

Article

Spatiotemporal Rainfall Variability and Trends over the Mahi Basin, India

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Abstract: Climate change can have an influence on rainfall that significantly affects the magnitude frequency of floods and droughts. Therefore, the analysis of the spatiotemporal distribution, variability, and trends of rainfall over the Mahi Basin in India is an important objective of the present work. Accordingly, a serial autocorrelation, coefficient of variation, Mann–Kendall (MK) and Sen’s slope test, innovative trend analysis (ITA), and Pettitt’s test were used in the rainfall analysis. The outcomes were derived from the monthly precipitation data (1901–2012) of 14 meteorology stations in the Mahi Basin. The serial autocorrelation results showed that there is no autocorrelation in the data series. The rainfall statistics denoted that the Mahi Basin receives 94.8% of its rainfall (821 mm) in the monsoon period (June–September). The normalized accumulated departure from the mean reveals that the annual and monsoon rainfall of the Mahi Basin were below average from 1901 to 1930 and above average from 1930 to 1990, followed by a period of fluctuating conditions. Annual and monsoon rainfall variations increase in the lower catchment of the basin. The annual and monsoon rainfall trend analysis specified a significant declining tendency for four stations and an increasing tendency for 3 stations, respectively. A significant declining trend in winter rainfall was observed for 9 stations under review. Likewise, out of 14 stations, 9 stations denote a significant decrease in pre-monsoon rainfall. Nevertheless, there is no significant increasing or decreasing tendency in annual, monsoon, and post-monsoon rainfall in the Mahi Basin. The Mann–Kendall test and innovative trend analysis indicate identical tendencies of annual and seasonal rainfall on the basin scale. The annual and monsoon rainfall of the basin showed a positive shift in rainfall after 1926. The rainfall analysis confirms that despite spatiotemporal variations in rainfall, there are no significant positive or negative trends of annual and monsoon rainfall on the basin scale. It suggests that the Mahi Basin received average rainfall (867 mm) annually and in the monsoon season (821 mm) from 1901 to 2012, except for a few years of high and low rainfall. Therefore, this study is important for flood and drought management, agriculture, and water management in the Mahi Basin.

Keywords: innovative trend analysis; Mahi Basin; Mann–Kendall test; normalized accumulated departure from the mean; pre-monsoon and post-monsoon; seasonal and annual analysis



Citation: Pawar, U.; Hire, P.; Gunathilake, M.B.; Rathnayake, U. Spatiotemporal Rainfall Variability and Trends over the Mahi Basin, India. *Climate* **2023**, *11*, 163. <https://doi.org/10.3390/cli11080163>

Academic Editor: Nir Y. Krakauer

Received: 3 July 2023

Revised: 27 July 2023

Accepted: 29 July 2023

Published: 31 July 2023



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1. Introduction

A comprehensive analysis of rainfall distribution, variability, and trends has great importance for flood and water scarcity management and designing hydraulic structures [1,2]. According to Chiew and McMahon [3], an examination of precipitation trends is essential for understanding the probable future trend of rainfall. Several scholars have emphasized that long-term data analysis is indispensable to forecast the accurate future tendency of rainfall for the planning and management of water in connection with climate variation and

increasing population [4–9]. The World Meteorological Organization [10] has highlighted some important points regarding the good qualities of data for trend analysis, such as periods, record length, and quality of data. Investigations of rainfall distribution, variability, and trends have received the attention of several researchers across the world [11–15]. Moreover, the growth or reduction in the intensity of yearly rainfall, temperature, and evaporation is one of the most noteworthy effects of global warming [16,17]. Although globally average rainfall displays a positive trend, at the continental and regional levels, precipitation indicates rising and declining trends [18]. The regional examination of yearly rainfall trends over the different regions of Africa denotes an increasing trend of rainfall significantly [19]. Likewise, Wang et al. [20] described a positive trend (rise) in rainfall over East Asia in 2008. In contrast, a declining tendency of precipitation in South Asia has been observed since the 1950s [21]. Liu et al. [22] observed precipitation trends (increases or decreases) in the Yellow River Basin during 1961–2006. According to Perera et al. [23] precipitation did not show noteworthy increasing or decreasing tendencies in the monthly rainfall over Trinidad and Tobago from 1981 to 2017.

According to Thapliyal and Kulshreshtha [24], the average annual rainfall (AAR) in India did not indicate an increasing or decreasing trend across the country from 1875 to 1989. Nevertheless, Sinha Ray and Srivastava [25] stated that during the southwest monsoon, some parts of India reported a positive propensity for heavy spells of rainfall from 1901 to 1990. Sharma et al. [26] identified an increasing tendency in annual rainfall during 1943–1993 over the Himalayan region. Likewise, Goswami et al. [7] recognized a remarkably increasing trend of extreme precipitation (magnitude and frequency) in central India from 1951 to 2000. Recently, Bharatha et al. [27] observed a significant increasing trend in monsoon rainfall over Shimsha Basin (Southern India) from 1989 to 2018. Singh et al. [28] noted a greater variability along with decreasing propensity in rainfall over river basins in central India during the last 100 years (1901–2000). Moreover, they [28] mentioned a decline of 2% to 19% in the annual rainfall over river basins in India (1901–2000). A comparative rainfall trend analysis study revealed that rainfall over the Ganga Basin between 1871 and 1994 was stable compared to the Brahmaputra and Meghna Basin [29]. According to research by Kumar and Jain [30], out of the 22, 15 basins in India showed a decreasing tendency for rainy days and yearly precipitation from 1951 to 2004. Recent past studies on the rainfall (annual and monsoon) over the Narmada Basin reported declining trends in the average annual rainfall (AAR) from 1901 to 2002 [31]. Likewise, Sharma et al. [32] described a decreasing tendency in the annual rainfall (total) from 1944 to 2013 over the upper Tapi Basin.

Trend analysis is the best technique to recognize future fluctuations in hydrometeorological elements for risk management, flood and drought monitoring, and water resource planning, design, and management [33,34]. Numerous investigators in the world and India have reported either positive or negative tendencies in hydrological and meteorological elements using the widely accepted techniques of trend analysis such as Mann–Kendall (MK), Sen’s slope (SS), and innovative trend analysis (ITA) [35–48]. However, the major disadvantage of the MK test is that it is not appropriate for time-series data in which autocorrelation or periodicities exist. In spite of this disadvantage, the MK test is widely applied in hydrometeorological trend analysis because it does not rely on the length of the time-series data and does not require data to follow a normal distribution [49]. An investigation of spatiotemporal rainfall tendencies has an importance for flood and drought management to check crop failures in India [50]. Moreover, India’s socioeconomic prominence and economy are ultimately based on agriculture [51]. Numerous scholars have observed the precipitation trend, pattern, and distribution of rainfall either using rain gauge stations or satellite-gridded datasets in India [48,52–54]. According to Patakamuri et al. [55] and Singh et al. [56], investigations of rainfall variability and rainfall distribution have great importance for agriculture mainly in rain-fed regions in India. Fluctuations in climatic extremes produce flood and drought events that affect agriculture, food, and water [48,57]. However, the effect of extreme events differs in space and time throughout the world [58].

The Mahi River is the lifeline of the northwestern part of India because it is the major source of water (surface water and groundwater) for agriculture, industry, and human life. Moreover, it is known for flash floods due to heavy rainfall resulting from low-pressure systems (LPSs). A few studies on rainfall patterns, variability and trends in the Mahi Basin have been conducted in the past [59,60]. However, none of these studies were based on long-term rainfall data. Therefore, an attempt was made to study rainfall variability, distribution, trends, and change detection in the rainfall of the Mahi Basin using long-term (1901–2012) rainfall data.

2. Materials and Methods

2.1. Study Area

The Mahi River is the third-largest interstate west-flowing river of peninsular India that flows in western India (Figure 1). It originates near the Minda village (Sardarpur) in the Dhar district of Madhya Pradesh at an altitude of 500 m ASL. Its total length is 583 km and meets the Gulf of Khambhat in Gujarat. The Mahi Basin extends between $22^{\circ}30'$ and $24^{\circ}20'$ N latitudes and $73^{\circ}00'$ and $74^{\circ}20'$ E longitudes. The basin covers the areas of Madhya Pradesh, Rajasthan, and Gujarat, with a drainage basin area of 34,842 km² (Figure 1).

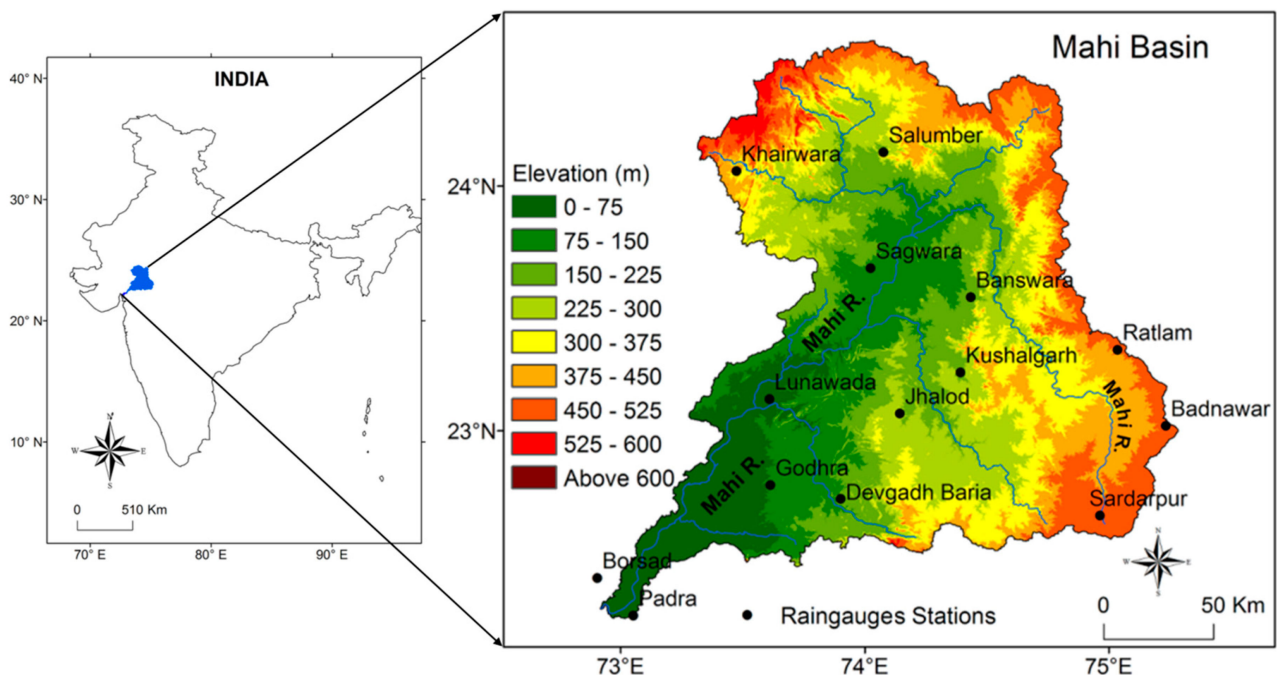


Figure 1. Mahi Basin location and study area map.

2.2. Data Used

The long-term monthly rainfall data (1901–2012) of 14 rain gauge stations in the Mahi Basin, namely, Badnawar, Banswara, Borsad, Devgad Baria, Godhra, Jhalod, Khairwara, Kushalgarh, Lunawada, Padra, Ratlam, Sagwara, Salumber, and Sardarpur, were used for the analysis of the rainfall distribution, variability, and trends over the basin (Figure 1). Monthly precipitation records were acquired from the India Meteorological Department (IMD). Moreover, digital elevation model (DEM) data were acquired from the United State Geological Survey (USGS) website (<https://earthexplorer.usgs.gov>), accessed on 20 August 2019.

2.3. Methodology

The fundamental objective of this study is to comprehend the precipitation distribution, erraticism, and trends in the Mahi Basin on an annual and seasonal scale. Therefore, the long-term rainfall data were categorized into four periods: (i) Monsoon (June–September), (ii) Post-monsoon (October to November), (iii) Winter monsoon (December to February), and (iv) Pre-monsoon (March to May). First, PAST version 4.03 software was used to check the serial autocorrelation in the rainfall time series. The classified data were computed by applying basic quantitative methods (mean, standard deviation (σ), and coefficient of variation (Cv)). Further, the precipitation inconsistency over the Mahi Basin was characterized by a normalized accumulated departure from the mean (NADM) and rainfall departure from the mean (%). The inverse distance weighted (IDW) technique was used for the interpolation of point rainfall values to show a spatial distribution. In addition, digital elevation model (DEM) data were used to show the elevation variation in the basin, to generate the Mahi Basin, Mahi River, and its tributaries. The rainfall trend analysis methodology is as follows.

2.3.1. Coefficient of Variation (CV)

An analysis of the rainfall variation in the Mahi Basin was calculated by Equation (1):

$$CV = \frac{\sigma}{\bar{X}} \times 100 \quad (1)$$

where σ and $\bar{X}$ are the standard deviation and mean rainfall for the annual and seasonal scales.

2.3.2. Mann–Kendall (MK) Test

The Mann–Kendall test was used to identify the significant rainfall trends over the Mahi Basin [61,62]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(X_j - X_k) \quad (2)$$

where X_j and X_k are the data points for rainfall, n is the length of data j and k ($k > j$), respectively, and $\text{sgn}(X_k - X_j)$ is the sign function as follows:

$$\text{sgn}(\alpha_j - \alpha_i) = \begin{cases} +1, & \text{if } (X_j - X_k) > 0 \\ 0, & \text{if } (X_j - X_k) = 0 \\ -1, & \text{if } (X_j - X_k) < 0 \end{cases} \quad (3)$$

S approximates a normal distribution with a mean of 0 when n is equal to 10. The variance can be found as given in Equation (4):

$$\text{VAR}(S) = \frac{1}{18} [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)] \quad (4)$$

where t and $\sum_t$ are the extent of any given tie indicates and the summation of all ties. The value of Z_c is computed using Equation (5):

$$Z = \begin{cases} \frac{S-1}{\text{VAR}(S)^{1/2}}, & S > 0 \\ 0, & S = 0 \\ \frac{(S+1)}{\text{VAR}(S)^{1/2}}, & S < 0 \end{cases} \quad (5)$$

where Z is the standard normal variate; an increasing (or decreasing) trend can be identified based on the positive (negative) values of Z . A noteworthy trend is observed, and the null hypothesis is rejected when $|Z| > Z_{1-\alpha/2}$. All the outcomes were confirmed at $\alpha = 0.05$ ($Z = \pm 1.96$) and $\alpha = 0.10$ ($Z = \pm 1.66$) significance level.

2.3.3. Sen's Slope (SS)

The Sen's slope method [63] was applied to study the magnitude of rainfall change by using the following equations:

$$Q_i = \frac{Y_j - Y_k}{j - k}, i = 1, 2, \dots, N \quad (6)$$

where Y_j and Y_k are values in a series at time j and k ($j > k$), respectively. Q_i is Sen's estimator of slope. If there is a single datum in each time period, then $N = n[n - 1]/2$, where n is the number of time periods. However, if the number of values in every year are many, then $N < n[n - 1]/2$, where n is total number of observations. First, N values were ordered from the minimum to maximum. Then, the median of slope (β) is calculated as follows:

$$\beta = \begin{cases} \frac{Q_n + 1}{2} & \text{if } N \text{ is odd} \\ \frac{1}{2} \left(\frac{Q_n}{2} + \frac{Q_n + 2}{2} \right) & \text{if } N \text{ is even} \end{cases} \quad (7)$$

2.3.4. Innovative Trend Analysis (ITA) Method

The innovative trend analysis (ITA) method was developed by Şen [64,65] to look at trends in streamflow, temperature, and rainfall. The primary step in ITA is to divide the long-term data into two equal halves, with each half-series' data being arranged independently in ascending order. An ordinate (X-axis) and an abscissa (Y-axis) are used to plot this subset of data. The diagram in Figure 2 is divided into two equal triangles by the 1:1 (45°) line of no trend. The inclining and declining tendency of the data is depicted in an area above and below the 1:1 line [65]. When all the data points in the scattergram are on or near the 1:1 line, no discernible trend in the time series can be seen.

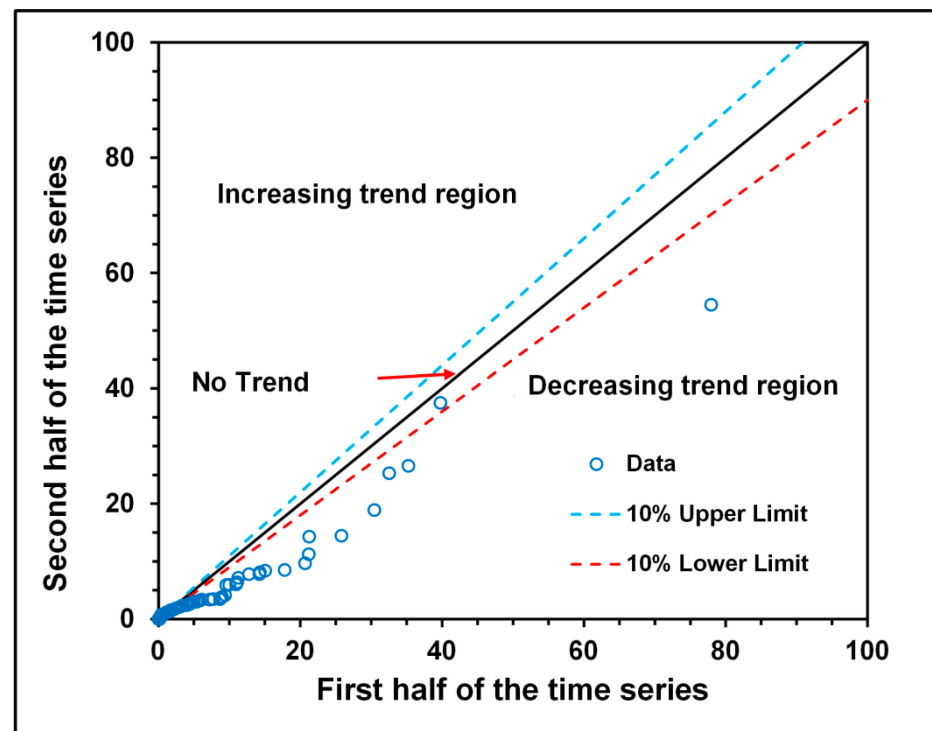


Figure 2. Illustration of the ITA method, Red arrow indicates line of 'No Trend'.

2.3.5. Pettitt's Test

The Pettitt's test (nonparametric test) developed by [66] Pettitt (1979) is useful for change detection. The null hypothesis denotes no change in the time series, whereas

the alternative shows a change point exists in the data series. In order to reject the null hypothesis, the test statistic should be larger than the critical value.

$$X_k = 2 \sum_{i=1}^k r_i - k(n+1), k = 1, 2, \dots, n \quad (8)$$

If a break occurs in the time series, then the value of X_k reaches the maximum or minimum near the break year k , which is defined as follows:

$$X_K = \max_{1 \leq k \leq n} |X_k| \quad (9)$$

3. Results and Discussion

3.1. Serial Autocorrelation Analysis

Serial correlation in a hydrometeorological data series can have effect on trend and change-point detection tests [67]. According to numerous studies, the presence of a positive serial correlation in time-series data increases the Type I error in the MK test, and it will lead to an over-rejection of the null hypothesis of no trend [68–70]. According to Yue and Wang [1], the presence of serial correlation in hydrometeorological data will affect the results of the MK test. Therefore, to obtain precise outcomes of the trends of rainfall in the Mahi Basin, serial autocorrelation was checked, and the results were represented by correlograms at various time lags for the annual and seasonal rainfall (Figure 3). For various time lags, all correlograms demonstrated that the rainfall values (annual and seasonal) were within the 95% confidence limit (upper and lower). This demonstrates that the time-series data do not exhibit serial autocorrelation. Independence within hydrometeorological time-series data is an important postulation of trend detection tests such as the MK test [67]. Due to the nonexistence of serial autocorrelation, the time-series data were directly used for fundamental statistical analyses, the MK test, and Pettitt's test of change-point detection for the analysis of rainfall on the annual and seasonal scale in the Mahi Basin. Serinaldi and Kilsby [71] mentioned the significance of the existence and nonexistence of sequential association in hydrometeorological data in the MK and Pettitt's test.

3.2. Rainfall Characteristics of the Mahi Basin

The Mahi Basin receives monsoon rainfall from mid-June with the inception of the southwest monsoon. Figure 4 shows the interannual fluctuations in annual rainfall from 1901 to 2012 with some years (1927, 1959, 1973, 1976, and 2006) of high rainfall linked with a low-pressure system (LPS) [57]. Almost 95% of the rainfall (821 mm) occurs in the monsoon months (Table 1). The monthly rainfall distribution in the Mahi Basin significantly varies in time and space (Figures 5 and 6). July was the wettest (288.7 mm) month across the basin, which accounted for 33.3% of the AAR. About 64.1% of the rainfall in the Mahi Basin occurred in July (33.3%) and August (30.8%) (Table 1). The post-monsoon rainfall (30.3 mm) was more than the winter (6.1 mm) and pre-monsoon rainfall (9.0 mm) in the basin. Table 1 indicates that the mean monthly rainfall (MMR) variation ranged between 56.1% (February) and 14.2% (July) in the Mahi Basin.

Table 1. Rainfall statistics summary of the Mahi Basin (1901–2012).

Time	Rainfall (mm)	SD (mm)	Cv (%)	Contribution to Annual Rainfall (%)
January	2.4	1.2	51.3	0.3
February	1.4	0.8	56.1	0.2
March	1.6	0.7	41.1	0.2
April	1.1	0.4	38.0	0.1
May	5.9	2.2	37.5	0.7
June	111.7	21.2	19.0	12.9
July	288.7	40.9	14.2	33.3

Table 1. Cont.

Time	Rainfall (mm)	SD (mm)	Cv (%)	Contribution to Annual Rainfall (%)
August	267.4	38.1	14.3	30.8
September	150.6	24.9	16.6	17.4
October	21.7	6.4	29.3	2.5
November	8.9	2.3	25.3	1.0
December	2.3	1.0	43.3	0.3
Monsoon	821.0	220.4	26.8	94.8
Post-monsoon	30.3	36.2	119.6	3.5
Winter	6.1	7.8	127.2	0.7
Pre-monsoon	9.0	12.6	142.1	1.0
Annual	867.0	221.4	25.5	

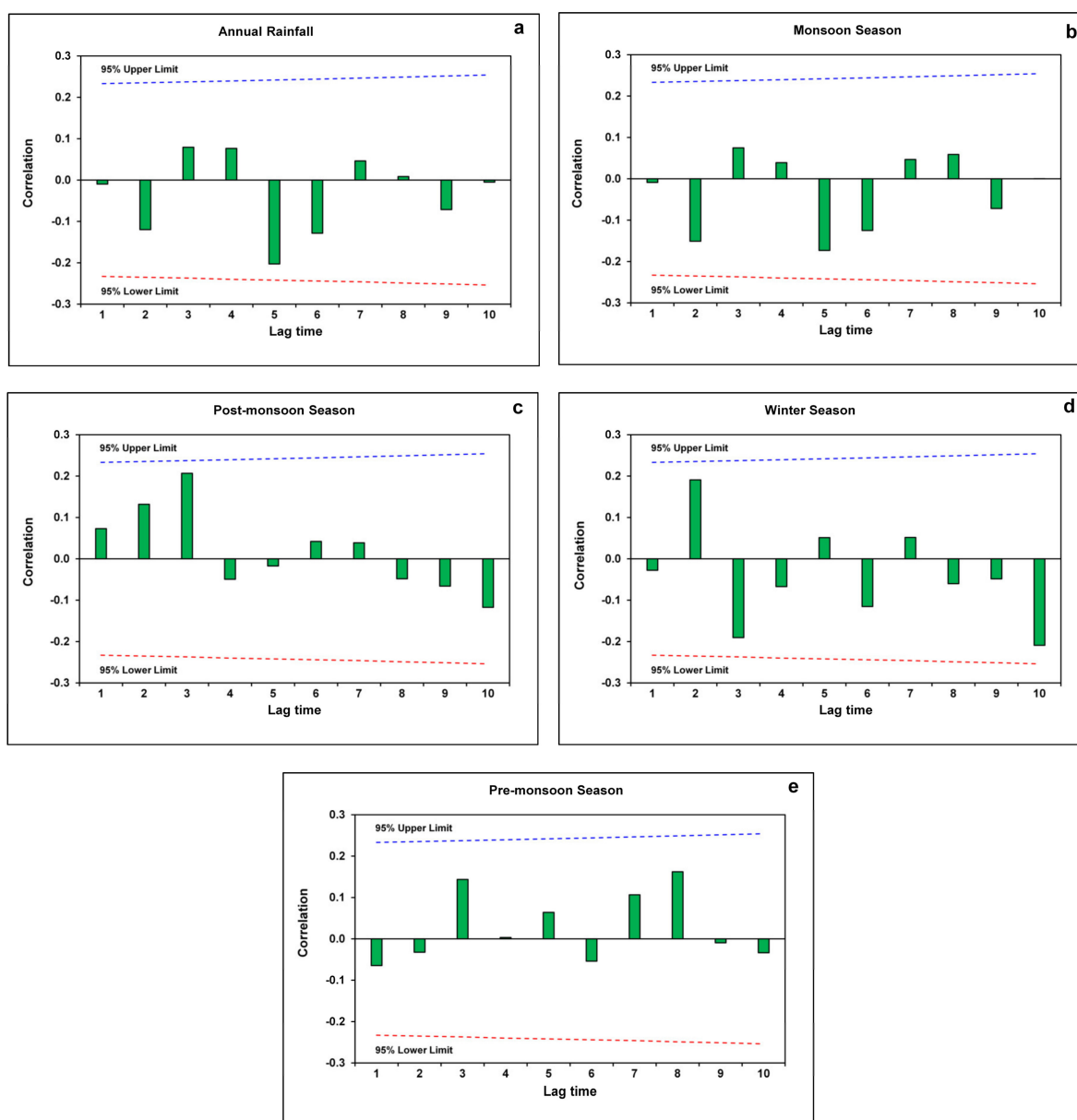


Figure 3. Correlogram for rainfall of the Mahi Basin: (a) For Annual; (b) For Monsoon Season; (c) For Post-monsoon Season; (d) For Winter Season; (e) For Pre-monsoon Season.

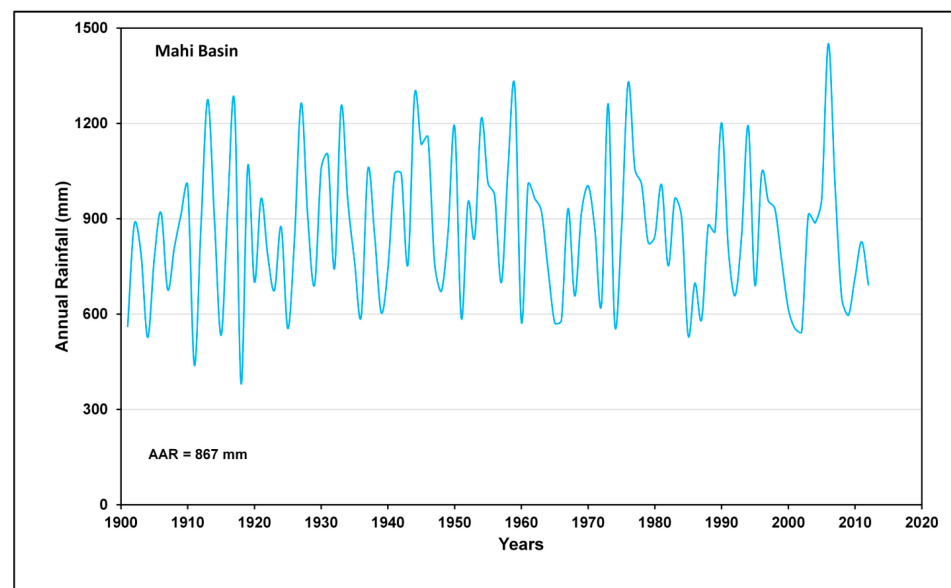


Figure 4. Annual rainfall of the Mahi Basin from 1901 to 2012.

3.3. Rainfall Distribution (Annual and Seasonal) over the Mahi Basin

Large oscillations with epochal behavior in the rainfall over the monsoonal regions of the world are the most prominent feature [72]. According to Pawar and Hire [59], low-pressure systems (LPSs) significantly affect the AAR as well as average monsoon rainfall (AMR) of the basin and are a major cause of inundations in the Mahi Basin. Therefore, it is essential to understand the rainfall distribution (annual and seasonal) in the basin (Table 2). The AAR varied between 649 mm (Khairwara) and 1012.8 mm (Banswara), and the AMR ranged between 610.7 mm (Khairwara) and 959.6 mm (Banswara) (Table 2). During the post-monsoon season, Sardarpur received the highest (43.4 mm) rainfall in the basin. All the rain gauge stations received more than 93% of their rainfall in the monsoon season (Table 2). Therefore, it shows that the hydrometeorological features of the basin are considerably associated with monsoon rainfall. Figures 5 and 6 indicate that all the rainfall stations receive the maximum rainfall during the monsoon season (June to September), and rainfall in the non-monsoon season is very negligible.

Table 2. Average annual and seasonal rainfall distribution in the Mahi Basin.

Stations/Basin	AAR	Monsoon	Post-Monsoon	Winter	Pre-Monsoon	Monsoon	Non-Monsoon
	(mm)	(mm)	(mm)	(mm)	(mm)	%	%
Badnawar	878.0	829.1	39.2	5.0	4.7	94.4	5.6
Banswara	1012.8	959.6	35.2	9.1	8.9	94.7	5.3
Borsad	823.9	791.8	23.6	2.9	5.6	96.1	3.9
Devgadh Baria	959.0	919.5	28.2	3.7	7.5	95.9	4.1
Godhra	956.8	914.9	28.4	4.2	9.3	95.6	4.4
Jhalod	813.8	767.6	31.8	6.4	8.0	94.3	5.7
Khairwara	649.0	610.7	20.3	5.2	12.9	94.1	5.9
Kushalgarh	1010.9	953.0	38.1	7.6	12.2	94.3	5.7
Lunawada	769.8	735.4	22.7	3.9	7.9	95.5	4.5
Padra	906.5	869.2	30.4	4.1	2.8	95.8	4.2
Ratlam	943.4	879.2	39.9	12.2	12.1	93.2	6.8
Sagwara	759.8	720.3	25.4	5.8	8.3	94.8	5.2
Salumber	691.3	652.2	22.8	6.4	10.0	94.3	5.7
Sardarpur	904.4	842.7	43.4	7.8	10.5	93.2	6.8
Mahi Basin	867.0	821.0	30.3	6.1	9.0	94.8	5.2

Note: Bold values in the table show the highest AAR and seasonal rainfall.

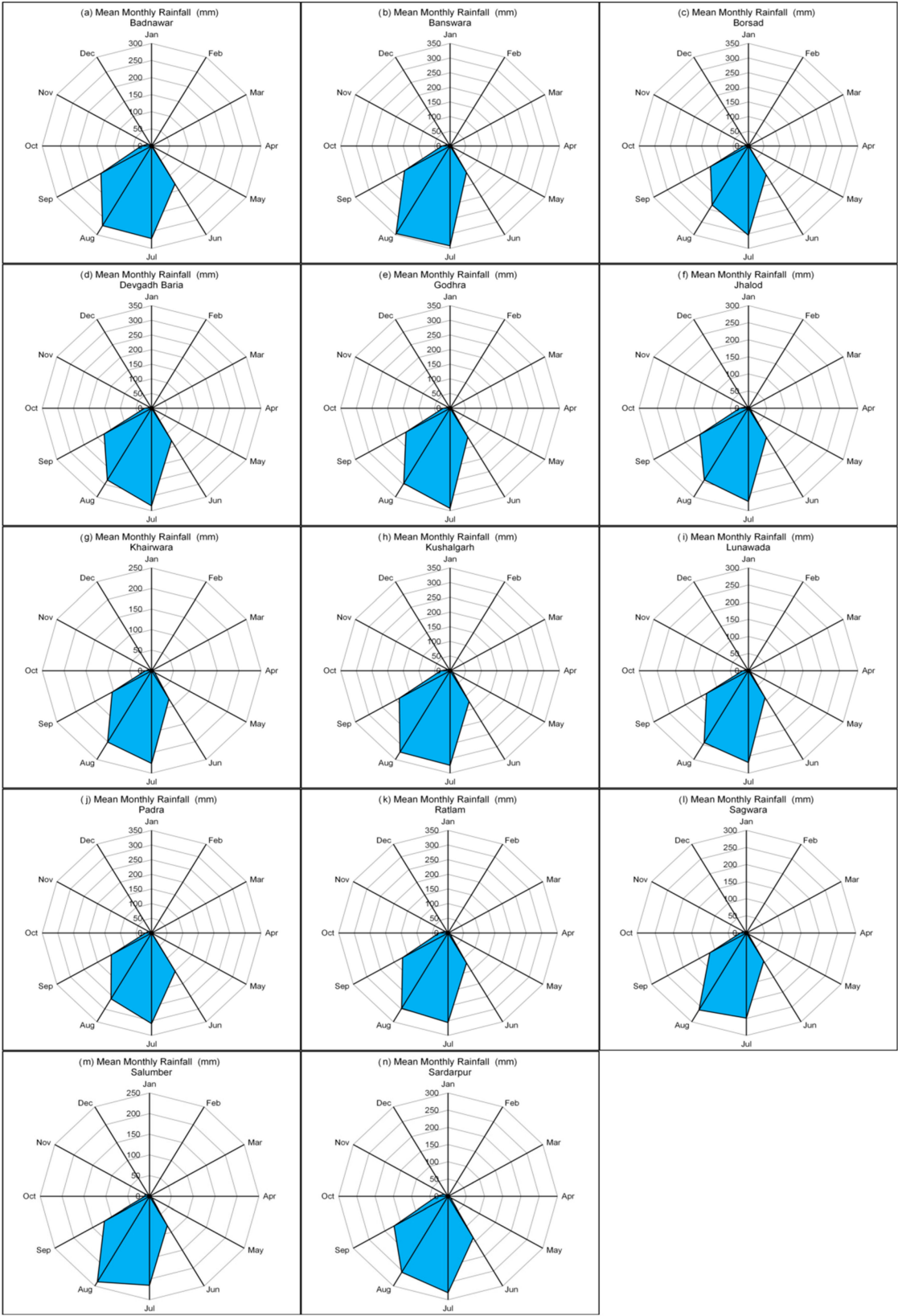


Figure 5. Station wise mean monthly rainfall distribution.

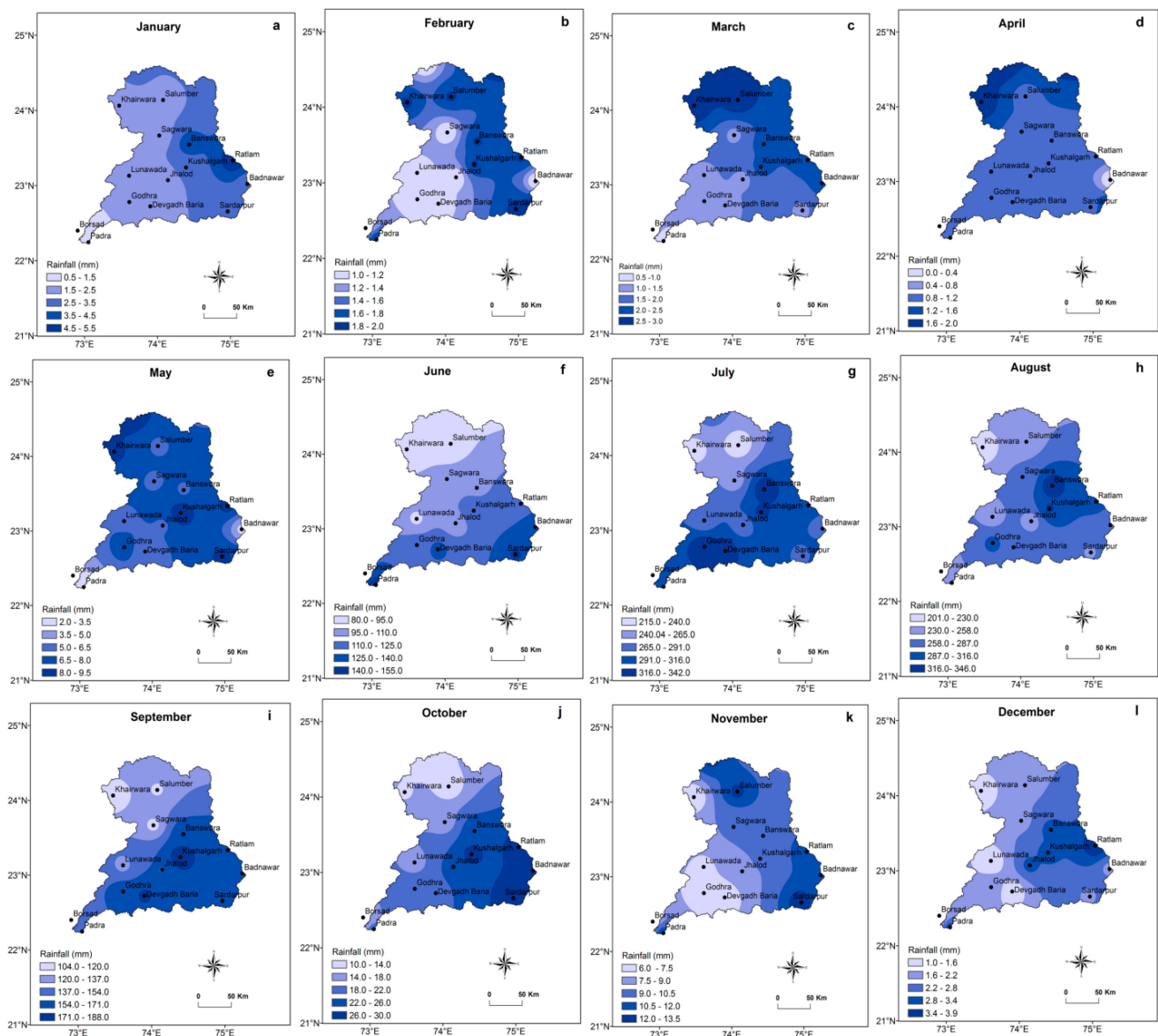


Figure 6. Spatial distribution of the mean monthly rainfall of the Mahi Basin: (a) For January; (b) For February; (c) For March; (d) For April; (e) For May; (f) For June; (g) For July; (h) For August; (i) For September; (j) For October; (k) For November; (l) For December.

Figure 7 shows that AAR and AMR decrease from the east and southeast part of the Mahi Basin toward the northwestern and western catchment of the basin. The central and eastern part of the Mahi Basin receives the maximum AAR and AMR (>900 mm), specifically, at Banswara, Devgadhi Baria, Godhra, Kushalgarh, and Ratlam (Figure 7a,b). The western catchment area of the basin receives less precipitation in the post-monsoon period due to the early withdrawal of the monsoon (Figure 7c). The northern and north-western catchment of the Mahi Basin receives the maximum precipitation in the winter and pre-monsoon months due to the effect of western disturbances (Figure 7d,e). Dimri and Mohanty [73] noted the features of the western disturbances (WDs) over the western Himalayas in 2009.

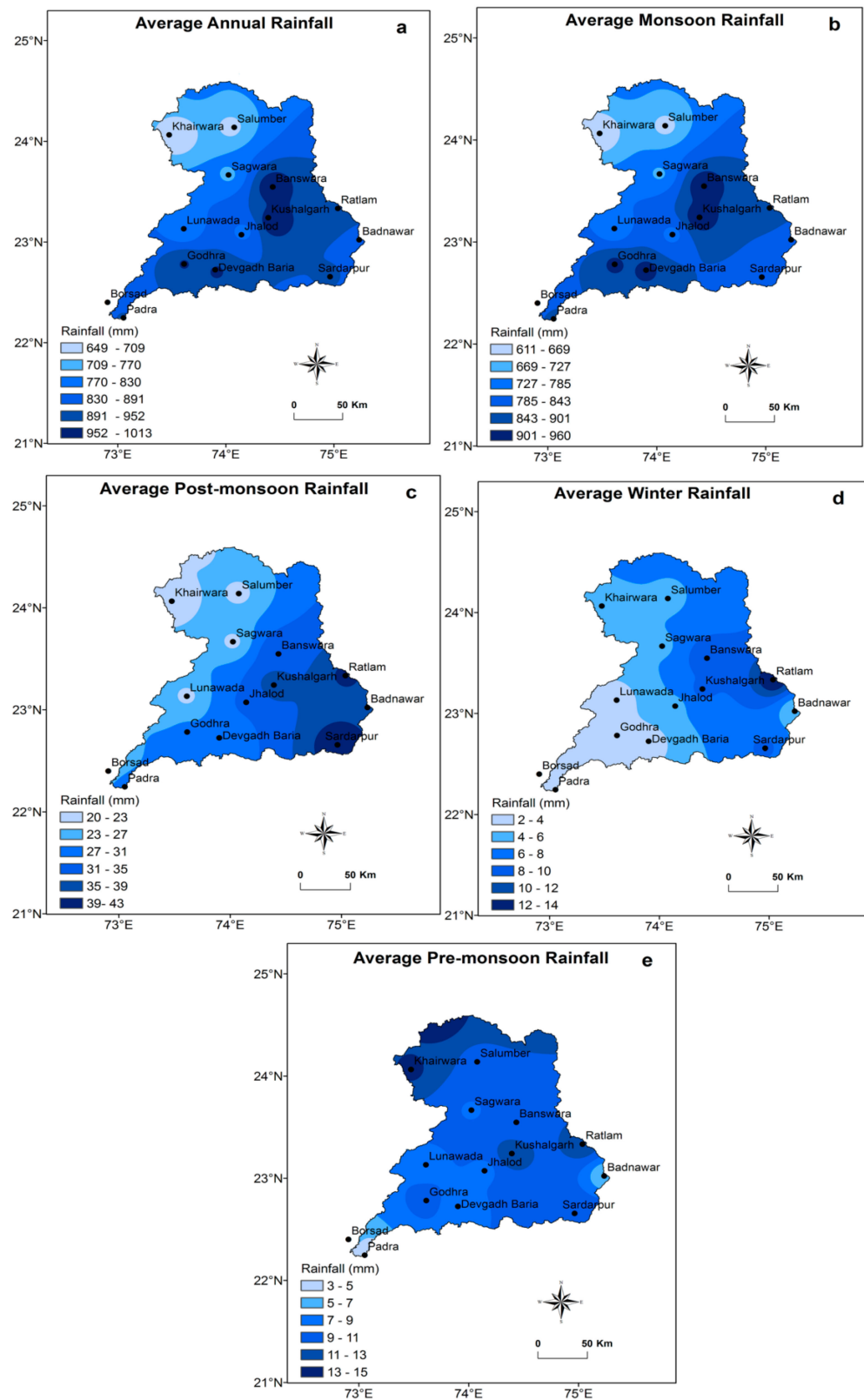


Figure 7. Average rainfall distribution in the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

3.4. NADM and Rainfall Departure from the Mean

The rainfall disparity on the annual and seasonal scales is one of the characteristics of the monsoon [74]. The long-term variation in monsoon rainfall is very well understood

by the NADM. It is one of the most effective and frequently applied quantitative methods and can resolve successive properties contained by long-term data [75–78]. Normally, monsoon rainfall shows an epochal nature, alternating between 30 years of dry and wet monsoons [79]. According to Joseph [80,81], tropical disturbances originate above the Bay of Bengal and move in the direction of west and northwest and have a significant impact on the epochal behavior of the monsoon. The NADM graph of the Mahi Basin shows a period of below-average rainfall from 1901 to 1930 and above-average rainfall between 1930 and 1990, followed by a period of fluctuating conditions of the annual and monsoon rainfall (Figure 8a,b). Kripalani et al. [82] also detected random oscillations in annual rainfall and the epochal behavior of above-average and below-average rainfall for decadal rainfall. The maximum positive departure from the mean in the annual and monsoon rainfall represents wet years associated with major floods in the Mahi Basin, such as 1927, 1952, 1959, 1973, 1976, and 2006 [59]. The percent departure from mean rainfall shows a remarkable negative departure from the AAR and AMR during 1901–1930 (Figure 8a,b). The maximum positive departure in annual and monsoon rainfall was associated with LPSs and floods in the basin [59]. Post-monsoon rainfall showed the maximum years of the negative departure of rainfall with notable phases of dry periods (Figure 8c). The winter rainfall shows some remarkable years of the maximum positive departure from the mean rainfall (Figure 8d). Further, Figure 8e shows that pre-monsoon rainfall was recurrently below the long-term average of the pre-monsoon rainfall of the basin.

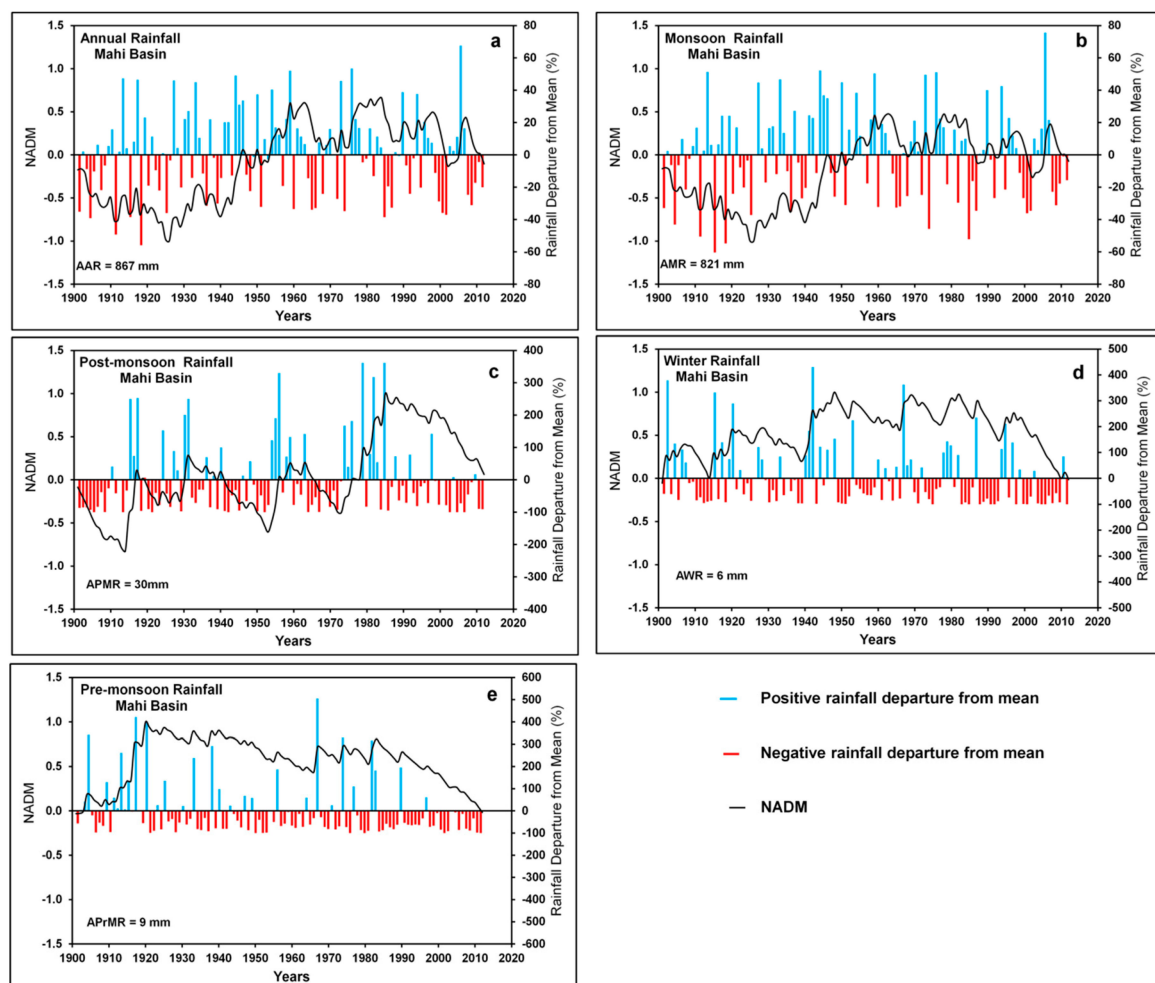


Figure 8. NADM and rainfall departure from the mean rainfall of the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

3.5. Rainfall Variation over the Mahi Basin

The AAR and AMR of the Mahi Basin did not show significant variations in rainfall (Figure 9a,b). However, rainfall variations are remarkable in the non-monsoon season (Figure 9c–e). The annual and seasonal variations increase from the eastern Mahi Basin toward the west (Figure 9a–e). The highest variations in the AAR and AMR were observed for the Padra station (Figure 9a,b). The lowest variability in the AAR and AMR was reported for the Badnawar station (Figure 9a,b). Figure 9c indicates the average post-monsoon rainfall (APMR) variability ranges between 110% (Sardarpur) and 210% (Borsad). Moreover, the AWR variability ranges between 125% and 350% (Figure 9d). The highest average pre-monsoon rainfall variability (313%) was noticed for the Padra station (Figure 9e). The winter and pre-monsoon rainfall show higher variability in the Mahi Basin (Figure 9d,e). The interannual and interseasonal dissimilarity in rainfall is a significant characteristic of the southwest monsoon [83]. Jhajharia et al. [84] reported a greater variability in rainy days during the non-monsoon season than the monsoon. Guhathakurta and Saji [85] also emphasized that the examination of rainfall variability has great significance for better water resource planning, as well as flood and drought disaster management.

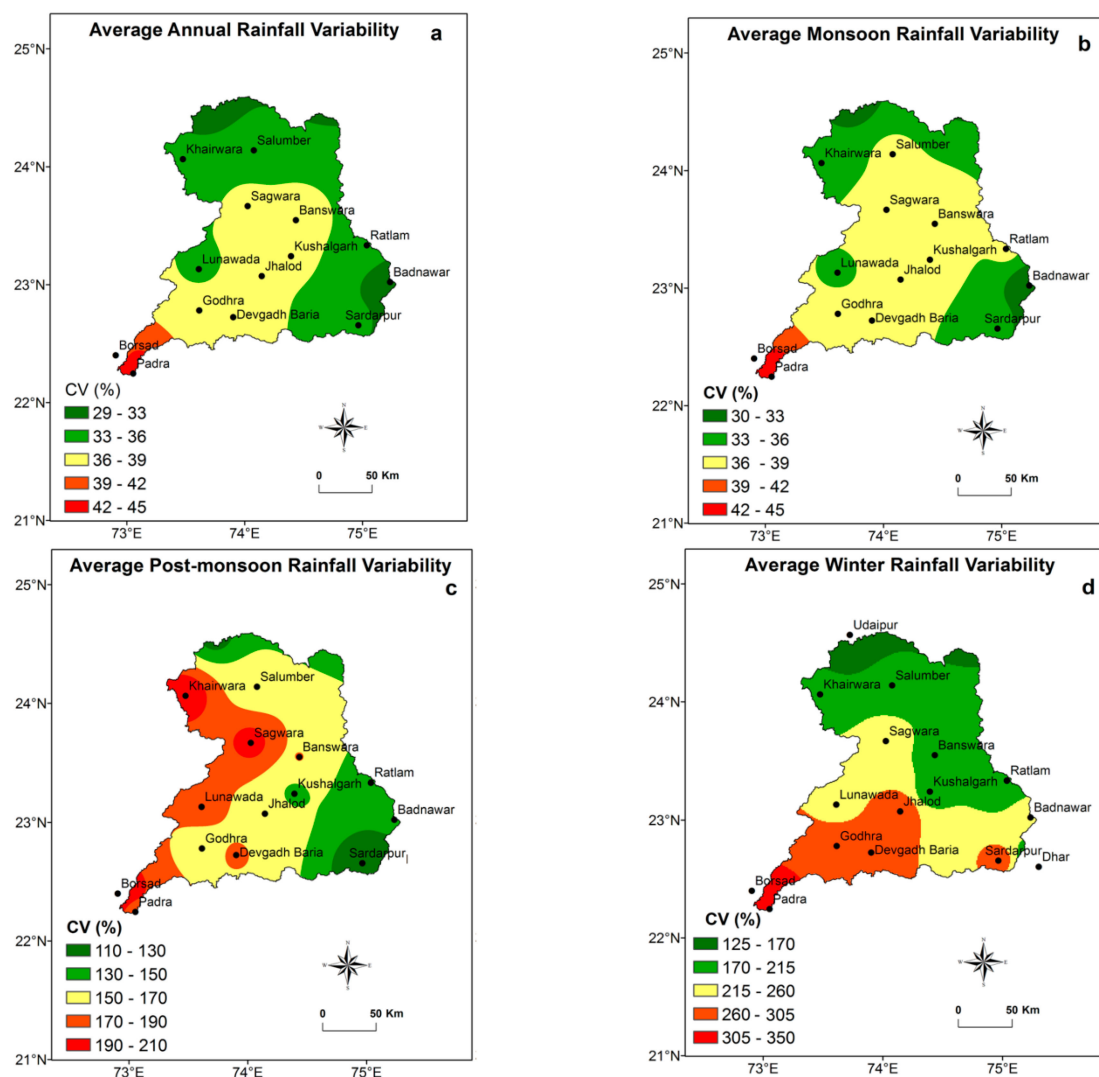


Figure 9. Cont.

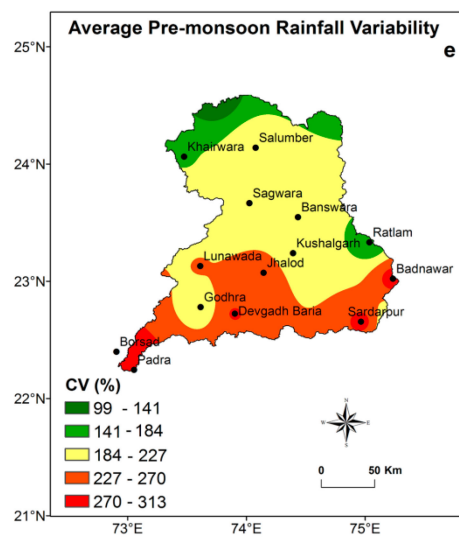


Figure 9. Rainfall variations in the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

3.6. Rainfall Trend and Magnitude Change in the Mahi Basin

A significant increasing trend of annual rainfall was noted for the Banswara, Ratlam, and Sagwara stations, whereas the Devgadhi Baria, Godhra, Khairwara, and Padra stations denoted a significant decreasing rainfall trend on the annual scale (Table 3; Figure 10a). The Godhra station showed a substantial decrease in monsoon rainfall from 1901 to 2012 (1.89 mm/y). Conversely, Ratlam and Sagwara denoted a noteworthy increasing tendency (1.5 mm/y) in monsoon rain from 1901 to 2012 (Table 3; Figure 10b). The post-monsoon rainfall does not exhibit a statistically important decreasing or increasing trend in the Mahi Basin (Table 3; Figure 10c). A noteworthy declining trend of winter precipitation was detected for nine stations, excepting Badnawar, Kushalgarh, Padra, Salumber, and Sardarpur (Table 3; Figure 10d). A significant decrease in pre-monsoon rain was identified for the Badnawar, Borsad, Devgadhi Baria, Godhra, Jhalod, Khairwara, Lunawada, Padra, and Sardarpur stations (Table 3; Figure 10e). On the basin scale, a substantial declining tendency was observed for the winter (0.02 mm/y) and pre-monsoon rainfall (0.04 mm/y) during 1901–2012 (Table 3). The annual and monsoon rainfall neither displayed a major increasing nor decreasing tendency on the basin scale. Likewise, Kumar and Jain [30] mentioned that out of 22 river basins in India under investigation, only 2 basins showed noteworthy trends, and the rest of the basins neither indicated an increase nor decrease in annual and seasonal rainfall significantly. Nevertheless, Mooley and Parthasarathy [76] and Thapliyal and Kulshreshtha [24] notified that there is no remarkable positive or negative trend in mean annual rain over India. Therefore, it is concluded that the rainfall trend (increasing or decreasing) was observed in certain pockets of India in the non-monsoon period [25]. This declining trend in seasonal rainfall could be decreasing the frequency of WDs over the northwestern part of India [86]. Moreover, Shekhar et al. [87] observed a decrease in winter rainfall in the Western Himalayan Region (WHR).

Furthermore, the rainfall trend over the Mahi Basin was denoted by ITA graphs (Figure 11a–e). The ITA plots for the annual, monsoon, and post-monsoon rainfall represent that almost all the data points are either on the 1:1 line (no trend) or fall between the 10% upper and lower limits (Figure 11a–c). The ITA graphs obtained for winter and pre-monsoon rainfall show that all the data points are below the 10% lower limit (11d–e). Therefore, it is specified that winter and pre-monsoon rain in the Mahi Basin have significantly declined in the last 112 years. On the basin scale, the comparative rainfall trend analyses of the MK and ITA indicated insignificant increasing or decreasing trends in the annual and monsoon rainfall.

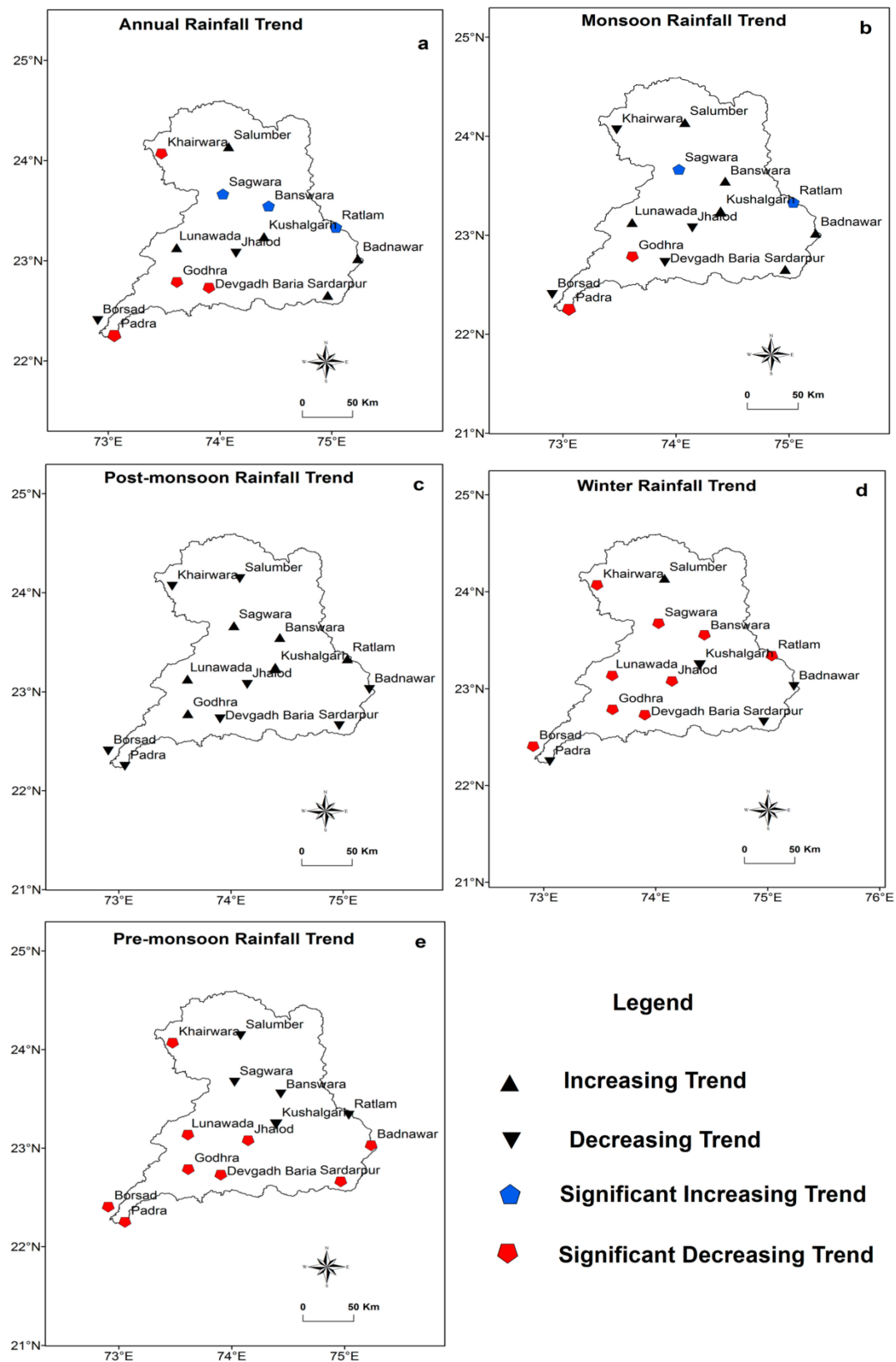


Figure 10. Rainfall trends in the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

Table 3. Summary of the rainfall trend analysis (Mann–Kendall and Sen’s slope).

SN	Stations	Annual		Monsoon		Post-Monsoon		Winter		Pre-Monsoon	
		MK z	SS mm/y	MK z	SS mm/y	MK z	SS mm/y	MK z	SS mm/y	MK z	SS mm/y
1	Badnawar	1.24	1.52	1.11	1.50	−0.54	0.00	−0.83	0.00	−2.74	0.00
2	Banswara	1.68	1.77	1.34	1.6	0.61	0.00	−2.10	0.00	−1.54	0.00
3	Borsad	−0.45	−0.67	−0.68	−0.58	−0.86	0.00	−3.59	0.00	−3.60	0.00
4	D. Baria	−1.65	−1.63	−1.22	−1.37	−0.41	0.00	−4.22	0.00	−4.65	0.00
5	Godhra	−1.71	−1.92	−1.71	−1.89	0.49	0.09	−4.46	0.00	−3.43	0.00
6	Jhalod	−0.47	−0.33	−0.13	−0.13	−0.45	0.00	−4.45	0.00	−4.94	0.00
7	Khairwara	−1.78	−1.25	−1.37	−1.07	−0.07	0.00	−4.17	0.00	−2.30	0.00
8	Kushalgarh	0.5	55	0.27	0.33	1.39	0.14	−1.01	0.00	−0.18	0.00
9	Lunawada	0.45	0.38	0.33	0.28	1.09	0.04	−2.97	0.00	−2.78	0.00
10	Padra	−1.88	−6.11	−1.64	−5.04	−1.13	−0.25	−0.58	0.00	−1.99	0.00
11	Ratlam	1.88	1.83	1.86	1.56	1.31	0.01	−2.34	−0.01	−1.61	−0.05
12	Sagwara	1.75	1.41	1.68	1.50	0.10	0.00	−1.72	0.0	−1.49	0.00
13	Salumber	0.53	0.36	0.94	1.16	−0.08	0.27	0.54	0.03	0.20	0.00
14	Sardarpur	0.06	0.07	0.20	0.25	−0.26	0.00	−1.25	0.00	−1.93	0.00
15	Mahi Basin	−0.23	−0.14	0.02	0.01	0.90	0.03	−2.44	−0.02	−2.48	−0.04

Bold values are statistically significant at 0.05%, and bold and italic values are statistically significant at 0.10%.

However, there are some critics of the usage of the ITA method for determining climatic trends [88]. The research presented here is not built on the ITA method but on the often-used MK test. Understanding these critics of the ITA method, the results from the MK test and Sen’s slope estimator test were compared against the ITA method.

3.7. Analysis of Change-Point Detection Tests of Rainfall

Pettitt’s test of change-point detection was used to identify the existence of changes in the annual and seasonal rainfall series from 1901 to 2012 (Table 4). The analysis of change-point detection showed that all stations in the Mahi Basin under investigation denoted similar years of shift in annual and monsoon rainfall except Sagwara (Table 4). It strongly suggested that changes (increasing or decreasing) in the monsoon rainfall are eventually reflected in the annual rainfall. Therefore, it is specified that the Mahi Basin is influenced by monsoon rainfall. There are notable variations in years of post-monsoon, winter, and pre-monsoon rainfall from 1901–2012 (Table 4). In addition, annual and seasonal rainfall shifts on the basin scale are represented in Figure 12a–e. On the basin scale, an annual and monsoon rainfall shift was noted after 1926 (Figure 12a,b). According to Pawar et al. [57,59], the shift in the annual and monsoon rainfall of the basin might be influenced by low-pressure systems that affect the rainfall of the Mahi Basin [57,59]. In the case of the post-monsoon season, a shift in rainfall pattern was observed after 1953 (Figure 12c). Nevertheless, the winter and pre-monsoon seasons denoted shifts in rainfall after 1982 and 1933, respectively (Figure 12d,e).

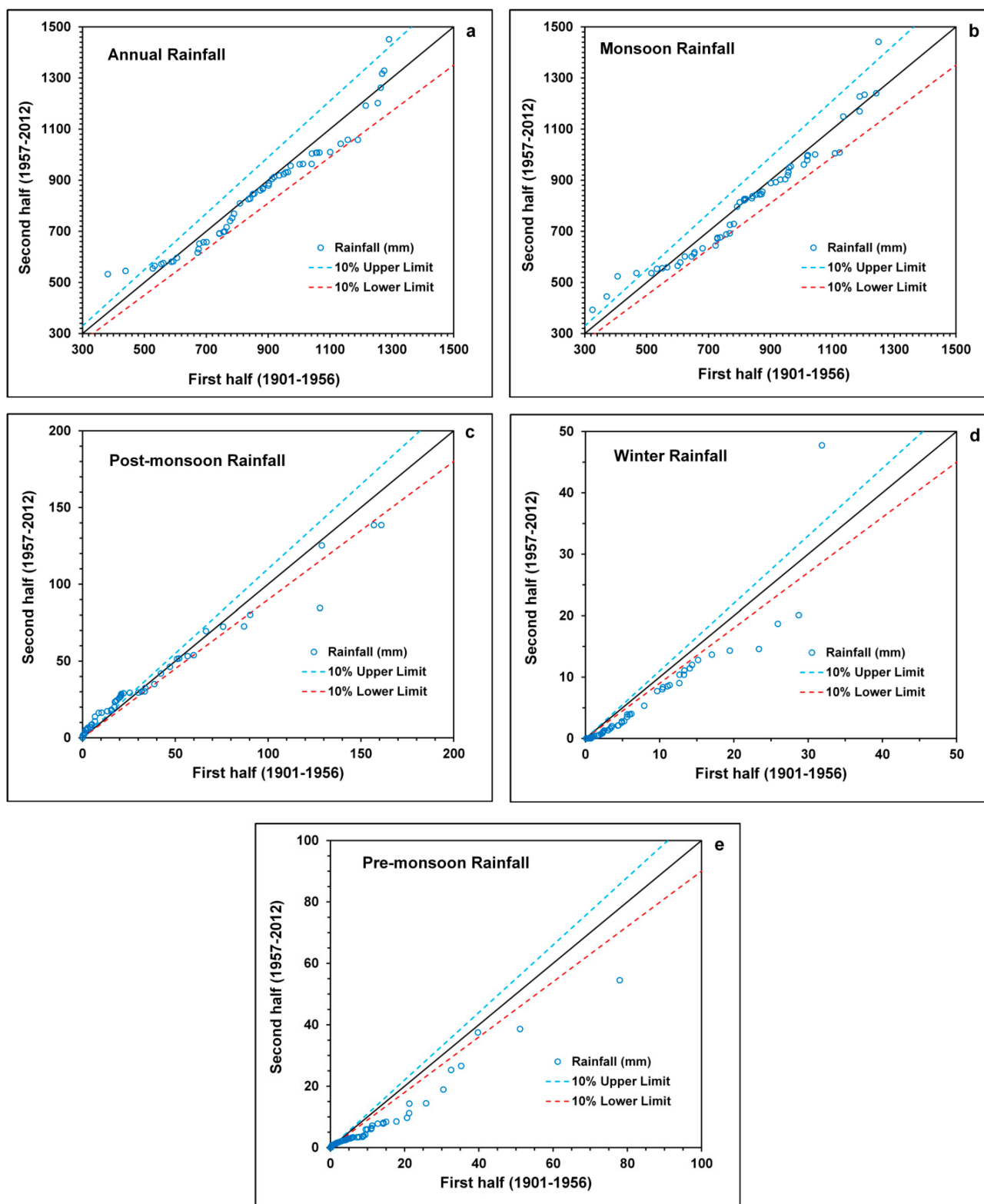


Figure 11. Rainfall trends by ITA over the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

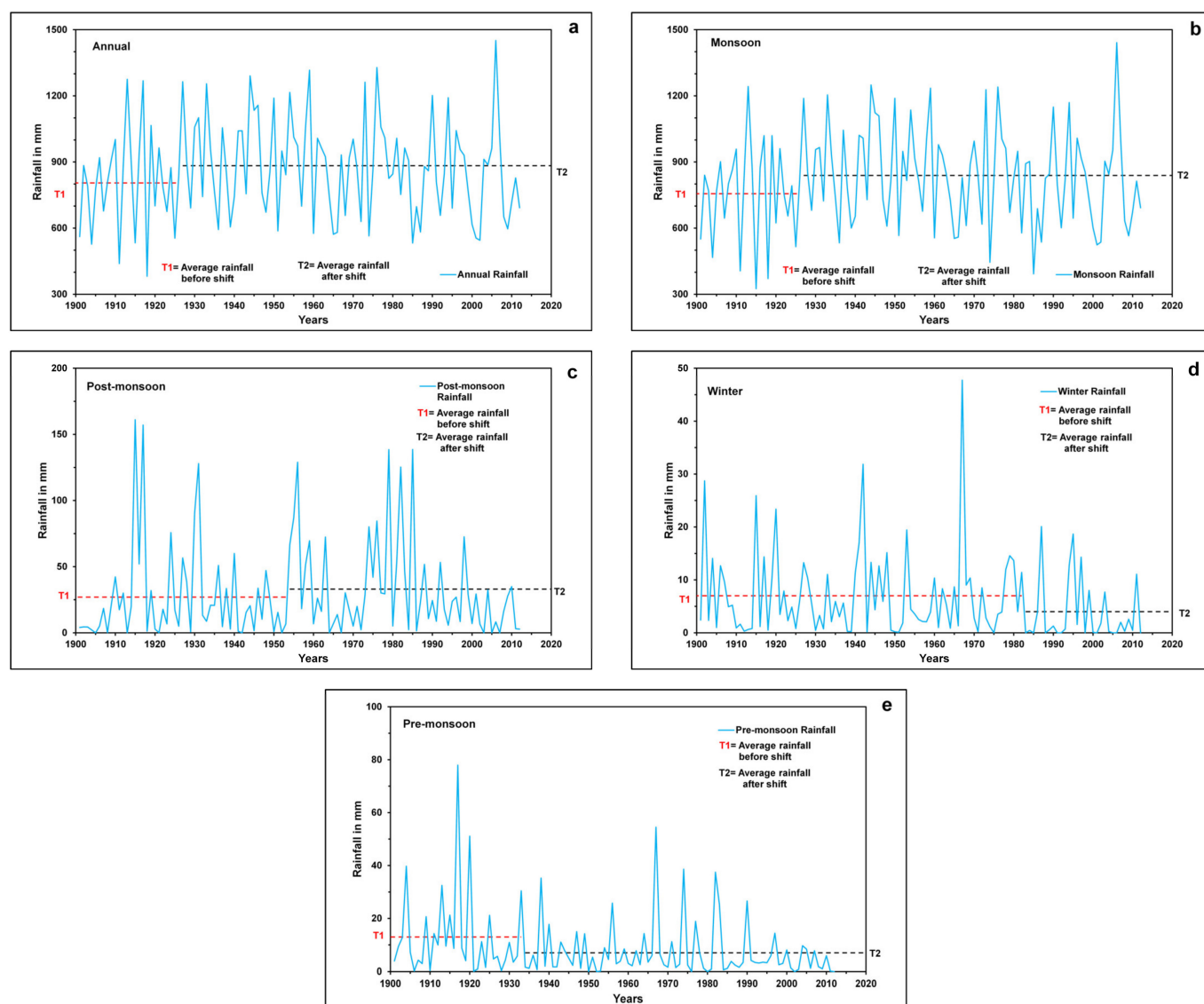


Figure 12. Rainfall change-point detection using Pettitt's test for rainfall in the Mahi Basin: (a) For Annual; (b) For Monsoon; (c) For Post-monsoon; (d) For Winter; (e) For Pre-monsoon.

Table 4. Summary of the rainfall change-point detection using Pettitt's test.

Stations/Basin	Annual Rainfall		Monsoon Rainfall		Post-Monsoon Rainfall		Winter Rainfall		Pre-Monsoon Rainfall	
	Shift	Year	Shift	Year	Shift	Year	Shift	Year	Shift	Year
Badnawar	Yes	1957	Yes	1957	Yes	1953	Yes	1957	Yes	1938
Banswara	Yes	1940	Yes	1940	Yes	1972	Yes	1982	Yes	1943
Borsad	Yes	1959	Yes	1959	Yes	1985	Yes	1948	Yes	1959
D. Baria	Yes	1962	Yes	1962	Yes	1963	Yes	1955	Yes	1947
Godhra	Yes	1959	Yes	1959	Yes	1926	Yes	1942	Yes	1957
Jhalod	Yes	1984	Yes	1984	Yes	1988	Yes	1968	Yes	1967
Khairwara	Yes	1963	Yes	1963	Yes	1973	Yes	1948	Yes	1933
Kushalgarh	Yes	1926	Yes	1926	Yes	1953	Yes	1997	Yes	1916

Table 4. Cont.

Stations/Basin	Annual Rainfall		Monsoon Rainfall		Post-Monsoon Rainfall		Winter Rainfall		Pre-Monsoon Rainfall	
	Shift	Year	Shift	Year	Shift	Year	Shift	Year	Shift	Year
Lunawada	Yes	1940	Yes	1940	Yes	1953	Yes	1944	Yes	1947
Padra	Yes	1929	Yes	1929	Yes	1931	Yes	1943	Yes	1928
Ratlam	Yes	1932	Yes	1932	Yes	1954	Yes	1967	Yes	1962
Sagwara	Yes	1964	Yes	1978	Yes	1964	Yes	1974	Yes	1936
Salumber	Yes	1946	Yes	1946	Yes	1917	Yes	1922	Yes	1918
Sardarpur	Yes	1978	Yes	1978	Yes	1903	Yes	1963	Yes	1962
Mahi Basin	Yes	1926	Yes	1926	Yes	1953	Yes	1982	Yes	1933

4. Conclusions

Spatiotemporal rainfall analysis showed that the central Mahi Basin receives the maximum rainfall (>900 mm) compared to other parts of the basin. Moreover, winter and pre-monsoon rain spells were observed in the northern and northwestern catchments of the basin. However, the seasonal rain of the basin varied between 26.8% (monsoon) and 142.1% (pre-monsoon). The NADM showed a period of below-average rainfall from 1901 to 1930 and above-average rainfall between 1930 and 1990, followed by a period of fluctuating conditions. The high rainfall variability was observed throughout the post-monsoon, winter, and pre-monsoon seasons. The rainfall trend analysis revealed that annual, monsoon, and post-monsoon rainfall do not show statistically significant decreasing or increasing trends on the basin scale. Nevertheless, a statistically significant declining trend was observed for winter and pre-monsoon rainfall in the Mahi Basin. A noteworthy reduction in annual and monsoon rainfall was observed for Godhra, while Ratlam and Sagwara showed a remarkable rise (1.5 mm/yr.) in monsoon and annual rain (1.83 mm/yr. and 1.49 mm/yr.) from 1901 to 2012. Likewise, 9 stations out of 14 showed a significant decline in winter and pre-monsoon rainfall. The MK test and ITA analyses show that annual, seasonal, and post-monsoon rainfall did not exhibit a substantial rise or fall on the basin scale. A change-point detection showed that after 1926, annual and monsoon rainfall in the Mahi basin shifted (increased). However, there is no significant increase in the annual and monsoon rainfall of the basin. Therefore, it is concluded that rainfall in the Mahi Basin is steady.

Author Contributions: Conceptualization, U.P. and P.H.; methodology, U.P.; software, U.P.; validation, U.P., P.H. and M.B.G.; formal analysis, U.P.; investigation, U.P.; resources, P.H.; data curation, U.P.; writing—original draft preparation, U.P. and P.H.; writing—review and editing, M.B.G. and U.R.; visualization, U.P.; supervision, P.H. and U.R.; project administration, U.P.; funding acquisition, U.P., P.H. and U.R. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are extremely grateful to the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), Government of India, Project Number: EMR/2016/002590, dated 21 February 2017, for providing financial support to carry out this research work.

Data Availability Statement: Data used in this manuscript can be requested for research purposes from the corresponding authors.

Acknowledgments: The authors are very thankful to the India Meteorological Department (IMD), Pune, for providing the rainfall data.

Conflicts of Interest: The authors declare no conflict of interest.

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