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ABSTRACT

Globally, climate change and extreme weather events are occurring more frequently, impacting water resources and farming systems. Therefore, spatio-temporal analysis of long-term rainfall is much needed to understand the variability of rainfall occurrence. The present study attempts to analyse spatio-temporal rainfall change scenarios in the 20th century (1901–2000) over Bundelkhand, one of the drought hit regions of India. Analysis shows that major rainfall contributed from 3 months, i.e. July, August and September. However, decreasing rainfall trend during monsoon season and increasing trend during pre-monsoon and post-monsoon season indicates the scenario of shifting rainfall from normal occurrence. This result is supported by decreasing seasonality index (SI) (1.94–1.1). The northern part of the region witnessed positive annual and monsoon rainfall trend but the southern part observed negative trend. Pettitt's test indicates 1983 is the most probable change year with 0.95 probability, after which annual and monsoon rainfall was found decreasing. Wavelet analysis revealed that extreme rainfall occurrence was observed with a periodicity of 2–16 years. However, Bundelkhand rainfall pattern depicts declining rainfall trends, heading towards a further drier phase with more irregular rainfall in the coming era. The study will serve as future reference in similar regions in the world to determine vital weather patterns which may impact farming systems.

Key words | 20th century, PCE, Pettitt's test, rainfall analysis, SI, wavelet analysis

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INTRODUCTION

The impact of climate change plays a pivotal role for future agricultural planning and crop production in the world, including India (Piao *et al.* 2010). Water resources have decreased in many regions across the world due to global climate change which is more alarming in arid, semi-arid as well as fragile ecological regions. In the climate change scenario, drought and flood are the main two problems faced by Indian agriculture. Climate of a particular region is the driving force for selection of farm enterprises and determining the potential productivity. In particular, moisture regime is one of the most important factors which influences farm management practice and extent of risk involved. Out of 140 million hectares, approximately 68% of the net sown area of India is prone to drought (Gupta *et al.* 2014; Alam *et al.* 2015a, 2015b). In India, 103 districts and 16 states out of a total of 688 districts and 29 states are chronically drought prone (Gupta *et al.* 2014). It is also reported that around 33% of the cropped area receives less than 750 mm of rainfall annually which are defined as 'hotspots' of the drought region. One such hotspot which has been in the national as well as international news for its dire socio-economic condition is the geographical heartland of India, the Bundelkhand region. Since crop production, livestock rearing and seasonal out-migration provide more than 90% of the rural income in Bundelkhand

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region (Samra 2008), the effect of recurrent drought on this region is palpably devastating.

The impact of climate change is evidently visible in Bundelkhand region in India which experiences at least one severe drought years in every eight years (Alam *et al.* 2012, 2014). The food grain production in the Bundelkhand districts has decreased by 58%, which is very serious for the agriculture-based society and economy. Failure in agriculture has become a cyclical phenomenon (Jain 2009) and very poor productivity in the Bundelkhand region (1.4 times lower than other parts of central India) has been reported (Khan *et al.* 2012). Being vulnerable to climate change, semiarid and prone to drought, Bundelkhand is one of the least socio-economically developed regions in India. Increasing demands on natural resources and harsh and worsening bio-physical conditions, combined with more frequent drought caused by climate change, further exacerbate the region's vulnerability. The report on Bundelkhand – *kalahandi* of Central India (2009) in a Right to Information Act in 2006 reply stated that 1,275 farmers had committed suicide in the region between 2001 and 2005 due to uncertain rainfall in the recent two to three decades.

Temperature is not the limiting factor in Bundelkhand region for crop growth and development; rather water is the main limiting factor for crop productivity (Alam *et al.* 2016). In this region, rainfall is the primary source of water and warrants the main consideration for crop production, but this is the most variable among all the meteorological parameters. Moreover, droughts are being experienced almost on a regular basis because of abnormal and scanty rainfall. The amount, onset, intensity, duration and spatial variability of rainfall occurrence decides the agricultural management practised in the region. As the soil moisture plays the paramount role, better understanding on seasonal and annual rainfall trends could provide robust technical information for improving land and water management and enhance crop productivity in the face of climate change.

In hydrology as well as in climatological studies trend analysis plays an important role, and has become predominantly imperative in the climate change scenario (Karpouzos *et al.* 2010). Therefore, detailed analysis of spatial and temporal distribution of rainfall patterns on a regional scale will provide prerequisite parameters for judicious planning and preparedness for climate resilient agriculture. In the present study, attempts have been made to analyse rainfall data of the 20th century (1901–2000) from 13 districts of Bundelkhand region to evaluate the spatio-temporal rainfall change scenarios over the last centuries. The findings of this study could serve as a baseline reference for future research, watershed management, planning and also enrich the understanding of precipitation features of Bundelkhand region in India as well as for other similar regions in the world.

MATERIALS AND METHODS

Study area

The Bundelkhand region (Figure 1) is located between 23°20′ and 26°20′ N latitude and 78°20′ and 81°40′ E longitude. It lies between the Indo-Gangetic Plain to the north and the Vindhya Range to the south. It is a gently sloping upland along with barren hilly terrain with sparse vegetation.

The agriculture of the region mainly depends on the rainfall as most of the cropped land is under rain-fed conditions with limited irrigation facilities. The annual rainfall varies from 438.4 to 1,334.2 mm across the region with an average value of 834.2 mm. Intermittent and continuous dry spells are a common phenomenon in this region. The region has 13 districts; seven in the state of Uttar Pradesh (UP): Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda and Chitrakut; and six in the state of Madhya Pradesh (MP): Datia, Tikamgarh, Chattarpur, Damoh, Sagar and Panna. It covers an area of 7.08 million hectares (mha).

Rainfall data

Monthly rainfall data (mm) of 13 districts of Bundelkhand region were collected from the Indian Institute of Tropical Meteorology (IITM) for the period 1901–2000 'Homogeneous Indian Monthly Rainfall Data Sets'. The data from IITM are the most authentic source of meteorological data in India. For evaluating seasonal rainfall pattern, the entire year is divided into four seasons: summer

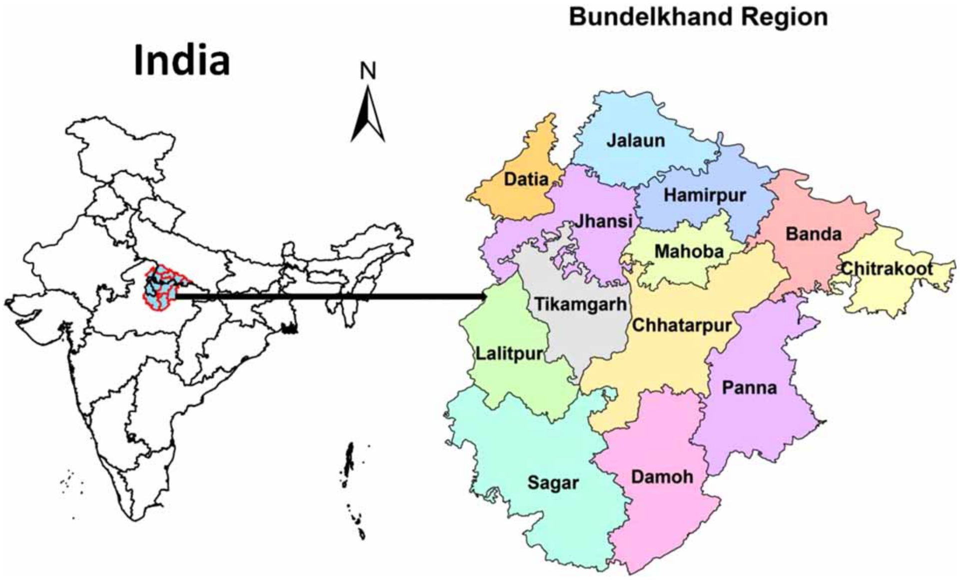

Figure 1 | Location of Bundelkhand region.

(March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February). Various statistical analyses were carried out to analyse and assess the temporal trend in the rainfall time series.

Trend analysis

In the present study Mann–Kendall trend test (MK test) (Mann 1945; Kendall 1975) was applied to detect the existing trend in annual and seasonal rainfall. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. Most of the previous trend analyses of hydrologic data have been performed using this technique (Hirsch & Slack 1984; Gan 1998). The MK test is recommended by the World Meteorological Organization and has been widely used to test for trends in hydrological and meteorological data, including precipitation, temperature and runoff (Li *et al.* 2008; Zang & Liu 2013). To know the magnitude of slope of trend Theil–Sen estimator, the Sen's slope (Sen 1968) has been used. This non-parametric method is used to estimate the magnitude of an existing trend, which is expressed as the rate of change per year. The Sen's slope estimator can be used to estimate this rate when the trend can be demonstrated to be linear (Zang & Liu 2013). Jana *et al.* (2016) has also analysed the trends of rainfall and rainy days of Agra district in India using MK test and Sen's slope.

Change-point analysis

A non-parametric approach developed by Pettitt (1979) was used to detect change-points in rainfall time-series. It is a rank based and distribution free test for detecting a significant change in the mean of a time series and it is particularly useful when no hypothesis required to be made about the location of the change point. The Pettitt test has been widely applied to detect changes in the observed climatic as well as observed hydrological time series (Verstraeten *et al.* 2006; Mu *et al.* 2007; Zhang & Lu 2009; Gao *et al.* 2010; Salarijazi *et al.* 2012).

Continuous wavelet transform

For a time series, x_t, that has a continuous scale but a discrete recording sequence and $t = 0,\ldots,\ t-1$, then the wavelet function (Ψ), which depends on a time variable (η), is generally defined as (Partal & Küçük 2006):

$$\Psi(\eta) = \Psi(\mathrm{s}, \gamma) = \frac{1}{\sqrt{s}}\Psi\left(\frac{t-\gamma}{s}\right) \tag{1}$$

where t represents time; variable γ is the translation factor (time shift) of the wavelet over the time series; and variable s ranging from 0 to $+\infty$ denotes the wavelet scale (scale factor). When $\gamma = 0$ and $s = 1$, $\Psi(t)$ represents the mother wavelet – all wavelets following this computation are the rescaled (translated and dilated) versions of the mother wavelet. In order to be acceptable as a wavelet, the function $\Psi(\eta)$ has to satisfy the condition of having zero mean (implying the existence of oscillations) and be localized in time–frequency space (Torrence & Compo 1998). As can be seen in Equation (1), when s is less than 1, $\Psi(\eta)$ corresponds to a high-frequency function; when s is greater than 1, $\Psi(\eta)$ corresponds to a low-frequency function.

The wavelet coefficients ($W\Psi$) of continuous wavelet transform (CWT) for the time series x_t (with equal time interval, δt), is calculated using the convolution of x_t with the scaled and translated versions of the wavelet, $\Psi(\eta)$ (Partal & Küçük 2006):

$$W_{\Psi}(s, \gamma) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \Psi^{*}\left(\frac{t-\gamma}{s}\right) \delta t \tag{2}$$

where the asterisk symbol represents the complex conjugate numbers. If the scale (s) and translation (γ) functions are smoothly changed according to time t, a scalogram can be produced from the calculation, revealing the amplitude of a specific scale and how it fluctuates over time (Torrence & Compo 1998).

Precipitation concentration index

The precipitation concentration index (PCI) (Oliver 1980), an indicator of rainfall concentration (de Luis *et al.* 2000, 2011), was calculated on annual scales to evaluate the pattern of rainfall distribution in a year.

$$PCI_{annual} = \frac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i\right)^2} \times 100 \tag{3}$$

where p_i is the monthly rainfall for month $_i$. The lowest theoretical value of PCI is 8.3, implying a perfect uniformity in rainfall distribution (i.e. the same amount of rainfall occurs in each month), while a PCI value of 16.7 indicates that the total rainfall is concentrated in half of the period and a PCI value of 25 demonstrates that the total rainfall occurred in one-third of the period (de Luis *et al.* 2011).

Seasonality index

Seasonality index (SI) is also used to quantify the degree of variability in monthly rainfall regimes based on the monthly distribution (Walsh & Lawer 1981; Guhathakurta & Saji 2013; Nair *et al.* 2014). The SI is calculated as:

$$SI = \frac{1}{R} \sum_{i=1}^{12} \left| X_n - \frac{\bar{R}}{12} \right| \tag{4}$$

where X_n is the mean rainfall of month n and $\bar{R}$ is the mean annual rainfall. Theoretically, the SI can vary from zero (if all the months have equal rainfall) to 1.83 (if all the rainfall occurs in 1 month). According to Kanellopoulou (2002), the SI can be classified according to characteristic rainfall regimes as (i) seasonal (SI = 0.60–0.79), (ii) markedly seasonal with a long drier season (SI = 0.80–0.99), (iii) most rain in 3 months or less (SI = 1.00–1.19) and (iv) extreme with all rain in 1–2 months (SI $\geq$ 1.20).

RESULTS AND DISCUSSION

Spatial rainfall distribution

Results pertaining to spatial rainfall analysis indicate that Bundelkhand region receives annual rainfall with a range of about 627–1,589 mm with an average value of 1,091 mm rainfall (Table 1). Out of 13 districts, five districts (Chhatarpur, Damoh, Panna, Sagar and Jalaun) show higher mean annual rainfall with more than 1,100 mm over the last 100 years. However, Sagar district witnessed the highest maximum rainfall of 1,988 mm with 24.25% variation, whereas Datia received the lowest minimum rainfall (401 mm). Figure 2 depicts the spatial distribution of pre-monsoon, monsoon, post-monsoon and winter rainfall over Bundelkhand region. It shows that the

Table 1 | Area coverage of Bundelkhand region, extreme rainfall events, annual mean and coefficients of variations (CV)

Districts	Area (km^2)	% TGA	Minimum rainfall (mm)	Maximum rainfall (mm)	Mean rainfall (mm)	CV%
Banda	4,413	5.99	502.03	1,580.17	1,073.36	22.11
Chhatarpur	8,687	11.79	643.64	1,682.10	1,142.03	21.21
Chitrakoot	3,216	4.36	472.43	1,708.83	1,088.21	23.33
Damoh	7,306	9.92	614.58	1,847.64	1,199.58	20.37
Datia	2,902	3.94	401.91	1,436.35	926.15	23.64
Hamirpur	4,121	5.59	516.77	1,382.90	992.29	21.40
Jhansi	5,024	6.82	467.47	1,498.63	989.55	22.19
Lalitpur	5,039	6.84	525.81	1,790.10	1,095.30	23.62
Mahoba	2,884	3.91	579.39	1,518.61	1,066.48	20.93
Panna	7,135	9.68	617.58	1,695.84	1,187.73	20.20
Sagar	10,252	13.91	597.40	1,988.11	1,190.64	24.25
Jalaun	4,565	6.45	440.17	1,276.244	902.08	22.41
Tikamgarh	5,200	7.06	521.27	1,685.28	1,078.29	22.44
Whole region	73,681	100.00	627.04	1,588.99	1,091.44	20.26

TGA, Total geographical area.

pre-monsoon and winter rainfall is higher in the eastern region and decreasing towards the western side. However, the northern side receives more rainfall than the southern side in these seasons. In the case of post-monsoon rainfall, the southern side observed more rainfall than the north. The monsoon rainfall pattern indicates that the south-east and north-west parts are the least rainfall receivers during the season. In brief, the north-western part which includes Datia, Jhansi and Lalitpur, are the driest areas in the region.

Monthly and seasonal rainfall characteristics

The monthly rainfall distribution pattern indicates that July, August and September receive the higher rainfall of about 100–369 mm, whereas March, April and May witnessed less and inconsistent rainfall (Table 2). At 75% probability level, July and August receive higher rainfall, 155.44 and 202 mm rainfall respectively, against the annual rainfall of 751.67 mm. It also reveals that July and August rainfalls are the highest contributor to the annual rainfall with a contribution of 31.15 and 33.87% respectively. The seasonal rainfall analysis implies that the monsoon season receives the maximum rainfall of about 991.23 mm and is the highest contributor (90.82%) to the annual rainfall amount. During the monsoon season, rainfall occurrence follows a consistent pattern with low CV (21.42%) whereas non-monsoon seasons receive highly erratic rainfall with more than 70% variation.

Monthly trend

The non-parametric test using Sen's slope estimator was employed to assess the magnitude of trend of rainfall pattern over the study period from 1901 to 2002 (Table 3). It shows that there is a positive but insignificant trend in most of the districts during January, March, April and October. Chittorpur district experienced a positive and significant trend in rainfall amount (0.094 mm year^{-1}) during January whereas Datia (0.035 mm year^{-1}), Jhansi (0.038 mm year^{-1}) and Tikamgarh (0.041 mm year^{-1}) witnessed positive and significant rainfall trends during October at 90% confidence level. Although it shows a statistically significant trend, Daniel (1978) reported that this may have very little impact in a practical sense and vice versa. For the region as a whole, rainfall occurrence in July has significantly decreased in all the districts with an overall reduction of 0.923 mm year^{-1}. Out of 13 districts, four districts (Chattarpur, Damoh, Panna and

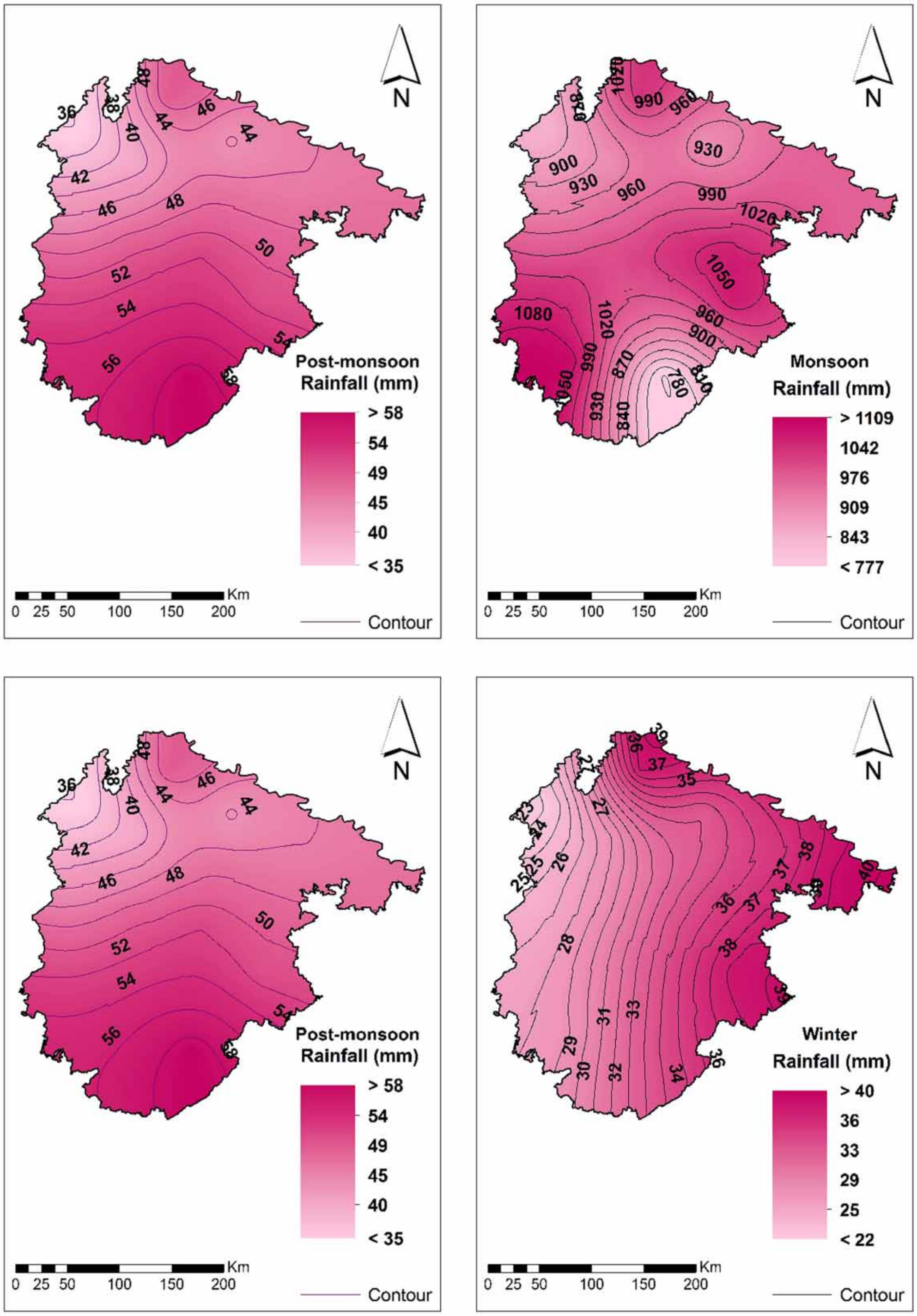

Figure 2 | Spatial distribution of average seasonal rainfall (pre-monsoon, monsoon, post-monsoon, winter) over Bundelkhand.

Tikamgarh) have experienced a rainfall reduction of more than 1 mm year^{-1} at 90% confidence level. In the month of June, although a positive trend was observed in all the studied districts, statistically significant changes at 90% confidence interval were found in two districts, Banda (0.28 mm year^{-1}) and Chittorkut (0.354 mm year^{-1}). On the other

Table 2 | Monthly and seasonal rainfall characteristics over Bundelkhand region (1901–2002)

Year	Minimum (mm)	Maximum (mm)	Mean	SD	CV%	Probability (at 75%)	Contribution to annual rainfall (%)
Jan	0.16	94.17	19.33	18.23	94.31	4.67	1.77
Feb	0.06	61.5	12.85	13.27	103.33	3.09	1.18
Mar	0	49.76	9.49	11.18	117.81	3.38	0.87
Apr	0	19.77	4.28	4.83	112.79	3.04	0.39
May	0	28.82	6.15	6.29	102.29	2.67	0.56
Jun	13.52	284.74	100.66	61.51	61.11	26.14	9.22
Jul	78.84	704.08	339.96	125.17	36.82	155.44	31.15
Aug	120.64	733.06	369.72	117.81	31.86	202	33.87
Sep	4.62	365.73	180.9	85.93	47.5	51.69	16.57
Oct	0.25	104.05	24.71	26.54	107.42	3.7	2.26
Nov	0.09	102.48	14.54	24.25	166.81	3.15	1.33
Dec	0	70.28	8.86	12.62	142.39	2.71	0.81
Annual	627.04	1,588.99	1,091.44	221.12	20.26	751.67	100.00
Monsoon	546.11	1,533.3	991.23	212.29	21.42	663.74	90.82
Pre-monsoon	0.09	72.98	19.92	14.02	70.39	4.66	1.83
Post-monsoon	0.44	164.35	48.1	36.56	76.01	9.11	4.41
Winter	0.24	102.69	32.18	22.72	70.62	7.47	2.95

hand, August and September showed relatively mixed trends at the district level but with an overall decreasing trend for the entire region. The finding is in conformity with Alam *et al.* (2016) which suggested that sowing of kharif crops has to be done during the second week of June for maximum utilization of rain water in this region.

Table 3 | Sen estimator of slope (mm year^{-1}) for monthly rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Banda	0.072	−0.005	0.000	0.002	0.021*	0.280**	−0.766	−0.604	0.076	0.032	0.000	0.000
Chattarpur	0.040	−0.007	0.001	0.000	0.027*	0.319	−1.029*	−0.113	−0.221	0.047	0.000	0.000
Chittorkut	0.094**	−0.011	0.000	0.005	0.015**	0.354**	−0.823	−0.804	0.085	0.028	0.000	0.000
Damoh	0.028	−0.006	0.000	−0.001	0.026	0.220	−1.014*	0.207	−0.331	0.065	0.000	0.000
Datia	0.000	0.000	0.005	0.002	0.036*	0.170	−0.669	0.518	−0.049	0.035**	0.000	0.000
Hamirpur	0.030	−0.004	0.000	0.003	0.028*	0.270	−0.620	−0.188	0.039	0.042	0.000	0.000
Jhansi	0.005	−0.003	0.003	0.000	0.032*	0.242	−0.819**	0.333	−0.094	0.038**	0.000	0.000
Lalitpur	0.011	0.000	0.006	0.000	0.030*	0.207	−0.984**	0.582	−0.347	0.039	0.000	0.000
Mahoba	0.032	−0.005	0.000	0.000	0.028*	0.313	−0.842**	−0.127	−0.115	0.039	0.000	0.000
Panna	0.053	−0.009	0.000	0.000	0.027**	0.331	−1.049*	−0.340	−0.178	0.054	0.000	0.000
Sagar	0.017	−0.004	0.002	0.000	0.025**	0.134	−0.941**	0.601	−0.443	0.044	0.000	0.000
Jalaun	0.004	−0.003	0.000	0.002	0.034*	0.202	−0.497	0.114	0.115	0.039	0.000	0.000
Tikamgarh	0.012	−0.003	0.001	0.000	0.032*	0.261	−1.005*	0.393	−0.209	0.041**	0.000	0.000
Whole region	0.037	−0.008	0.001	0.002	0.035*	0.289	−0.923*	−0.023	−0.181	0.056	0.000	0.000

* and ** indicate statistical significance at 95% and 90% confidence level as per the Mann–Kendall test, respectively (+ for increasing and – for decreasing).

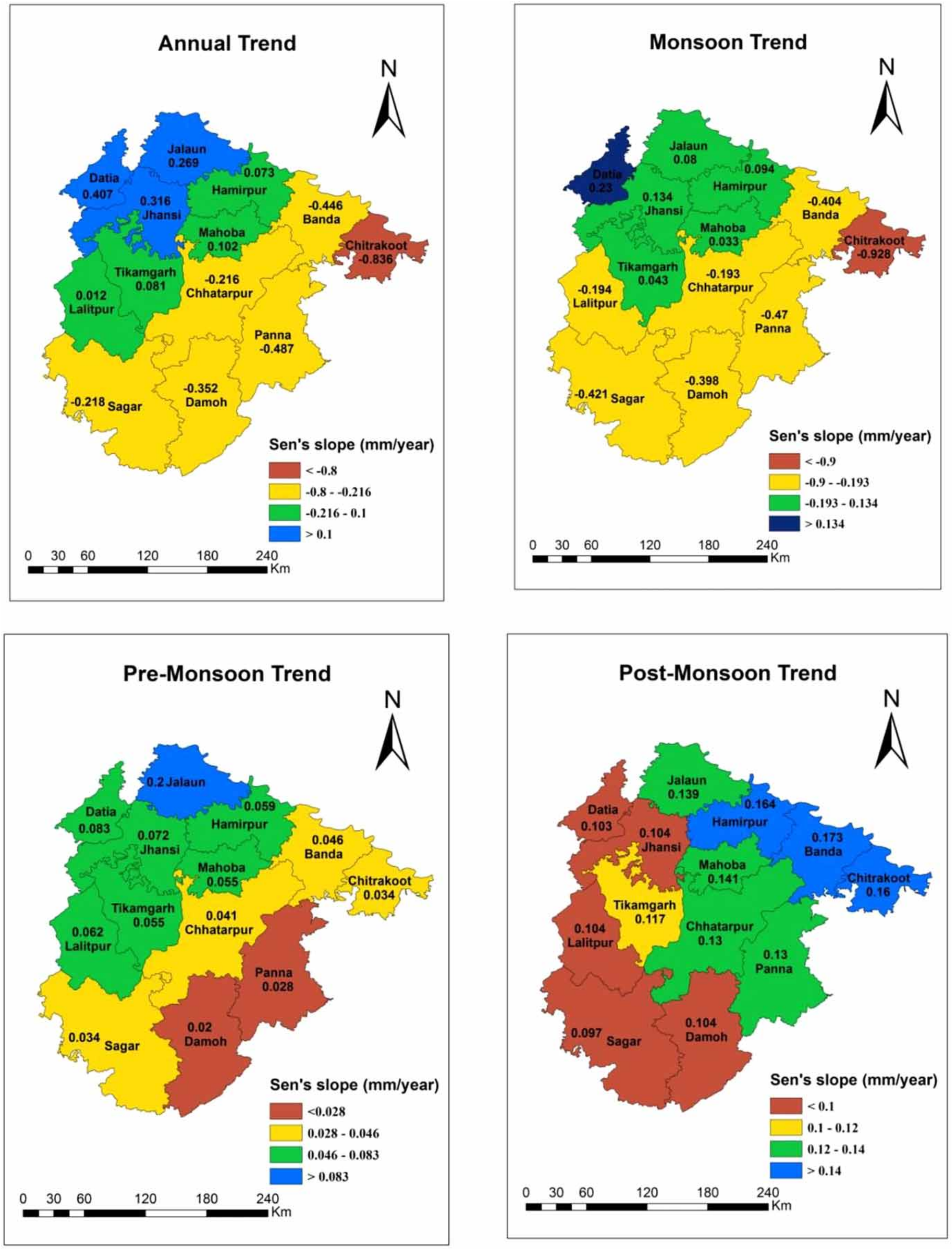

Figure 3 | Sen's slope (magnitude of trend) for different district in the study area.

Seasonal and annual trend

The magnitude of seasonal rainfall trend was also analyzed and is graphically presented in Figure 3 to compare the district wise rainfall changes occurring over the period. The rainfall pattern of the monsoon season, which is the most critical period for agriculture, decreased over seven districts in the lower part of the region. Similarly, during the winter season a very small and non-significant increasing trend of rainfall was observed in 11 districts. Overall, the annual and monsoon trends show quite similar changing patterns among the districts, except Lalitpur district. In both cases, the upper part of the Bundelkhand region experienced an increasing trend of rainfall with a maximum of 3% increase, whereas the lower part shows a decreasing trend which indicates that there is an urgent need for contingency planning in those areas. It can be noticed that, in the case of pre-monsoon and post-monsoon rainfall, all the districts have witnessed an increasing trend which suggests that there was a signal of shifting in rainfall patterns as seasonal rainfall during the monsoon was declining while increasing in pre- and post-monsoon season.

Decadal trend

In order to examine the decade wise annual and seasonal rainfall pattern changes, decadal rainfall analysis was carried out (Table 4). Here, the frequencies of wet year and dry years was calculated by considering a year as a wet year if rainfall was more than the summation of mean and standard deviation and as a dry year if rainfall was less than the mean minus standard deviation. Decadal rainfall analysis indicates that two consecutive decades, i.e. 1941–50 and 1951–60, received the highest rainfall of more than 10% of normal rainfall with a total of seven wet years and one dry year as compared to other decades. The decade 1990–2000 seems to be the dry decade where decadal mean rainfall was 12.55% less than the normal with three dry years and only one wet year. However, after 1960, it was found that the annual rainfall and frequency of wet years are decreasing and dry years are increasing. A similar trend was found in the case of decadal monsoon rainfall patterns since the monsoon season is the highest contributor to the annual rainfall. After 1960, decadal monsoon rainfall showed a declining trend with an increased deficit period and decreased wet period. On the other hand, the decadal pre-monsoon rainfall pattern does not show any precise trend as such but the last two consecutive decades between 1980 and 2000 observed higher rainfall than the norm. In a similar way, the decadal post-monsoon and winter rainfall showed slightly mixed characteristics of rainfall pattern. However, the overall statistics reveal that as a whole, Bundelkhand region experienced more dry years than wet years annually as well as seasonally, except for winter season. Krishnakumar *et al.* (2009) reported that Kerala

Table 4 | Decadal mean (% change from normal), frequency of excess and deficit rainfall years

	Annual			**Monsoon**			**Pre-monsoon**			**Post-monsoon**			**Winter**		
Decade	**Mean**	**Excess**	**Deficit**	**Mean**	**Excess**	**Deficit**	**Mean**	**Excess**	**Deficit**	**Mean**	**Excess**	**Deficit**	**Mean**	**Excess**	**Deficit**
1901–1910	–9.82	0	2	–8.46	0	2	–25.76	0	2	–29.80	0	5	–11.79	2	1
1911–1920	–6.63	1	2	–7.86	1	2	44.92	3	1	–6.14	1	3	–1.65	1	2
1921–1930	3.07	1	1	3.26	1	1	–17.97	1	4	18.84	2	1	–13.54	1	1
1931–1940	6.54	1	0	7.65	1	0	–0.68	2	1	2.13	1	1	–16.31	0	0
1941–1950	11.34	4	1	12.48	4	1	–8.08	1	2	–22.83	1	1	39.24	2	0
1951–1960	10.67	3	0	10.54	3	0	4.31	1	2	14.99	3	2	12.12	1	0
1961–1970	2.96	2	3	3.70	3	3	8.24	1	0	–2.70	2	1	–14.65	1	4
1971–1980	1.87	1	2	1.79	2	2	–28.78	1	4	22.01	2	0	–6.55	2	2
1981–1990	–2.73	2	4	–3.55	1	4	6.57	0	0	–1.19	2	2	14.53	2	1
1991–2000	–12.55	1	3	–14.35	1	4	17.01	2	0	2.94	1	2	1.23	3	2
Entire period		**16**	**18**		**17**	**19**		**12**	**16**		**15**	**18**		**15**	**13**

Table 5 | Most probable change year by Pettitt's test

District	Probable change year	Trend	*P*-value
Banda	1982	Decrease	0.072
Chattarpur	1983	Decrease	0.051
Chittorkut	1982	Decrease	0.046
Damoh	1983	Decrease	0.042
Datia	1985	Decrease	0.159
Hamirpur	1982	Decrease	0.133
Jhansi	1985	Decrease	0.141
Lalitpur	1978	Decrease	0.072
Mahoba	1983	Decrease	0.079
Panna	1983	Decrease	0.041
Sagar	1978	Decrease	0.056
Jalaun	1941	Increase	0.161
Tikamgarh	1983	Decrease	0.088
Bundelkhand region			
Annual	1983	Decrease	0.071
Monsoon	1983	Decrease	0.048
Pre-monsoon	1956	Increase	0.217
Post-monsoon	1954	Increase	0.162
Winter	1963	Decrease	0.378

state experienced more deficit years than the excess year on an annual basis during 1987–2007 whereas there were multi-decadal variations with clustering of dry or wet anomalies in the Indian summer monsoon as reported by Pant & Rupa Kumar (1997). Patra *et al.* (2012) also found that the overall characteristics of the long-term and decadal annual as well as monsoon rainfall over the region declined in nature during 1871–2006 in Odisha state of India. Such irregular rainfall in Bundelkhand region has a major impact on rain-fed agriculture causing crop failure, frequent agricultural drought and migration of inhabitants in the region. Therefore, strategic agricultural planning is very much required to face the changing climate through suitable crop varieties, agronomic practices, resource conservation measures and water harvesting structures for supplemental irrigation etc.

Change point analysis

Pettitt's test was employed to analyse the probable change year of annual and seasonal rainfall trends in the region. A similar probable change point year was found for annual as well as monsoon rainfall. After 1983, annual and monsoon rainfall shows a significant declining trend over the year at probability levels of 0.90 and 0.95, respectively (Table 5). On the other hand, pre- and post-monsoon rainfall show an increasing trend from 1955, but the change point was found non-significant at 95% probability level. District-wise analysis shows that all the districts are in agreement with the change year of around 1983 and experienced the decreasing trend afterwards, except Jalaun district. From Figure 4, it can also be visualized that, though non-significant, an increasing rainfall trend was observed both for annual and monsoon rainfall from the year 1915 but from the year 1983 rainfall started decreasing. A non-significant change point of trend has been observed in the case of pre- and post-monsoon. Similar results were

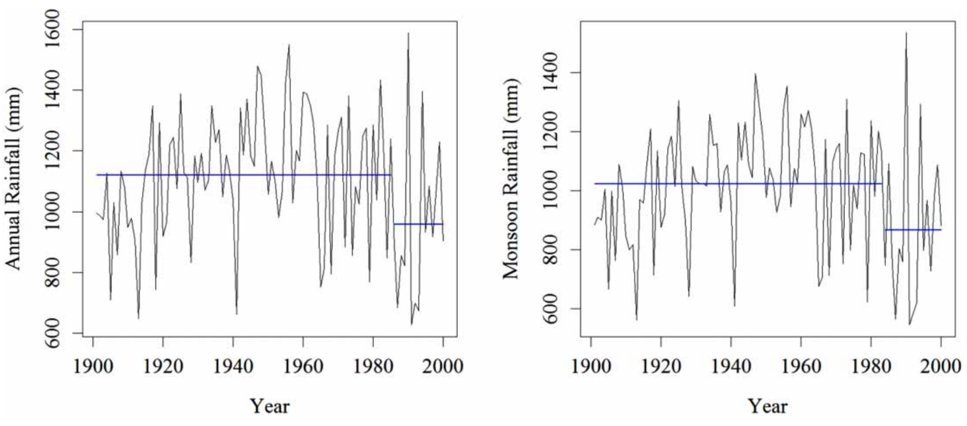

Figure 4 | Time series along with change year using Pettittchange point analysis for (a) annual and (b) monsoon rainfall for Bundelkhand region.

experienced for Agra district in India where a significant change point has been observed during 1990, since then the annual and monsoon rainfall started decreasing (Jana *et al.* 2016).

Annual and seasonal rainfall periodicity analysis

Wavelet analysis of Bundelkhand rainfall dataset was employed to reveal any significant periodicity existing in the trends of average annual rainfall (Figure 5). From Figure 5(a) and 5(b), it can be noted that annual and monsoon wavelet power shows a quite similar pattern of distribution over the years. However, the annual and monsoon rainfall pattern show a periodicity of 4–16 years in the initial half of the century (i.e. during 1910–1970) and thereafter a longer periodicity of 2–32 years was found. However, in recent decades, i.e. after 1985, a stronger periodicity of 2–8 years with significantly higher wavelet power was observed which suggests that the frequency of extreme rainfall occurrence has increased (periodicity of 7–8 years) than before (2–32 years). This increased frequency of extreme rainfall event is more deleterious than the climate change

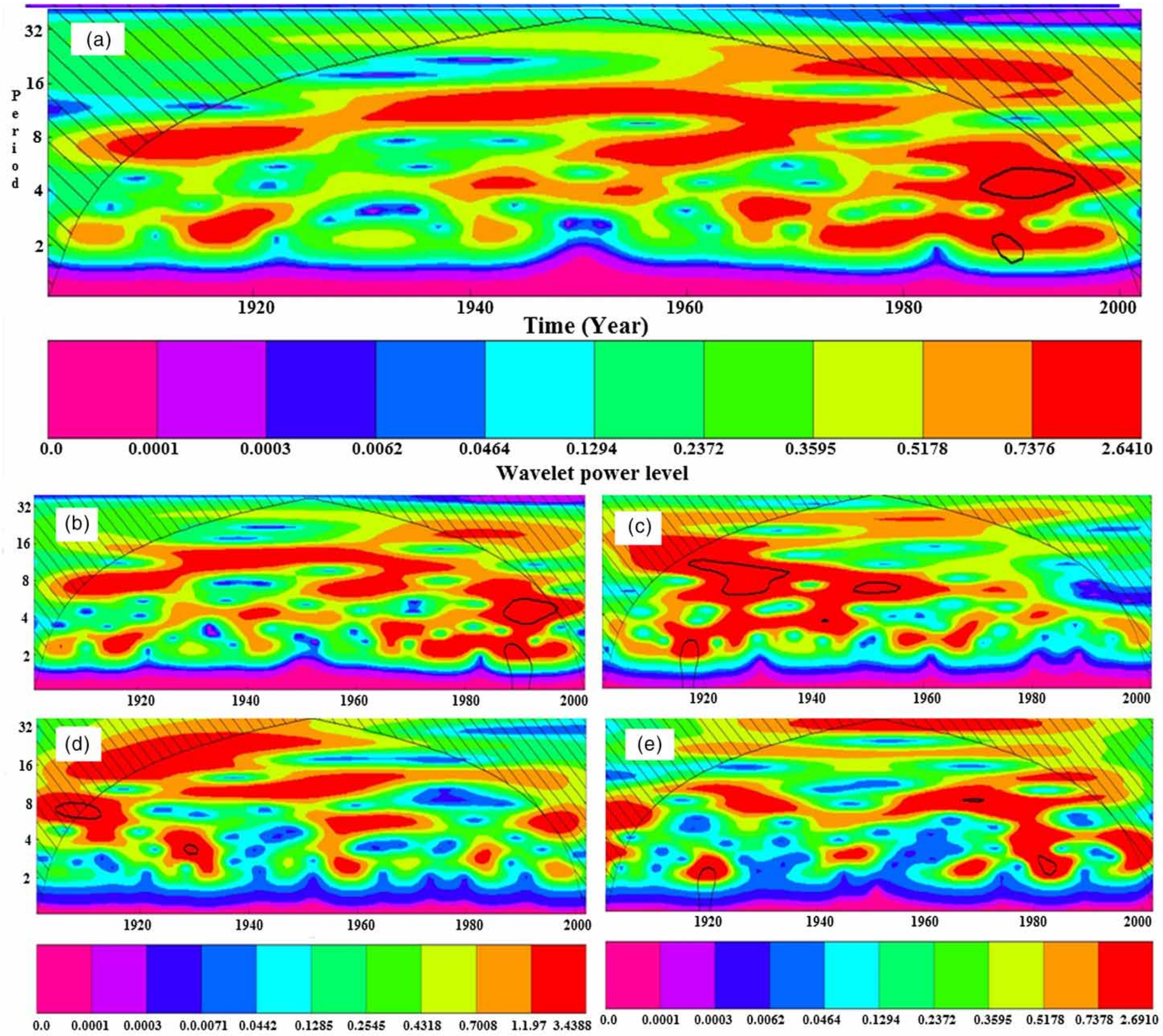

Figure 5 | Wavelet analysis for (a) annual, (b) monsoon, (c) pre-monsoon, (d) post-monsoon and (e) winter rainfall of Bundelkhand region.

impact on agriculture as the impact of climate change on agriculture can be mitigated but to lessen the effect of weather extremes is very difficult. In a similar way, Thomas & Prasannakumar (2016) reported a periodicity of 2–8 years found in annual and seasonal rainfall patterns in Kerala state, India. In the case of pre- and post-monsoon rainfall, higher wavelet power is confined within 2–16 years in the initial half of the century and in the later half, no prominent periodicity exists as such (Figure 5(c) and 5(d)). On the contrary, winter rainfall shows a prominent periodicity of 2–8 years in the latter half of the century (Figure 5(e)). Overall, the wavelet power spectrum of various seasonal rainfall does not show any consistent periodicity, except the monsoon season.

Rainfall concentration in monthly rainfall

In order to assess the pattern of rainfall distribution within a year, the PCI was calculated on an annual and seasonal basis and its temporal change pattern is presented in Figure 6. According to Oliver's (1980) classification, a PCI value from 16–20 represents an irregular rainfall distribution concentrated in the one third of the period, whereas a PCI value of more than 20 indicates a strongly irregular rainfall pattern over the period. Bundelkhand region's annual PCI reveals a very highly irregular rainfall distribution with a PCI value of more than 20 in all the years except 1997. In other words, annual rainfall in Bundelkhand region is unevenly distributed among the months, rather it is highly

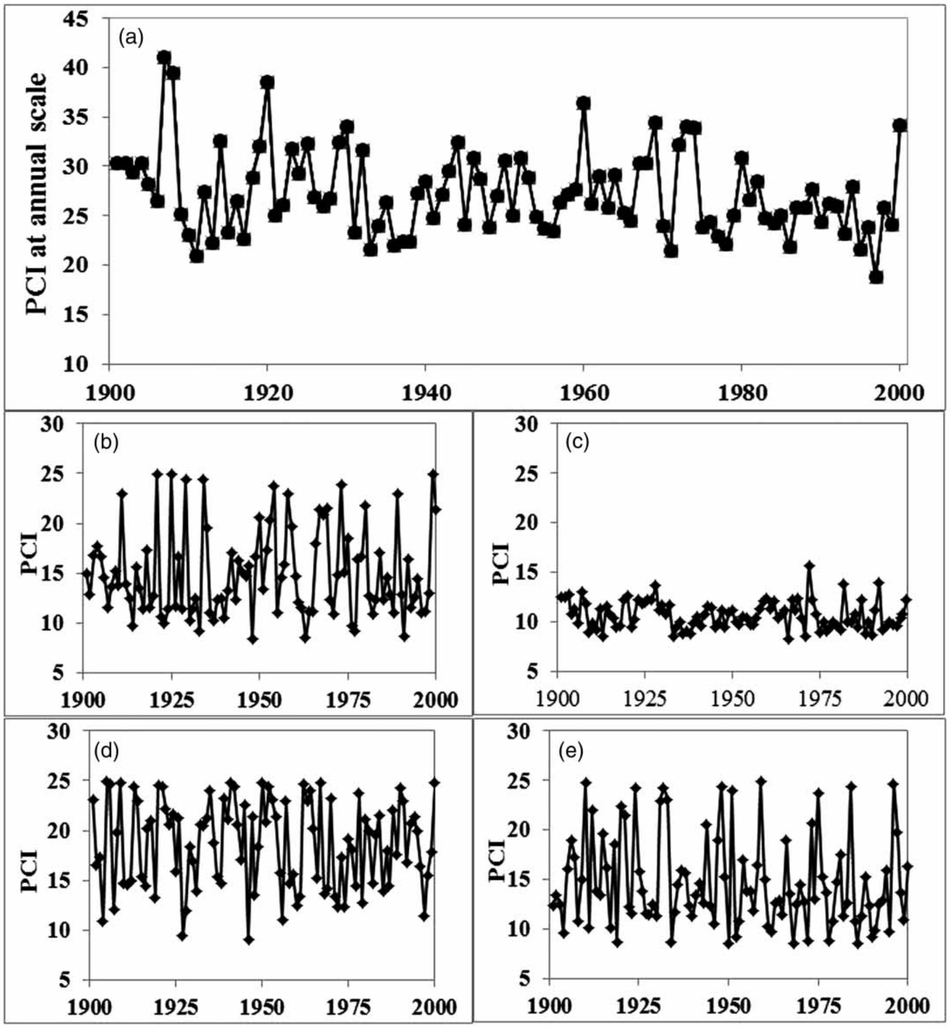

Figure 6 | Temporal variation of PCI of (a) annual, (b) pre-monsoon, (c) monsoon, (d) post-monsoon and (e) winter.

concentrated in one third of the year. Since Monsoon rainfall is the main contributor to the annual rainfall amount, therefore the annual PCI result also supports the statement that the major fraction of the annual rainfall occurs during the 3–4 months of monsoon season. On the other hand, the seasonal scale PCI finds a mixed rainfall distribution in the case of pre-monsoon, post-monsoon and winter rainfall. The PCI value of the three seasons vary between a theoretical minimum value of 8.3 and up to the value of 25, therefore showing a mixed variability in rainfall concentration. This further indicates the highly irregular and unpredictable nature of rainfall occurrence during the seasons which drastically affects the pre-*kharif* and *rabi* crops in the region. However, the monsoon season PCI shows a relatively stable and uniform rainfall distribution among the monsoon months with a range of 8.3–15.7. From the temporal change pattern of monsoon PCI (Figure 6c), it can also be noted that after 1965, the year wise fluctuation of monsoon PCI value increased with a higher range value (8.3–15.7) than before, indicating the increased irregular rainfall occurrence in the season.

SI analysis

Since there was a high variation of rainfall concentration found in the rainfall pattern, hence, a decade wise SI analysis was applied to view the temporal trend in the rainfall concentration (Figure 7). In general, a low SI value indicates the better distribution of rainfall between the months whereas a high SI value implies more irregularity in the monthly distribution in a year. The decadal SI values show a mixed and not so prominent trend existing in the study period but, all the decades show a very high SI value (>1) with the maximum in three decades, i.e. 1900–1910, 1921–1930 and 1961–1970. The high SI value also proves that the annual rainfall amount is mainly concentrated in 2–3 months, i.e. in the monsoon season. Though there is a mixed trend in the decadal SI values, overall a slight decreasing trend was found in the time series. This mixed trend may be supported by the inconsistent rainfall occurrence over the region and the generic decreasing trend agrees with the fact that monsoon rainfall is decreasing and on the other hand pre- and post-monsoon rainfall is increasing which in fact reduces the rainfall concentration disparity in the monthly rainfall. A similar result was reported by Thomas & Prasannakumar (2016) for Kerala state where the SI value was reduced from 0.8 to 0.72 during 1871–2012. However, no significant trends in SI value were found in case of the districts of Kerala as reported by Nair *et al.* (2014).

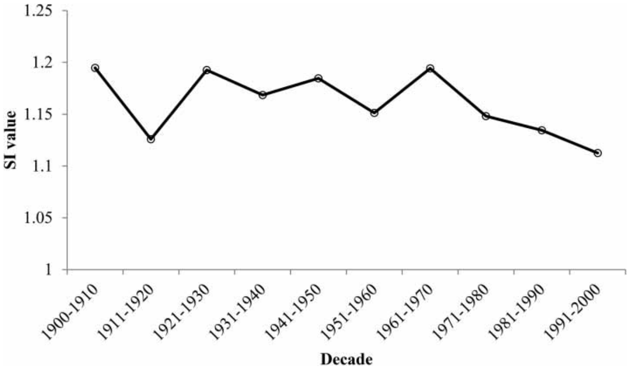

Figure 7 | SI value over Bundelkhand for different decades.

Using MK test, Sens slope and change point analysis, trend analysis of weather parameters was carried out in the Karun River watershed located in the southwest of Iran (Salarijazi *et al.* 2012), Pieria Region in Greece (Karpouzos *et al.* 2010) and Ontario Great Lakes Basins in Ontario (Ahmed *et al.* 2014). Our study indicates that for more comprehensive understanding of these weather parameters CWT, SI, RCI may also be studied for these regions as weather parameters are highly unpredictable and stochastic in nature.

CONCLUSIONS

It can be concluded that for Bundelkhand region, the monsoon rainfall is the major contributor to the annual rainfall and it has higher consistency over the other seasons. PCI analysis also supports the fact that the annual rainfall amount is unevenly distributed among months, rather it is concentrated in the 2–3 months of the monsoon season in the year. However, in time series, the monsoon as well as annual rainfall trend was found negative while pre- and post-monsoon rainfall was increasing in most of the districts of the studied region, indicating the deviation of the rainfall timing from the normal occurrence. It was also found that seven districts located in the northern part of the region received increased annual as well as monsoon rainfall with a positive trend whereas other districts witnessed a negative rainfall trend. Two consecutive decades, i.e. 1941–50 and 1951–60, were found to be the wettest decades during the 20th century. Decadal rainfall analysis revealed that Bundelkhand region experienced more dry years than wet years for annual as well as in the pre-monsoon, monsoon and post-monsoon seasons thereby signifying that rainfall occurrence in the region is more prone towards dry spells which can adversely impact agriculture in the future. Besides that, wavelet power analysis found increasing frequency of annual and monsoon extreme rainfall events with stronger periodicity of 2–8 years in the recent decades after 1985. Therefore, strategic contingency planning is required urgently for Bundelkhand region to overcome the brunt of uncertain climate change with extreme weather events. A decline in monsoon rainfall and increase in post- and pre-monsoon rainfall will require research towards development of stress tolerant varieties, efficient cropping systems matching with changing rainfall pattern, resource conservation technologies, water harvesting, and micro-irrigation for drought proofing. The information generated under the present study has immense scope in preparing comprehensive adaptation and mitigation strategies to cope with the climate change scenario in Bundelkhand region and the methodology can be applied in other similar regions in the world. Thus the findings of the paper have a broader palpability and world-wide implications.

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