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Precipitation trend analysis of Sindh River basin, India, from 102-year record (1901–2002)

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Abstract

The study of long-term precipitation record is critically important for a country, whose food security and economy rely on the timely availability of water. In this study, the historical 102-year (1901–2002) rainfall data of the Sindh River basin (SRB), India, were analyzed for seasonal and annual trends. The Mann–Kendall test and Sen's slope model were used to identify the trend and the magnitude of the change, respectively. Spatial interpolation technique such as Kriging was used for interpolating the spatial pattern over SRB in GIS environment. The analysis revealed the significantly increasing precipitation trend in both seasonal and annual rainfall in the span of 102 years.

Keywords: **trend analysis; change-point analysis; annual rainfall series; Sindh River basin**

1. Introduction

Precipitation is a vital part of the hydrologic cycle and changes in its pattern directly influence the water resources of concerned regions (Chahine, 1992; Islam *et al.*, 2012b). Changes in rainfall response as a result of climate change are now alarming to hydrologists and water resource managers (Ben-Gai *et al.*, 1998), as these changes in rainfall quantity and frequency are currently altering the pattern of streamflows and demands, spatial and temporal distribution of runoff, soil moisture, and groundwater reserves (Islam *et al.*, 2012a; Srivastava *et al.*, 2014). Changes in precipitation showed a significant impact on society; therefore its up-to-date information is needed to estimate the spatial distribution and variability at all points of the territory (Yaduvanshi *et al.*, 2015). The drastic change in precipitation trend would lead to hazardous events like flood and drought (Srivastava *et al.*, 2015). The amount of precipitation determines the recharge of aquifer and the level of the soil moisture for agricultural crop production (Gupta *et al.*, 2014). Hence, regular monitoring of precipitation is required for a better food security, as temporal change in precipitation distribution impact cropping patterns and productivity (Kumar *et al.*, 2010).

In India, attempts have been made in the past to determine trends in the rainfall at national and regional scales. Trend analysis has proved to be a useful tool by providing useful information on the possibility of changes in the future (Yue and Hashino, 2003; Islam *et al.*, 2014). Several studies have addressed the important issue of trends in rainfall in India since last century. In this context, Guhathakurta and Rajeevan (2008) have reported that there is no clear long-term trend in average annual rainfall documented over the country like India. Karpouzos and Kavalieratou (2010) found an overall decreasing trend in annual rainfall from the 33-year (1974–2007) rainfall data, over Pieria region, Greece. In India, Kumar *et al.* (2010) reported large spatial and temporal variations in rainfall trend. Out of 30 subdivisions in the country, half of the regions showed an increasing trend in annual rainfall with significantly increasing trends over Haryana, Punjab, and Coastal Karnataka. Rathod and Aruchamy (2010) found the central and northern parts of the district indicated the highest annual rainfall variability, while the eastern and south western parts showed the lowest. In the Vattamalaikarai sub-basin, Tamil Nadu, India, Vennila (2007) has reported declining trends in monthly and seasonal rainfall. Similarly, Dash *et al.* (2007) showed decreasing trend of monsoon rainfall over north east India, east Madhya Pradesh and adjoining areas, and parts of Gujarat and Kerala.

To understand the nature of the rainfall variations, more studies are required for different geographical

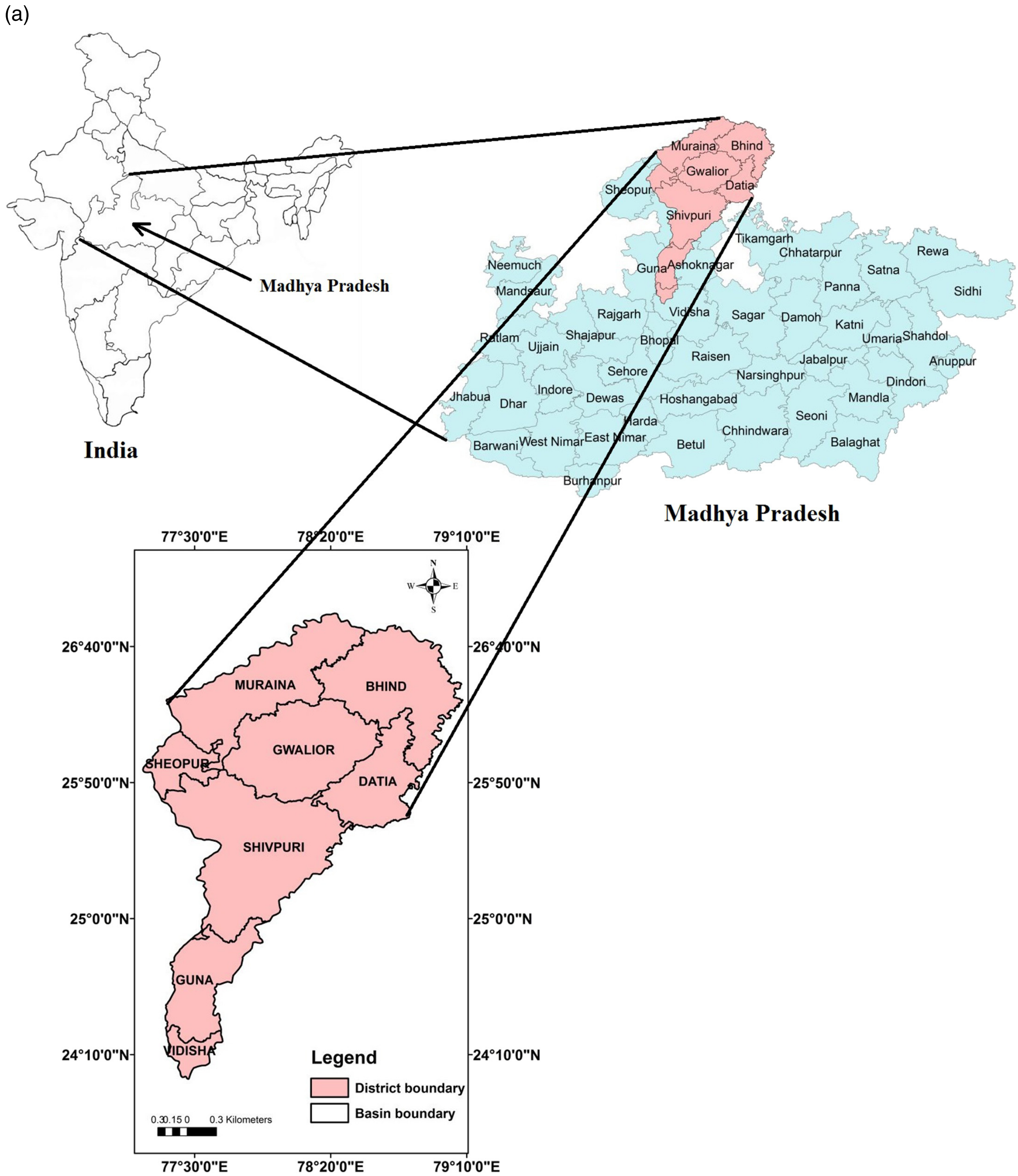

Figure 1. (a) Study area and distribution of meteorological stations, (b) Kendall *Z*-statistics and the annual rainfall trend, (c) Kendall *Z*-statistics and the seasonal rainfall trend, (d) Inter-annual variability in annual rainfall (%CV), (e) Inter-annual variability in seasonal rainfall (%CV).

regions. In purview of the above, the aim of this paper focuses on analyzing the patterns and variability of rainfall in Sindh River basin (SRB), Madhya Pradesh, India. The manuscript is divided into following sections: Section 2 describes the study area and the measured data sets. Section 3 covers the different methodologies and GIS techniques used in this study. The results of the analyses are presented and discussed in Section 4. Section 5 provided the final remark and conclusion of this study.

2. Study area

Sindh River originates in Vidisha district of Madhya Pradesh, India. Total catchment area of the Sindh river in Madhya Pradesh is 26 699 km^2 with length of 470 km. Major tributaries of Sindh are Mahuar, Parbati, Pahuj, and Kunwari. The study area and geographical position of the selected stations are presented through Figure1(a). The study area extends from 21°17′N to 26°36′N and 74°02′E to 82°26′E covering in total eight

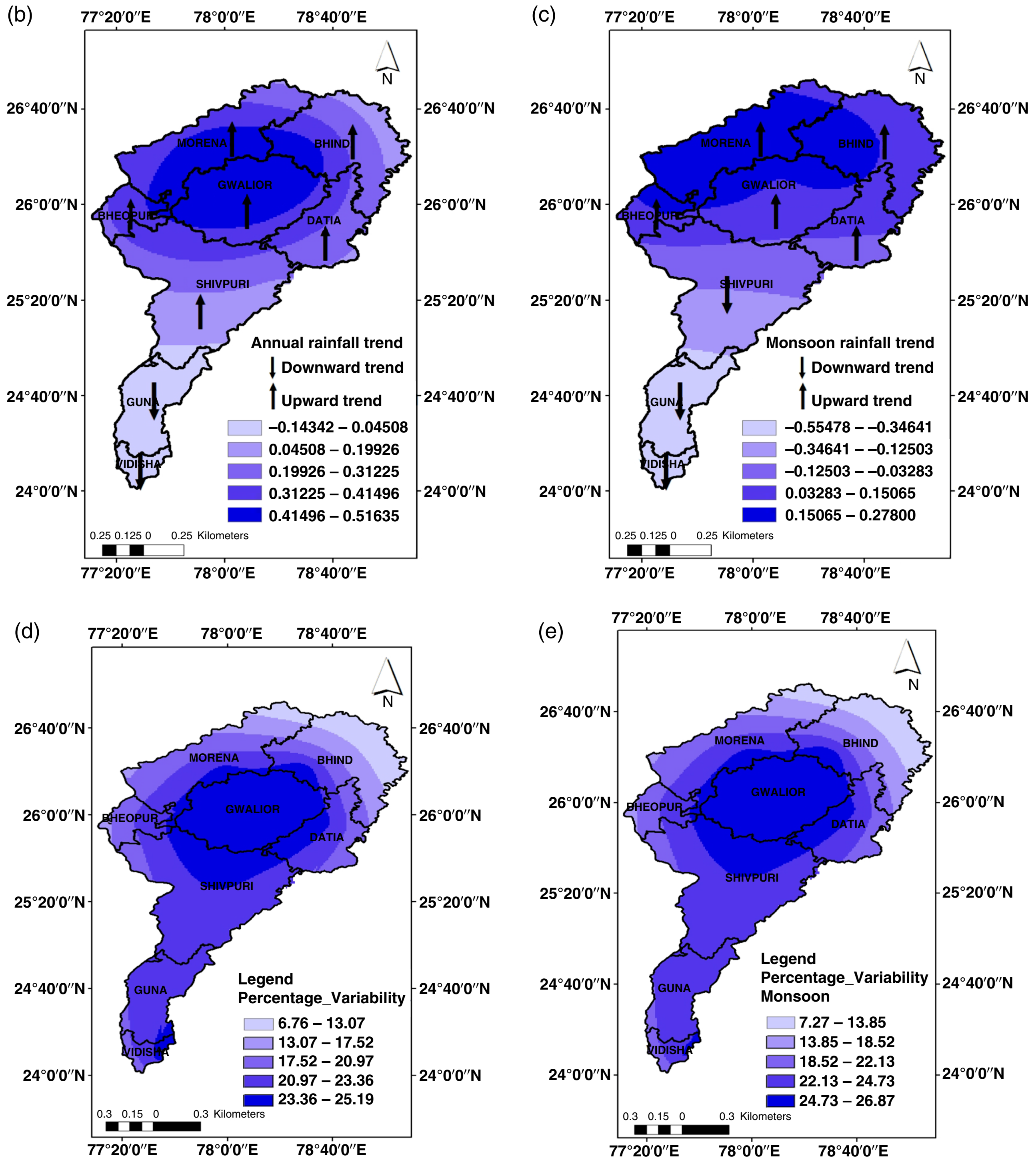

Figure 1. Continued

districts. SRB has a subtropical climate with variable temperature in the basin. The hottest place is Bhind in summer where temperature reaches up to 45 °C. Precipitation value increases from west to east and lowers toward north. The basin receives maximum precipitation from June to September.

3. Methodology

The daily rainfall data of eight districts of SRB for a period of 1901–2002 were obtained from the website: http://www.indiawaterportal.org/met_data/, to examine the spatial and temporal variability in the rainfall data series. According to the IMD, four prominent seasons namely: (1) winter (December–February), (2) summer (March–May), (3) monsoon (June–September), and (4) post-monsoon (October–November) are existing in India. The coordinates of available stations are presented in Table 1.

The monthly rainfall data were used to compute the annual and seasonal (June–September) time series. In this study, the magnitude of changes in

Table 1. Geographic characteristics of the stations used in the study.

S. no.	Station	Latitude (decimal degree)	Longitude (decimal degree)
1	Bhind	26.34	78.48
2	Muraina	26.30	78.00
3	Gwalior	26.14	78.15
4	Sheopur	25.31	76.46
5	Shivpuri	25.25	77.39
6	Guna	24.38	77.19
7	Vidisha	23.33	77.48
8	Datia	25.41	78.28

a time series was determined using a nonparametric method known as Sen's estimator (Sen, 1968), while the statistical significance was analyzed through Mann–Kendall (MK) test (Mann, 1945; Kendall, 1946).

3.1. Magnitude of trend

In addition to identify whether a trend is present in the data sets or not, a parameter called slope estimator β, which was extended by Hirsch *et al.* (1982) is also used from the equations as proposed by Sen in 1968. In other words, β is the median over all possible combinations of pairs for the whole data set (Hirsch *et al.*, 1982). A positive value of β indicates an 'upward trend' (increasing values with time), while a negative value indicates a 'downward trend' (decreasing value with time) (Karpouzos and Kavalieratou, 2010). Here the slope (β) of all data pairs is computed as:

$$\beta = \frac{x_j - x_i}{j - i} \tag{1}$$

where x_j and x_i are considered as data values at time j and i ($j > i$), respectively. The median of these N values of β is represented as Sen's estimator of slope. Sen's estimator is computed as $Q_{\text{med}} = \beta\ (N+1)/2$, if N appears to be odd, and in case of even the equation becomes $Q_{\text{med}} = \{\beta\ (N/2) + \beta\ [(N+2)/2]\}/2$. At the end, Q_{med} is computed by two-sided test at 100 $(1-\alpha)\%$ confidence interval and then a true slope can be obtained by the nonparametric test. Positive value of Q_{med} indicates an upward or increasing trend and vice versa in case of negative value (Babar and Ramesh, 2013).

3.2. Significance of trend

The nonparametric MK test is considered as one of the best methods to detect trend in time series because of its robust nature (Libiseller and Grimvall, 2002). The MK test is used to detect monotonic (either increasing or decreasing) trends. As there are chances of outliers to be present due to extreme rainfall events, the nonparametric MK test is useful because its statistic is based on the (+ or −) signs, rather than the values of the random variable, and therefore, the determined trends are less affected by the outliers (Helsel and Hirsch, 1992). To detect trend in the rainfall time series, assuming that the time series is independent, the MK statistic S is described as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}\left(x_j - x_i\right) \tag{2}$$

where x_i and x_j are sequential data for the ith and jth terms; n is the sample size; and

$$\operatorname{sign}\left(x_j - x_i\right) = \begin{cases} +1, & \text{if } x_j - x_i > 1 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 1 \end{cases} \tag{3}$$

The statistic S is approximately Gaussian when $n = 18$ with the mean $E(s)$ and variance $\text{Var}(S)$ of the statistic S given by the expressions:

$$E(s) = 0,\ \text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

However, if tie exist in the data set, then expression for Var(S) has to be adjusted and becomes:

$$\text{Var}(S) = \frac{\left\{ n(n-1)(2n+5) - \sum_{p=1}^{q} t_p \left(t_p - 1\right)\left(2t_p + 5\right) \right.}{18} \tag{5}$$

The variable q and t_p in Equation (5) are number of tied groups and number of data values in the pth group, respectively. The standardized statistic (Z) for one-tailed test of the statistic S is given as follows:

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{6}$$

If Z_{mk} is positive, then the trend is increasing and vice versa.

4. Results and discussion

4.1. Statistical characteristics of annual and seasonal rainfall

Basic statistical attributes of annual and seasonal (June–September) rainfall events for the period of 102 years (1901–2002) of SRB were analyzed, such as mean, standard deviation (SD), and coefficient of variation (CV) (Table 2). Mean and SD of the annual rainfall data of different districts varied from 808 to 1053 mm and 177.38 to 250.60 mm, respectively. In case of seasonal rainfall, these values varied from 753.99 to 971.77 mm over the period of 1901–2002. This basic statistic indicates that the regions with greater rainfall have less variability than the regions with relatively lower rainfall. The scrutiny of annual and seasonal rainfall records showed that the maximum rainfall was 1847.30 mm in Vidisha in year 1934, and minimum rainfall of 349.12 mm in Bhind in 1913.

Table 2. Statistical summary of annual and seasonal rainfall of Sindh River basin.

	Mean		Median		Standard deviation		Coefficient of variation (CV, %)	
Station	**Annual**	**Monsoon**	**Annual**	**Monsoon**	**Annual**	**Monsoon**	**Annual**	**Monsoon**
Bhind	841.88	772.65	846.47	780.41	210.40	206.63	24.99	26.74
Muraina	815.37	755.09	824.02	758.23	199.48	197.67	24.47	26.18
Gwalior	875.97	809.06	891.86	829.43	207.89	204.67	23.73	25.30
Sheopur	808.37	753.99	808.89	762.09	177.38	175.27	21.94	23.25
Shivpuri	920.17	851.21	930.04	860.43	200.77	196.39	21.82	23.07
Guna	841.77	769.21	838.21	761.16	178.60	172.12	21.22	22.38
Vidisha	1053.87	971.77	1013.53	938.35	250.60	240.51	23.78	24.75
Datia	926.15	854.21	944.11	885.07	218.93	214.19	23.64	25.07

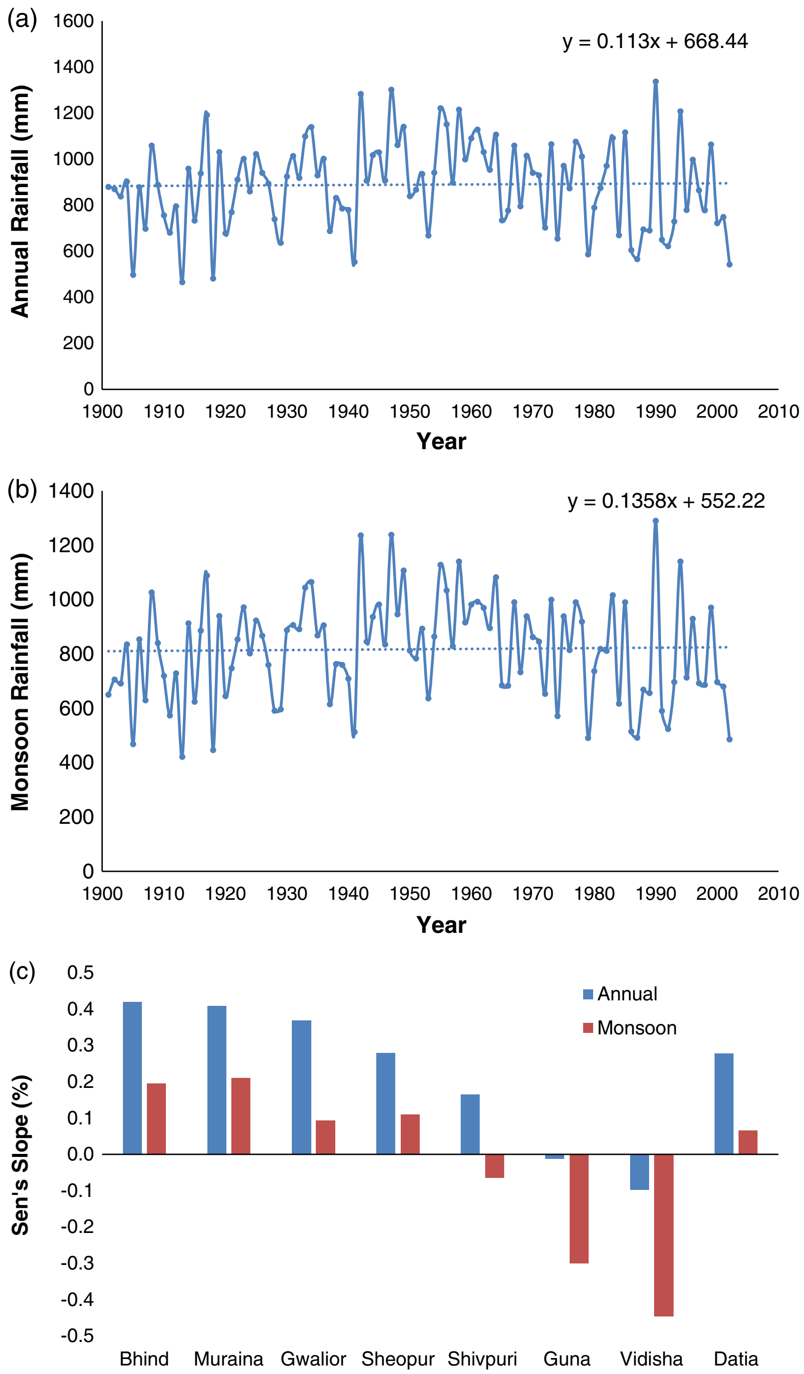

Figure 2. (a) Mean annual rainfall distribution, (b) Mean monsoon rainfall distribution, (c) Sen's slope (%) for the annual and monsoon rainfall.

Table 3. Result for trend analysis of annual and monsoon rainfall (at 5% level of significance).

Station	Annual rainfall (over 102 years)				Monsoon rainfall (over 102 years)			
	Test apply	*Z*-statistics	Trend	Sen's slope (β)	Test apply	*Z*-statistics	Trend	Sen'sslope (β)
Bhind	MK	0.496	Increasing	0.42	MK	0.249	Increasing	0.19
Muraina	MK	0.513	Increasing	0.41	MK	0.279	Increasing	0.21
Gwalior	MK	0.508	Increasing	0.37	MK	0.126	Increasing	0.09
Sheopur	MK	0.402	Increasing	0.28	MK	0.161	Increasing	0.11
Shivpuri	MK	0.167	Increasing	0.16	MK	−0.097	Decreasing	−0.06
Guna	MK	−0.015	Decreasing	−0.01	MK	−0.472	Decreasing	−0.30
Vidisha	MK	−0.144	Decreasing	−0.10	MK	−0.555	Decreasing	−0.45
Datia	MK	0.332	Increasing	0.28	MK	0.073	Increasing	0.06

4.2. Trend analysis

The MK and Sen's slope estimator have been used for the determination of the trend. The trend analysis is carried out for the SRB by using average annual and monsoon (June–September) rainfall data. The brief details of the results are presented in the following subsections.

4.2.1. Seasonal and annual rainfall trends

Monsoon season provides maximum contribution to annual rainfall in India, predominantly during the months of June, July, August, and September. The rainfall trends of annual and seasonal rainfall are shown in Figure 2(a–b). The increasing trend was observed in annual and seasonal rainfall time series with the slope of 0.11 and 0.13, respectively.

The results of the MK test and the *Z*-statistics revealed the trend in the time series for both annual and seasonal cycles (Table 3) with the magnitude of trend. All tests are considered at 5% level of significance. Both positive and negative trends were identified using the MK test in the annual and seasonal rainfall data (Figure 2(c)). As seen from the Table 3, the significant increasing trends were found in annual and seasonal rainfall time series for the entire study area except Guna and Vidisha districts, which exhibit a significantly decreasing trend. The magnitudes of positive trends were recorded at the Shivpuri (0.16) and Bhind (0.42) districts (Table 3) while the negative trends were recorded in the districts Guna (−0.01) and Vidisha (−0.10). The magnitudes of trend in monsoon rainfall varied between $-0.45\,\text{mm year}^{-1}$ in Vidisha to $0.21\,\text{mm year}^{-1}$ in Muraina districts. The stations viz. Bhind, Muraina, Gwalior, Shoepur, Shivpur and Datia shows increasing trend in annual rainfall whereas in monsoon rainfall Shivpuri, Guna and Vidisha shows negative trends except remaining stations.

4.2.2. Analysis of annual and seasonal rainfall variability patterns

The variation in rainfall represents a general characteristic of the data set. However, from agricultural view-point, it is essential to understand the seasonal variations for precise assessment of supplemental water requirements. The study of rainfall variability pattern using CV for a period of 1901–2002 (102 years) for SRB indicates that the inter-annual variability was highest for the entire river basin (Figure 1(c) and (d)). The inter-annual variability of post-monsoon rainfall was greater than that of annual rainfall as given in Table 2 and Figure 1(e). Minimum values of CV fall to 21.11% for annual rainfall and 22.38% during the monsoon seasons, whereas the seasonal rainfall variability was found maximum in Bhind (26.74%) (Table 2). In overall a high variation in rainfall was seen which indicated that the areas with higher inter-annual variability in rainfall are more susceptible to floods and droughts.

5. Conclusions

The study was carried out to estimate the rainfall trend using the MK and Sen's slope estimators. The *Z*-value of MK test represents both positive and negative trends of rainfall in the area. All stations of the SRB showed a positive trend except Guna and Vidisha, which reported a significantly decreasing trend (*Z*-value) and slope for both annual and seasonal rainfall. Similar information were also confirmed by Sen's slope that indicate a periodic change in the magnitude of the slope and the rainfall. The overall analysis indicated an increasing trend in the rainfall of SRB during the monsoon seasons. From all the statistical test results, it can be concluded that there is evidence of some change in the trend of rainfall in span of 102 years. The analysis of rainfall data and findings could be useful for irrigation and agricultural managers and helpful for managing water resources in the basin.

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