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Spatio-temporal variation of rainfall over Bihar State, India

Pratibha WARWADE[1) ABCDEF], Shalini TIWARI[1) ABCDEF], Sunil RANJAN[1) ABCDEF], Surendra K. CHANDNIHA[2) ABCDEF], Jan ADAMOWSKI[3) ABCDEF] ✉

1) Central University of Jharkhand, Centre for Water Engineering and Management, Ranchi, India
2) National Institute of Hydrology, Surface Water Hydrology Division, Roorkee, Uttarakhand, India
3) McGill University, Department of Bioresource Engineering, 21 111 Lakeshore Road, Ste Anne de Bellevue, QC H9X 3V9, Canada; jan.adamowski@mcgill.ca

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Abstract

This study detected, for the first time, the long term annual and seasonal rainfall trends over Bihar state, India, between 1901 and 2002. The shift change point was identified with the cumulative deviation test (cumulative sum – CUSUM), and linear regression. After the shift change point was detected, the time series was subdivided into two groups: before and after the change point. Arc-Map 10.3 was used to evaluate the spatial distribution of the trends. It was found that annual and monsoon rainfall trends decreased significantly; no significant trends were observed in pre-monsoon, monsoon, post-monsoon and winter rainfall. The average decline in rainfall rate was –2.17 mm·year^{-1} and –2.13 mm·year^{-1} for the annual and monsoon periods. The probable change point was 1956. The number of negative extreme events were higher in the later period (1957–2002) than the earlier period (1901–1956).

Key words: *climate change, hydrology, rainfall, spatio-temporal variation*

INTRODUCTION

The spatial and temporal distribution of rainfall is important in hydrology, water resource management, agriculture, as well as policy making and planning with regards to climate change [HAMMOURI *et al.* 2015]. The uneven distribution of rainfall may result in a mismatch between water availability and demand in which case irrigation structures are required to redistribute water in accordance with the requirements of a specific region. The incidence of extreme rainfall events is also an important parameter for the design of dams, spillways, flood protection structures and drainage networks [JAGADEESH, ANUPAMA 2014]. The Intergovernmental Panel on Climate Change (IPCC) reported that the intensity of spatial, inter-seasonal and inter-annual variability of rainfall events have increased in Asia over the past few decades [TEAM *et al.* 2014. A rise in mean global temperature of about 0.74°C between 1906 and 2005 and greater rainfall variability have also occurred [SOLOMON *et al.* 2007; ŻMUDZKA 2012]. These changes affect various issues such as crop water requirements, evapotranspiration, ground water level depletion, environmental flows, trans-boundary issues and interstate disputes, among others. Many hydrological studies have been carried out around the world with regards to water issues related to rainfall and temperature (e.g. NICHOLLS, LAVERY [1992], RODRIGUEZ-PUEBLA *et al.* [1998], MOHAPATRA *et al.* [2003], GOSWAMI *et al.*

[2006], GALLANT *et al*. [2007], GUHATHAKURTA, RAJEEVAN [2008], TASCHETTO, ENGLAND [2009], CHOWDHURY, BEECHAM [2010], PHILANDRAS *et al*. [2011], AYALEW *et al*. [2012], MARTINO *et al*. [2012], CZARNECKA, NIDZGORSKA-LENCEWICZ [2012], PETRIE *et al*. [2014], ARAGHI *et al.* [2015], CHANDNIHA *et al.* [2016], WARWADE *et al.* [2016], INAM *et al*. [2017]).

Studies from around the world show that rainfall variability is increasing on both a spatial and a temporal basis. For example, in the Australian and Canadian prairies [AKINREMI *et al.* 2001]; in the Haihe River Basin, China [LU *et al*. 2015]; and in Turkey, particularly in January, February and September [PARTAL, KAHYA 2006]. Various studies on rainfall trends have also been carried out in in India [GUHATHAKURTA, RAJEEVAN 2008; KOTHYARI, SINGH 1996; PARTHASARATHY, DHAR 1974; 1978; SARKAR *et al*. 2004; SEN ROY, BALLING 2004], and it has been reported that Indian monsoon rainfall is strongly affected by atmospheric factors viz. regional pressure anomalies [DUGAM, KAKADE 2003], cyclonal activities [PATTANAIK, RAJEEVAN 2007] and sea surface temperature variations [GOSWAMI *et al*. 2006], thereby making monsoon rainfall less predictable [MANI *et al*. 2009]. PATTANAIK, RAJEEVAN [2010] assessed long term trends in the Indian monsoon season from 1951 to 2005, and found extreme rainfall events increased and low rainfall events decreased. Extreme climatic and weather events have increased over the last few decades [KARL, EASTERLING 1999]. In Kerala in South India, a significant decreasing rainfall trend was found in the southwest monsoon and an increasing trend was found in the post-monsoon season [KRISHNAKUMAR *et al*. 2009]. In various Indian states such as Punjab, Haryana, Rajasthan and Madhya Pradesh, increasing rainfall trends in the annual and southwest monsoon occurred during 1901 to 1982 [PANT, HINGANE 1988]. In central India and the adjoining part of the Peninsula, a trend in rising annual rainfall between 1901 and 1960 was recorded [PARTHASARATHY, DHAR 1974].

Although various studies on climate change have been carried out in the central, northern and southern parts of India, little has been done in the eastern region. Our investigation therefore focuses on Bihar, an eastern state of India and studies the annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter) rainfall variation in terms of trend, magnitude and extreme events at 37 weather stations. Various statistical techniques such as the Mann–Kendall (MK) test, Sen's slope estimator, change percentage and break point analysis are used and supported by a linear regression test. This rainfall trend analysis is important to facilitate the planning and management of sustainable water resources in the region.

STUDY AREA

The state of Bihar borders on Uttar Pradesh (to the West), Jharkhand (to the South) and West Bengal (to the North-East) and is the 13th-largest state in India with a surface area of 94,163 km^2 (Fig. 1). It is the third most populous state with over 100 million inhabitants. About 6,764 km^2 are covered by forest which is about 7.2% of the total geographical area of Bihar state. The state is bifurcated by the Ganges River which flows from West to East. Bihar lies between 24°37'58" N to 27°33'86" N latitude and between 83°21'47" E to 88°19'41" E longitude. The average temperature varies from 10°C in the winter to 34°C in the summer and the weighted average annual rainfall of the state is approximately 1170 mm [India Water Portal 2010].

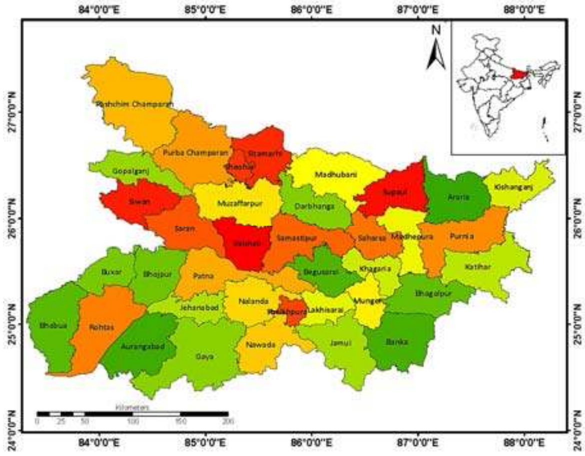


Fig. 1. Geographical locations of different districts over the study area (Bihar State); source: own elaboration

MATERIALS AND METHODS

The long term (1901–2002) monthly rainfall data were acquired from the India water portal site [India Water Portal 2010]. This monthly rainfall time series has been used in other studies [CHANDNIHA *et al.* 2016; DUHAN, PANDEY 2013]. In the present study, the 1901 to 2002 rainfall time series were segregated into 5 data sets viz. annual (1) and seasonal (4) as characterized by the India Meteorological Department (IMD) guidelines: monsoon (June–Sept); post-monsoon (Oct–Nov); winter (Dec–Feb) and pre-monsoon (Mar–May). Missing values and consistency of the long-term data set were checked and the presence of serial dependency over the time series was determined by applying lag-1 auto-correlation [CUNDERLIK, BURN 2004]. The non-parametric Mann–Kendall trend and Sen's slope estimator test were applied to monthly, annual and seasonal data sets for all the districts in Bihar [KENDALL 1975; PINGALE *et al.* 2016; SEN 1968; THEIL 1950]. The Mann–Kendall test was applied at a 95% confidence level and overall results are represented by positive significant, negative significant, positive and negative trends. Regression analysis was also utilized for estimating the relationship among the variables [JAGADEESH, ANUPAMA 2014]. A possible shift change (break point) was detected using the cumulative deviation test at a confidence level of 95% [BUISHAND 1982]. This test can still apply when there are slight departures from normality. The cumulative deviation (CD) test is based on the adjusted partial sums or cumulative deviations from the mean. Sequential analysis, specifically the cumulative sum (CUSUM) test, was used to monitor the change detection in the series [TABARI *et al.* 2012].

INVERSE DISTANCE WEIGHTED TECHNIQUE

In the present study, the inverse distance weighted (IDW) interpolation technique was used for the spatial maps of precipitation for 37 stations in Bihar State [LEBEL *et al.* 1987; SINGH, CHOWDHURY 1986].

The inverse distance weighting tool is already available in ArcMap. In the IDW methodology, the weight of any known point is set to be inversely proportional to its distance from the estimated point [CHEN, LIU 2012]. It is calculated as follows:

$$\hat{x} = \frac{\sum_{i=1}^{n} \frac{1}{d_i} x_i}{\sum_{i=1}^{n} \frac{1}{d_i}} \tag{1}$$

Where: $\hat{x}$ = value to be estimated; x_i = known value; $d_1, d_2, d_3, \ldots, d_n$ = distance from the n data points to the point estimated n.

BRIEF METHODOLOGY OF MANN-KENDALL TEST AND SEN'S SLOPE ESTIMATOR

1. The Pettitt Mann–Whitney (PMW) test distinguishes the most likely change year in the yearly precipitation sequence [PETTIT 1970]. The details of the PMW test is given below [DUHAN, PANDEY 2013]:
   Assume a time series $\{X_1, X_2, \ldots, X_n\}$ with a length n and where t is the time of the most likely change point. Two samples, $\{X_1, X_2, \ldots, X_n\}$ and $\{X_{t+1}, X_{t+2}, \ldots, X_n\}$, can then be derived by dividing the time series at time t. An index, U_t, is derived via [DUHAN, PANDEY 2013]:

$$U_t = \sum_{i=1}^{t} \sum_{j=1}^{T} \text{sgn}\left(X_i - X_j\right) \tag{2}$$

$$\text{sgn}\left(X_i - X_j\right) = \begin{cases} 1 \text{ if } \left(X_i - X_j\right) > 0 \\ 0 \text{ if } \left(X_i - X_j\right) = 0 \\ -1 \text{ if } \left(X_i - X_j\right) < 0 \end{cases} \tag{3}$$

   A plot of U_t against t for a time series with no change point would result in a continually increasing value of U_t. However, if there is a change point (even a local change point) then U_t would increase up to the change point and then begin to decrease. This increase followed by a decrease may occur several times in a time series, indicating several local change points. So there is still the question of determining the most significant change point. We can identify the most significant change point t where the value of $|U_t|$ is maximum [DUHAN, PANDEY 2013].

$$K_t = \max_{1 \le t \le T} |U_t|$$

   The approximated significance probability $p(t)$ for a change point [PETTITT 1979] is given as:

$$p = 1 - \exp\left[\frac{-6K_T^2}{T^3 + T^2}\right] \tag{4}$$

   The change point is statistically significant at the time t with a significance level of α when probability $p(t)$ exceeds $1 - \alpha$.
   The autocorrelation coefficient distinguishes the nearness of serial correlation within the data series [SIEGEL, CASTELLAN 1988].
2. The Mann–Kendall (MK test has been applied to the non-auto correlated/auto correlated sequences to distinguish the presence of patterns in yearly and seasonal precipitation [HAMED, RAO 1998; KENDALL 1975].
   The MK statistic, S, is defined as [HAMED, RAO 1998; KENDALL 1975]:

$$\mathrm{S} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\left(x_j - x_i\right) \tag{5}$$

Where: $x_1, x_2, x_3, \ldots, x_n$ represents n data points where x_j represents the data point at the time j of data (time series); and $x_j - x_i = \theta$

$$Sgn(\theta) = \begin{cases} 1 & if\ \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & if\ \theta < 0 \end{cases} \tag{6}$$

Under the assumption that the data are independent and identically distributed, the mean and variance of the S statistic in Eq. (2) are given by [KENDALL 1975] as:

$$E[S] = 0$$

$$\text{Var}(\mathrm{S}) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5)}{18} \tag{7}$$

Where: m = the number of groups of tied ranks, each with t_i tied observations.

The original MK statistic, designated by Z and the corresponding p-value (p) of the one-tailed test was computed as [DUHAN, PANDEY 2013]:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{If } S > 0 \\ 0 & \text{If } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{If } S < 0 \end{cases} \tag{8}$$

$$p = 0.5 - \phi(|Z|)$$

$$\phi(|Z|)=\frac{1}{\sqrt{2\pi}}\int_{0}^{|Z|}e^{-\frac{t^2}{2}}dt \qquad (9)$$

If the *p*-value is small enough, the trend is quite unlikely to be caused by random sampling. The *Z* values are approximately normally distributed, and a positive *Z* value larger than 1.96 (based on normal probability tables) denotes a significant increasing trend at the significance level of 0.05, whereas a negative *Z* value lower than –1.96 shows a significant decreasing trend.

Thiel and Sen's slant estimator test served to estimate the magnitude of a trend [SEN 1968; THIEL 1950].

3. In this method, the slope estimates of *N* pairs of data are first calculated using the following expression [SEN 1968]:

$$Q_i=\frac{x_j-x_k}{j-k} \quad \text{for} \quad i=1,2,3,......,\ n \qquad (10)$$

Where: x_j and x_k are data values at time *j* and *k* ($j > k$) respectively.

The median of these *N* values of Q_i is Sen's estimator of slope, which is calculated as [SEN 1968]:

$$\beta=\begin{cases} Q_{[(N+1[N/2])/2]} & N\,is\,odd \\ \frac{1}{2}\left(Q+Q_{(N+2)/2}\right) & N\,is\,even \end{cases} \qquad (11)$$

A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series data.

PERCENTAGE CHANGE

The percentage change phenomenon is used for comparison between two scenarios in a time series. Change percentage was computed by approximating it with a linear trend [DUHAN, PANDEY 2013; PINGALE *et al.* 2015; YUE, HASHINO 2003]. The percentage change was calculated as:

$$Percentage\,Change(\%)=\frac{\beta(Length\,of\ year)}{Mean}\times 100$$

RESULTS AND DISCUSSION

SERIAL CORRELATION IN THE SERIES

The presence of any positive or negative correlations may affect the trend detection procedure [YUE, HASHINO 2003]. Hence, lag-1 serial correlation is used to check the presence of any existing trends in the series before applying the MK test. Results of the autocorrelation test show that all the series were found to be non-autocorrelated (Tab. 1). The MK test was then applied to the non-autocorrelated data series at the 5% significance level over 102 years. Figure 2 shows the deviation of rainfall from the mean value with the help of linear regression. The annual and monsoon graphs illustrate prominent decreasing rainfall trends and a sudden change after the mid-century. Pre-monsoon, post-monsoon and winter seasons do not show clear trends.

Table 1. Values of change points and autocorrelation coefficients

Station No	Station	Cumulative deviation (*t*)	CUSUM (*t*)	Autocorrelation coefficient (ρ_k)
1	Araria	**1956**	1959	0.141
2	Aurangabad	1978	1950	0.221
3	Banka	1959	1973	0.101
4	Begusarai	**1956**	1963	0.170
5	Bhagalpur	**1956**	1959	0.096
6	Bojpur	1964	1964	0.279
7	Buxar	1964	1973	0.264
8	Darbhanga	**1956**	1974	0.159
9	Gaya	1978	1950	0.224
10	Gopalganj	1987	1987	0.308
11	Jamui	1978	1963	0.167
12	Jehanabad	1978	1964	0.255
13	Bhabua	1982	1973	0.155
14	Katihar	**1956**	1959	0.062
15	Khagaria	**1956**	1959	0.138
16	Kishanganj	**1956**	**1956**	0.158
17	Lakhisarai	1959	1963	0.186
18	Madhepura	**1956**	1959	0.123
19	Madhubani	**1956**	1959	0.156
20	Munger	1959	1973	0.153
21	Muzafferpur	1987	1974	0.220
22	Nalanda	1964	1964	0.224
23	Nawada	1978	1964	0.219
24	Paschim Champaran	1963	1988	0.256
25	Patna	1964	1978	0.247
26	Purba Champaran	1987	1987	0.265
27	Purnia	**1956**	1959	0.101
28	Rohtas	1978	1973	0.197
29	Saharsa	**1956**	1959	0.127
30	Samastipur	**1956**	1959	0.165
31	Saran	1987	1974	0.287
32	Sheikhpura	1959	1964	0.203
33	Sheohar	1987	1987	0.229
34	Sitamarhi	**1956**	1987	0.198
35	Siwan	1987	1987	0.307
36	Supaul	**1956**	1959	0.135
37	Vaishali	1964	1978	0.226

Source: own study.

SHIFT IN RAINFALL TIME SERIES FROM 1901 TO 2002

Table 1 indicates 1956 as the most probable change point in the annual rainfall time series as obtained from the CD test and supported by the CUSUM test and linear regression (Fig. 2). Hence the entire time series (1901–2002) was divided into two segments, from 1901 to 1956 (before change point) and from 1957 to 2002 (after change point), and further climate variability was analysed considering the divided time series.

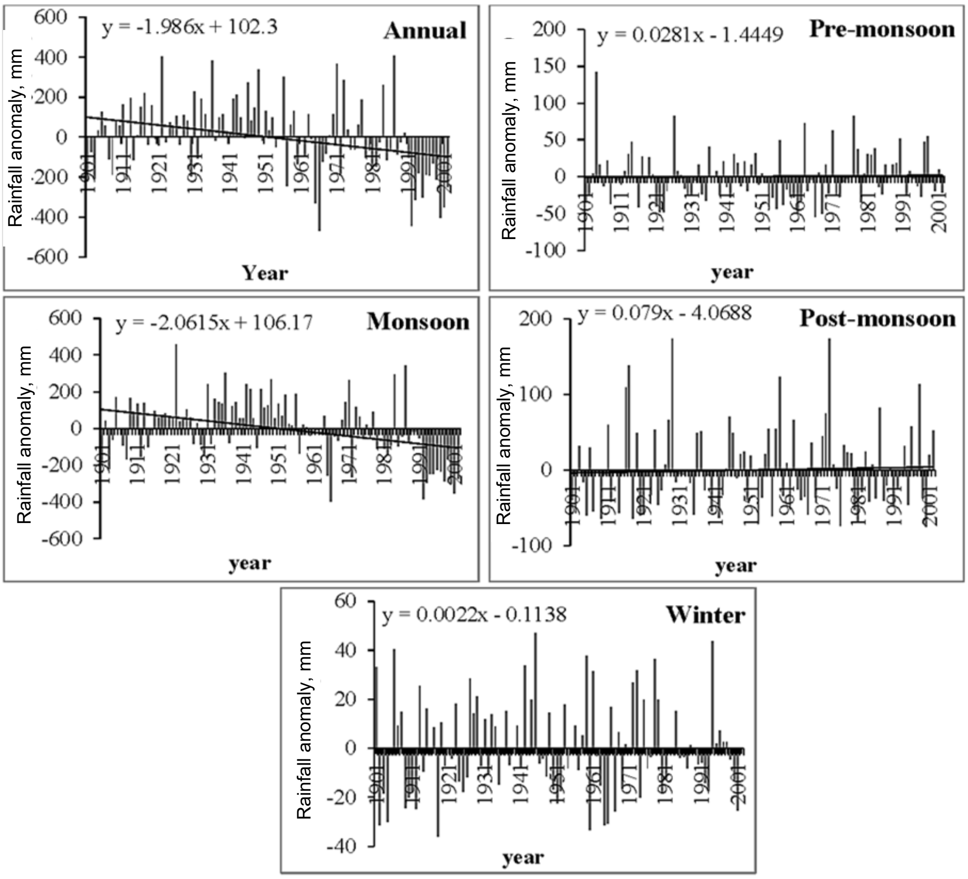


Fig. 2. Annual and seasonal rainfall trend (1901–2002) deviation from the mean value by the linear regression method; source: own study

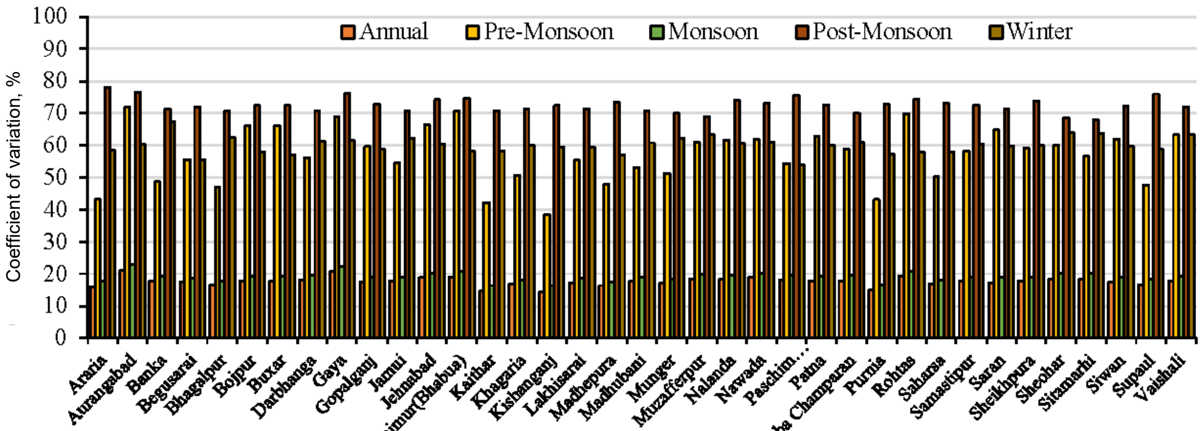


Fig. 3. Rainfall variability on an annual and seasonal basis at all stations; source: own study

RAINFALL VARIABILITY

Predicting variation in rainfall is important from an agricultural point of view for accurate estimation of crop water requirements. Rainfall variability patterns over 1901 to 2002 for 37 stations in Bihar using the coefficient of variation (*CV*) indicates that the inter-annual variability of post-monsoon rainfall is greater than that of the annual rainfall. The *CV* ranges from 14.37% to 21.1%, from 16.38% to 22.81%, from 53.99% to 67.28%, from 38.44% to 71.88 % and from 67.89% to 78.08% for annual, monsoon, winter, pre-monsoon and post-monsoon, respectively. The average rainfall in Bihar (with average variability) is 1169.24 mm (17.69%), 988.05 mm (19.19%), 65.54 mm (57.02%), 79.04 mm (72.50%) and 38.97 mm (60.04%) in annual, monsoon, pre-monsoon, post-monsoon and winter, respectively (Fig. 3). Overall, there is a high variation in rainfall; areas with high inter-annual variability in rainfall are generally more susceptible to floods and droughts [PANDEY, RAMASATRI 2001; TURKEŞ 1996].

The highest variability was observed in post-monsoon precipitation (78.08%) and the lowest variability in annual precipitation (14.37%) over the 102 years as reported by CHANDNIHA *et al*. [2016] for Jharkhand, a border state.

DISTRIBUTION OF AVERAGE RAINFALL IN BIHAR

The average rainfall distribution of the monsoon season over 102 years as a proportion of average annual rainfall for 37 stations (Fig. 4) shows that the monsoon contributed an average of 84.58% to the total average annual rainfall in Bihar. Individual stations experienced not less than 73.49% of their rainfall during the monsoon. The other seasons did not make a significant contribution to the average annual rainfall. Hence, further trend analysis was carried out for annual and monsoon rainfall time series.

TRENDS IN RAINFALL

Spatial and temporal trends in annual and seasonal rainfall between 1901 and 2002

The direction (*Z* value), magnitude of the trend (*Q*), and percentage change (change %) for annual and seasonal rainfall for the entire state of Bihar over 102 years (1901–2002), 56 years (1901–1956) and 46 years (1957–2002) are shown in Table 2 (Table 2 is on a seasonal basis, while Table 3 is on a station basis).

Positive and negative values of *Z* indicate increasing and decreasing trends, respectively. Significant negative trends for annual and monsoon rainfall for 1901–2002 and 1957–2002 and a significant positive trend for 1901–1956 were observed. The rest of the seasons showed non-significant trends for all time periods. Annual and monsoon rainfall declined at rates of –2.17 mm·year^{-1} and –2.12 mm·year^{-1} during 1901 to 2002, respectively, and at much greater rates from 1957 to 2002 (–5.36 and –5.87 mm·year^{-1}, respectively). From 1901 to 1956, annual and monsoon rainfall increased at rates of 3.01 mm·year^{-1} and 2.98 mm·year^{-1}, respectively. The highest percent reduction was observed in the monsoon season (–21.84%) which had an impact on the decreased annual rainfall (–18.92%) during 1901–2002.

Table 3 contains *Z* values and mean percent change for annual, monsoon, pre-monsoon, post-monsoon and winter rainfall at each station in the study area. All 37 stations had significant negative trends on an annual basis with *Z* values varying from –1.97 to –3.48. The spatial distribution of annual and seasonal rainfall trends at the 37 stations is depicted in Figure 5. Stars and pentagons denote significant and non-significant negative trends while triangles and diamonds denote significant and non-significant positive trends, respectively. The maximum reduction in annual rainfall was 19–22% in the northwest and south-

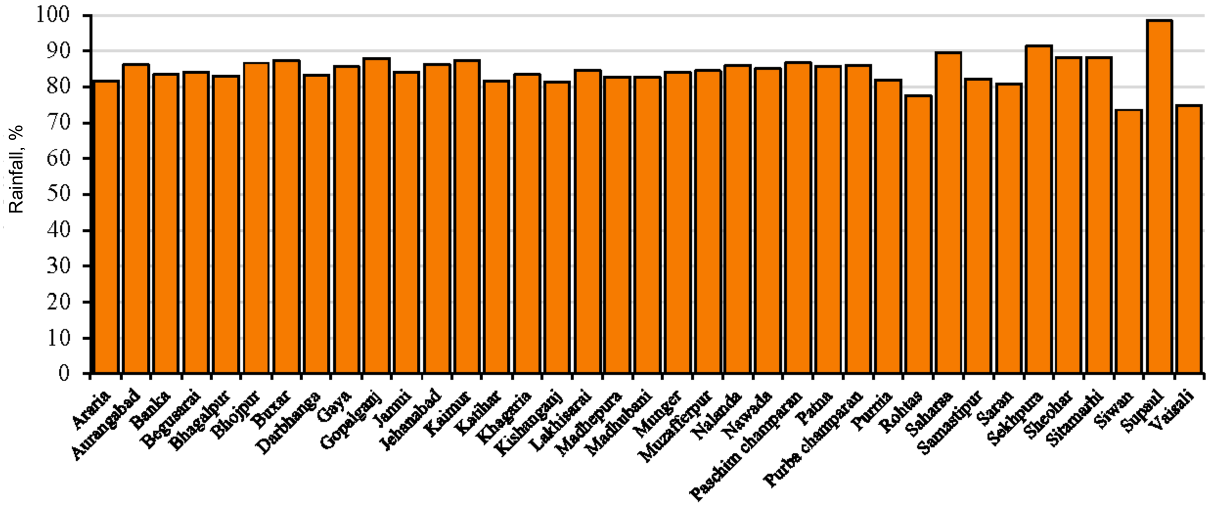


Fig. 4. Distribution of average monsoon rainfall (%) with respect to average annual rainfall (1901–2002) at different stations; source: own study

Table 2. Mann–Kendall test and percent change of annual and seasonal rainfall during 1901–2002, 1901–1956 and 1957–2002 for the entire study area

Time	1901–2002			1901–1956			1957–2002		
	Q	*Z* value	change (%)	*Q*	*Z* value	change (%)	*Q*	*Z* value	change (%)
Annual	–2.17	**–2.95**	–18.92	3.01	**2.16**	13.75	–5.36	**–2.23**	–23.32
Pre-monsoon	0.05	0.38	8.30	–0.10	–0.30	–6.52	0.68	1.64	43.75
Monsoon	–2.12	**–3.28**	–21.84	2.98	**2.29**	15.91	–5.87	**–2.74**	–30.18
Post-monsoon	0.11	0.56	14.14	0.41	1.07	28.28	0.09	0.13	6.00
Winter	0.01	–0.05	3.57	0.18	0.78	24.89	0.02	0.13	3.54

Explanations: *Q* = magnitude of the trend, *Z* value = direction; bold value shows significant trend.
Source: own study.

Table 3. Mann–Kendall *Z* values (direction) and change percentage (1901–2002)

Station No.	Stations	Annual		Monsoon		Pre-monsoon		Post-monsoon		Winter	
		Z value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %
1	Araria	**–2.33**	–13.39	**–3.00**	–18.29	0.51	7.05	0.29	5.64	0.56	10.22
2	Aurangabad	**–2.26**	–16.55	**–2.19**	–18.29	0.06	1.24	0.50	11.20	–0.04	–0.54
3	Banka	**–3.21**	–21.17	**–3.72**	–24.88	0.31	5.80	1.86	30.65	–1.49	–31.97
4	Begusarai	**–3.20**	–20.01	**–3.78**	–23.83	0.43	7.90	1.07	20.75	–0.60	–11.53
5	Bhagalpur	**–3.41**	–19.64	**–3.79**	–24.04	0.40	6.32	1.57	28.01	–0.67	–14.23
6	Bojpur	**–3.07**	–18.47	**–2.97**	–19.41	0.25	5.48	0.28	6.16	–0.02	–0.13
7	Buxar	**–2.90**	–17.60	**–2.76**	–18.16	0.32	6.81	0.46	2.41	0.23	3.66
8	Darbhanga	**–3.23**	–20.80	**–3.67**	–24.31	0.57	10.00	0.37	6.37	0.12	2.75
9	Gaya	**–2.41**	–16.77	**–2.37**	–19.12	0.10	1.96	0.78	16.62	–0.15	–1.91
10	Gopalganj	**–3.07**	–20.35	**–3.19**	–22.01	0.25	10.44	–0.29	–5.64	0.68	13.14
11	Jamui	**–3.22**	–20.84	**–3.44**	–23.20	0.36	5.29	1.43	32.99	–1.16	–21.29
12	Jehanabad	**–2.89**	–18.29	**–2.85**	–20.03	0.15	3.26	0.46	10.59	–0.01	–0.01
13	Bhabua	**–2.07**	–14.00	**–2.12**	–14.79	0.19	3.63	0.43	10.10	0.33	6.48
14	Katihar	**–2.67**	–13.62	**–3.50**	–18.12	0.57	8.04	1.34	22.22	–0.35	–7.65
15	Khagaria	**–3.15**	–20.04	**–4.00**	–24.14	0.51	8.31	1.06	20.43	–0.71	–13.24
16	Kishanganj	**–1.97**	–10.30	**–2.53**	–14.33	0.73	9.41	0.48	8.63	0.50	9.04
17	Lakhisarai	**–3.24**	–20.86	**–3.64**	–23.90	0.41	6.78	1.28	26.20	–0.83	–15.22
18	Madhepura	**–3.08**	–17.37	**–3.89**	–21.71	0.46	6.55	0.86	14.94	0.04	–0.68
19	Madhubani	**–3.04**	–18.63	**–3.43**	–22.79	0.53	8.96	0.18	3.65	0.47	10.38
20	Munger	**–3.24**	–20.73	**–3.80**	–24.90	0.46	7.38	1.30	26.71	–1.05	–22.05
21	Muzafferpur	**–3.27**	–21.72	**–3.54**	–22.69	0.60	9.53	0.10	2.14	0.10	1.75
22	Nalanda	**–2.89**	–20.17	**–3.24**	–22.34	0.13	3.01	0.63	14.64	–0.08	–1.22
23	Nawada	**–2.76**	–19.13	**–3.02**	–21.77	0.17	3.73	1.15	24.72	–0.33	–6.07
24	Paschim Champaran	**–3.17**	–20.59	**–3.45**	–23.15	0.45	6.96	–1.00	–20.81	1.06	20.54
25	Patna	**–3.08**	–20.08	**–3.34**	–21.44	–0.19	4.13	0.50	9.88	–0.19	–2.85
26	Purba Champaran	**–3.08**	–20.00	**–3.27**	–22.07	0.56	8.69	–0.48	–9.10	0.55	13.30
27	Purnia	**–2.57**	–14.08	**–3.48**	–18.29	0.57	7.81	1.00	16.01	–0.12	–1.83
28	Rohtas	**–2.25**	–15.02	**–2.20**	–15.97	0.11	2.94	0.39	9.45	0.21	3.58
29	Saharsa	**–3.18**	–18.75	**–3.87**	–23.35	0.46	7.42	0.90	16.05	–0.23	–6.55
30	Samastipur	**–3.29**	–20.58	**–3.77**	–25.40	0.54	8.49	0.57	12.59	–0.27	–4.55
31	Saran	**–3.48**	–21.27	**–3.26**	–22.15	0.47	9.02	0.14	3.85	–0.04	–0.51
32	Sheikhpura	**–3.09**	–19.85	**–3.36**	–23.21	0.17	3.90	0.94	20.23	–0.30	–5.62
33	Sheohar	**–3.07**	–20.61	**–3.39**	–21.88	0.54	7.31	–0.15	–1.76	0.31	6.21
34	Sitamarhi	**–2.98**	–19.74	**–3.27**	–22.54	0.58	8.82	–0.17	–3.62	0.53	10.88
35	Siwan	**–3.27**	–20.96	**–3.19**	–22.62	0.61	10.28	–0.11	–1.92	0.52	9.81
36	Supaul	**–2.74**	–15.52	**–3.46**	–21.25	0.43	6.09	0.26	5.64	0.69	13.44
37	Vaishali	**–3.48**	–21.10	**–3.55**	–23.47	0.44	8.50	0.41	7.86	–0.27	–4.62

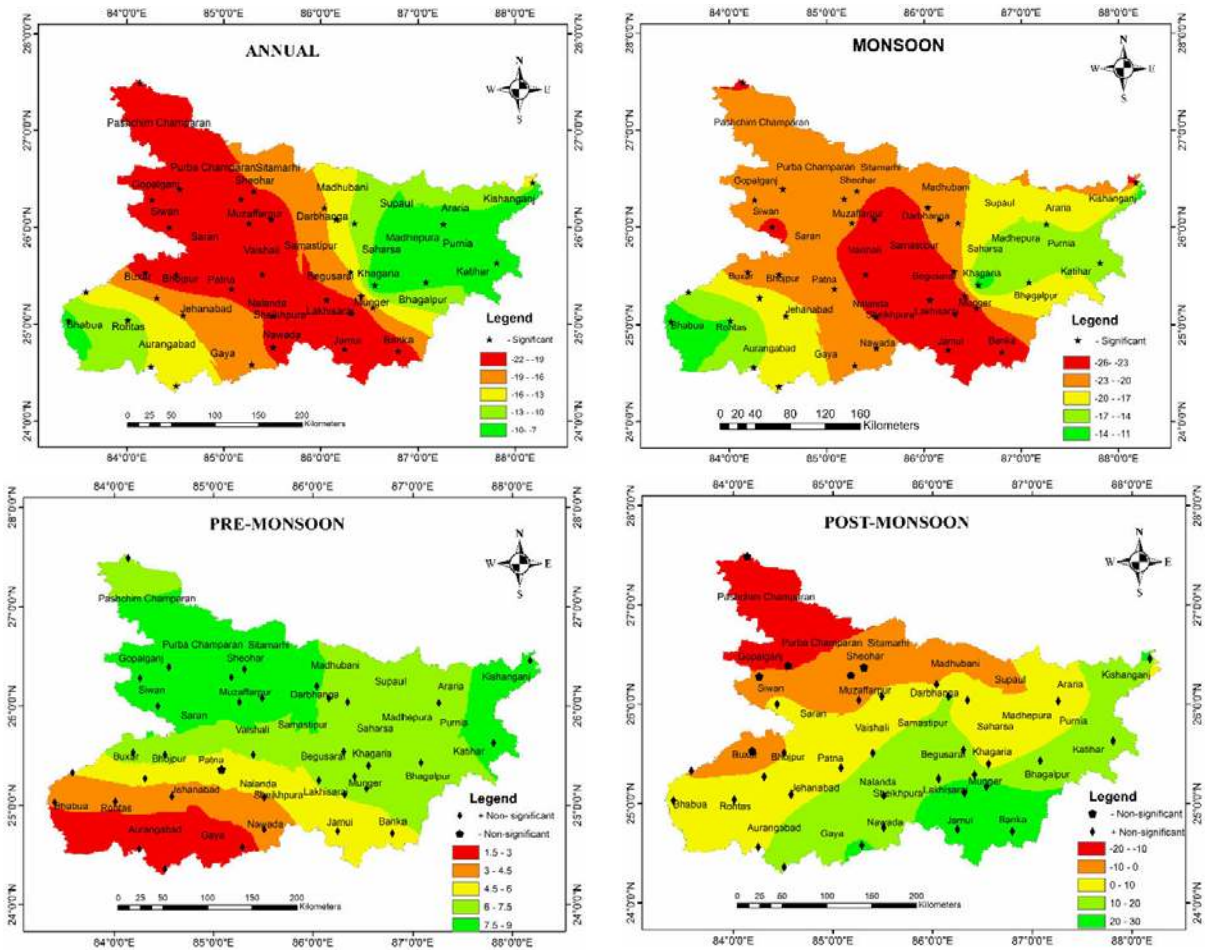
Legend: <–15% | 0–(–15%) | 0–15 | >15%

Explanation: bold values indicate significant trend.
Source: own study.

east parts of the state and the lowest reduction in rainfall was in the eastern and south-western parts. All 37 stations had more than a 10% decrease in rainfall during 1901–2002.

The monsoon season showed a dominant and significant decreasing rainfall trend for all 37 stations in Bihar with *Z* values ranging from –4.0 to –2.12 (Tab. 3). The maximum drop in monsoon rainfall varied from 23% to 26% in the central part of Bihar although all stations saw a significant decreasing trend ranging from 11% to 26% (Fig. 5). The pre-monsoon season showed non-significant increasing trends at all stations except Patna in central Bihar and *Z* values ranged from –0.19 to 0.73. The percent change in rainfall was positive over the entire area (1.5–9.0%) with the north-western and eastern parts showing a greater increase than the South-West. The post-monsoon season showed insignificant mixed trends and *Z* values ranged from –1.0 to 1.86. There was a non-significant negative trend in the North-West part of the state ranging from a decrease in rainfall of up –20% to –10%. The greatest drop occurred at the Paschim Champaran station with declines being lower towards the Purba Champaran, Gopalganj, Sheohar, Sitamarhi, Siwan and Buxar stations (up –10% to 0%). Non-significant positive trends were observed at 32 stations in the South-East part of Bihar with the greatest rainfall increase occurring at Banka, Jamui, Lakhisarai and Munger (20–30%).

The winter season had insignificant and mixed trends with the *Z* value varying from –1.49 to +1.06. The percent change in rainfall trends went from large and positive in the North-West (Paschim Champaran, Purba Champaran, Gopalganj, Sitamarhi, Supul and Madhubani) to large and negative in the South (Banka and Jamui).



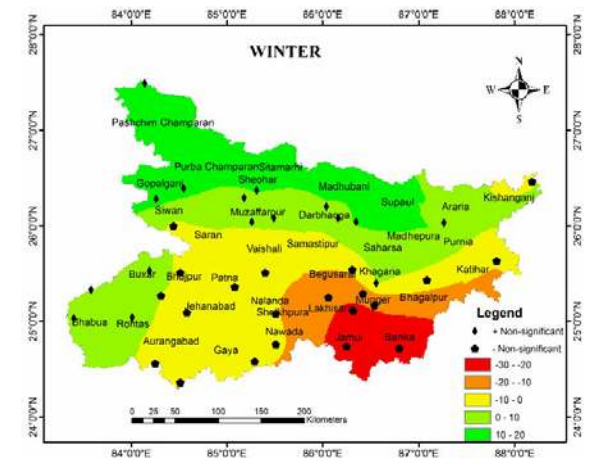


Fig. 5. Spatial distribution of annual and seasonal percent change of rainfall and level of significance at 37 stations from 1901 to 2002; stars and pentagons denote significant and non-significant negative trends, triangles and diamonds denote significant and non-significant positive trends, respectively; source: own study

For the annual and monsoon periods of precipitation, the magnitude of trend decreased for all stations. This result is in agreement with CHANDNIHA *et al*. [2016], who reported a decreasing rate of monsoon rainfall over Jharkhand, which is a neigh boring state of Bihar.

The magnitude of the rainfall trend over 102 years was obtained from Sen's slope estimator. Figure 6 illustrates the change in rainfall rate at each station in mm·year^{-1} over the span 1901–2002. The annual and monsoon periods clearly showed a reduced rainfall rate while most of the stations in the pre-monsoon, post-monsoon and winter had a rising rate of change. The maximum decrease is –2.62 mm·year^{-1} and –2.69 mm·year^{-1} (Paschim Champaran) and the smallest decrease is –1.34 mm·year^{-1} and –1.45 mm·year^{-1} (Kaithar) for monsoon and annual rainfall, respectively. These results reflected the rainfall scenario in Bihar between 1901 and 2002 and indicated some noticeable changes. Significant variation in monsoon rainfall has considerable influence on the Indian economy and agriculture. In Bihar, the observed decrease in monsoon rainfall may create difficulties in the agricultural sectors, industrial and domestic water supply, as demand is increasing continuously with growing urbanization.

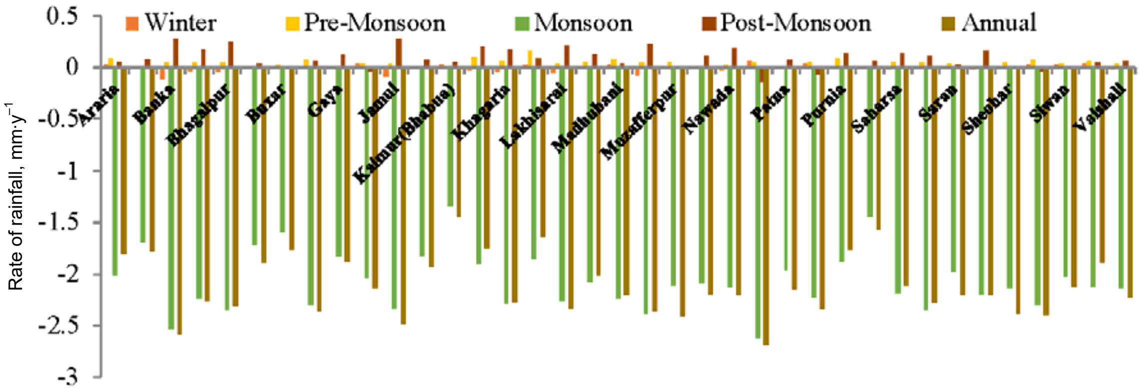


Fig. 6. Change in rainfall rate (mm·year^{-1}) at each station during 1901–2002; source: own study

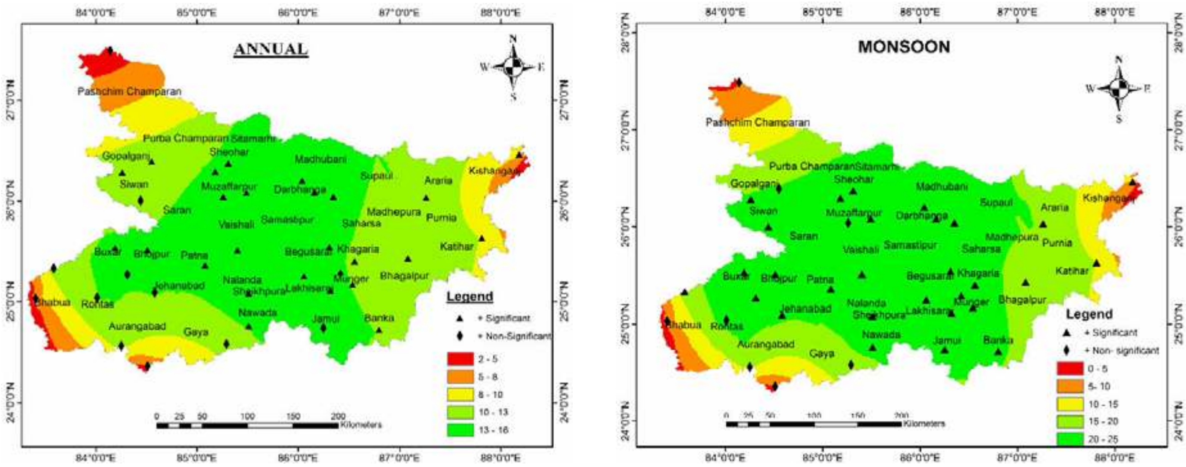


Fig. 7. Spatial distribution of annual and monsoon rainfall in terms of percentage change from 1901 to 1956; source: own study

Trends from 1901 to 1956

Spatial variation of annual and monsoon rainfall in terms of percent change before the change point (1901–1956) is depicted in Figure 7. Triangles and diamonds represent positive significant and positive non-significant trends, respectively, for each station in the study area. The change in annual and monsoon rainfall is similar across the study region. Z values vary from 1.19 to 2.79, from 1.55 to 2.79, from –1.44 to 0.62, from –0.2 to 2.48 and from –0.08 to 1.52 for annual, monsoon, pre-monsoon, post-monsoon and winter, respectively (Tab. 4). Most of the stations (25 and 29 stations in annual and monsoon periods, respectively) were positive significant and some (11 and 8 stations in annual and monsoon periods, respectively) were positive non-significant. The range in percent change of rainfall was 2% to 16% and 0% to 25% for annual and monsoon rainfall, respectively. The central part of Bihar had the highest percentage change, 13% to 16% for annual rainfall and 20% to 25% for monsoon rainfall. The lowest change was noticed at Paschim Champaran, Kishanganj and Bhabua (2% to 5% and 0% to 5% for annual and monsoon rainfall, respectively). The annual and monsoon rainfall of Bihar state significantly increased before the change point of 1956.

Trends from 1957 to 2002

The results of the time series 1957–2002 portrayed the opposite rainfall scenario to the 1901–1956 period, although it is similar to the entire time series, 1901–2002. Spatial variation of annual and monsoon rainfall in terms of mean percentage change is shown in Figure 8. Stars and pentagons represent the negative significant and negative non-significant trends, respectively, for each station. Most of the stations (29 and 33 stations in annual and monsoon, respectively) were negative significant and a few (8 and 4 stations in annual and monsoon, respectively) were negative non-significant. In the other series (1901–2002 and 1901–1956) there was no significant trend in the pre-monsoon season, but in the latest period (1957–2002) the rainfall changed drastically with 14 stations having significant increasing trends in Bihar. Z values varied from –3.14 to –0.13, from –3.58 to –0.42, from 0.04 to 2.45, from –2.41 to 1.53 and from –0.8 to 1.7 for annual, monsoon, pre-monsoon, post-monsoon and winter, respectively (Tab. 5). The rate of decline was highest (Gopalganj) in the western part of the state and lowest (Kishanganj) in the eastern part (for 1957–2002). The percent change of rainfall decline was from –31% to –1% and from –40% to –5% for annual and monsoon rainfall, respectively. There was

Table 4. Mann–Kendall *Z* values (direction) and change percentage (1901–1956)

Station No.	Stations	Annual		Monsoon		Pre-monsoon		Post-monsoon		Winter	
		Z value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %
1	Araria	**2.51**	12.67	**2.45**	14.71	–0.93	–18.30	1.38	28.72	0.84	21.80
2	Aurangabad	1.44	13.57	1.75	15.76	0.06	0.63	0.76	15.23	0.40	10.70
3	Banka	**2.07**	13.63	**2.27**	15.00	–0.16	–5.57	1.73	45.59	0.12	4.72
4	Begusarai	**2.64**	16.19	**2.75**	17.45	–0.18	–4.48	1.46	41.85	0.62	17.78
5	Bhagalpur	**2.79**	13.21	**2.48**	16.09	–0.53	–8.68	**2.48**	39.26	0.83	39.26
6	Bojpur	1.79	13.22	**2.11**	15.64	–0.08	–1.16	0.82	19.75	0.80	24.78
7	Buxar	1.94	13.28	**2.21**	15.50	–0.23	–8.59	–0.20	–0.07	1.00	27.27
8	Darbhanga	**2.57**	15.31	**2.65**	18.41	–0.29	–6.53	1.17	30.68	1.10	35.96
9	Gaya	1.52	13.58	1.60	14.81	0.09	5.02	0.87	24.21	0.12	4.50
10	Gopalganj	**2.17**	12.60	**2.14**	15.72	–0.57	–10.30	0.56	12.00	1.51	40.30
11	Jamui	1.93	14.35	**2.04**	14.26	–0.08	–2.10	0.11	46.73	–0.08	46.73
12	Jehanabad	1.87	14.04	**2.09**	15.26	0.13	5.10	0.94	24.19	0.59	13.12
13	Bhabua	1.90	14.80	1.94	18.40	–0.18	–5.14	0.42	8.65	0.95	22.44
14	Katihar	**2.20**	11.36	**2.52**	13.14	–0.54	–11.00	1.46	33.33	0.67	20.02
15	Khagaria	**2.68**	14.52	**2.72**	16.15	–0.30	–6.89	1.52	40.92	0.88	22.61
16	Kishanganj	**2.40**	11.68	**2.54**	15.29	–0.76	–14.98	1.44	23.27	0.70	16.84
17	Lakhisarai	**2.37**	15.28	**2.57**	17.29	–0.18	–3.61	1.62	44.94	0.43	12.12
18	Madhepura	**2.66**	14.09	**2.74**	16.07	–0.59	–13.37	1.45	37.26	0.95	37.26
19	Madhubani	**2.38**	15.24	**2.45**	17.71	–0.45	–10.89	1.14	30.95	1.22	37.90
20	Munger	**2.45**	15.27	**2.65**	17.00	–0.23	–3.86	1.55	41.79	0.76	20.90
21	Muzafferpur	**2.34**	15.00	1.55	16.82	–0.08	–1.39	1.00	29.37	1.14	38.81
22	Nalanda	**2.04**	13.98	**2.10**	15.18	–0.09	–5.16	0.86	30.19	0.45	10.96
23	Nawada	1.73	11.91	1.86	14.91	–0.04	–1.71	1.27	39.58	–0.02	–1.06
24	Paschim Champaran	1.19	5.79	1.82	12.22	–1.44	–26.23	0.28	8.73	1.11	33.13
25	Patna	**2.00**	14.07	**2.17**	15.69	0.62	–0.38	0.90	27.31	0.62	16.79
26	Purba Champaran	**1.97**	12.25	1.93	14.78	–0.60	–10.61	0.69	15.66	1.28	40.60
27	Purnia	**2.26**	12.15	**2.52**	13.39	–0.63	–13.63	1.44	31.60	0.71	18.75
28	Rohtas	1.63	14.08	1.89	17.34	–0.21	–5.27	0.72	16.36	0.71	20.14
29	Saharsa	**2.71**	15.88	**2.79**	16.45	–0.47	–10.36	1.46	38.17	0.97	28.48
30	Samastipur	**2.56**	17.29	**2.76**	17.75	–0.12	–3.46	1.22	33.22	0.73	20.32
31	Saran	**2.06**	13.86	**2.37**	15.93	–0.11	–3.32	0.94	19.44	0.98	36.42
32	Sheikhpura	**2.21**	15.31	**2.41**	16.21	–0.16	–3.11	1.15	40.32	0.39	12.23
33	Sheohar	**2.24**	13.82	**2.10**	16.27	–0.29	–4.93	0.97	28.29	1.22	36.41
34	Sitamarhi	**2.24**	13.80	**2.76**	16.88	–0.42	–6.32	1.03	27.69	1.12	41.08
35	Siwan	**2.30**	14.43	**2.21**	17.43	–0.21	–7.05	0.66	14.00	1.52	39.93
36	Supaul	**2.48**	14.51	**2.55**	15.99	–0.81	–15.35	1.31	29.22	0.94	25.69
37	Vaishali	1.85	12.85	**2.27**	15.92	0.11	1.85	0.98	27.97	0.62	25.07

<–15% | 0–(–15%) | 0–15 | >15%

Explanation: bold values indicate significant trend.
Source: own study.

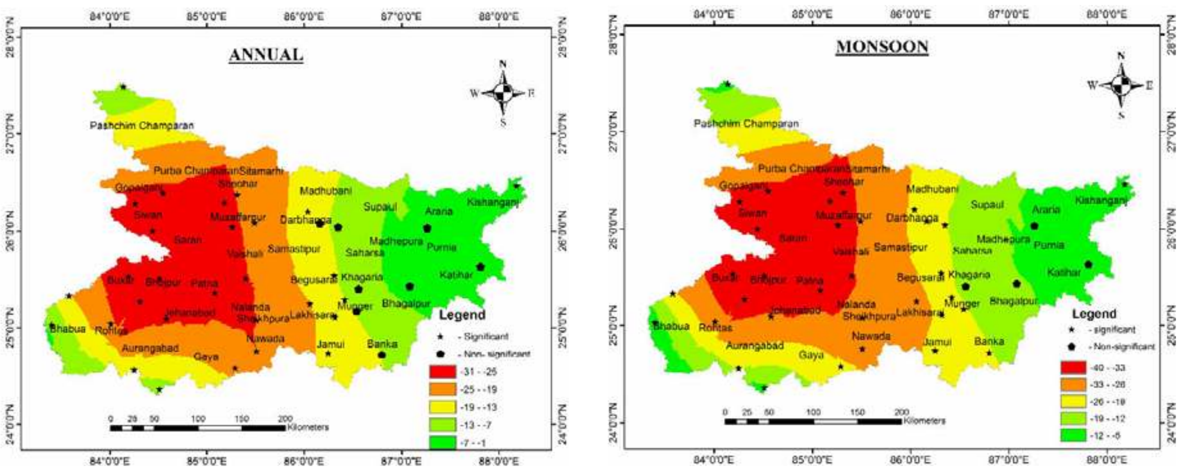


Fig. 8. Spatial distribution of annual and monsoon rainfall in terms of percent change from 1957 to 2002; source: own study

Table 5. Mann–Kendall *Z* values (direction) and change percentage (1957–2002)

Station No.	Stations	Annual		Monsoon		Pre-monsoon		Post-monsoon		Winter	
		Z value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %	*Z* value	change %
1	Araria	–0.45	–4.24	–1.17	–11.83	**2.56**	55.44	–0.05	–0.80	1.53	55.58
2	Aurangabad	**–2.39**	–30.37	**–2.42**	–34.32	0.51	18.11	0.27	12.90	0.13	3.51
3	Banka	–1.57	–16.76	**–2.46**	–22.57	1.52	41.57	0.08	1.57	0.02	0.74
4	Begusarai	**–2.41**	–23.63	**–2.94**	–32.61	1.82	47.40	–0.02	–1.02	–0.15	–5.07
5	Bhagalpur	–0.30	–16.41	**–2.41**	–22.63	1.59	39.49	**–2.41**	1.68	0.64	1.68
6	Bojpur	**–3.09**	–30.35	**–3.22**	–37.22	0.97	35.27	0.31	11.46	0.17	4.48
7	Buxar	**–3.07**	–31.58	**–3.20**	–40.28	0.70	27.35	0.47	3.19	0.13	5.69
8	Darbhanga	**–2.52**	–24.03	**–3.24**	–32.85	**2.63**	72.82	0.00	–0.30	–0.49	–13.85
9	Gaya	**–2.29**	–28.40	**–2.35**	–30.89	0.78	21.30	0.17	8.69	0.06	0.74
10	Gopalganj	**–2.90**	–32.25	**–3.22**	–39.73	1.33	36.99	0.34	16.50	–0.38	–11.11
11	Jamui	**–2.12**	–18.94	**–2.59**	–25.61	1.48	38.10	1.53	4.73	–0.34	4.73
12	Jehanabad	**–2.80**	–28.69	**–2.95**	–34.93	0.87	30.71	0.21	7.86	0.21	7.47
13	Bhabua	**–2.44**	–30.60	**–2.67**	–35.10	0.17	6.18	0.39	17.30	0.47	9.55
14	Katihar	–0.68	–5.00	–1.69	–13.64	**2.16**	44.82	0.19	4.62	1.70	52.88
15	Khagaria	**–2.03**	–19.87	**–3.09**	–29.87	1.91	44.67	0.00	–0.02	–0.13	–2.70
16	Kishanganj	–0.13	2.00	–0.42	–4.99	**2.61**	54.92	0.13	4.62	1.69	63.16
17	Lakhisarai	**–2.58**	–24.62	**–2.84**	–31.71	1.53	43.77	0.17	5.69	–0.27	–5.80
18	Madhepura	–1.78	–16.55	**–2.65**	–23.31	**2.05**	48.61	0.08	2.34	0.61	2.34
19	Madhubani	**–2.06**	–20.54	**–2.77**	–27.77	**2.75**	75.85	–0.08	–2.68	–0.27	–11.77
20	Munger	**–2.16**	–23.52	**–2.86**	–29.77	1.61	40.34	0.17	3.67	–0.19	–7.43
21	Muzafferpur	**–2.94**	–28.57	**–3.18**	–37.93	**2.39**	61.71	0.21	11.03	–0.70	–28.41
22	Nalanda	**–2.50**	–28.51	**–2.82**	–32.68	1.21	35.20	–0.02	–0.33	0.10	2.09
23	Nawada	**–2.16**	–25.52	**–2.56**	–29.81	1.02	32.24	0.10	4.05	–0.10	–3.74
24	Paschim Champaran	**–2.65**	–26.61	**–3.18**	–31.67	1.89	44.04	0.34	10.38	0.30	9.83
25	Patna	**–2.78**	–28.81	**–3.11**	–35.04	0.04	40.89	0.11	5.44	0.04	2.06
26	Purba Champaran	**–2.61**	–28.88	**–2.94**	–36.17	**2.21**	50.39	0.55	16.08	–0.78	–23.27
27	Purnia	–0.76	–6.65	–1.82	–14.94	**2.21**	48.50	–0.02	–0.48	1.53	52.36
28	Rohtas	**–2.42**	–29.34	**–2.65**	–33.77	0.30	11.32	0.33	15.59	0.44	11.76
29	Saharsa	**–2.01**	–19.66	**–2.90**	–27.88	**2.05**	46.62	0.00	0.49	0.15	6.84
30	Samastipur	**–2.56**	–27.03	**–3.37**	–33.43	**2.14**	58.31	–0.19	–8.00	–0.32	–10.15
31	Saran	**–3.64**	–32.11	**–3.58**	–39.66	1.63	46.52	0.28	19.84	–0.06	–2.83
32	Sheikhpura	**–2.63**	–26.92	**–2.69**	–31.56	1.27	35.85	–0.08	–4.15	–0.02	–0.77
33	Sheohar	**–2.82**	–29.64	**–3.01**	–36.44	**2.33**	59.38	0.34	14.70	–0.80	–27.10
34	Sitamarhi	**–2.56**	–25.82	**–3.37**	–34.64	**2.73**	69.94	0.30	13.05	–0.72	–29.88
35	Siwan	**–3.24**	–31.92	**–3.26**	–40.91	1.27	39.09	0.46	14.36	–0.42	–13.89
36	Supaul	–1.21	–12.87	**–2.23**	–21.19	**2.52**	61.26	0.02	0.78	0.81	31.13
37	Vaishali	**–3.11**	–29.59	**–3.43**	–37.53	1.91	53.74	0.15	7.22	0.02	0.27

<–15% 0–(–15%) 0–15 >15%

Explanation: bold values indicate significant trend.
Source: own study.

a large and significant decrease in percent change of monsoon rainfall (from –40% to –33%) observed at Sheohar, Muzafferpur, Vaishali, Patna, Bhojpur, Bhabua, Saran, Siwan and Gopalganj in the western part of Bihar.

The present study indicated that there was a significant rainfall reduction observed over the entire study area from 1957 to 2002 during the monsoon season. On other hand, the post monsoon rainfall increased significantly at some stations. The increase in rainfall during the post monsoon may reduce the irrigation requirements in rabi season, but kharif crops may need supplemental water during the monsoon season. This changing pattern of precipitation may influence future water availability especially for agricultural purposes. The economy of the study area is highly dependent on agriculture (monsoon rainfall dependent) and these results may be very useful for water management and sustainable development. Similar to our study, an increasing trend in precipitation in the state of Jharakhand, to the South of Bihar, was found during 1901–1949; this was reversed during the subsequent period (1950–2011) [CHANDNIHA *et al.* 2016].

EXTREME EVENTS

The number of extreme rainfall events was calculated and different years were categorized on the basis of extreme events (greater than +10% and –10%) in annual and monsoon rainfall. The extreme events were calculated by taking the difference between average rainfall and actual rainfall and then dividing the difference with the average rainfall. The average rain-

Table 6. Extreme events during different time zones

Year	1901–2002		1901–1956 and 1957–2002		Year	1901–2002		1901–1956 and 1957–2002	
	annual %	monsoon %	annual %	monsoon %		annual %	monsoon %	annual %	monsoon %
1901	–18.62	–18.54	–22.82	–23.50	1952	2.90	6.78	10.20	15.93
1902	–5.96	4.07	–10.82	–2.26	1953	8.16	18.41	15.84	28.55
1903	–17.69	–22.30	–21.94	–27.03	1954	–4.00	2.48	2.81	11.26
1904	3.09	–6.24	–2.23	–11.95	1955	–0.56	1.61	6.50	10.32
1905	10.84	16.94	5.11	9.82	1956	25.50	19.04	34.41	29.24
1905	4.94	–0.04	–0.48	–6.13	1957	–20.91	–13.97	–15.30	–6.60
1907	–9.51	–9.26	–14.18	–14.78	1958	5.25	2.20	12.72	10.96
1908	–16.08	–17.00	–20.41	–22.05	1959	11.12	0.74	19.01	9.38
1909	6.66	16.76	1.15	9.65	1960	–11.45	–3.91	–5.17	4.33
1910	5.10	9.20	–0.33	2.55	1961	–0.06	0.36	7.04	8.96
1911	13.87	13.64	7.99	6.73	1962	–7.74	–0.46	–1.20	8.06
1912	–18.24	–15.64	–22.46	–20.78	1963	10.02	0.46	17.83	9.07
1913	16.70	14.08	10.67	7.13	1964	–0.77	6.77	6.27	15.92
1914	–9.86	–10.10	–14.52	–15.57	1965	–28.27	–26.11	–23.17	–19.77
1915	0.80	–0.36	–4.40	–6.42	1966	–39.90	–40.19	–35.64	–35.07
1916	12.85	9.71	7.02	3.03	1967	–10.25	–4.23	–3.88	3.97
1917	19.07	6.04	12.92	–0.42	1968	–6.70	–6.68	–0.07	1.32
1918	–3.01	7.13	–8.02	0.61	1969	0.76	4.72	7.91	13.69
1919	13.71	7.82	7.84	1.26	1970	9.74	14.36	17.53	24.16
1920	–0.50	5.48	–5.63	–0.94	1971	31.46	26.60	40.79	37.45
1921	–3.29	5.94	–8.28	–0.51	1972	–15.83	–26.63	–9.86	–20.34
1922	34.33	46.45	27.39	37.54	1973	24.20	11.93	33.02	21.53
1923	–2.20	3.48	–7.25	–2.82	1974	3.31	6.21	10.65	15.31
1924	6.52	5.82	1.02	–0.62	1975	–5.17	–5.69	1.56	2.39
1925	4.01	10.62	–1.36	3.88	1976	–5.13	1.80	1.60	10.52
1926	9.06	5.94	3.43	–0.51	1977	5.23	–4.78	12.70	3.38
1927	–2.98	–8.41	–7.99	–13.99	1978	15.97	9.17	24.20	18.53
1928	9.42	3.03	3.77	–3.24	1979	–8.70	–10.94	–2.22	–3.31
1929	7.10	–8.57	1.57	–14.14	1980	–5.47	–0.05	1.24	8.51
1930	–16.75	–14.97	–21.05	–20.14	1981	–13.20	–10.85	–7.04	–3.22
1931	19.76	24.66	13.58	17.07	1982	–12.48	–14.85	–6.27	–7.56
1932	–8.98	–8.45	–13.68	–14.03	1983	–2.13	–8.58	4.82	–0.75
1933	16.45	16.02	10.44	8.95	1984	22.19	29.82	30.86	40.94
1934	9.84	14.46	4.17	7.49	1985	–9.93	–9.92	–3.54	–2.21
1935	2.99	13.92	–2.33	6.98	1986	–5.81	–4.35	0.87	3.85
1936	32.89	30.25	26.02	22.32	1987	34.82	34.61	44.39	46.14
1937	–1.22	–7.97	–6.32	–13.57	1988	–7.44	–6.76	–0.88	1.23
1938	8.36	12.27	2.77	5.44	1989	–1.92	–1.98	5.04	6.42
1939	9.49	14.72	3.84	7.74	1990	1.92	–1.99	9.15	6.41
1940	2.66	5.34	–2.64	–1.08	1991	–8.63	–4.98	–2.14	3.16
1941	2.26	5.33	–3.02	–1.09	1992	–37.96	–38.77	–33.56	–33.53
1942	16.41	24.50	10.40	16.92	1993	–26.80	–29.83	–21.60	–23.81
1943	18.48	21.94	12.36	14.52	1994	–15.17	–25.26	–9.15	–18.86
1944	8.38	5.54	2.78	–0.89	1995	–25.74	–25.08	–20.47	–18.66
1945	–0.30	–10.74	–5.45	–16.18	1996	–15.99	–22.48	–10.03	–15.84
1946	23.42	22.03	17.05	14.60	1997	–16.34	–23.71	–10.41	–17.17
1947	7.00	11.56	1.47	4.76	1998	–11.04	–29.09	–4.73	–23.02
1948	12.53	12.62	6.72	5.76	1999	–18.30	–16.69	–12.50	–9.55
1949	28.94	26.78	22.28	19.06	2000	–34.50	–30.47	–29.86	–24.51
1950	–1.20	5.32	–6.31	–1.09	2001	–30.04	–35.60	–25.07	–30.08
1951	11.37	13.87	5.62	6.94	2002	–21.07	–27.88	–15.46	–21.70

(light grey)	<-10%
(dark grey)	>+10%

Note: different colours show different periods.
Source: own study.

fall was the average of 102 years (1901–2002), 56 years (1901–1956) and 46 years (1957–2002). Years with extreme rainfall events of more than 10% (positive) from 1901 to 2002 are 1901, 1903, 1908, 1912, 1930, 1957, 1960; 1965–1967, 1972, 1981, 1982 and 1992–2002. Overall, 26 out of 102 years experienced an extreme annual event of negative rainfall, i.e., more than a 10% decrease while 24 years experienced an extreme positive event of rainfall of more than 10% change. During the earlier period (1901–1956), only 5 years of negative extreme events were observed compared to 17 years of positive extreme events annually. In the most recent period (1957–2002), 19 years out of 46 had negative extreme events and there were no positive extreme events noticed annually (Tab. 6). The period of 10 years from 1992–2002 was the negative extreme events which reflected the significant reduction of rainfall in recent years. This study indicated that the frequency of negative extreme events was greater in the latest period (1957–2002) compared to the earlier period. Based on the present study, Bihar is likely to become a drought prone area; there were more negative extreme events over the entire period as well as the latest period (1992–2002) having a continuous 10 years of rainfall reduction. Uncertain and erratic distribution of precipitation as well as a lack of state water resources planning is the major limitation to crop growth in the region.

In this study, annual and monsoon rainfall showed significant variability and rainfall decline was most prominent in the recent 10-year period. These results conform with those of KRISHNAKUMAR *et al.* [2009], KUMAR, JAIN [2011], DUHAN, PANDEY [2013], PRANUTHI *et al*. [2014] and JAIN *et al.* [2017]. Rainfall of summer seasons showed insignificant increasing trends [KRISHNAKUMAR *et al.* 2009]. In the study area, all the important irrigation practices are based on monsoon rainfall; based on our study monsoon trends have high variability, which will have effects on irrigation. It can be seen how trend and change point detection techniques are very useful for irrigation as well as water resources planning in this area.

CONCLUSIONS

The present study involved the observation of seasonal and annual precipitation trends at 37 weather stations in the state of Bihar, India from 1901 to 2002. The study showed decreasing rainfall trends at all 37 stations in annual and monsoon periods. Annually, the magnitude of the trend varied from –2.69 mm·year^{-1} in Paschim Champaran to –1.45 mm·year^{-1} in Bhabua. During the monsoon season, a negative significant trend was obtained at all the stations with the largest declines at Paschim Champaran (–2.62 mm·year^{-1}) and the smallest at Bhabua (–1.34 mm·year^{-1}). Seasonal trends indicated a non-significant rise in pre-monsoon rainfall with a maximum magnitude at Kishanganj (0.160 mm·year^{-1}) and a minimum magnitude at Aurangabad (0.005 mm·year^{-1}). During the post-monsoon season, most of the stations showed positive non-significant trends but some showed negative non-significant trends. The magnitude of the trend varied from a maximum at Jamui (0.277 mm·year^{-1}) to a minimum at Paschim Champaran (–0.15 mm·year^{-1}). The winter season also did not exhibit any significant increasing or decreasing trends and a non-significant mixed trend was observed. Overall, a declining trend in rainfall magnitude was found over Bihar from 1901 to 2002.

The most probable year of change in the observed rainfall trends was 1956. The trend from 1901 to 1956 showed increasing rainfall in Bihar while from 1957 to 2002 the trend was negative. The numbers of extreme negative rainfall events have increased in frequency during the last 46 years and this resulted in the overall 102-year negative rainfall trend. The resultant annual decrease is about –23.32% from 1957 to 2002 and –18.92% from 1901 to 2002 in Bihar. The impact of monsoon rainfall is found to be dominant over the average annual rainfall. The average monsoon rainfall declined up to –21.84% from 1901–2002, and up to –0.18% from 1957–2002. The declining trend in the latest decade has changed the overall scenario of rainfall in the study area and this rainfall variability may impact future climatic conditions and agricultural practices. Analyses of the precipitation data should be useful for irrigation and agricultural managers and could play an important role in managing water resources more effectively and sustainably in the state.

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**Pratibha WARWADE, Shalini TIWARI, Sunil RANJAN,
Surendra K. CHANDNIHA, Jan ADAMOWSKI**

Przestrzenna i czasowa zmienność opadów w stanie Bihar w Indiach

STRESZCZENIE

W badaniach prezentowanych w niniejszej pracy wykryto po raz pierwszy długookresowe trendy rocznych i sezonowych wartości opadów w indyjskim stanie Bihar w latach 1901–2002. Stosując kumulatywny test odchyleń (CUSUM – ang. cumulative deviation test) i regresję liniową zidentyfikowano punkt zwrotny. Następnie serie czasowe zostały podzielone na dwie grupy: przed i po punkcie zwrotnym. Do oceny przestrzennego rozkładu trendów zastosowano program Arc-Map 10.3. Stwierdzono, że trendy rocznych i monsunowych opadów znacząco malały. Nie zaobserwowano istotnych trendów w odniesieniu do opadów przed monsunem, po monsunie i w okresie zimowym. Średnie zmniejszenie ilości opadów wynosiło 2,17 mm rok^{-1} i 2,13 mm rok^{-1} odpowiednio dla opadów rocznych i monsunowych. Prawdopodobnym punktem zwrotnym był rok 1956. Liczba skrajnych negatywnych zjawisk była większa w okresie 1957–2002 niż w okresie 1901–1956.

Słowa kluczowe: *hydrologia, opady, zmiana klimatu, zmienność w czasie i przestrzeni*