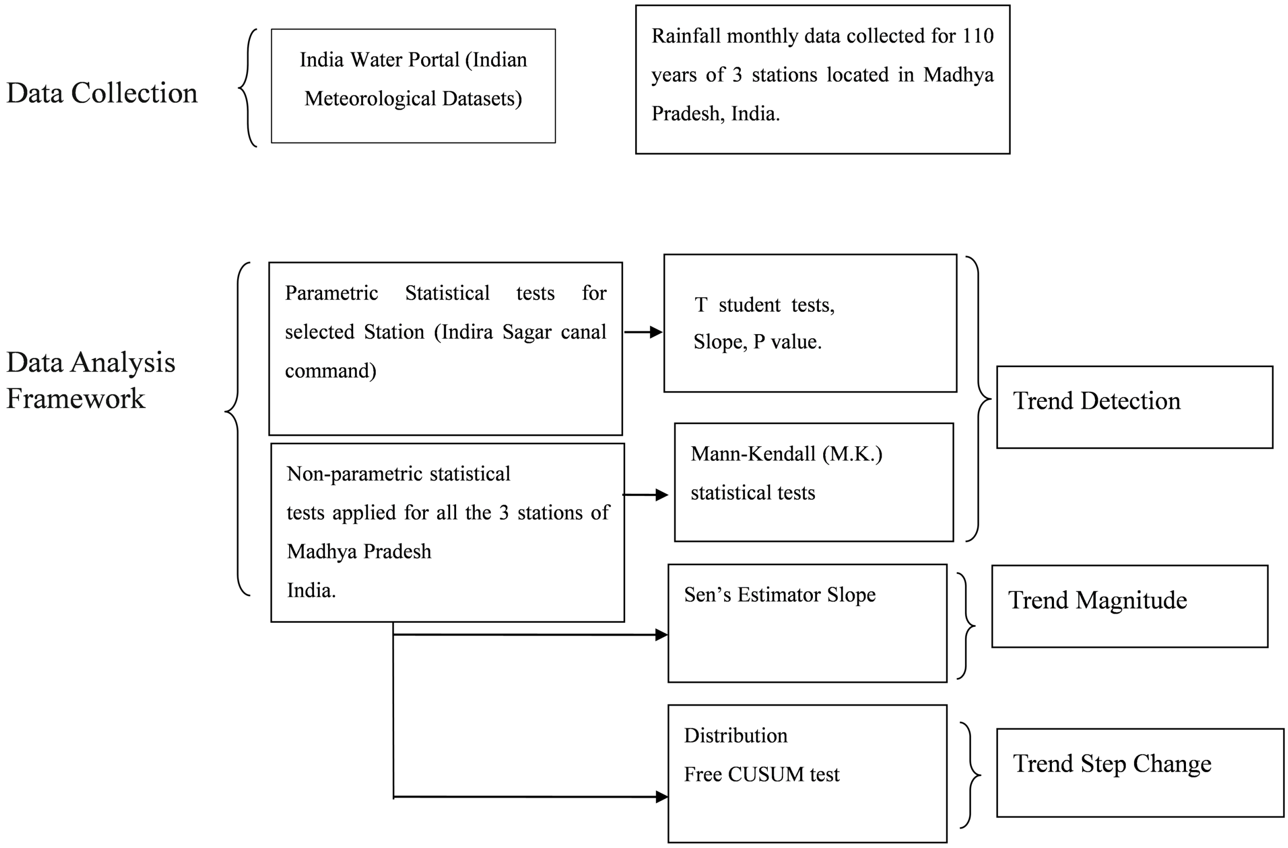

Figure 2. Data collection and trend analysis framework.

Following the pre-whitening of data series, standard precipitation characteristics were calculated, including mean (μ), standard deviation (σ), and the coefficient of variation (C_v) for monthly scales across all three stations. Subsequently, the student-t parametric method was applied to detect trends in the pre-whitened rainfall data series. This parametric test involves considering the linear regression of the random variable Y on time X. The Pearson correlation coefficient (r) was computed using the equation provided by Haan (1977) (with detailed explanations available in the supplementary material).

Non-parametric rank-based tests, specifically the MK test, were then employed to identify trends in the time series data, offering robustness to extremes and suitability for skewed variables (Hamed, 2008). Non-parametric trends are preferable in cases where the data is non-normally distributed and contains outliers (Helsel & Hirsch, 1992, 2002; Birsan et al., 2005). Then, the Sen's Slope Estimator was applied in the time series to calculate the true slope in the presence of a linear trend, utilizing a simple non-parametric procedure developed by Sen (1968) detailed explanation with equations are given in supplementary material.

Finally, the Cumulative Sum (CUSUM) test was implemented to determine the most probable year when a significant shift occurred in rainfall trends. This test involves comparing successive observations with the series median to detect changes in the mean of a time series after a specific number of observations

(McGilchrist & Woodyer, 1975; Chiew & McMahon, 1993; Kundzewicz & Robson, 2004).

3. Results and Discussion

3.1. Serial Correlation Analysis

Initially, the serial correlation (autocorrelation) test was applied to the all-time series to check the randomness available in the data. Then the pre-whitening method was employed to remove the effects of serial correlation from rainfall time series data before applying certain statistical tests. The outcome reveals that after removing randomness from the series by the pre-whitening method, serial correlation coefficients were found statistically insignificant (**Table 1**). In this study, removing randomness from a rainfall series typically refers to the process of identifying and eliminating or reducing the effects of random variability or noise in the data. Rainfall data often exhibit random fluctuations due to various factors such as atmospheric conditions, weather patterns, and measurement errors. By removing randomness, analysts aim to uncover underlying patterns, trends, or signals in the data that may be obscured by random noise (Von Storch & Navarra, 1995). Further, an MK test with Sen's slope estimator was applied for trend analysis. The results of the serial correlation coefficient after pre-whitening analysis for 1901 to 2010 are presented in **Table 1**.

3.2. Rainfall Characteristics and Parametric Test

Rainfall characteristics of the Indira Sagar Region for the period of 1901-2010 are presented in **Table 2**. The mean (μ) annual rainfall of the region is 781.4 mm with a standard deviation (σ) of 170 mm and the coefficient of Skewness of annual rainfall is −0.003. In addition, the coefficient (C_v) of variation for the mean annual rainfall is 21.8%. Monsoon contributes 88.3% of the annual rainfall in the region, whereas rainfall in the winter is the least (0.45%). During the monsoon season, the coefficient of variation is low (23.4%) as compared to other seasons, which shows a dependable monsoon rainfall. Monthly rainfall in June, July, and August can be considered as dependable. Also, the spatial and temporal distribution of daily precipitation during monsoon season and in these months is irregular at different parts of the region though showing a dependable nature when summed for the whole period. Here, dependable monsoon rainfall implies a level of reliability and predictability in the occurrence of monsoon rainfall, suggesting

Table 1. Values of serial correlation coefficient after pre-whitening the rainfall series at the stations.

Stations	Location of stations		Serial Correlation Coefficient				
	latitude (N)	longitude (E)	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
Barwani	22.04	75.05	−0.026	0.129	−0.038	−0.035	−0.066
West Nimar	21.92	75.74	−0.008	0.081	−0.010	−0.037	−0.014
East Nimar	22.19	76.29	0.040	0.211	−0.035	0.052	−0.031

Table 2. Standard statistics of seasonal and annual rainfalls for 1901-2010.

Stations Precipitation Totals	Barwani				East Nimar				West Nimar			
	(μ)	(σ)	C_v (%)	CS	(μ)	(σ)	C_v (%)	CS	(μ)	(σ)	C_v (%)	CS
Annual	866	193.96	22.39	0.11	777	162.55	20.91	0.08	701	155.84	22.23	−0.20
Pre-monsoon	13	12.00	89.13	0.75	18	15.15	86.01	0.58	14	11.08	76.50	0.39
Monsoon	752	188.12	25.02	0.12	696	150.24	21.57	0.13	621	147.48	23.73	−0.16
Post-monsoon	45	39.35	87.17	0.63	54	45.38	84.49	0.32	44	35.62	80.79	0.77
Winter	1	1.96	164.4	1.68	5	7.18	149.93	1.26	2	3.38	176.61	1.30

Note: μ = Mean of the rainfall data series, σ = Standard Deviation, C_v = Coefficient of Variation, and CS = Coefficient of Skewness.

Table 3. Annual and seasonal rainfall trend values of the parametric test (1901-2010) for selected stations.

Stations Precipitation Totals	Barwani			East Nimar			West Nimar		
	Slope	t Stat	P-value	Slope	t Stat	P-value	Slope	t Stat	P-value
Annual	0.093	−0.237	0.812	0.266	−0.006	0.994	0.435	0.414	0.679
Pre-monsoon	0.006	−0.283	0.777	0.055	−0.010	0.991	0.002	0.760	0.448
Monsoon	0.165	−1.074	0.284	0.106	−0.855	0.394	0.466	−0.213	0.831
Post-monsoon	0.054	0.813	0.417	−0.142	1.566	0.120	−0.007	0.814	0.417
Winter	0.007	−0.264	0.791	−0.015	0.689	0.492	0.016	0.206	0.836

that it occurs consistently over time and can be counted upon for sustaining ecosystems and human activities. However, Spatial variations and fluctuations in monsoon patterns can impact the dependability of monsoon rainfall, leading to challenges such as droughts, floods, and agricultural losses. Therefore, understanding the factors influencing monsoon variability and improving forecasting capabilities are essential for ensuring the dependability of monsoon rainfall and mitigating its associated risks. Furthermore, an outcome of the parametric (student-t) test is presented for three stations namely, Barwani, East Nimar, and West Nimar (Table 3).

3.3. Rainfall Non-Parametric (MK Test) Trend Analysis

Annual

Results of the MK test and CUSUM test are presented for three stations namely, Barwani, East Nimar, and West Nimar (Table 4 and Table 5). The entire study region received high rainfall in the years 1973 for Barwani and West Nimar, with amounts exceeding 1376 mm, and 1123 mm, and year 1944, the regions of East Nimar experienced 1237 mm of rain, respectively, over the course of a century. However, the 5-year moving average for the region, considering all three stations, showed a significant decline in the trend of annual rainfall from 1900 to 1930 and 2000 to 2010 on a decadal basis (Figures 3(a)-(c)). A 5-year moving average to identifying and analyzing trends over 110 years, particularly if

Table 4. Annual and seasonal rainfall trend values of non-parametric (MK) test (1901-2010), for selected stations.

Stations Rainfall Totals	Barwani			East Nimar			West Nimar		
	Zmk	Sen slope (β)	Sen's estimate (B)	Zmk	Sen slope (β)	Sen's estimate (B)	Zmk	Sen slope (β)	Sen's estimate (B)
Annual	−0.17	−0.10	854.9	−0.47	−0.24	789.9	0.96	0.43	695.1
Pre-monsoon (Mar-May)	−1.01	−0.02	9.99	0.25	0.01	13.1	0.34	0.01	12.0
Monsoon (June-Sept)	−0.22	−0.14	739.0	−0.35	−0.18	700.5	0.96	0.44	606.7
Post-monsoon (Oct-Nov)	0.56	0.05	31.4	−1.00	−0.11	56.3	0.11	0.01	33.5
Winter (Dec-Feb)	−1.61	−0.01	2.7	−1.12	−0.03	11.2	−1.10	−0.01	6.1

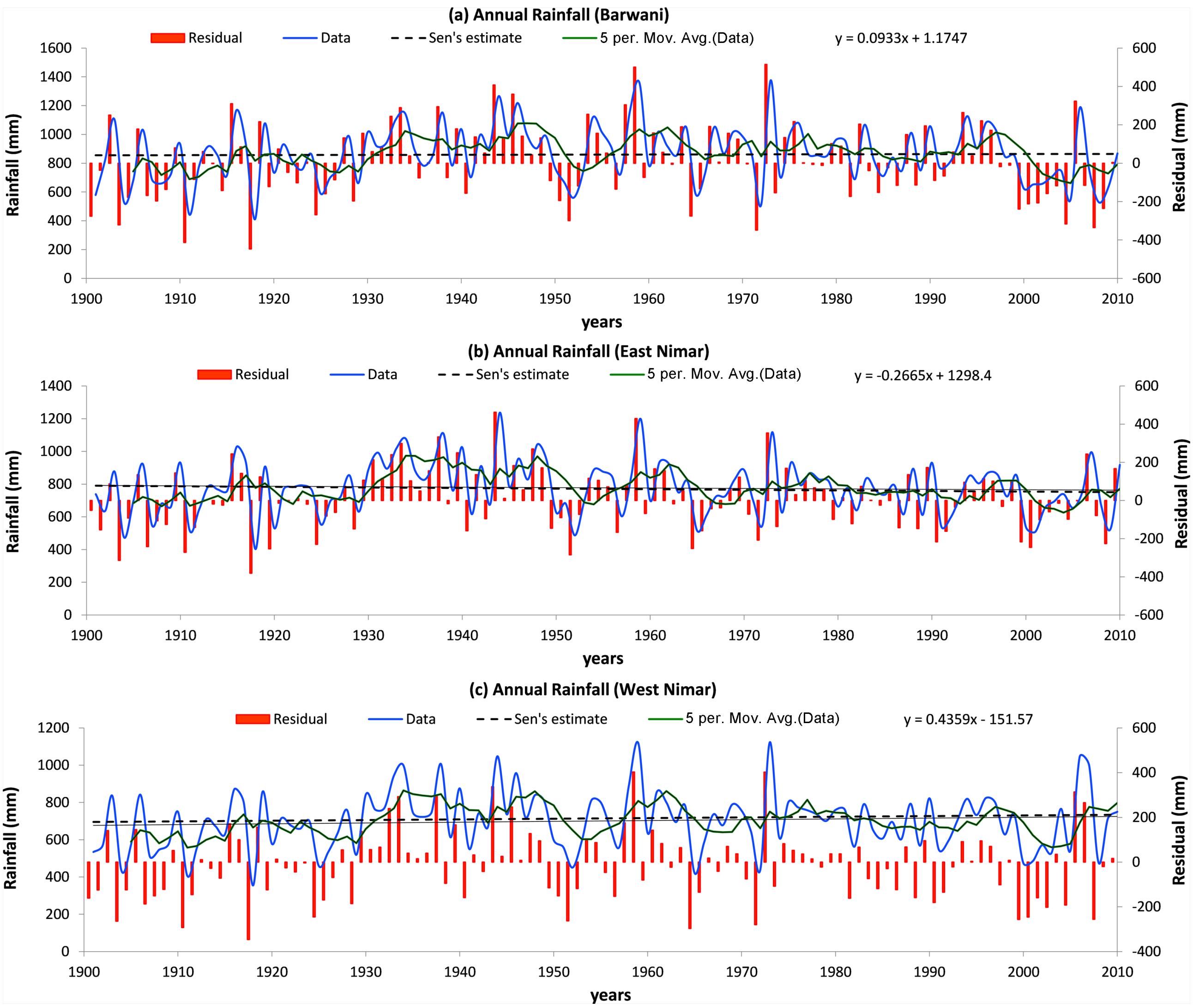

Figure 3. Annual rainfall trends over Indira Sagar Region (1901-2010).

there is a gradual or long-term decline or increase in the data. By averaging data over 5 years, the moving average can highlight underlying trends while reducing the influence of short-term fluctuations. However, Figure 3 also shows the inter-decadal variability and oscillations of the average annual rainfall time series for the period of 1901-2010. This observation can provide valuable insights into the complex dynamics of regional climate variability and inform adaptive responses to the changing environment of ISR. Additionally, the results of the MK test on the annual rainfall series for all three stations are shown in Figure 8(a). The test revealed that the trends in the annual rainfall time series for Barwani and West Nimar were consistently positive, while for East Nimar, the trend was negative.

While the annual trend in the region does not reach statistical significance at a 90% confidence level ($\alpha = 0.10$). Furthermore, the Sen's estimator of slope was employed to determine the rate of change of the observed trends in all the rainfall time series. The mean annual rainfall over the Indira Sagar Region showed a long-term insignificant trend. It is important to note that a statistically significant trend may not be practically significant and vice versa may also be true (Daniel, 1978).

Seasonal rainfall trend

Pre-monsoon

In the Indira Sagar region, there is a noticeable upward trend in annual rainfall in Barwani from 1985 to 2005 in the pre-monsoon season (see Figure 4(a)). Similarly, stations in East and West Nimar exhibit increasing rainfall trends from 2000 to 2010 (refer to Figure 4(b) and Figure 4(c)). This rising trend is reflected in the overall analysis through regression analysis, attributed to the increase in moving averages. Nonetheless, when subjected to the MK test, the results for the pre-monsoon precipitation series at all three stations are depicted in Figure 8(b). These results indicate a positive monotonic trend in pre-monsoon rainfall time series at the East and West Nimar stations between 1901 and 2010. However, the statistical significance of the pre-monsoon trend in the region does not reach the 90% confidence level ($\alpha = 0.10$). Sen's estimates alongside corresponding residuals are presented in Figure 4.

Monsoon

Figure 5 illustrates the monsoon trend across the Indira Sagar Region from 1901 to 2010, focusing on the stations Barwani, East Nimar, and West Nimar. Analysis of rainfall data for the monsoon season revealed a decreasing trend observed from 2000 to 2008 at all three stations, as depicted in Figures 5(a)-(c). Regression analysis was conducted to assess this trend. Additionally, the Mann-Kendall (MK) test was performed on the monsoon time series, which contributes a significant percentage (88.33%) to the total annual precipitation. The results indicated that the monsoon trend in the region over the last century was statistically insignificant at the 90% confidence level. However, for the Barwani and West Nimar stations, the MK test statistics showed positive values, while for East Nimar, a negative value was obtained (Figure 8(c)). This suggests a monotonic upward trend for Barwani and West Nimar, whereas East Nimar exhibited

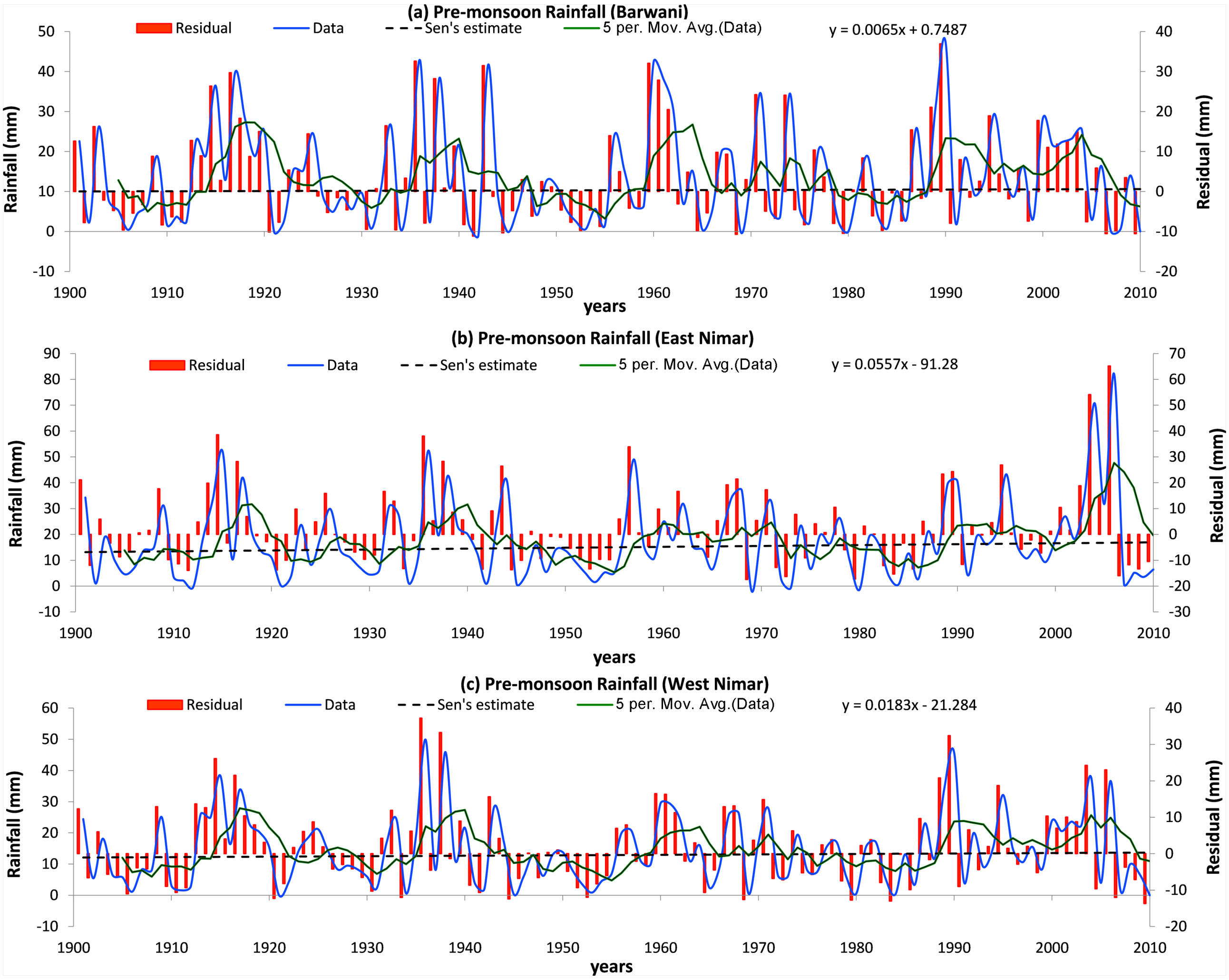

Figure 4. Pre-monsoon trend over Indira Sagar Region (1901-2010).

a slight downward trend over the century. Sen's slope and estimates, along with corresponding residuals, are presented in Figure 5 for all the selected stations. These findings provide valuable insights into the long-term rainfall trends in the region, offering important implications for water canal management and conservation planning initiatives.

Post-monsoon

For the past decades in this area, the three stations have exhibited a positive trend in rainfall from 1995 to 2004, during reservoir construction, but after construction shows a decreasing trend to the post-monsoon season (as depicted in Figures 6(a)-(c)). The results of the MK test for the regional basis for all the stations show insignificant (no trend) at a 90% confidence level (Figure 8(d)). Although Sen's estimates and corresponding residuals are illustrated in Figure 6, it is noteworthy that Barwani and West Nimar display a positive trend (i.e., an upward trend), while East Nimar shows a decreasing trend over the course of the study.

Winter

The linear trend during the winter season exhibited a consistent downward

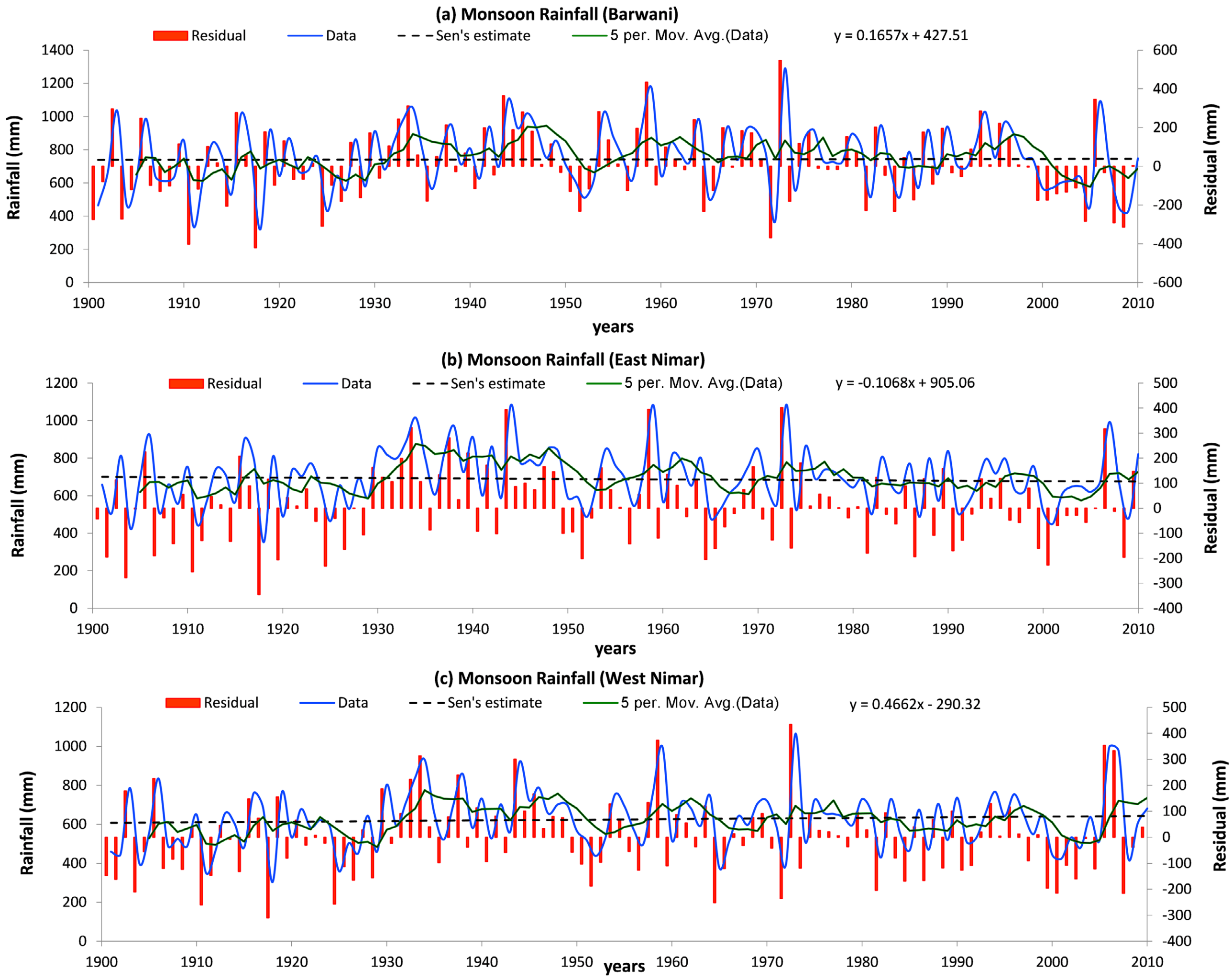

Figure 5. Monsoon trend over Indira Sagar Region (1901-2010).

trajectory across all three stations, as depicted in Figures 7(a)-(c). Sen's estimates, along with the corresponding residuals, are visible in the same figure. Furthermore, Figure 8(e) displays the results of the MK test. For the winter season, the monotonic trend reveals statistically significant findings at the 90% confidence level ($\alpha = 0.10$), with the Z statistics indicating negative values for all stations within the region. These results underscore a notable decline in winter rainfall trends, suggesting potential implications for regional water resource management and ecosystem dynamics.

Existence of Shift Change in the Indira Sagar Region

The distribution-free CUSUM test was applied to test the hypothesis to check the existence of a step (shift) change in rainfall time series during the period of study. The results for annual and seasonal precipitation time series for all three stations of the region are shown in Table 5.

4. Conclusions

A long-term analysis of rainfall data (1901-2010) in the Indira Sagar Region of

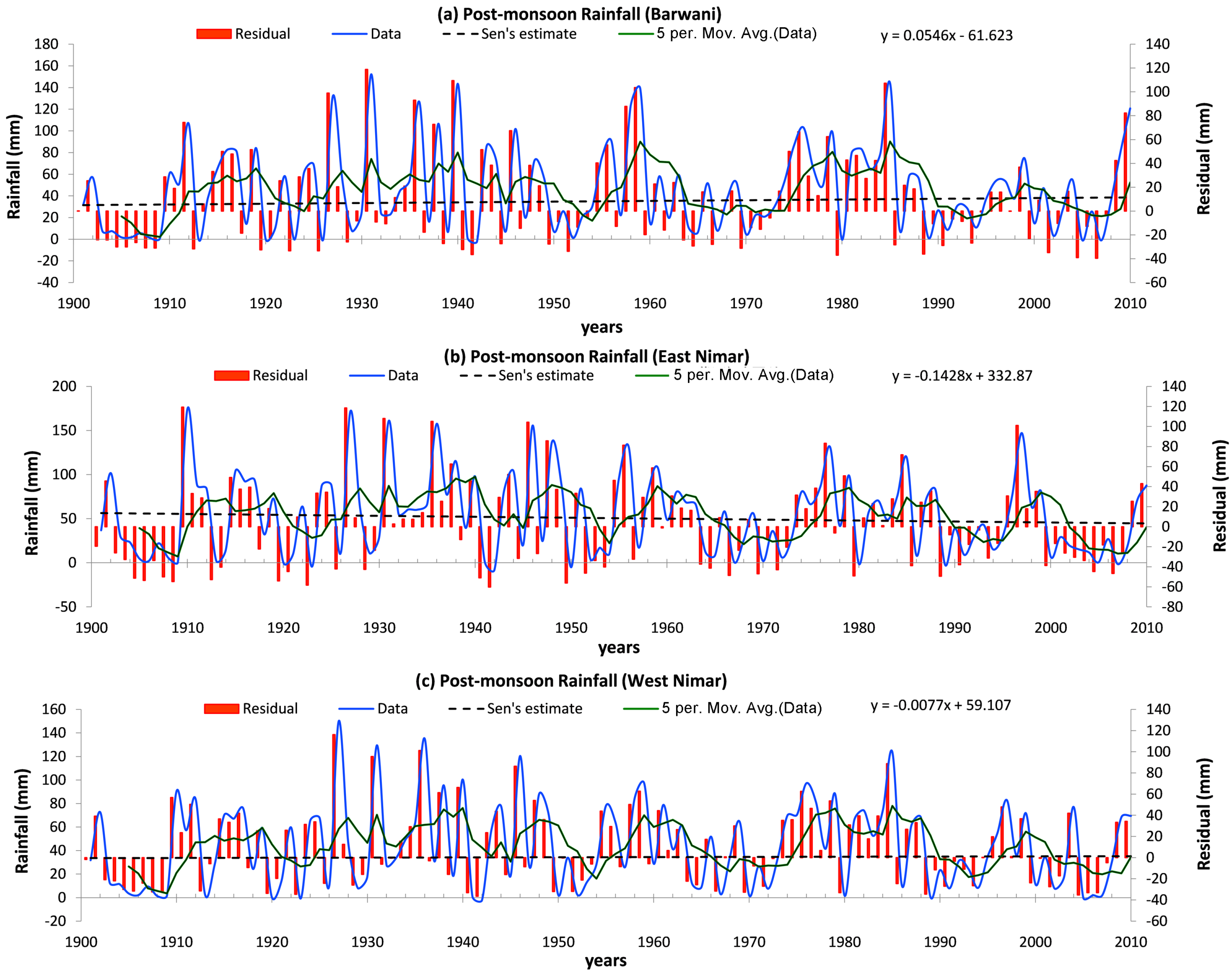

Figure 6. Post-monsoon trend over Indira Sagar Region (1901-2010).

Table 5. Detection of annual and seasonal rainfall data series year shift changes for the period 1901-2010 using CUSUM methods at all three stations.

Stations Precipitation Totals	Barwani		East Nimar		West Nimar	
	Max deviation	Year of change	Max deviation	Year of change	Max deviation	Year of change
Annual	9	1997	9	1929	13	1929
Pre-monsoon	6	1988	11	1955	6	1912
Monsoon	8	1988	12	1978	11	1913
Post-monsoon	7	1973	10	1988	7	1909
Winter	8	1918	7	1999	7	1923

Madhya Pradesh, India, has indicated no significant change in annual precipitation. However, annual, and seasonal trends excluding the winter season for the region, Barwani and West Nimar showed increasing (upward) rainfall trend, whereas, East Nimar showed a decreasing trend. The winter season indicates a decreasing trend for all stations in the region. The annual change point year of

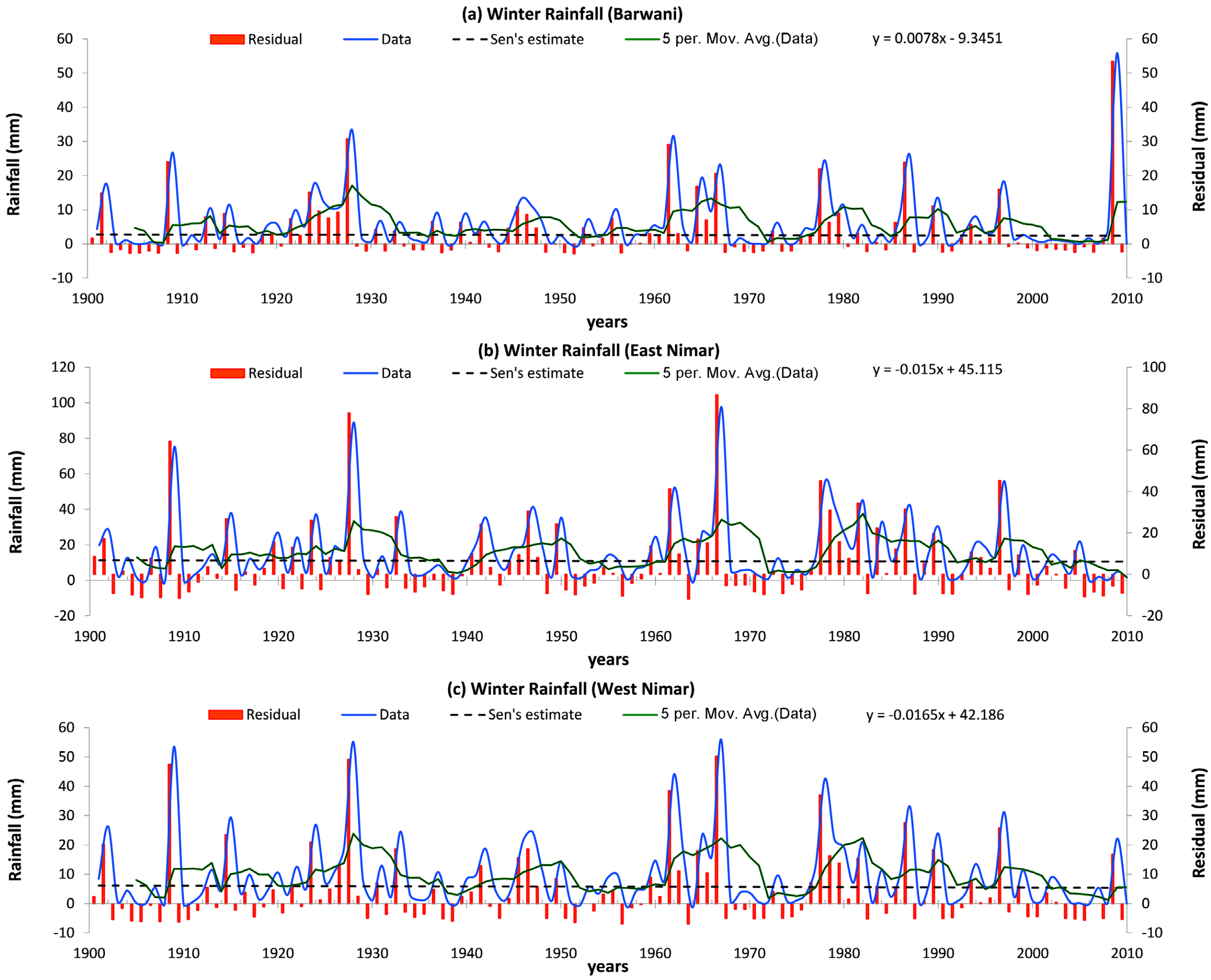

Figure 7. Winter trend over Indira Sagar Region (1901-2010).

the insignificant upward shift change was 1997 for Barwani and 1929 for West Nimar, however, for East Nimar there was a downward shift over the region. The spatial analysis of the trend indicates that increasing trends of rainfall were found in stations located on the West side (Barwani and West Nimar) and a decreasing trend at East Nimar station of the region. However, the spatial and temporal resolution of the data can influence trend analysis outcomes. Coarse-resolution data may mask localized trends, while inadequate temporal resolution may overlook short-term fluctuations or abrupt changes in the data. However, uncertainty in trend estimates can arise from sampling variability, model assumptions, or parameter estimation, which should be appropriately accounted for and communicated. Minor climate changes may have affected the magnitude and timing of rainfall within the region. Overall, significant seasonal changes in rainfall will impact water management in the agricultural areas and hydropower generation in the region. In addition, it would be important to further investigate the impact of climate change on natural resources.

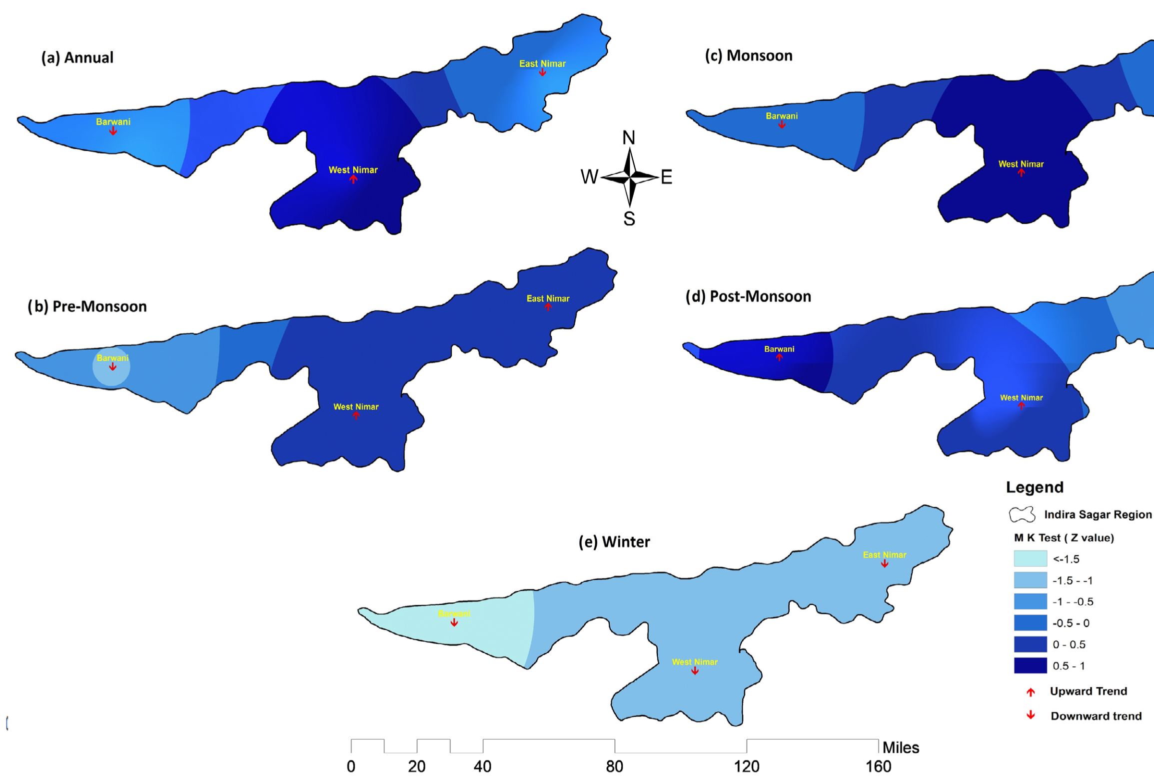

Figure 8. Values of Z statistics of MK test for the annual and seasonal rainfall data series (1901-2010).

Future Prospects: The future exploration of surface temperature analysis concerning reservoir construction presents an avenue for enhancing our comprehension of hydrological, ecological, climatological, and socioeconomic dynamics. This research endeavor can serve as a cornerstone for evidence-based decision-making, fostering sustainable water resource management and environmental conservation efforts. For instance, there is an opportunity to delve into the socioeconomic implications of changes in surface temperature attributed to reservoir construction. This includes assessing impacts on agriculture, water resource management, human health, energy consumption, and outdoor recreational activities. Additionally, there is a need to formulate adaptive management strategies and offer policy recommendations based on the findings of surface temperature analysis. These recommendations aim to bolster sustainable reservoir management practices, mitigate adverse environmental effects, and strengthen ecosystem resilience in response to climate change.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Supplementary Material

1.1. Influence of Serial Correlation

The serial correlation coefficient (r_k) of a discrete time series for lag-k is estimated as follows:

$$r_k = \frac{\sum_{k=1}^{n-k}\left(X_t - \bar{X}_t\right)\left(X_{t-k} - X_{t+k}\right)}{\left[\sum_{k=1}^{n-k}\left(X_t - \bar{X}_t\right)^2\left(X_{t+k} - \bar{X}_{t+k}\right)^2\right]^{0.5}} \quad (1)$$

where, r_k is the lag-k serial correlation coefficient of the series. The hypothesis of serial independence is then tested by the lag-1 autocorrelation coefficient as H_0: $r_1 = 0$ against H_1: $|r_1| > 0$ using the test of significance of serial correlation (Yevjevich, 1971) following Rai et al. (2010),

$$\left(r_k\right)_{t_g} = \frac{-1 \pm t_g\left(n-k-1\right)^{1/2}}{n-k} \quad (2)$$

where, $\left(r_k\right)_{t_g}$ is the normally distributed value of r_k, t_g is the normally distributed statistic at g level of significance. The value of t_g are 1.645, 1.965 and 2.326 at a significance level of 0.10, 0.05 and 0.01 respectively. If $|r_k| \ge \left(r_k\right)_{t_g}$, the null hypothesis about serial independence is rejected at the significance level α (here 0.05). For the non-normal series, MK test is an appropriate choice for the trend analysis (Yue & Pilon, 2004; Basistha et al., 2008). Therefore, the MK test has been used wherever the serial correlation is not significant at 5% significance level.

1.2. Pre-Whitening

The method of pre-whitening was applied to remove the effect of serial correlation and autocorrelation on the non-parametric test. Lettenmaier et al. (1994) suggested that the effects of serial correlation upon trend tests in such applications could be assumed negligible; concern about the potential impacts of autoregressive processes upon trend analysis nevertheless appears to be gaining momentum. For e.g., assessments of the potential effects of urbanization and climate change upon river behavior undertaken by Leith & Whitfield (2000) and Zhang et al. (2001), respectively, applied the prewhitening or deserialization scheme of Von Storch & Navarra (1995) to deal with serial correlation:

$${}^{pw}x_i = x_i - cx_{i-1} \quad (3)$$

where ${}^{PW}X$ is the pre-whitened data to be used in the subsequent trend analysis and c is the lag-1 serial correlation coefficient as determined directly from the data using Equation (3). Pre-whitening is utilized only if observed r is greater than some critical value, C_{criti} taken to be 0.1 by Von Storch & Navarra (1995).

1.3. Parametrical Statistical Test

There are many parametric methods, which have been applied for detection of trends. The parametric test considers the linear regression of the random variable Y on time X.

T-Student Test

The regression coefficient b1 (or the Pearson correlation coefficient *r*) was computed from the data. It is known (Haan, 1977) that the statistic.

$$t = \frac{r\sqrt{n-2}}{\sqrt{n-r^2}} = \frac{b_1}{s/\sqrt{ss_x}} \tag{4}$$

Follows Student's *t* distribution with degrees of freedom $n - 2$, where n is the sample size, s is the standard deviation of residuals, and SS_x is the sums of squares of the independent variable (time in trend analysis). The hypothesis H_0: $\rho = 0$ (or $\beta_1 = 0$) is tested against the hypothesis H_1: $\rho \neq 0$ (or $\beta_1 \neq 0$) at a chosen level of significance α, where ρ and β_1 are the population values, respectively, of the correlation coefficient and regression coefficient. The hypothesis that there is no trend is rejected when the t value computed by Equation (4) is greater in absolute value than the critical value $t_{\alpha/2}$ (Onoz & Bayazit, 2003).

1.4. Non-Parametric Statistical Test

Non-parametric trends can be adopted in the case with the required data to be non-normally distributed and containing outliers in the data (Helsel & Hirsch, 1992; Birsan et al., 2005).

1.4.1. MK Test

The MK test is a non-parametric rank-based test for identifying trends in time series data and robust to the power of extremes and fitting for application with skewed variables (Hamed, 2008).

The MK test searches for a trend in a time series without specifying whether the trend is linear or nonlinear (Pingale et al., 2016). The trend test is applied to a time series x_i ranked from $i = 1, \cdots, n-1$, and x_j ranked from $j = i+1, 2, \cdots, n$. Each data point x_i is used as a reference point and is compared with all other data points x_j such that

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} +1 > \left(x_j - x_i\right) \\ 0 = \left(x_j - x_i\right) \\ -1 < \left(x_j - x_i\right) \end{cases} \tag{5}$$

The alternative hypothesis H1 of a two-sided test is the distribution of X_i and X_j are not identical for all $i,j \leq n$ with $k \neq j$. And the Kendall statistics S is estimated by (Kahya & Kalayci, 2004).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{6}$$

The variance of the statistic S is defined by

$$Var(S) = \frac{n(n-1)(2n+5) - \sum t_i(i)(i-1)(2i+5)}{18} \tag{7}$$

where t_i denotes the number of ties up to sample i.

The test statistics z_c is estimated as

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \tag{8}$$

The standardized MK test statistics (Z_{mk}) follows the standard normal distribution with a mean of zero and variance of one. The null hypothesis for the no trend is accepted in a two-sided test for trend if $|Z_{mk}| \le Z_{1-\alpha/2}$ (here $\alpha = 0.1$) and the null hypothesis for the no trend is rejected if $|Z_{mk}| \ge Z_{1-\alpha/2}$. Failing to reject the null hypothesis does not mean that there is no trend but it indicates that there is insufficient evidence to conclude that trend exists in the time series or not (Helsel & Hirsch, 2002). A positive value of Z_{mk} indicates an "upward trend" and a negative value indicates 'downward trend'.

1.4.2. Sen's Slope Estimator

This method is applied where the trend is assumed linear and represents change per unit time. In the time series, where a linear trend is present, the true slope was calculated by using a simple non-parametric procedure developed by Sen (1968). The slope estimate of N pairs of data are first computed by

$$\beta = \frac{x_j - x_k}{j-k} \quad \text{for} \quad i = 1, 2, 3, \cdots, N \tag{9}$$

where, x_j and x_k are data values at times j and k ($j > k$) respectively. The meridian of these N values of β is a Sen's estimator of the slope. If N is odd, then Sen's estimator is computed by $\beta_{\text{med}} = \beta_{(N+1)/2}$ and if N is even, then Sen's estimator is computed by $\beta_{\text{med}} = \left[Q_{N/2} + Q_{(N+2)/2} \right] / 2$. Finally, Q_{med} is tested by a two-sided test at 100 ($1 - \alpha$)% confidence interval and a true slope may be obtained by the non-parametric test.

1.5. Shift Detection Using CUSUM Test

This non-parametric rank-based method was used to identify in which year an abrupt change has occurred in the precipitation time series. In particular, successive observations were compared with the median of the series to detect a change in the mean of a time series after a number of observations (McGilchrist & Woodyer, 1975; Chiew & McMahon, 1993; Kundzewicz & Robson, 2004). The Cusum is computed as follows (Kiely, 1999):

$$S_i = \sum_{i=1}^{i} x_i - \overline{x} \tag{10}$$

where $\overline{x}$ is the average value of the time series. A possible change has occurred when S_i is a maximum. In this study, the magnitude of S_i was calculated for the time series with significant changes.

1.6. Moving Average

In 17th century, De Moivre introduced the concept of moving averages in his work on probability theory. Later, Jeffreys (1939) discussed the use of moving averages in statistics and their relevance in analyzing time series data. The moving average computation, a series of averages of different subsets were generated from the full data set. Given a series of numbers and a fixed subset size, the moving average was obtained by first taking the average of the first subset. The fixed subset size was then shifted forward, creating a new subset of numbers, which is averaged. This process was repeated for the entire data series. The plot-line connecting all the (fixed) averages is the moving average. Thus, a moving average is not a single number, but it is a set of numbers, each of which is the average of the corresponding subset of a larger set of data points.

2 MK Test Monthly trend analysis results:

The trend in monthly rainfall series (1901-2010) for all three stations of a region was evaluated using the non-parametric test (**Table S1**). The trend was decreasing in most of the months for all three stations. Only the month of August showed the statistically significant increasing trend at the 95% and 99% confidence level for all 3 stations. An upward trend can be seen in the month of May and October whereas there is a significant downwards trend in April, July, and December. Consequently, it would be expected that increasing rainfall in the month of May and decreasing in July. The same phenomena would happen in the months of October and December. The distribution-free CUSUM test was applied to test the hypothesis to check the existence of a step (shift) change in precipitation time series during the period of study. The results for annual and seasonal precipitation time series for all three stations of the region are shown in **Table S1**.

Table S1. Monthly precipitation trend analysis during the years 1901-2010.

Stations Rainfall Totals	Barwani			East Nimar			West Nimar		
	Zmk	Sen slope (β)	Sen's estimate (B)	Zmk	Sen slope (β)	Sen's estimate (B)	Zmk	Sen slope (β)	Sen's estimate (B)
Jan	−0.71	0.000	0.10	−0.05	0.000	1.75	−0.57	−0.001	0.51
Feb	−1.21	0.000	0.01	−0.63	−0.002	0.75	−0.56	0.000	0.31
Mar	−1.19	0.000	0.83	−0.38	−0.002	3.32	0.41	0.001	1.06
Apr	−2.63	−0.003	0.71	−1.44	−0.008	1.78	−2.30	−0.005	1.29
May	−0.61	−0.007	3.63	0.42	0.006	2.27	0.13	0.001	4.45
Jun	−0.57	−0.115	151.88	−0.93	−0.197	132.45	−0.45	−0.087	121.12
Jul	−1.68	−0.525	282.88	−0.93	−0.255	256.28	−0.95	−0.232	219.53
Aug	2.96	0.777	148.28	2.54	0.593	179.25	2.90	0.717	135.33
Sep	−0.95	−0.243	147.60	−0.79	−0.166	121.16	−0.35	−0.076	107.02
Oct	1.18	0.052	12.45	0.06	0.005	14.16	0.84	0.026	11.59
Nov	−0.76	−0.003	2.62	−1.60	−0.019	5.416	−1.19	−0.012	5.51
Dec	−1.13	−0.001	0.79	−2.20	−0.008	1.931	−1.79	−0.004	1.24
Annual	−0.17	−0.100	854.95	−0.47	−0.242	789.99	0.96	0.435	695.16