



Characterization of meteorological drought over a dryland ecosystem in north western India

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Abstract

Droughts are the greatest and the most recurrent climatic hazard that frequently strikes India, fetching serious water deficiencies, economic failures and unfriendly social events. An investigation of regional droughts can help policy makers in achieving the goals of sustainable governance of water resources. Hence, this study examined the characteristics of meteorological drought over the dryland ecosystem of Rajasthan state in north western India, based largely on diurnal rainfall statistics of 33 stations for the period 1961–2017. For investigating meteorological drought, standardized precipitation index (SPI) was computed at various time spans such as early (June to August), mid (August to September), late (September to October) and whole *kharif* season (June to October) as well as annually (January to December) to study the deficiency or surplus of water about its normal availability. In the same way, primary drought attributes, for example severity, frequency, magnitude, duration, intensity, return periods and trends, were computed and their distribution maps were prepared by employing geospatial techniques. During the study period, nearly half of the years experienced a meteorological drought at all-time scales. Fascinatingly, more than 90 percent of them were of mild drought, whereas severe and extreme droughts were unusual. Surprisingly, during the year 2002, all stations experienced a mixture of normal, moderate, severe and extreme droughts. The drought frequency followed an order of mid-season > whole *kharif* season > early season > late season > annual. The western, northern and southern parts (low to moderately elevated) experienced wetter conditions (significant at 95% confidence level). In contrast, the north eastern, eastern and south eastern regions (moderately to highly elevated) witnessed increased drier situations, though statistically it was found non-significant. Finally, the results of this study suggest that the investigation of SPI-based meteorological drought will be helpful in developing effective drought management plans over the dryland ecosystem.

Keywords Drought · SPI · Severity · Magnitude · Return period · Trend·

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1 Introduction

Drought is a frequent feature of climatic variations. It is believed to be the costliest, multifaceted and least conceived among all the environmental hazards (Vicente-Serrano et al. 2015). It occurs in almost all regions of the world, including humid and affects more people than any other threat in the world (Masud et al. 2015). Droughts account for about 5 percent of natural disasters, causing about 30 percent of damages with respect to all calamities (Bin et al. 2011). Drought killed more than 11 million people and consequently 2 billion were hurt since the nineteenth century (Gopalakrishnan 2013). It varied from other threats as its beginning and termination are difficult to monitor (McKee et al. 1993). Its impacts may stay for years after termination, resulting in significant adverse effect on infrastructure, agriculture, livestock, forestry, fisheries, food production, tourism and aquatic resources (Gidey et al. 2018; Mustafa and Rehman 2018; Almazroui 2019). Similarly, it can show the way to extensive starvation, indiscriminate relocation of population, degradation of natural resources, political conflicts, social anxiety and worry (Kelley et al. 2015). Recently it was acknowledged that human-induced global warming is advancing the global hydrological cycle, which in turn is modifying the temporal and spatial arrangement of rainfall globally (Allen and Ingram 2002; Alan et al. 2003). In the future, a warmer climate will increase the frequency, severity, and likelihood of hydrological extremes, such as drought, in many parts of the world (Easterling et al. 2000; Bin et al. 2011).

In the past, researchers and scientists developed numerous drought indices such as Palmer Drought Severity Index (PDSI) (Palmer 1965), Rainfall Anomaly Index (RAI) (Van Rooy 1965), Surface Water Supply Index (SWSI) (Shafer and Dezman 1982), Palfai Aridity Index (PAI) (Palfai 1990), Standardized Precipitation Index (SPI) (McKee et al. 1993), Vegetation Condition Index (VCI) (Kogan 1995), Effective Drought Index (EDI) (Byun and Wilhite 1996), Reconnaissance Drought Index (RDI) (Tsakiris et al. 2007), Perpendicular Drought Index (PDI) (Ghulam et al. 2007), Standardized Runoff Index (SRI) (Shukla and Wood 2008) and Standardized Precipitation Evaporation Index (SPEI) (Vicente-Serrano et al. 2010a) around the world at regional, national and global scale to detect and monitor the meteorological drought. Currently, these indices are the significant ways to precisely detect the expanse, start, length, strength and severity of drought episodes in quantitative terms (Vicente-Serrano et al. 2010a, b; Zambrano et al. 2017). Among these indices, the use of a particular index depends on the need, local climatic conditions, and data availability. Contrastingly, SPI suggested by McKee et al. (1993) had distinct merits, i.e., simplicity to calculate, broader applicability, tailored for multiple time scales, incorporates only rainfall as input data and the least affected by geographical and topographical differences (Bazrafsham et al. 2014). Of late, SPI was extensively used in drought estimation, supervising, watching and forecasting universally (Spinoni et al. 2014) as well as over several climatic zones namely, Africa (Dutra et al. 2013; Dhurmea et al. 2019), Europe (Barker et al. 2016), North America (Ford and Lobosier 2014), West Asia (Zakhem and Kattaa 2016; Awchi and Kalyana 2017; Mustafa and Rahman 2018; Mossad and Alazba 2018) and South–East Asia (Du et al. 2012; Zin et al. 2013; Rahman et al. 2018; Kundu et al. 2020). Therefore, this index was chosen for supervising of droughts, which can be helpful for classifying severity of meteorological drought over a large geographical area, i.e., the dryland ecosystem (Rajasthan state) of north western India.

India has a long history of droughts and about 16 percent area is prone to a shortage of rainfall annually, affecting about 50 million persons (Dutta et al. 2015). Recently, few studies specifically quantified meteorological drought by employing rainfall data at

regional scales in India (Kundu et al. 2015, 2020; Patel and Yadav 2015). Amrit et al. (2017) analyzed the meteorological drought characteristics in central India using Percent Departure (PD) method and revealed that the region faced severe drought events, with a maximum rainfall deficiency of 75 percent. Sarkar et al. (2020) studied the drought conditions over the Upper Seonath basin of Chhattisgarh by employing VCI, NDVI and RAI and found about 60 percent area of the basin under severe drought. Malik et al. (2021) used the Effective Drought Index (EDI) and detected increasing drought and wet conditions over Uttarakhand. Swain et al. (2021) applied Simplified Rainfall Index (RI_s) over the Narmada River basin and revealed a significantly higher frequency, severity and persistence of droughts over the basin. Of late, SPI was applied extensively for quantifying meteorological drought in various administrative, hydrological and climatic regions of India using long-term rainfall data from on field rain gauge stations and satellite-based gridded rainfall datasets (Mishra and Desai 2005; Bhuiyan et al. 2006; Patel et al. 2007; Pai et al. 2011; Kumar et al. 2012; Dutta et al. 2013, 2015; Kundu et al. 2015, 2020; Patel and Yadav 2015; Sahoo et al. 2015; Thomas et al. 2016; Sarma and Singh 2019; Mallenahalli 2020). Similarly, droughts are of major concern over the dryland ecosystem of Rajasthan and were studied by employing indices like, SPI, RAI, NDVI, VCI, SWSI for whole and in parts of the Rajasthan (Bhuiyan et al. 2006; Jain et al. 2010; Dutta et al. 2013, 2015; Ganguli and Reddy 2013; Dhakar et al. 2013; Sehgal and Dhakar 2016). Recently, Pingale et al. (2014) reported a notable escalation in temperature over Rajasthan, and expected to influence the occurrence of rainfall and subsequently the chances of drought. Remarkably, very few studies over India as well as dryland ecosystem of Rajasthan investigated the drought characteristics, namely, severity, frequency, magnitude, duration, intensity, return periods, trend, truncation level and intra-seasonal vulnerability at five-time scales, four coinciding with the principal *kharif* period and one corresponding to whole year. To fill this research gap, this study investigated the following threefold objectives: (1) to determine the SPI at multiple time scales such as early (June to August), mid (August to September), late (September to October) and whole *kharif* season (June to October) along with annual time span (January to December) over dryland ecosystem using rainfall records for the period 1961–2017, (2) to compute and generate the maps of meteorological drought characteristics e.g. severity, frequency, magnitude, duration, intensity and return periods at multiple time scales using geospatial techniques, (3) to work out the direction of trends in rainfall and meteorological drought severity using nonparametric (Mann–Kendall, Sen’s slope estimator) and parametric (simple linear regression) tests over the dryland ecosystem to provide a baseline for mitigation of droughts. A characterization of meteorological drought is critical to comprehend the nature of droughts. A major novelty of this study is that it will not only assess the seasonal vulnerability of drought, but it will also evaluate and compare intra-seasonal vulnerability at five time scales, four coinciding with the principal *kharif* period, i.e. quarterly SPI (June to August), bi-monthly SPIs (August to September and September to October) and quinque-monthly SPI (June to October) matching with early, mid, late, and whole *kharif* period, respectively, whereas one corresponds to annual SPI (January to December). As the whole state of Rajasthan is at high risk of drought due to climate change (Pingale et al. 2014) and resultantly its impacts cannot be avoided completely. However, an assessment of drought based on different indices and advanced tools, better understanding of response can be generated to mitigate the impacts of drought. Finally, the outcome of this study may provide a scientific platform for water resource managers to develop drought-proofing strategies and the mitigation of damages on account of droughts over the dryland ecosystem.

2 Study area

The Rajasthan state, located in north western India, is the largest state in the country. It covers a widespread area of 3,42,239 km² covering about 10.4 percent of the India's total geographical area. The state extends between 23° 30' to 30° 11' north latitudes and 69° 29' to 78° 17' E longitudes (Fig. 1). The altitude of terrain in the state varies from 6 to 1698 m above mean sea level (amsl). The state has various topographic features, such as the Thar Desert in the north west, sandy plains in the north east, the Aravalli Hills (spreading from north east to south west) in the center, and a plateau in the south east. The Thar Desert covers about 70 percent area of the state. The state is characterized by less rainfall, high temperature differences, high evapotranspiration, frequent droughts, lack of perennial rivers, scarce vegetal cover, nomadic population, and dependency of humans on animal rearing. Further, the state has a predominantly an agrarian society with an agro-pastoral economy. Of the total cultivated area, only 20 percent is irrigated, due to 1 percent of the country's total water resources availability in the state. The onset and length of the monsoon controls the efficiency of *kharif* as well as *rabi* season crops. The yields of crops are sensitive to rainfall and wetter years are largely associated with higher yields.

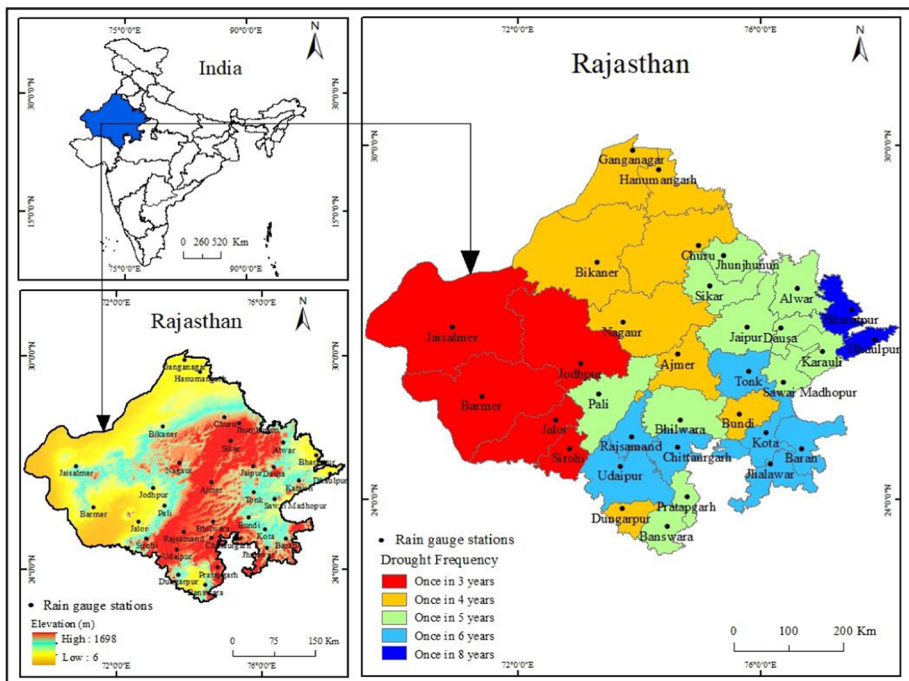


Fig. 1 Map showing the geographical location of study area in India along with meteorological stations and frequency of droughts

3 Data and methods

3.1 Data collection and database preparation

This study used daily rainfall data of 57-years uniformly (1961–2017) for 33 rain gauge stations, for meteorological drought investigation, covering all the districts (Fig. 1). The day-to-day rainfall information was procured from the Department of Water Resources, Government of Rajasthan, Rajasthan, India, which was accessible from their web portal (www.waterresources.rajasthan.gov.in). Geographical location and elevation information of the stations are provided in Table 1. The key difficulty with the rainfall analysis was the loss of records. Therefore, out of more than 400 stations, only 33 stations having hardly any loss of records were selected. The daily rainfall records in this dataset were available from 1957; however, the year 1961 was considered as the base of year, as the data is consistent for the selected 33 stations only after 1961. Nevertheless, few rain gauge stations had missing rainfall observations which were filled in before undertaking the further analysis. The normal ratio method was employed to estimate the escaped rain depths of the preferred station by preferring the rain depths of the three contiguous stations. Considering the geographic location of stations, a distance matrix was prepared to compute the stations contiguity. In this study, the estimation of missing rainfall data was made to support the linkage of data for computation and enhance the precision of SPI results. The checking of data quality was an opening step before the investigation, as outliers can extremely affect the rainfall amount and subsequently the drought analysis (You et al. 2008). To ensure the homogeneity, double mass curve technique and student's *t*-tests were employed on rainfall time-series for all stations. None of the stations showed a breakpoint in double-mass curves and displayed almost linearity, which suggested the homogeneity in data. Similarly, the student's *t*-test had not revealed any break point or statistically significant difference in time-series of rainfall at a 95% level of significance. Finally, the daily rainfall statistics were aggregated for months, seasons and years for each station, which was used to develop SPI so as to recognize droughts over the dryland ecosystem.

3.2 Computation of meteorological drought

Meteorological drought was computed by using the SPI method. This method was first developed by McKee et al. (1993) at the Colorado Climatic Centre for defining, delineating, detecting, monitoring, and comparing meteorological drought across spatiotemporal scales. McKee et al. (1993) accepted that the shortfall of precipitation had unusual impacts on the wetness of soils, the flow of streams, levels of ground water, snowpack, and storage of water bodies, which led them to develop the SPI for multiple time scales. Technically, SPI was determined by bisecting the difference between the mean seasonal rainfall and its long-duration seasonal rainfall mean by its standard deviation which was mathematically expressed as:

$$\text{SPI} = \frac{x_{ij} - x_{im}}{\sigma} \quad (1)$$

where x_{ij} is the seasonal month-wise rainfall at i th station and of the j th observation, x_{im} the long duration rainfall means and σ expresses the standard deviation. At least 30-years of minimum rainfall statistics is essential to determine the SPI, as the smaller one is most

Table 1 Basic rainfall characteristics of selected 33 stations over dryland ecosystem of north western India between 1961 and 2017

Stations	Latitude	Longitude	Elevation (m)	Mean rainfall (mm)	Maximum rainfall (mm)	Year	Minimum rainfall (mm)	Year	SD (mm)	C _v	C _k	C _s	Z	β	R
Ajmer	26°27'	74°37'	608	551.0	1163.0	1975	205.3	1987	194.7	35.34	1.07	0.85	-0.25	-3.80	0.66
Alwar	27°34'	76°36'	288	662.8	1445.1	1996	223.8	1987	230.7	34.80	1.12	0.62	0.00	-0.10	0.86
Banswara	23°33'	74°27'	229	1070.1	2591.0	2006	509.8	1966	385.6	36.03	3.28	1.33	0.28	9.60	0.60
Baran	24°52'	76°40'	259	850.2	1739.0	2013	254.0	2002	300.3	35.32	0.66	0.93	-0.81	-20.2	0.39
Barmer	25°45'	71°24'	185	275.9	759.0	2006	37.1	1968	165.7	60.06	0.89	1.01	2.21*	26.0*	0.07+
Bharatpur	27°13'	77°30'	180	631.2	1041.0	2005	218.5	1978	172.7	27.36	0.06	-0.26	0.65	6.70	0.48
Bhilwara	25°44'	74°20'	421	664.8	1120.0	2006	307.0	2009	210.1	31.61	-0.96	0.19	-0.09	-1.70	0.91
Bikaner	28°01'	73°18'	240	271.8	482.2	1983	32.0	2002	104.6	38.51	-0.45	0.16	1.54	15.3	0.10
Bundi	25°27'	75°38'	365	710.7	1245.4	1996	275.5	2002	186.9	26.30	0.41	0.41	-0.10	-0.90	0.84
Chittaurgarh	24°53'	74°38'	400	805.7	1556.5	2016	389.7	1965	216.5	26.88	1.78	0.95	1.19	17.9	0.24
Churu	28°18'	74°58'	296	396.9	690.2	1977	165.0	1965	146.7	36.96	-0.88	0.32	2.02*	27.4*	0.04*
Dausa	26°54'	76°20'	341	632.2	1363.2	1975	300.0	2002	238.9	37.79	1.82	1.25	-0.09	-1.50	0.58
Dhaulpur	26°42'	77°53'	175	659.8	1319.6	2008	171.8	1978	241.8	36.65	0.65	0.62	0.36	7.80	0.50
Dungarpur	23°51'	73°43'	301	767.8	1611.0	2006	319.0	2008	270.3	35.21	0.87	0.73	1.11	28.6	0.14
Ganganagar	29°55'	73°53'	178	281.3	666.0	1983	78.6	1968	130.2	46.28	1.30	0.93	2.84**	26.2**	0.02*
Hanumangarh	29°35'	74°19'	181	248.6	547.0	2010	75.5	1974	108.6	43.68	0.16	0.53	1.02	7.50	0.25
Jaipur	26°55'	76°50'	425	596.0	1155.8	1977	85.0	1984	230.1	38.62	-0.04	0.41	-0.43	-10.6	0.55
Jaisalmer	26°55'	70°55'	243	196.8	512.8	2006	26.4	1969	115.9	58.93	1.17	0.70	2.35*	21.7*	0.01*
Jalor	25°21'	72°37'	162	433.5	1047.4	1990	51.3	1969	242.1	55.86	-0.07	0.81	1.77+	29.5+	0.07+
Jhalawar	24°36'	76°09'	314	936.1	1614.5	2006	375.0	1968	292.2	31.22	-0.26	0.60	0.83	19.9	0.38
Jhunjhunum	28°08'	75°23'	350	406.5	828.0	2010	123.0	2002	155.0	38.12	-0.48	0.27	-0.33	-5.00	0.81
Jodhpur	26°18'	73°02'	258	374.1	815.0	1990	91.0	2002	166.3	44.48	-0.46	0.49	0.37	5.40	0.73
Karauli	26°30'	76°01'	283	740.7	1329.4	1975	275.5	2017	256.4	34.63	-0.56	0.35	-0.30	-6.80	0.74
Kota	25°08'	76°05'	269	737.7	1475.5	1971	325.0	1965	231.2	31.35	0.48	0.57	-0.55	-13.1	0.45
Nagaur	27°12'	74°45'	208	388.4	1259.0	1975	110.0	2009	200.8	51.71	5.66	1.82	0.18	2.20	0.92

Table 1 (continued)

Stations	Latitude	Longitude	Elevation (m)	Mean rainfall (mm)	Maximum rainfall (mm)	Year	Minimum rainfall (mm)	Year	SD (mm)	C_v	C_k	C_s	Z	β	R
Pali	25°47'	73°20'	210	329.6	1018.6	1979	90.0	1972	171.4	52.01	-0.26	0.68	1.37	25.0	0.24
Pratapgarh	24°03'	74°47'	506	936.5	1668.7	1973	359.7	1966	298.7	31.90	-0.30	0.43	2.19*	53.4*	0.04*
Rajsamand	25°45'	74°05'	362	553.0	1039.0	2010	190.0	1969	179.9	32.55	0.55	0.44	1.78 ⁺	22.8 ⁺	0.04*
Sawai Madhopur	25°59'	76°22'	417	790.3	1249.0	2016	295.0	1984	245.0	31.00	-0.57	-0.06	1.49	35.4	0.14
Sikar	27°37'	75°09'	432	497.1	1090.0	1977	124.0	2009	225.5	45.38	-0.26	0.52	0.21	5.30	0.89
Sirohi	24°36'	72°43'	358	630.5	1577.6	1973	190.9	1987	320.5	50.83	0.63	0.94	0.01	1.00	0.97
Tonk	26°10'	75°48'	281	631.3	1200.0	2013	221.3	2002	207.9	32.94	0.25	0.45	0.50	9.40	0.47
Udaipur	24°11'	73°55'	578	594.5	1095.5	1973	215.1	1989	186.0	31.29	-0.15	0.11	0.67	10.3	0.60
Rajasthan	27°02'	74°21'	312	583.4	839.2	1975	276.6	2002	221.1	37.90	-0.61	0.09	1.30	16.0	0.39

**99% significant level, * 95% significant level, standard deviation (SD), coefficient of variation (C_v), kurtosis (C_k), skewness (C_s), Mann–Kendall (Z), Sen slope estimator (β) and Regression (R)

unlikely to capture the character of climatic fluctuations (Wu et al. 2001, 2005). Further rainfall was statistically undistributed normally, therefore, the long-duration rainfall records were then suitably shaped into a skewed distribution through gamma probability function with zero average and difference of one only (Sönmez et al. 2005). The monthly precipitation time series were modelled using the gamma distribution, whose probability density function was expressed as:

$$g(x) = \frac{1}{\beta\alpha\gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0, \quad (2)$$

where $\alpha > 0$ was a shape parameter, $\beta > 0$ was a scale parameter, and $x > 0$ was the precipitation. Fitting the distribution to the data requires α and β to be estimated. Edwards and Mckee (1997) suggested estimating these parameters using the approximation of Thom (1958) for maximum likelihood, as shown below:

$$\hat{\alpha} = \frac{1}{4A} \left[1 + \sqrt{1 + \frac{4A}{3}} \right] \quad (3)$$

$$\hat{\beta} = \frac{\bar{X}}{\hat{\alpha}} \quad (4)$$

whereas for n observations,

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (5)$$

The period 1961–2017 was taken as the base period for fitting the probability distribution. Integrating the probability density function with respect to x and inserting the estimates of α and β yields an expression for the cumulative probability $g(x)$ of an observed amount of precipitation occurs for a given month and time scale was obtained. Since the gamma distribution was undefined for $x=0$, therefore, gamma distribution was used, viz. $H(x) = q + (1-q)g(x)$, $q = P(x=0) > 0$, where $P(x=0)$ is the probability of zero distributions. The cumulative distribution was then transformed into the standard normal distribution to yield the SPI. After the statistical fitting and transformation, region-specific deviations were largely minimized (Liu et al. 2012). Accordingly, a drought episode resulted when SPI values were consistently negative and attains a value of -1.0 or less. In contrast, the drought incident came to a termination point when the values of SPI changed in a positive direction. Subsequently, the wetting and drying events were classified into eight categories, for example, SPI values ≥ 2.00 represented extremely wet conditions, severely wet conditions prevailed when SPI values ranged from 1.50 to 1.99, while 1.00 to 1.49 values of SPI indicated moderately wet, mild wet from 0.00 to 0.99, mild dry conditions from -0.99 to 0.00, moderately dry from -1.49 to -1.00 , severely dry -1.99 to -1.50 , and extremely dry conditions when SPI values were ≤ -2.00 . At first, McKee et al. (1993) worked out the values of SPI at 3-, 6-, 12-, 24- and 48 months schedule. The 3- and 6-months SPIs are usually linked to short-term situations and hence suitable for soil moisture and agricultural impact assessment (Ji and Peters 2003). The medium-term time scale i.e., 12 months SPI reveals about annual water supply condition, about ground water, stream flow and reservoir levels (Potop et al. 2012). The 24 months or larger values of SPI express the perpetual condition of drought, which may be useful for examining socio-economic impacts (Zhang and Jia 2013; Potop et al. 2014). For this study, SPI

values were considered at five-time scales, four coinciding with the principal *kharif* period, i.e., quarterly SPI (June to August), bi-monthly SPIs (August to September and September to October) and quinque-monthly SPI (June to October) matching with early, mid, late, and whole *kharif* period, respectively, whereas one corresponds to annual SPI (January to December). The study of SPI for whole *kharif* period besides early, mid and later periods of *kharif* cropping season was considered owing to the occurrence of drought episodes over these periods, influencing the growth of crops and revealing the contribution of rainfall deficiency over these periods to the whole *kharif* period deficiency. Apart from this, a brief spell of drought over the dryland ecosystem may have substantial damaging effects on the farming affairs.

3.3 Characteristics of meteorological drought

The SPI yields a shortage or surplus of water in relation to its normal availability. An understanding of major drought characteristics revolves around the severity, frequency, magnitude, duration, intensity, and return period (Hayes et al. 2004). In this investigation, these characteristics of drought were computed station-wise separately for early, mid, late, and whole *kharif* period, apart from the annual time scale. The computational procedure of these drought characteristics is summarized in the following sections:

3.3.1 Drought severity (S_D)

It implies toward a particular limit of SPI values. The more negative is the SPI records, the more severe the dry conditions will be. The accumulation of negative SPI values preceded and followed by positive SPI values is called severity. For example, drought severity values ranging within -1.00 to -1.49 , -1.50 to -1.99 and ≤ -2.00 were categorized as moderate, severe and extreme droughts, respectively. If it is considered regarding absolute values, the severity of a drought D was calculated as:

$$\text{Drought Severity } (S_D) = \sum_{i=1}^D \text{SPI}_i \quad (6)$$

3.3.2 Drought frequency (F_D)

Drought frequency is the proportion of occurrence of the sum total of rainless months and that of the overall spell of investigation in months. It was used to measure the liability of drought for the investigation period and expressed in percentage with respect to occurrence of drought (Wang et al. 2014; Tan et al. 2015). It was calculated as a fractional frequency and showed the probability of months that had SPI values less than or equal to the threshold level of drought ($\text{SPI} < 0$). Mathematically, it was calculated as:

$$\text{Drought Frequency } (F_D) = \frac{n}{N} \quad (7)$$

where n is the number of drought months and N is the total number of months during the study period.

3.3.3 Drought magnitude (M_D)

Drought magnitude is the sum total of water deficiency over the whole period of drought. It is the sum of negative deviations, i.e., the total decrease in rainfall values from their means and was mathematically computed as follows (Sirdas and Sen 2003):

$$M_{Dj} = \sum_{i=1}^m |\bar{X} - X_i| \quad (8)$$

where m is the number of water deficient years during the whole period of drought j , X_i is the depth of rainfall at month i and \bar{X} is the truncation level for all drought categories, as 0, -1.0 , -1.5 and -2.0 . Truncation was defined as the period when the deficiency of water became limited in such a way that conditions of drought no longer continued. The average monthly rainfall over the study period was considered as the level of truncation to measure the magnitude of drought for all stations considered in this study.

3.3.4 Drought intensity (I_D)

The division of the aggregated rainfall deficiency by drought span provides the intensity of drought (Sirdas and Sen 2003). The intensity of drought I_D of the j th parched duration is the proportion of M_D to its duration, D_D and was numerically represented as:

$$I_D = \frac{M_{Dj}}{D_{Dj}} \quad (9)$$

3.3.5 Drought duration (D_D)

Spinoni et al. (2014) stated that if a cycle of parched periods occurs first and next come a wet period, then it is termed as the period of dry duration. A drought event occurred when the rainfall of a particular year was lower than the specified truncation level (rainfall values below average values). The duration of a drought event was the number of consecutive days for which the rainfall deficiency remained below the specified truncation level at different time scales (Edossa et al. 2010; Jasim and Awchi 2020). It began when SPI was perpetually negative and extended to an intensity of -1.0 or slighter, although this episode ended as soon as the SPI value happened to be positive and is normally illustrated in years/months/weeks etc.

3.3.6 Return period (T_r)

This study used the concept of return period at first, developed by Gumbel (1958). It had considered the distribution of extremes in forecasting of upcoming extremes based

on how regularly it had occurred previously. It was estimated with less uncertainty, largely for smaller sample groups and was often applied for drought studies (Kim et al. 2002; Loukas and Vasiliades 2004; Ghosh 2019). In this study, the Gumbel probability distribution model was employed on the annual SPI data series, covering for a very long record, for about 57-years (1961–2017). Mathematically, it was expressed as:

$$S_T = S_m(1 + KC_V) \tag{10}$$

where S_T is the probable SPI with a return period of T years, C_v is the coefficient of variation, S_m is the mean of annual maximum SPI, K is the frequency factor represented by $(Y_T - \bar{Y})/\sigma$, in which Y_T is the reduced variate for T years, \bar{Y} is the mean value of reduced extremes and σ is the standard deviation of reduced extremes. Likewise, return periods for S_m were also estimated for each station. For this purpose, first $F(X)$ values were computed by employing Eqs. (11), (12), and (13):

$$F(X) = e[-e^{-b(X-a)}] \tag{11}$$

where a and b are two parameters of the moments of the population of annual extreme SPI series, and $F(X)$ is the likelihood of an annual maximum $S \leq X$. The parameters b and a were obtained using Eqs. (12) and (13):

$$b = \frac{\pi}{\sigma Q \sqrt{6}} \tag{12}$$

$$a = Q_m - \frac{\gamma}{b} \tag{13}$$

The return period for desired SPI (S_m) was computed by using Eq. (14):

$$T = \frac{1}{1 - F(X)} \tag{14}$$

where $F(X)$ is the probability of an annual SPI series obtained using Eq. (11).

3.4 Statistical analysis

For this study, statistical analyses such as the sum, frequencies, percentages, mean, standard deviation (SD), coefficient of variation (CV), skewness (C_s) and kurtosis (C_k) were carried out for each station for the period 1961–2017. Then, to detect the trends in SPI, both nonparametric (Mann–Kendall (MK) test, Sen’s Slope estimator) and parametric (simple linear regression) models were used. The MK test was found an excellent tool to examine the possible existence of significant trends in the time-series at various significance levels (Mayowa et al. 2015; Singh et al. 2020). The standard normal variable Z was used to detect the trend and its significance level. The positive (negative) values of Z showed rising (declining) trend in the time-series. In this study, the existence of statistically significant positive or negative trend was considered at 95% confidence level. The MK test is a rank-based test, which was used extensively for the verification of autocorrelation in the data series (Duhan and Pandey 2013). The test showed that if the lag-1 serial coefficient of the data is not statistically significant, then the MK test was performed without any modification to the original time series (Karpouzou et al. 2010; Luo et al. 2008; Pingale et al. 2014).

However, the existence of autocorrelation can increase the probability of detecting a significant trend (Bayazit and Onoz 2008). Therefore, in the present study, MK test was applied after pre-whitening for all stations and seasons to eliminate the effect of autocorrelation in the data series (Von Storch 1995; Partal and Kahya 2006; Mohammad and Jha 2014). Also, the nonparametric Sen's Slope estimator (Sen 1968) was used to detect the magnitude of the trend. It was closely associated with the MK test (Gilbert 1987) and provided a robust estimation of trend (Yue et al. 2002). Additionally, the parametric simple linear regression was also used to detect the trend in time-series in this study. These three methods were used widely in the time series investigations of the hydro-meteorological studies. A detailed discussion on these methods is available in (Deka et al. 2013; Pingale et al. 2014; Jaiswal et al. 2015; Mayowa et al. 2015; Singh et al. 2020). The above-mentioned methods were performed by using XLSTAT 2017 software.

3.5 Spatial investigation of meteorological drought

This study identified the geographical pattern of various drought attributes by employing the inverse distance weighting (IDW) interpolation technique. This technique is simple and among the most widely used interpolation techniques. This technique weights the influence of every contributing location by a normalized inverse of the interval from the master point to the interpolated point. It postulates that all contributing points have a weight, which declines with an increment in remoteness. It weights the locations nearer to the operating points larger than those farther away. This means that a drought feature or its extracted magnitude at a location of choice, was interpolated with the specified input data by applying weights that rested on the remoteness from respective stations and the intended position (Burrough and McDonnell 1998). The method yielded a uniform plane for the extraction of drought attributes, along with the unacceptable troughs and peaks. The interpolation of various droughts attributes using IDW technique was done by ArcGIS 10.2 software.

4 Results

4.1 Temporal and spatial characteristics of rainfall

4.1.1 Temporal variations of rainfall

A time-series plot exhibited that the mean annual rainfall over the dryland ecosystem of north western India was close to 584 mm, including high interannual variability ($SD=221.16$, $CV=37.90$), which ranged from 277 mm (in year 2002) to 839 mm (in year 1975) (Fig. 2). The lowest (highest) rainfall in the year 2002 (1975) may be attributed to prevalence of robust El-Nino (La-Nina) conditions (Bhardwaj et al. 2019). A station-wise time-series analysis of annual rainfall showed a high variation (increase and decrease) in the amount of rainfall at all stations within some years (Fig. 2). These plots also indicated toward aridity at each and every station. These observations were in correspondence to the findings of other studies on rainfall (Pingale et al. 2014; Meena et al. 2019). A steep variation in maximum and minimum yearly rainfall was registered at every station (Table 1). Additionally, both SD and CV had denoted the variability in annual rainfall and reliability of its persistence. The highest SD was observed at Banswara (386 mm), followed by Sirohi (321 mm) and Baran (300 mm) stations which are located at moderately elevated regions.

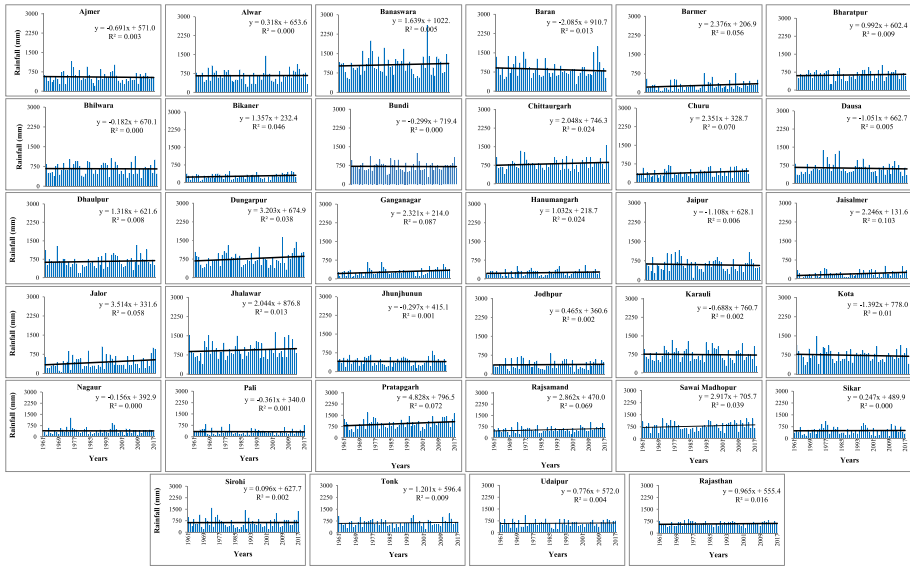


Fig. 2 Station-wise annual distribution of rainfall over dryland ecosystem of north western India between 1961 and 2017

The associated CV for annual rainfall varied from 26 percent (Bundi) to 61 percent (Barmer). These results of SD and CV clearly demonstrated steep variations in the volume of rainfall collected at each station yearly. Similarly, C_k and C_s are the measures of data peakedness, flatness and symmetry and their values for normal data distribution were zero or near zero. The positive values of C_k revealed the peaked distribution and vice versa. In the study area, Banswara and Nagaur stations had high C_k , whereas Bhilwara and Churu had low C_k . All the stations except Bharatpur and Sawai Madhopur had affirmative C_s , suggesting an increment in the quantity of rainfall than average. The dryland ecosystem exhibited non-significant rising trend in the amount of rainfall with a normal rate of rise close to 9.7 mm/decade. The station-wise mean yearly rainfall witnessed a significant rising trend at Barmer, Churu, Ganganagar, Jaisalmer and Pratapgarh stations which spread all over the state from low to high elevated regions. Among these stations, the maximum rate of increase was witnessed at Pratapgarh followed by Churu and Barmer. Apart from these five stations, Banswara, Bikaner, Chittaurgarh, Dhaulpur, Dungarpur, Hanumangarh, Jalore, Jhalawar, Rajsamand, Sawai Madhopur and Tonk stations also showed increasing but non-significant trends, whereas Baran, Dausa, Jaipur and Kota stations showed non-significant decreasing trends. The remaining stations over the dryland ecosystem showed almost constant trends in the annual rainfall.

4.1.2 Spatial distribution of rainfall

The spatial distribution of mean yearly rainfall over the dryland ecosystem between 1961 and 2017 is presented in Fig. 3. The mean annual rainfall exhibited rising rainfall tilts from west and north west to east and south east. The mean annual rainfall amount over the entire western and north western parts (low to moderately elevated)

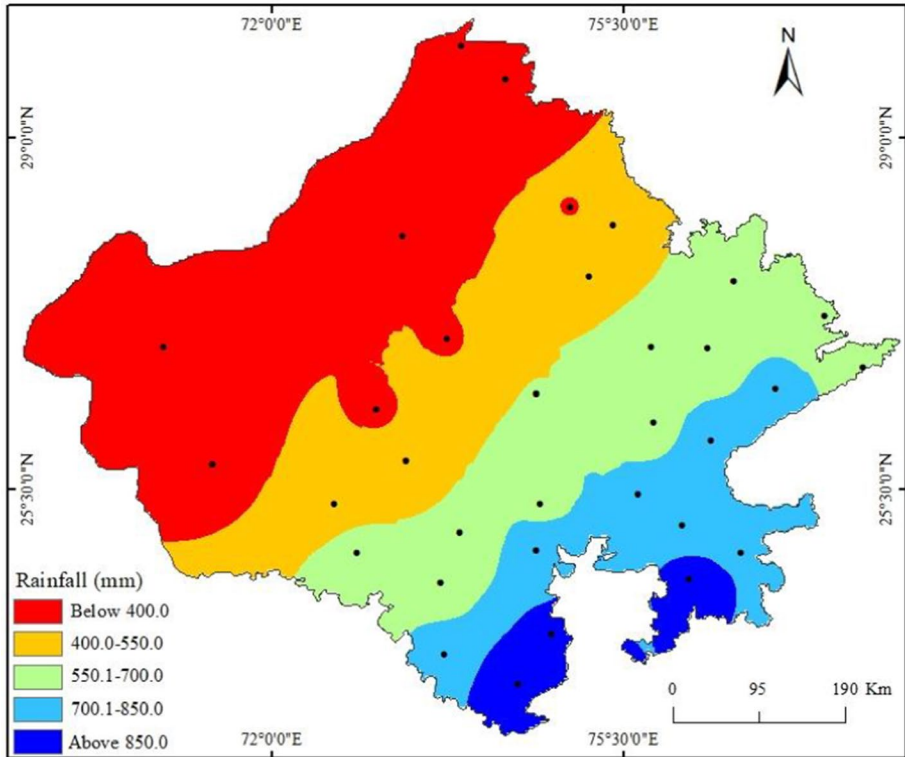


Fig. 3 Spatial distribution of annual rainfall over dryland ecosystem of north western India between 1961 and 2017

was observed less than 400 mm, whereas it was observed more than 850 mm over the south eastern parts (moderately to highly elevated). This decline in normal annual rainfall, running east to west, was mainly associated with the presence of Aravalli Mountains spreading north east to south west in central Rajasthan. The Arabian Sea branch of monsoon winds hit the eastern-facing slopes of these hills, therefore, south eastern parts received plenty of rainfall, whereas north western parts remained parched. The topography of the state is very complex and undulating, with the lowest and highest elevations of 6 m and 1698 m, which play a significant role on the rainfall pattern of the state (Fig. 1). Also, the moisture loss of monsoon winds with distance and position of Aravalli Mountains reduced the rainfall occurrence towards west from the south east. The lowest mean annual rainfall was observed at the Jaisalmer station (197 mm), whereas the highest at the Banswara (1070 mm) during 57-years study period (Table 1). According to Raju et al. (2013) the areas where normal annual rainfall was barely 550 mm were classified as arid zone, whereas the parts where annual normal rainfall exceeded 550 mm were termed as semi-arid zones. Following this classification, about 40 percent stations (12) experienced arid climate (west and north west) where average annual rainfall varied from 197 mm at Jaisalmer followed by 248 mm at Hanumangarh (low elevated region) to 497 mm at Sikar stations (high elevated region). The remaining

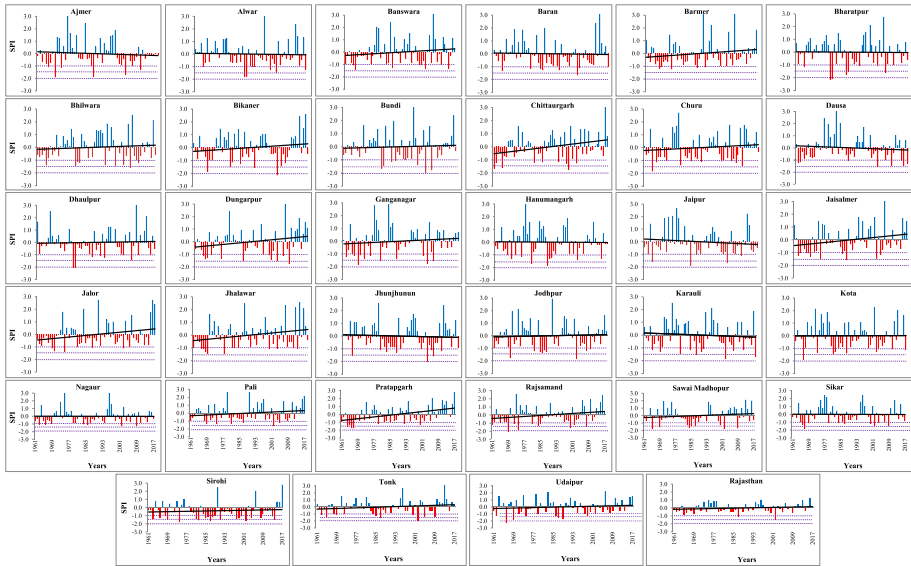


Fig. 4 Station-wise annual distribution of SPI values during early season over dryland ecosystem of north western India between 1961 and 2017

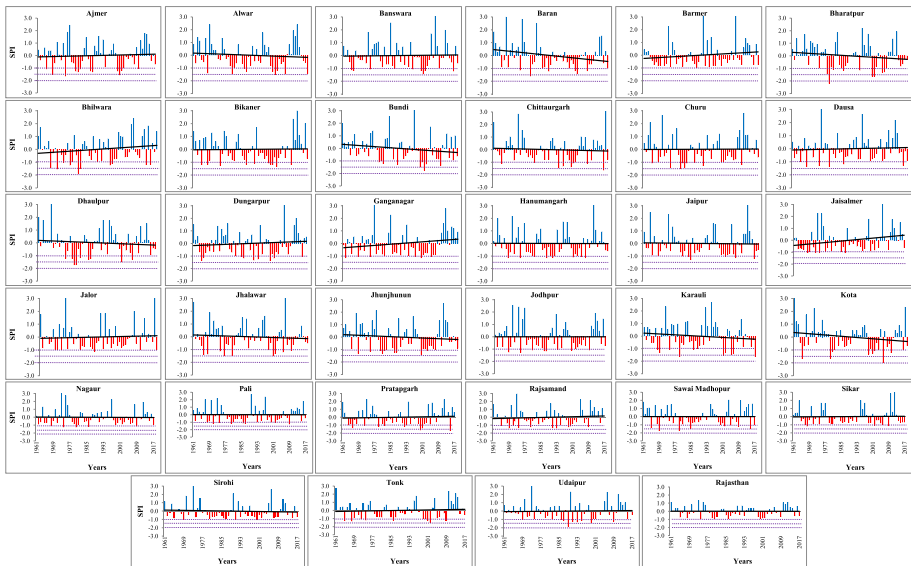


Fig. 5 Station-wise annual distribution of SPI values during mid-season over dryland ecosystem of north western India between 1961 and 2017

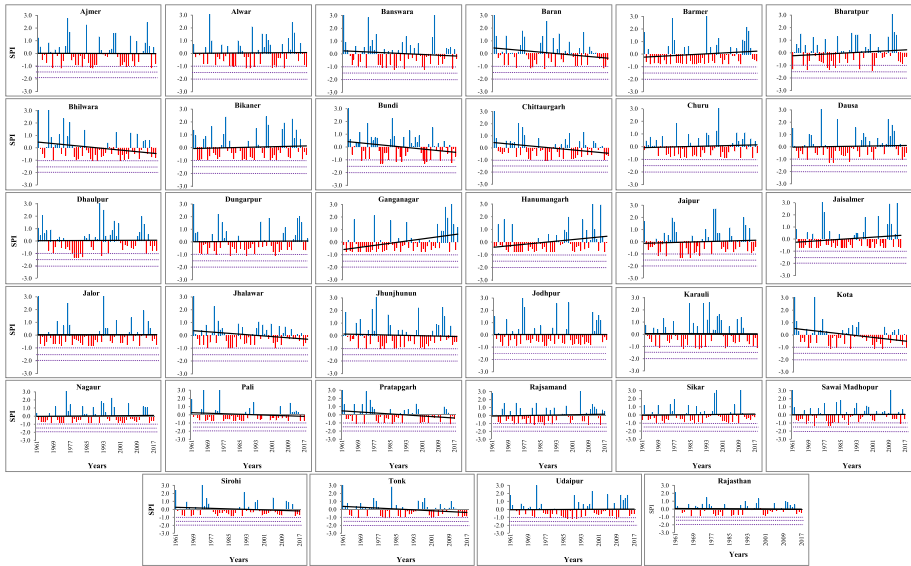


Fig. 6 Station-wise annual distribution of SPI values during late season over dryland ecosystem of north western India between 1961 and 2017

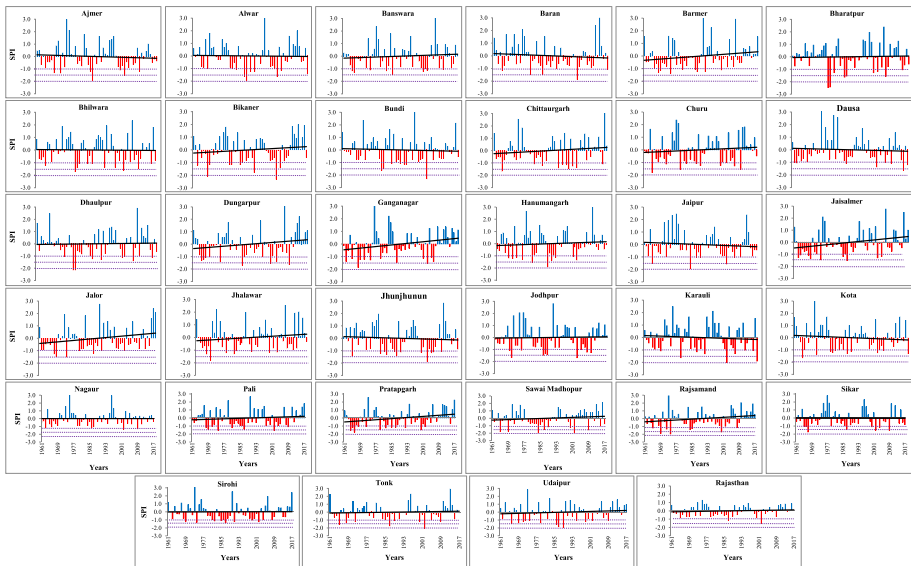


Fig. 7 Station-wise annual distribution of SPI values during whole *kharif* season over dryland ecosystem of north western India between 1961 and 2017

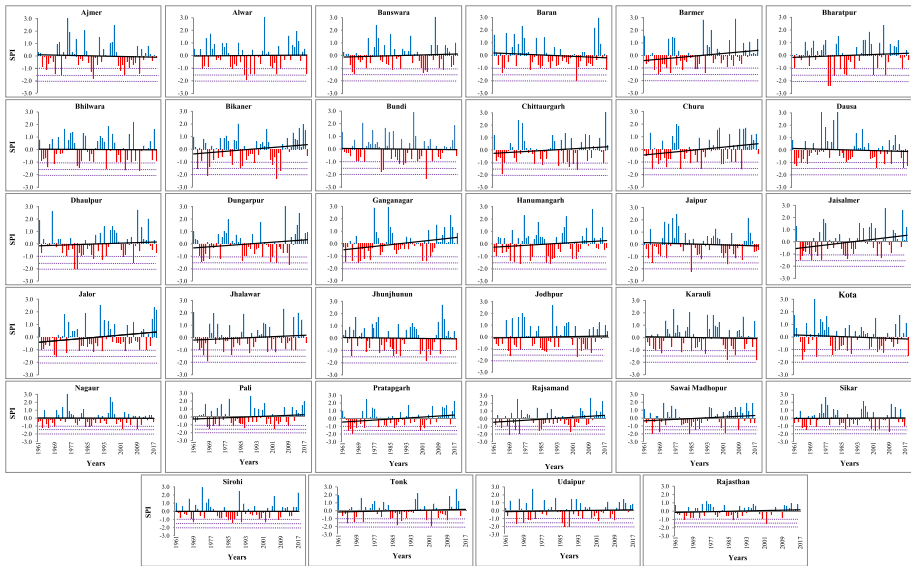


Fig. 8 Station-wise annual distribution of SPI values at annual time scale over dryland ecosystem of north western India between 1961 and 2017

21 stations (60 percent) experienced semi-arid climate where minimum rainfall was recorded at Ajmer (551 mm) and the highest rainfall (1070 mm) was recorded at Banswara station (Fig. 3; Table 1).

4.2 Temporal variations of meteorological drought

The SPI records at different time scales for the dryland ecosystem between 1961 and 2017 are presented in Figs. 4, 5, 6, 7 and 8. Noticeably, drought characteristics had changed with time and a mix of wet and dry spells were detected at different time steps.

4.2.1 Early season droughts

On the early season time step, only two drought episodes (1987 and 2002) with $SPI \leq -1.00$ were observed between 1961 and 2017 over the dryland ecosystem, whereas such drought episodes were widely prevalent among the stations (Fig. 4). At one time or the other, all stations experienced a drought in the year 2002. Maximum number of drought episodes with $SPI \leq -1.00$ were witnessed at Sirohi (20) followed by at Dungarpur (12) station. Similarly, extreme drought episodes in the year 1966, 1978 and 2002 with $SPI -2.22, -2.15$ and -2.14 at Udaipur, Bharatpur and Bikaner stations, respectively, were noteworthy. The greatest drought episode ($SPI = -2.22$) recorded at Udaipur station in the year 1966, had a return period of 29-years. In the area of study, a paired spell of five or more years of drought episodes were observed; the first spell occurred between 1965 and 1969, whereas the second occurred between 1984 and 1989. Among the stations, the longest drought period of 12-years each was witnessed at Sirohi (1991–2002) and Sawai Madhopur (1979–1990) stations.

4.2.2 Mid-season droughts

Mid-season SPI series (Fig. 5) represented a mixture of wet and dry years, but with a temporal variation. Like early season time step, all stations experienced drought in the year 2002. In the study area, four important drought events with $SPI \leq -0.90$ were observed between 1961 and 2017. Among them, drought of the year 2000 was found the most important with SPI of -0.93 . During the season, three consecutive drought periods were observed; first was from 1998 to 2003 (six years) and the second and third were from 1978–1982 to 1985–1989 (five years each). Among the stations, the longest drought period of 12-years was detected at Bikaner station from 1993 to 2004. Interestingly, a drought of mild, moderate, severe and extreme category was observed at each station in the years 1986 and 2002. The drought severity for the season was assessed and extreme drought ($SPI = -2.18$) was recorded at Bharatpur station in the year 1979 with a recurrence interval of 27-years.

4.2.3 Late season droughts

In the late season SPI time series (Fig. 6), three consecutive drought periods of five years each with different intensities were observed from 1978 to 1982, 1985 to 1989 and 2000 to 2004. During the season, the drought of 1968, with $SPI -0.89$ was found most important. Among the stations, the longest drought periods of 13 and 12-years were detected at Jalor (1977–1989) and Hanumangarh (1971–1982) stations, respectively. Apart from this, none of the station witnessed extreme drought episodes during the season. The late season trend line of SPI values mimicked the mid-season trend line and hence suggests toward a tendency of increased drought events. Remarkably, this season witnessed a consecutive drought period of three years at all stations, from 2000 to 2002.

4.2.4 Whole *kharif* season droughts

Based on the whole *kharif* season SPI plots (Fig. 7), the study period between 1961 and 2017 can be coarsely grouped into five uninterrupted excess and deficient episodes: (i) modest deficient episode (1979 to 1982); (ii) modest excess episode (1994 to 1998); (iii) fluctuating episode (2003 to 2017); (iv) peak deficit year (2002) and (v) peak surplus year (1975). Also, the analysis showed that at one time or the other, all stations experienced drought in the years 1987 and 2002. The lowest annual rainfall was recorded in 2002; however, the SPI plots displayed the maximum dryness during 1978 with $SPI-2.45$ at Bharatpur station accompanied by the year 1979 with $SPI-2.42$ for the corresponding station. Based on Gumbel probability distribution, these events had a return period of 37.5 and 35.5-years, respectively. Among the seasons, these drought events were found, the highest ever experienced extreme events. The drought episode at Dhaulpur station was the second-driest episode of the whole *kharif* season, in 1978 and 1979 ($SPI-2.15$ for both years). In addition to this, Bikaner station in the year 1968 ($SPI-2.06$), Jaipur in the year 1984 ($SPI-2.02$) and Alwar station in the year 1987 ($SPI-2.01$) witnessed extreme drought conditions. A diminishing trend of SPI values in the season indicated toward a tendency of wet conditions.

4.2.5 Annual droughts

From 12 months time lag SPI plots (Fig. 8), a complete absence of severe and extreme drought events was detected over the dryland ecosystem. However, two moderate drought events were detected in the years 2002 and 1987 amidst SPI records of -1.45 and -1.08 , respectively. Also, exceedingly high dryness with SPI less than -2.00 was consecutively recorded at Bharatpur and Dhaulpur stations in the years 1978 and 1979, respectively. The greatest drought event (SPI = -2.39) was observed at Bharatpur station during 1978 and 1979 with an estimated recurrence interval of 34.5-years. Like the whole *kharif* season, five uninterrupted excess and deficient phases were detected in the annual SPI: (i) modest deficient episode (1962–1966); (ii) modest excess episode (2010–2017); (iii) oscillating phase (2003–2017); (iv) peak deficit year (2002) and (v) peak surplus year (1975). Interestingly, at one time or the other, all stations experienced drought in the year 2002. The annual trend line of SPI values simulated the whole *kharif* season trend line and hence suggests that duration of wet spells will increase in future.

4.3 Spatial patterns of meteorological drought

The appraisal of drought severity provides valuable knowledge for management of water resources over a region. During the reporting period, the drought severity about SPI values at early, mid, late, whole *kharif* season and annual time spans was found to the tune of -0.72 , -0.71 , -0.60 , -0.73 and -0.74 , respectively. Drought severity for most stations (60 percent) at all-time spans except the late season was found ≤ -0.70 ; however, it had never crossed the end point of normal drought (i.e., 0.00 to -0.99). The drought severity in the state varied between -0.48 at Tonk (low elevated region) to -0.91 at Bharatpur station (moderately elevated region). Spatially speaking, there were distinct spatial differences in meteorological drought severity at multiple time scales (Table 2). Overall, north western, south eastern and north eastern parts (low to highly elevated) suffered from high drought severity, whereas central regions (highly elevated) had relatively low severity of droughts. Based on drought severity estimates, the five highest and least susceptible stations over the dryland ecosystem at five-time spans is exhibited in Table 3. Apart from the above, peak drought severity, on spatial scale, at early and whole *kharif* season exhibited a similar spatial arrangement with the maximum accumulation in north and north eastern parts spreading from low to highly elevated regions. At mid-season time scale, peak drought severity was found to be greatest in eastern parts, whereas low drought severity prevailed all over the state during late season. At the annual time span, peak drought severity was found greatest in eastern and south eastern areas (moderately to highly elevated) and extreme in northern parts (low elevated). Thus, making the parts of Great Indian Desert is more sensitive to long duration droughts. The driest year severity was similar to each other at early, whole *kharif* and annual time scales, which witnessed larger coverage of severe to extreme droughts over the northern, north eastern and eastern areas. However, at the remaining time scales the region experienced mild to moderate drought.

The spatial arrangement of percentage drought frequency events, referring to mild, moderate, severe and extreme droughts at multiple time scales, is presented in Fig. 9. It was noticed that the percentage of drought frequency of the respective category varied in stations as well as at multiple SPI time spans. As expected, it was observed that over a given period mild or normal droughts turned up repeatedly, whereas extreme dryness had turned up infrequently. While examining extreme dryness at variable periods, it was

Table 2 Station-wise severity of SPI values at different time scales: (a) drought severity, (b) peak drought severity and (c) driest year severity over dryland ecosystem of north western India between 1961 and 2017

Stations	Early season			Mid-season			Late season			Whole <i>kharif</i> season			Annual		
	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS
Ajmer	-0.64	-1.88	-0.68	-0.80	-1.67	-1.03	-0.72	-1.17	-1.67	-0.73	-1.94	-1.49	-0.77	-1.78	-1.58
Alwar	-0.66	-1.77	-1.08	-0.73	-1.52	-1.19	-0.68	-1.16	-1.43	-0.78	-2.01	-1.48	-0.67	-1.90	-1.70
Banswara	-0.68	-1.38	-0.17	-0.62	-1.43	-0.81	-0.60	-1.20	-1.31	-0.71	-1.37	-1.29	-0.78	-1.45	-1.21
Baran	-0.64	-1.65	-0.96	-0.68	-1.60	-1.43	-0.56	-1.21	-1.65	-0.67	-1.87	-1.99	-0.72	-1.99	-1.87
Barmer	-0.63	-1.24	0.00	-0.54	-0.98	-0.60	-0.69	-0.79	-1.00	-0.67	-1.39	-0.90	-0.73	-1.44	-0.90
Bharatpur	-0.84	-2.15	-0.38	-0.91	-2.18	-0.86	-0.66	-1.40	-1.10	-0.79	-2.45	-0.96	-0.8	-2.39	-1.18
Bhilwara	-0.79	-1.57	-0.92	-0.76	-1.86	-0.60	-0.68	-1.04	-1.34	-0.8	-1.77	-1.66	-0.7	-1.70	-1.65
Bikaner	-0.75	-2.14	-0.94	-0.70	-1.34	-1.34	-0.59	-0.94	-2.14	-0.78	-2.30	-2.29	-0.83	-2.29	-2.30
Bundi	-0.71	-1.99	-1.16	-0.76	-1.76	-1.25	-0.66	-1.26	-1.99	-0.74	-2.36	-2.33	-0.77	-2.33	-2.36
Chittaurgarh	-0.72	-1.77	-0.58	-0.71	-1.65	-0.44	-0.68	-1.07	-1.25	-0.7	-1.70	-1.55	-0.73	-1.92	-1.46
Churu	-0.72	-1.84	-0.86	-0.71	-1.49	-0.49	-0.59	-0.86	-0.77	-0.74	-1.79	-0.74	-0.65	-1.58	-1.01
Dausa	-0.69	-1.57	-0.14	-0.64	-1.37	-0.37	-0.53	-1.24	-1.57	-0.66	-1.62	-1.39	-0.79	-1.39	-1.37
Dhaulpur	-0.63	-2.04	-0.28	-0.73	-1.73	-0.23	-0.74	-1.30	-1.03	-0.76	-2.15	-0.85	-0.84	-2.02	-1.06
Dungarpur	-0.75	-1.76	-0.16	-0.77	-1.39	-0.67	-0.63	-1.10	-1.55	-0.68	-1.70	-1.48	-0.86	-1.66	-1.38
Ganganagar	-0.78	-1.84	-0.31	-0.66	-1.15	-0.76	-0.63	-0.75	-1.75	-0.71	-1.84	-1.41	-0.82	-1.56	-1.55
Hanumangarh	-0.75	-1.87	-0.34	-0.72	-1.16	-0.98	-0.53	-0.78	-1.38	-0.71	-1.92	-1.21	-0.7	-1.59	-1.36
Jaipur	-0.61	-1.92	-0.82	-0.71	-1.32	-0.91	-0.63	-1.31	-1.65	-0.66	-2.02	-1.62	-0.71	-2.22	-1.65
Jaisalmer	-0.68	-1.52	-0.19	-0.60	-1.06	-0.83	-0.55	-0.68	-1.45	-0.69	-1.53	-1.15	-0.74	-1.47	-1.30
Jalor	-0.58	-1.38	-0.15	-0.61	-1.13	-0.57	-0.58	-0.82	-1.11	-0.68	-1.52	-1.08	-0.66	-1.58	-0.98
Jhalawar	-0.68	-1.47	-0.47	-0.67	-1.51	-0.33	-0.73	-1.01	-1.05	-0.71	-1.83	-1.19	-0.66	-1.92	-1.16
Jhunjhunun	-0.80	-2.01	-0.63	-0.79	-1.40	-1.06	-0.59	-1.04	-2.01	-0.79	-1.87	-1.83	-0.73	-1.83	-1.87
Jodhpur	-0.76	-1.83	-0.33	-0.74	-1.27	-0.98	-0.50	-0.84	-1.83	-0.77	-1.69	-1.70	-0.82	-1.70	-1.69
Karauli	-0.79	-1.82	-1.03	-0.77	-1.64	-1.34	-0.49	-1.22	-1.82	-0.79	-2.00	-1.79	-0.69	-1.81	-2.00
Kota	-0.74	-1.91	-0.54	-0.83	-2.00	-0.44	-0.54	-1.11	-1.29	-0.71	-1.65	-1.19	-0.7	-1.78	-1.28
Nagaur	-0.61	-1.26	-0.85	-0.66	-1.26	-0.86	-0.57	-0.85	-1.26	-0.66	-1.36	-1.38	-0.78	-1.39	-1.36

Table 2 (continued)

Stations	Early season			Mid-season			Late season			Whole <i>kharif</i> season			Annual		
	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS	DS	PDS	DYS
	Pali	-0.69	-1.53	-0.37	-0.67	-1.25	-1.08	-0.70	-0.72	-1.53	-0.79	-1.54	-1.52	-0.79	-1.52
Pratapgarh	-0.78	-1.73	-0.83	-0.79	-1.72	-0.80	-0.54	-1.13	-0.86	-0.79	-1.76	-1.24	-0.71	-1.93	-1.05
Rajsamand	-0.72	-2.08	0.00	-0.66	-1.39	-0.36	-0.55	-1.21	-1.21	-0.79	-1.95	-1.05	-0.67	-2.02	-0.97
Sawai Madhopur	-0.75	-1.79	-0.75	-0.78	-1.74	-1.17	-0.59	-1.37	-1.79	-0.81	-1.97	-1.86	-0.65	-2.02	-1.97
Sikar	-0.68	-1.78	-0.69	-0.64	-1.19	-1.07	-0.50	-0.96	-1.44	-0.67	-1.74	-1.53	-0.72	-1.65	-1.49
Sirohi	-0.88	-1.77	-0.56	-0.55	-1.07	-0.72	-0.51	-0.84	-1.64	-0.74	-1.35	-1.36	-0.72	-1.37	-1.24
Tonk	-0.74	-1.90	-0.94	-0.74	-1.51	-1.51	-0.48	-1.09	-1.90	-0.7	-2.07	-1.97	-0.73	-1.97	-2.07
Udaipur	-0.83	-2.22	-0.51	-0.69	-1.83	-0.11	-0.77	-1.15	-1.00	-0.84	-1.94	-1.24	-0.76	-2.04	-1.09
Rajasthan	-0.72	-1.45	-1.44	-0.71	-0.93	-1.45	-0.60	-0.89	-1.45	-0.7339	-1.47	-1.45	-0.73	-1.45	-1.47

DS (drought severity), PDS (peak drought severity) and DYS (driest year severity)

Table 3 SPI based five highest and lowest drought vulnerable stations at different time scales over dryland ecosystem of north western India between 1961 and 2017

Seasons	Highest five vulnerable stations	Lowest five vulnerable stations
Early	Udaipur, Bharatpur, Bikaner, Rajsamand, Dhaulpur	Barmer, Nagaur, Jalor, Banswara, Jhalawar
Mid	Bharatpur, Kota, Bhilwara, Udaipur, Bundi	Barmer, Jaisalmer, Sirohi, Jalor, Ganganagar
Late	Bharatpur, Sawai Madhopur, Jaipur, Dhaulpur, Bundi	Jaisalmer, Pali, Ganganagar, Hanumangarh, Barmer
Whole <i>kharif</i>	Bharatpur, Bundi, Bikaner, Dhaulpur, Tonk	Sirohi, Nagaur, Banswara, Barmer, Jalor
Annual	Bharatpur, Bundi, Bikaner, Jaipur, Udaipur	Sirohi, Nagaur, Dausa, Barmer, Banswara

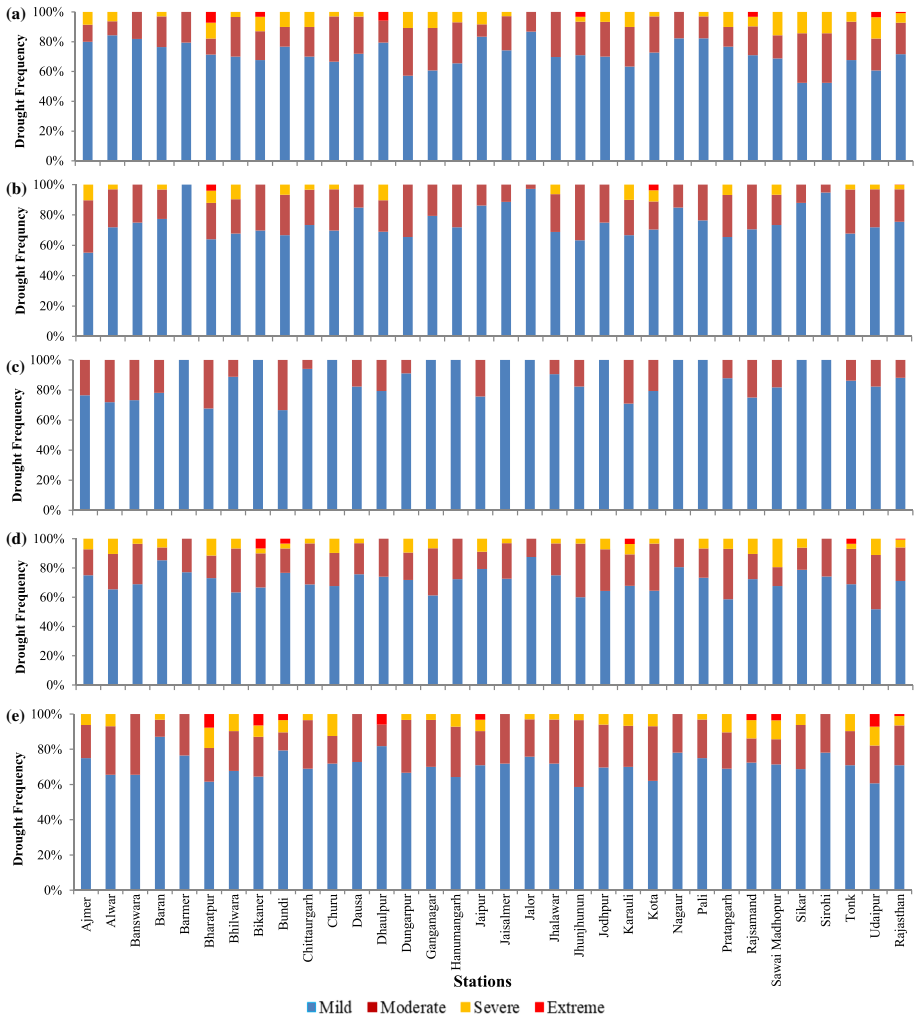


Fig.9 Station-wise mild, moderate, severe and extreme drought frequency at different time scales **a** early season, **b** mid-season, **c** late season, **d** whole *kharif* season and **e** annual over dryland ecosystem of north western India between 1961 and 2017

observed that extreme dryness mostly occurred in moderately to highly elevated regions, spread over small pockets in northern, north eastern and south eastern regions. However, when the drought classes (mild and above) were examined comprehensively at early, mid and late season time scales, then western (Great Indian Desert) and central regions were the areas where droughts occurred frequently (Fig. 10a–c). In the early *kharif* season and annual time spans, areas which were captured most commonly by aridity of mild and above classes were witnessed in western, central, north eastern and south eastern zones of the dryland ecosystem (Fig. 10d–e).

The geographical distribution of drought magnitude, duration and intensity is shown in Table 4. Annually, the maximum drought magnitude of 643 mm was witnessed at Banswara station, whereas the minimum magnitude of 157 mm was observed at Bikaner.

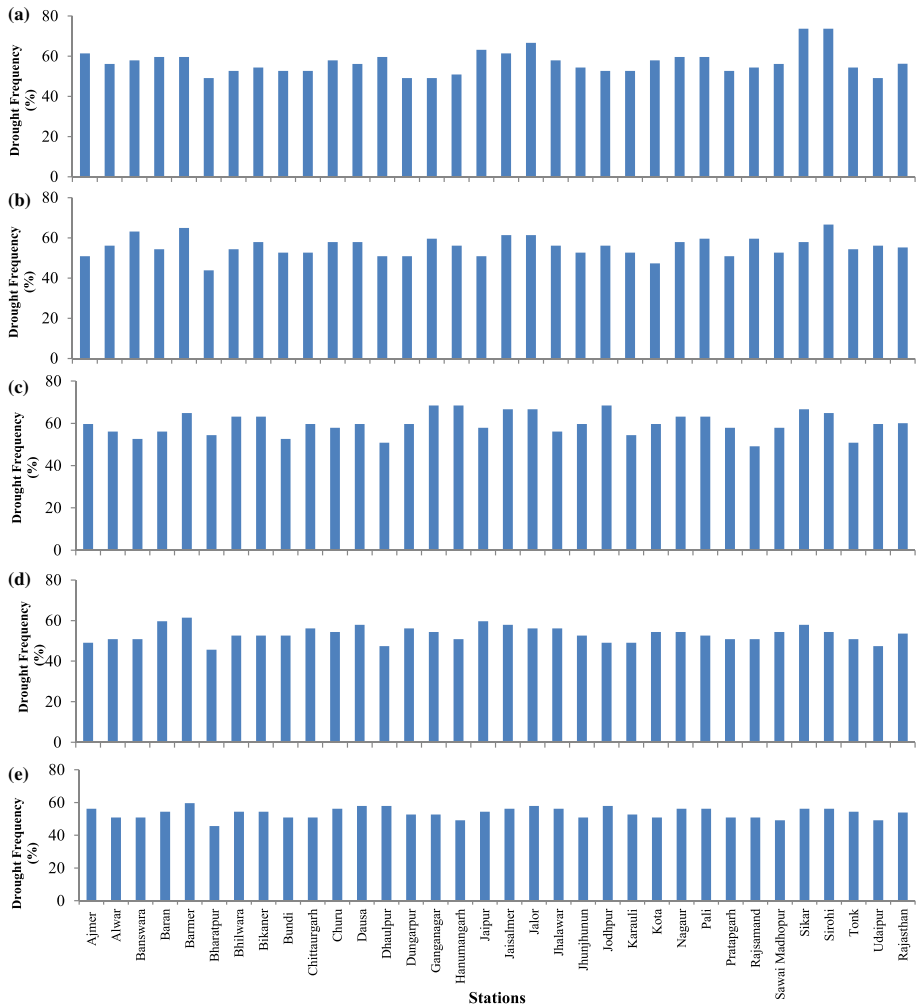


Fig. 10 Station-wise drought frequency at **a** early season, **b** mid-season, **c** late season, **d** whole *kharif* season and **e** annual time scales over dryland ecosystem of north western India between 1961 and 2017

Other stations which experienced greater drought magnitudes include Sawai Madhopur, Jhalawar, Pratnagarh and Pali stations that fall mostly in central, eastern and south eastern parts located in highly elevated regions of the state. Likewise, the maximum and minimum drought magnitudes of the whole *kharif* season were observed at Banswara and Bikaner stations, respectively, however, when evaluated for most parts of the dryland ecosystem, greater drought magnitudes were witnessed in moderately to highly elevated regions (south eastern parts only). Interestingly, low drought magnitudes were noticed during mid and late season time spans. Again, greater drought magnitudes were witnessed mostly in south eastern parts (highly elevated) during early season.

During the study period, average drought duration based on SPI at five-time spans for most stations (more than 75 percent) was 2–4 decades, while the state average value was recorded to the tune of 2.36, 2.32, 2.58, 2.31 and 2.24 decades, respectively. Among the

Table 4 Station-wise drought characteristics i.e., magnitude (M), duration (L) and intensity (I) at different time scales over dryland ecosystem of north western India between 1961 and 2017

Stations	Early season			Mid-season			Late season			Whole <i>Kharif</i> season					
	M	L	I	M	L	I	M	L	I	M	L	I	M	L	I
Ajmer	199.99	2.22	90.00	207.84	1.92	108.44	126.96	2.47	51.36	357.78	2.75	130.10	390.25	2.97	131.30
Alwar	205.92	1.75	117.67	368.74	3.25	113.46	151.79	2.25	67.46	310.64	1.81	170.99	292.70	1.83	159.66
Banswara	477.53	2.06	232.31	465.04	2.53	183.97	191.73	1.99	96.26	630.15	2.13	295.84	642.89	2.11	304.53
Baran	446.12	2.36	188.94	273.16	2.03	134.71	171.06	2.54	67.30	452.40	2.27	192.30	471.59	2.19	214.90
Barmer	203.21	2.17	93.79	200.37	2.99	67.10	87.13	2.86	30.45	269.62	2.46	109.67	238.39	2.33	102.17
Bharatpur	261.45	1.71	153.04	315.19	2.75	114.61	120.01	2.22	54.00	275.37	2.00	131.26	218.54	1.56	140.49
Bhilwara	321.24	2.08	154.19	227.23	2.23	112.05	132.37	2.50	52.95	357.78	2.75	130.10	330.96	2.03	163.21
Bikaner	176.67	2.89	61.15	112.22	2.44	45.91	69.42	2.44	28.40	152.56	2.31	66.04	156.65	1.57	99.81
Bundi	199.93	1.72	116.09	252.87	2.03	124.70	137.64	2.25	61.17	252.73	2.00	126.36	269.45	1.92	140.58
Chittaurgarh	401.35	2.67	150.51	298.96	2.28	131.25	154.38	2.44	63.16	374.00	2.58	174.68	400.13	2.64	151.62
Churu	191.89	2.44	78.50	128.74	1.99	64.82	66.49	2.17	30.69	235.71	2.38	105.36	195.45	1.75	111.68
Dausa	304.52	2.17	140.55	257.29	2.42	106.46	108.47	2.43	44.63	360.69	2.36	155.34	392.50	2.83	138.53
Dhaulpur	262.11	2.15	121.75	303.40	2.33	130.03	149.54	2.33	64.09	365.87	2.14	154.03	336.58	2.06	163.74
Dungarpur	276.43	1.76	156.71	402.05	2.39	168.30	200.86	2.89	69.40	481.60	2.58	196.07	487.91	2.39	204.24
Ganganagar	118.37	1.81	65.56	123.69	2.31	53.65	62.55	2.13	29.43	205.15	2.58	76.31	181.26	2.06	88.18
Hanumangarh	123.37	2.07	59.62	117.91	2.06	57.36	99.52	3.44	28.89	153.07	2.38	60.62	193.51	1.72	112.36
Jaipur	310.96	2.51	123.70	289.43	2.44	118.40	105.55	2.56	41.30	427.55	2.83	131.82	439.11	2.61	168.69
Jaisalmer	210.32	3.13	67.30	147.53	2.92	50.58	60.64	2.86	21.19	210.82	2.75	72.39	238.35	2.68	88.92
Jalor	495.11	3.78	131.06	197.66	2.00	98.83	132.41	3.33	39.72	416.19	2.62	153.20	395.64	2.22	178.04
Jhalawar	497.51	2.58	192.58	275.43	2.14	128.77	148.12	1.78	83.32	452.10	2.29	195.95	563.46	2.61	215.79
Jhunjhunum	260.57	2.64	98.74	188.34	2.17	86.93	69.44	2.08	33.33	293.67	2.42	121.31	254.39	2.00	127.20
Jodhpur	176.10	1.83	96.05	198.13	2.14	92.63	137.14	3.69	37.12	227.48	1.93	114.11	281.35	2.43	115.76
Karauli	283.46	1.71	165.93	306.40	2.14	143.25	124.89	1.94	64.30	449.14	2.33	206.79	424.39	2.06	206.46
Kota	256.30	2.04	125.53	281.95	2.08	135.34	127.28	2.56	49.81	341.19	2.13	152.69	470.27	1.93	243.66
Nagaur	257.15	2.51	102.29	134.46	1.92	70.66	87.15	2.97	29.32	230.67	1.88	116.49	276.83	2.13	130.27

Table 4 (continued)

Stations	Early season			Mid-season			Late season			Whole <i>Kharif</i> season			Annual		
	M	L	I	M	L	I	M	L	I	M	L	I	M	L	I
	Pali	433.32	3.24	133.90	287.60	2.94	97.68	111.91	2.86	39.11	386.60	2.31	161.25	492.15	3.04
Pratapgarh	336.30	1.82	184.83	265.55	1.89	140.53	214.92	3.17	67.87	470.03	2.00	236.86	550.52	2.58	213.37
Rajsamand	238.29	2.29	103.98	186.64	2.03	92.04	104.79	1.94	53.89	274.07	2.07	131.32	230.17	1.76	130.49
Sawai Madhopur	516.72	2.92	177.16	293.26	2.08	140.77	88.74	1.99	44.73	424.10	2.23	201.46	581.16	2.72	213.49
Sikar	307.56	2.44	125.82	293.90	3.00	97.97	88.77	2.97	29.87	349.58	2.43	141.00	379.01	2.42	156.83
Sirohi	879.34	3.99	220.60	389.20	3.13	124.55	216.93	3.36	64.54	521.09	2.21	232.04	466.57	2.13	219.56
Tonk	380.65	2.71	140.55	205.27	1.94	105.57	135.73	2.33	58.17	364.77	2.67	127.33	447.68	2.92	153.49
Udaipur	198.77	1.61	123.38	172.80	1.81	95.70	216.69	3.40	63.68	228.89	1.50	153.64	258.83	1.79	144.46
Rajasthan	309.35	2.36	130.11	247.52	2.32	107.18	127.30	2.58	50.33	342.52	2.31	149.23	362.08	2.24	151.94

M (drought magnitude), L (drought duration) and I (drought intensity)

time spans, the maximum duration of drought was recorded at Sirohi station experiencing a normal duration of 3.99 decades during early season time span, while the minimum value for the greatest drought duration was witnessed at Jaipur station with a normal record of 2.83 decades during the whole *kharif* season time scale. Conversely, it was found that minimum at Udaipur station having an average of 1.50 decades during *kharif* season time scale, whereas the largest value of minimum drought duration was detected at Bharatpur station by a mean value of 1.56 decades. Spatially speaking, at early, mid and late season time scales, the western, northern and central parts (low to moderately elevated) were more susceptible to somewhat longer duration of droughts (Table 4). However, during early

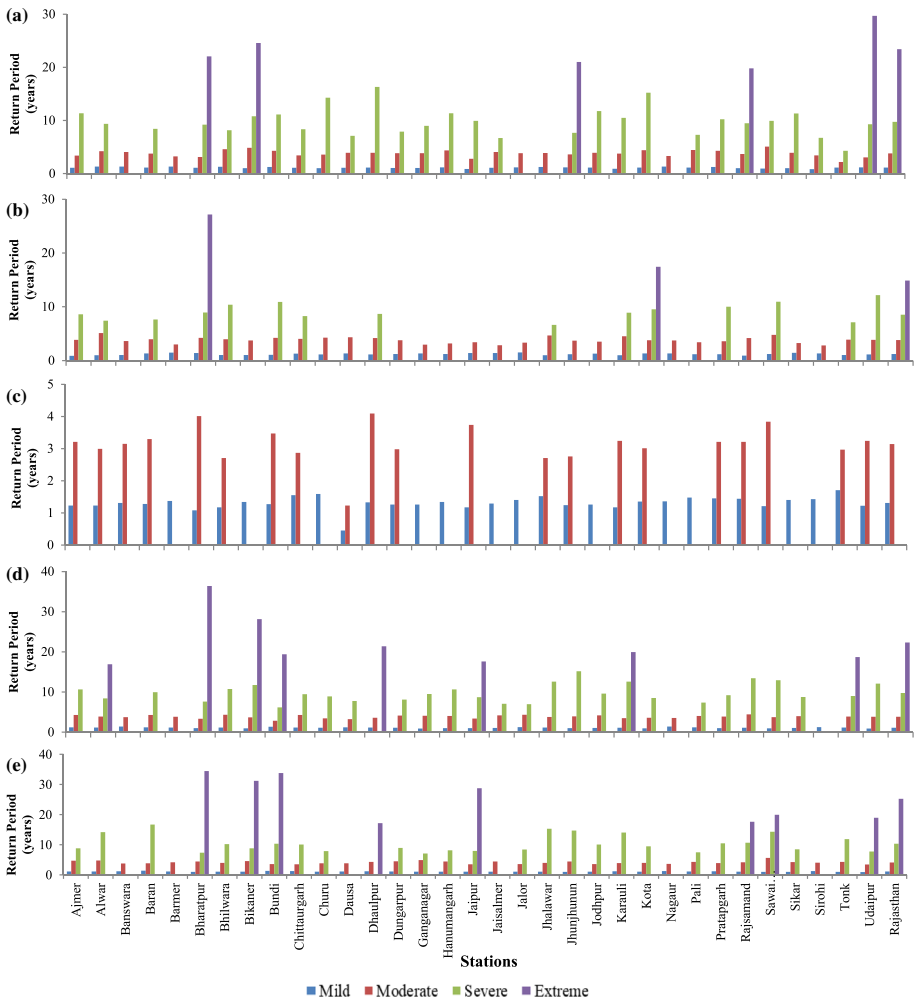


Fig. 11 Station-wise return periods of mild, moderate, severe and extreme drought at **a** early season, **b** mid-season, **c** late season, **d** whole *Khariif* season and **e** annual time scales over dryland ecosystem of north western India between 1961 and 2017

kharif season and annual time spans, it was found comparatively longer in smaller pockets of western, central and south eastern parts located in moderately to highly elevated regions.

Interestingly, the highest drought intensity was detected at Banswara station at all-time scales, with 232 mm/decade (early), 184 mm/decade (mid), 96 mm/decade (late), 296 mm/decade (whole *kharif*) and 304 mm/decade (annual), respectively. Similarly, minimum intensity was recorded at Hanumangarh station with 59.6 mm/decade (early), at Bikaner with 45.9 mm/decade (mid), at Jaisalmer with 21 mm/decade (late), at Hanumangarh with 60.6 mm/decade (whole *kharif*) and at Ganganagar station with 88.2 mm/decade (annual). The state average was 130.1, 108.7, 50.4, 149.1 and 160.4 mm/decade at early, mid, late, whole *kharif* and annual time scales, respectively, and concurrently, it may be the expected average rainfall deficiency over the dryland ecosystem in any future drought year at these time spans. The drought intensity at selected time scales is presented in Table 4.

Drought return periods contribute toward the likelihood of a drought event, which is hopefully applied for accommodating the mitigation measures. The estimated drought periods at various SPI time orders are presented in Fig. 11. Smaller return periods indicated the higher drought risk and vice versa. As it may be evidently noticed in Fig. 11a–c that return periods for mild and moderate drought conditions were smaller, whereas it was longer for severe and extreme droughts. In the area of study, return periods of severe drought at early, whole *kharif* and annual time scales (longer time scales) were noticed, smaller (below 20-years) in northern, southern, eastern and smaller pockets of western Rajasthan (Fig. 11d–e). Droughts below 20-years of return periods with an SPI in the range of -1.5 enveloped 70–80 percent of the dryland ecosystem. Moreover, the state of affairs reversed in the case of extreme drought. The return period count of extreme drought was observed to be highest over moderately to highly elevated regions spread over small pockets covering north western, eastern and south eastern regions, which suggest that these pockets are more frequently hit by extreme droughts. The spatial extent of drought return periods during the mid and late seasons (shorter time scales) is consistent with each other except the return period of severe drought during mid-season when it almost replicated the similar return periods as that of the longer time scales. On the entire state spectrum, the northern, southern and eastern parts (low to moderately elevated) were found more susceptible to recurrent attacks of severe drought; however, extreme drought hit more frequently in pockets, which were located over north western, eastern and south eastern zones (low to highly elevated). The return periods of largest-ever recorded drought at different time span over the dryland ecosystem are presented in Fig. 12.

Rainfall truncation level is the threshold level of rainfall beneath which conditions of drought get under way. In the study area, the development of drought conditions had increased coarsely from west and north west (low elevated) to east and south east (moderately to highly elevated) due to truncation level of rainfall (Fig. 13). This is not a surprising conclusion, since the eastern and south eastern parts were mainly associated with the position of Aravalli Mountains spreading north east to south west in the central zone of Rajasthan. At early, mid, whole *kharif* and annual time scales, the rainfall truncation level values were more over eastern and south eastern parts (highly elevated). In the late season time step, truncation rainfall values reached at their maximum, therefore, were more susceptible to droughts (Fig. 13c).

The spatial distribution in trends of drought is presented in Table 5. A visual inspection of drought trends at all-time scales nearly confirmed the results of each test, except the whole *kharif* season. Here it is important to reveal that drought severity was observed opposite to the rainfall trend analysis. Therefore, positive (increasing) trends indicated wet conditions, whereas negative (decreasing) trends indicated dry conditions. At all-time

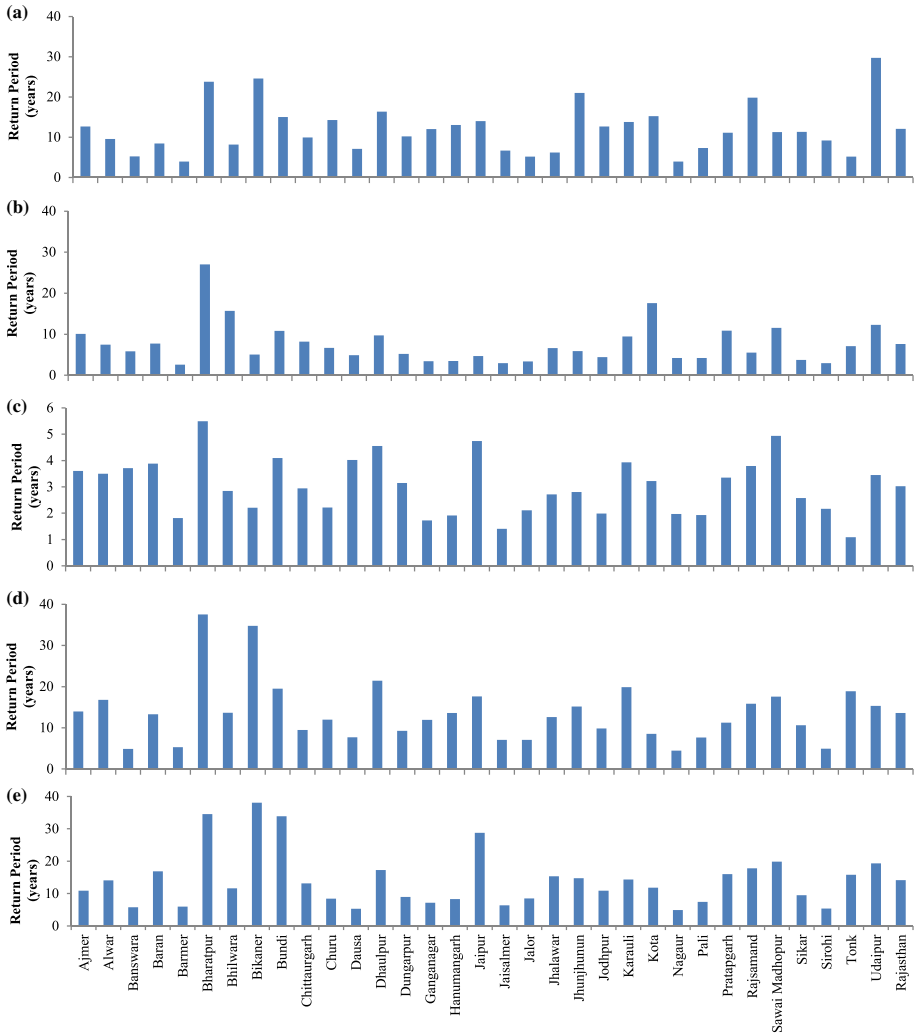


Fig. 12 Station-wise peak severity return periods at **a** early season, **b** mid-season, **c** late season, **d** whole *kharif* season and **e** annual time scales over dryland ecosystem of north western India between 1961 and 2017

spans, and the overall trends in SPI series were found positive in the dryland ecosystem. Remarkably, at all-time scales, only Baran station, despite the level of significance, witnessed increased dry conditions (negative trends) over the study period. At early season time scale, significant positive trends (wet conditions) were noticed at Chittaurgarh and Pratapgarh stations (southern parts), whereas at mid- and late season time spans, significant positive trends (significant at 95% confidence level) were observed all over the dryland ecosystem (Table 5). At whole *kharif* season time scale, significant increasing wet conditions (positive trends) were noticed at Ganganagar (northern), Jaisalmer (western) and Pratapgarh (southern) stations. Finally, at annual time scale, drought trends continued

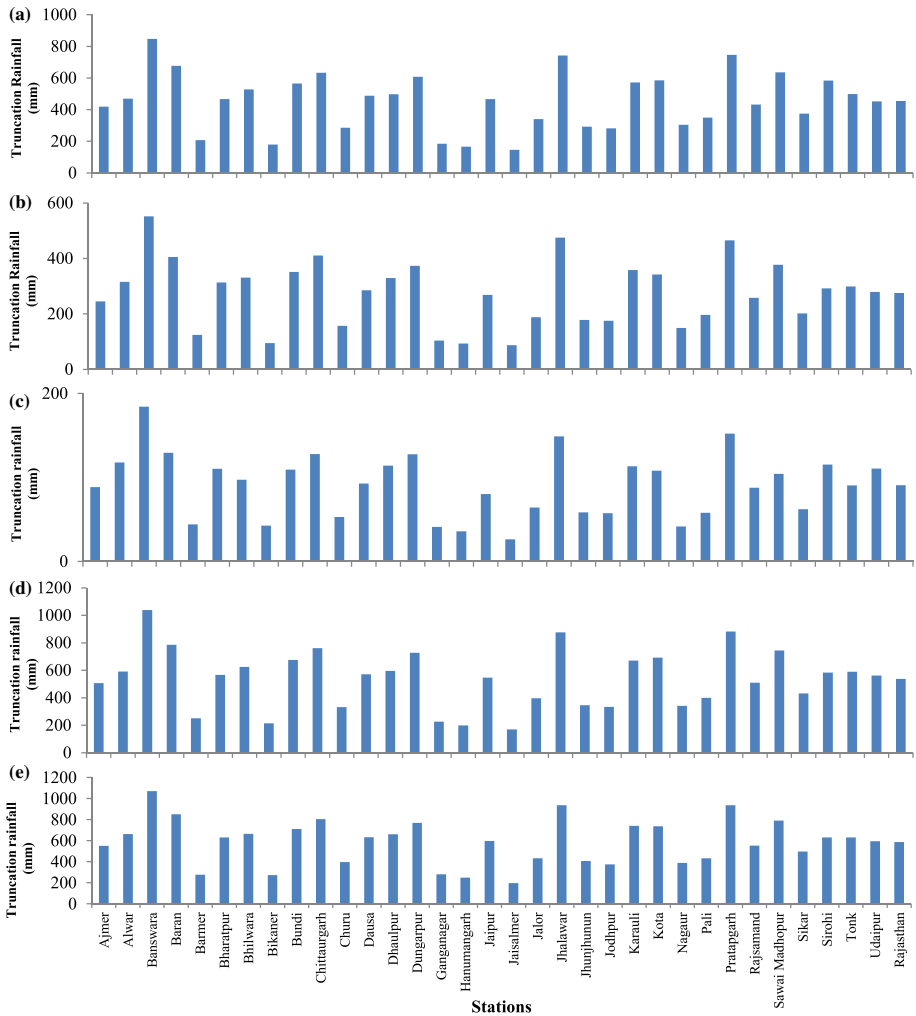


Fig. 13 Station-wise truncation level of rainfall for drought at **a** early season, **b** mid-season, **c** late season, **d** whole *kharif* season and **e** annual time scales over dryland ecosystem of north western India between 1961 and 2017

alike at Ganganagar, Jaisalmer and Pratapgarh apart from Barmer and Churu stations. Finally, it is important to point out that almost at all-time scales, the western, northern and southern parts (low to moderately elevated) of the dryland ecosystem experienced more wetter conditions (significant at 95% confidence level), whereas north eastern, eastern and south eastern regions (moderately to highly elevated) witnessed increased drier situations, though statistically it was found non-significant.

Table 5 Station-wise trend and level of significance by Mann–Kendall test, Sen’s slope estimator and Simple linear regression analysis at different time scales over dryland ecosystem of north western India between 1961 and 2017

Station	Early season			Mid-season			Late season			Whole Kharif season			Annual		
	Z	β	R	Z	β	R	Z	β	R	Z	β	R	Z	β	R
Ajmer	-0.250	-0.002	0.500	0.470	0.005	0.320	-0.180	0.002	0.510	-0.330	-0.030	0.530	-0.250	-0.010	0.660
Alwar	-0.970	-0.008	0.790	-0.960	-0.008	0.060	-0.170	0.001	0.020	-0.450	-0.040	0.840	0.000	0.000	0.870
Banswara	1.020	0.007	0.250	-0.420	0.002	0.450	-0.520	0.005	0.400	0.410	0.000	0.500	0.280	0.000	0.600
Baran	-0.810	-0.006	0.800	-1.880	-0.015	0.130	-1.390	-0.010	0.130	-1.010	-0.010	0.450	-0.810	-0.010	0.390
Barmer	1.650	0.009	0.180	0.990	0.005	0.860	1.530	0.005	0.560	1.930	0.010	0.140	2.21*	0.01*	0.070
Bharatpur	-0.310	-0.002	0.920	-1.340	-0.011	0.430	0.940	0.007	0.120	-0.060	0.000	0.790	0.650	0.000	0.480
Bhilwara	0.650	0.005	0.480	1.080	0.011	0.360	-1.270	-0.008	0.610	-0.190	0.000	0.880	-0.090	0.000	0.920
Bikaner	0.900	0.008	0.190	-0.330	0.002	0.580	0.630	0.002	0.060	1.090	0.010	0.280	1.540	0.020	0.110
Bundi	0.470	0.004	0.640	-1.760	-0.015	0.060	-1.390	-0.009	0.060	-0.460	-0.040	0.650	-0.100	0.000	0.840
Chittaurgarh	2.060	0.017*	0.020	-0.500	0.002	0.490	-1.140	-0.007	0.060	1.230	0.010	0.270	1.190	0.010	0.240
Churu	0.900	0.008	0.330	0.250	0.002	0.020	0.020	0.000	0.000	1.040	0.010	0.370	2.02*	0.01*	0.050
Dausa	-0.300	-0.003	0.440	0.440	0.003	0.120	0.480	0.003	0.460	-0.060	0.000	0.620	-0.090	0.000	0.590
Dhaulpur	-0.140	-0.001	0.750	-0.620	-0.004	0.080	-0.060	0.000	0.030	-0.110	0.000	0.820	0.360	0.000	0.500
Dungarpur	1.590	0.014	0.060	0.480	0.003	0.420	0.500	0.004	0.920	1.200	0.010	0.120	1.110	0.010	0.140
Ganganagar	1.410	0.012	0.360	1.450	0.010	0.180	2.760	0.011**	0.040	2.54**	0.02**	0.040	2.84**	0.02**	0.030
Hanumangarh	0.140	0.001	0.900	-0.190	0.001	0.420	1.930	0.008	0.000	0.480	0.000	0.500	1.020	0.010	0.240
Jaipur	-1.040	0.005	0.340	-0.500	0.003	0.220	0.460	0.004	0.570	-0.700	-0.010	0.430	-0.430	-0.010	0.550
Jaisalmer	1.800	0.014	0.050	2.130	0.013*	0.040	0.740	0.000	0.210	2.02*	0.01*	0.040	2.35*	0.01*	0.010
Jalor	1.600	0.010	0.050	0.750	0.004	0.540	1.070	0.005	0.030	1.640	0.010	0.060	1.770	0.010	0.070
Jhalawar	1.520	0.012	0.050	-0.540	-0.004	0.840	-0.250	0.001	0.080	0.980	0.010	0.260	0.830	0.010	0.390
Jhunjhunun	-0.720	-0.008	0.660	-0.780	0.002	0.150	-0.160	0.000	0.070	-0.630	-0.010	0.560	-0.330	0.000	0.810
Jodhpur	0.720	0.006	0.720	0.290	0.003	0.840	-0.120	0.000	0.140	0.320	0.000	0.810	0.370	0.000	0.730
Karauli	-0.860	-0.007	0.480	-1.050	-0.009	0.150	-0.350	0.002	0.010	-0.710	-0.010	0.490	-0.300	-0.010	0.740
Kota	-0.010	0.000	0.940	-1.210	-0.010	0.240	-0.01	-0.010	0.080	-0.670	-0.010	0.420	-0.550	-0.010	0.460
Nagaur	0.500	0.003	0.940	0.450	0.003	0.640	0.430	0.001	0.630	0.560	0.000	0.990	0.180	0.000	0.920

Table 5 (continued)

Station	Early season			Mid-season			Late season			Whole <i>Kharif</i> season			Annual		
	Z	β	R	Z	β	R	Z	β	R	Z	β	R	Z	β	R
	Pali	1.150	0.009	0.150	0.270	0.002	0.590	0.410	0.001	0.120	0.960	0.010	0.340	1.370	0.010
Pratapgarh	3.180	0.027**	0.030	0.610	0.005	0.770	-0.850	-0.006	0.530	2.15*	0.01*	0.030	2.19*	0.01*	0.040
Rajsamand	1.740	0.015	0.050	0.750	0.006	0.810	0.810	0.005	0.240	1.670	0.010	0.080	1.780	0.010	0.050
Sawai Madhopur	1.260	0.010	0.260	-0.170	0.002	0.020	0.620	0.006	0.010	1.050	0.010	0.350	1.490	0.010	0.140
Sikar	0.100	0.001	0.940	-0.240	0.002	0.240	-0.160	0.001	0.100	-0.070	0.000	0.970	0.210	0.000	0.890
Sirohi	0.120	0.001	0.520	-0.570	0.003	0.360	-0.500	0.002	0.580	-0.020	0.000	0.950	0.010	0.000	0.970
Tonk	0.980	0.009	0.170	0.310	0.003	0.070	-1.210	0.006	0.160	0.350	0.000	0.640	0.500	0.010	0.480
Udaipur	0.920	0.009	0.310	0.050	0.001	0.210	-0.480	0.003	0.220	1.040	0.010	0.390	0.670	0.010	0.610
Rajasthan	0.635	0.004	0.432	-0.069	0.000	0.355	0.095	0.001	0.235	0.349	-0.002	0.473	0.442	0.003	0.449

**99% significant level, * 95% significant level, Mann–Kendall (Z), Sen slope estimator (β) and Regression (R)

5 Discussion

The meteorological drought exploration is an important research theme over dryland ecosystems elsewhere in the world and Rajasthan state, located in north western India is no exception. Until now, drought over Rajasthan was mostly explored by employing the normalized difference vegetation index (NDVI), water supply vegetation index (WSVI), vegetation condition index (VCI), El Nino-Southern Oscillation (ENSO) index and standardized water level index (SWLI) (Bhuiyan et al. 2006; Jain et al. 2010; Dutta et al. 2013, 2015; Dhakar et al. 2013; Ganguli and Reddy 2013; Sehgal and Dhakar 2016). However, climate-based drought evaluation was lacking completely over the dryland ecosystem. Therefore, in this study, SPI was preferred over other indices due to its simplicity, effectiveness to measure droughts consistently at spatial and multiple time scales and broader applicability (Shah and Mishra 2015). The focal point of the current study was to explore the meteorological drought characteristics over the dryland ecosystem at multiple time scales. Therefore, this study explored the drought characteristics not at annual or for whole *kharif* season but also explored the drought conditions at intra-seasonal scale such as early, mid and late *kharif* period since droughts can be more damaging when occurring over a cropping period (Mishra and Cherkauer 2010). Drought occurrence over the cropping period may have far-reaching effects in the study area, where mass population revolve around farming activities for their source of income (Sehgal and Dhakar 2016). The study of intra-seasonal differences had far-reaching importance because every crop stage had its individual susceptibility to moisture and water availability. An assessment of such vulnerability during a cropping season (e.g., *kharif*) will help in the formulation of best management practices subject to which period of the crop growth was largely affected due to dryness. However, a couple of studies narrated the susceptibility of agriculture to drought in India, as well as over the dryland ecosystem (Murthy et al. 2015; Dutta et al. 2015), but an investigation by Pradhan et al. (2011) for the first time indicated toward crop stage-specific drought analysis in India. Recently, Ahmed et al. (2018) and Mekonen et al. (2020) described such drought analyses in Pakistan and Ethiopia, respectively. The present study on intra-seasonal exploration of meteorological drought may be among the earliest studies. In addition, a comprehensive investigation referring to drought characteristics at intra-seasonal scales over the dryland ecosystem may be among the firsts.

Dhakar et al. (2013) revealed that drought had differential impacts on crop growth conditions over dryland ecosystem due to greater inter-annual and inter-seasonal rainfall variations. During the study period, rainfall over the dryland ecosystem varied highly ($CV = 37.90$) and ranged from 277 mm (2002) to 839 mm (1975). It was observed from the analysis that most of the rainfall deficit years such as 1965, 1969, 1972, 1987, 2002 and 2009 occurred with El-Nino years (Bhardwaj et al. 2019). The station-wise mean annual rainfall revealed a statistically significant rising trend over Barmer, Churu, Ganganagar, Jaisalmer and Pratapgarh stations, which was found consistent with Singh et al. (2001). The magnitude of significant increasing trends varied from 53.4 mm/decade (Pratapgarh station) to 21.7 mm/decade (Jaisalmer station). The majority of stations located in western parts (low elevated) over the dryland ecosystem showed increasing trends, consistent with Kumar et al. (2010), Mondal et al. (2015) and Meena et al. (2019). Earlier, Lal et al. (2001) also projected that the western arid zone of India may collect larger than usual rainfall due to warming of climate. This increasing trend in the mean annual rainfall over parts of western Rajasthan can be highly beneficial for agriculture as well as recharging of groundwater. However, these results were in contrast with Pingale et al. (2014) and Singh

and Kumar (2015), who showed a decreasing, trend in the mean annual rainfall over the western parts of the dryland ecosystem. Interestingly, Guhathakurta and Rajeevan (2006) did not observe any trend in south west monsoon season rainfall over Indian region, but noticed substantial regional differences. Naidu et al. (2009) observed a rise in summer monsoon rainfall in south India, whereas a decrease in northern India. Nonetheless, for India as a whole, the summer monsoon rainfall did not show any trend (Kumar et al. 2010; Jain and Kumar 2012), while Ghosh et al. (2009) showed mixed trends in rainfall occurrence over different regions in India. Kumar et al. (2010) showed a decline in annual and monsoon rainfall, while a rise in winter, pre- and post-monsoon seasons for India. However, these trends were found statistically insignificant. Jain et al. (2013) did not detect any significant trend in annual rainfall occurrence over north east India, although seasonal trends were detected. However, several researchers showed a substantial rise in number and magnitude of extreme rainfall events over the Indian region (Goswami et al. 2006; Joshi and Rajeevan 2006; Krishnakumar et al. 2009; Pattanaik and Rajeevan 2010). Conversely, Guhathakurta et al. (2011) detected a decline in extreme rainfall events over central and north India, whereas an increase over peninsula, eastern and north eastern parts of India. Recently, Mukherjee et al. (2018) noticed a significant rising trend in number of extreme rainfall events and ascribed it to increasing anthropogenic warming.

During the study period, nearly half of the years experienced a drought and most of them (more than 90 percent) were mild drought, according to SPI classification, whereas severe and extreme droughts occurred infrequently, consistent with Degefu and Bewket (2015) but in contrast with Sternberg et al. (2011). The recurring droughts may decrease soil micro-nutrient and consequently the land productivity (Sharafati et al. 2020). More importantly, a greater occurrence of droughts may influence the poor population of rural areas, provoking them for migration to small and big cities. Also, this may augment social inequality, conflicts, and unrest (Khanian et al. 2018). The worst drought incident (SPI = -2.39) occurred at Bharatpur station in the years 1978 and 1979, with an estimated frequency of recurrence of 34.5 years. All meteorological stations experienced a mixture of mild, moderate, severe and extreme droughts in the year 2002 and farming activities had drastically affected because crops could not be sown at all (Samra 2004). Rainfall was low as much as 60 to 70 percent below normal over the entire dryland ecosystem (Waple and Lawrimore 2003). During the year, rainfall departure from the average was found as high as -33, -49 and -67 percent at Udaipur, Sirohi and Rajsamand stations, respectively (highly elevated). Owing to this, the estimated loss of actual crop-area percentage was found to the tune of 25, 50 and 85 percent, respectively. About four million ha of cultivable land was either left uncultivated or sowing was delayed during the year 2002 (Bhuiyan et al. 2006). Similarly, Ahmed et al. (2018) stated that the droughts during the year 2002 damaged 50–80 percent of Baluchistan's cultivated land and over 50 percent of the agricultural productivity. The above-mentioned findings were found consistent with overall awareness of people toward drought, consequences on growth of crops and resultant productivity (Bhuiyan et al. 2006).

The drought severity demonstrated an east to west divide, with eastern zone (moderately to highly elevated) were more drought-prone than the western zone (low elevated). In this study, the western, northern and southern parts (low to moderately elevated) experienced more wetter conditions (significant at 95% confidence level), consistent with other studies (Singh et al. 2001; Mundetia and Sharma 2014). An increase in trends of wet spells is attributed to local geographic (topographic, urban sprawl, pollution, land use change) and atmospheric circulation features (sea surface temperature, solar cycles etc.) (Tabari et al. 2011). Also, Field et al. (2012) reported similar observations of wet spells at global and regional scales. Since the study area is a water scarce region, therefore increasing wet

spells will boost the agricultural economy by equipping the irrigation efficiency, establishing water storage provisions and maximization of surface water by constructing small dams on rivulets. Conversely, north eastern, eastern and south eastern areas (moderately to highly elevated) witnessed increased drier situations, though statistically it was found non-significant. The increased drier situations in these areas were really noteworthy for planning and management of water resources since these areas are the chief producers of various food grain crops, causing a massive threat to food grain productivity, food safety and socio-economic susceptibility to drought, then to serious economic problems (Sehgal and Dhakar 2016). Also, the poor water availability can negatively impact the maintenance of valuable tree species diversity (Sharafati et al. 2020). In this context, the livelihoods of people and especially the farmers in most of these areas are believed to become more susceptible to drought if substantial adaptation strategies were not attempted (Field et al. 2012). Recently, Mallya et al. (2016) detected a rising trend in severity and frequency of droughts over Indian monsoon region, with an overall shift toward the agriculturally important areas. Like the dryland ecosystem of Rajasthan, Das et al. (2016) detected a rise in the frequency of droughts over eastern zone of India owing to decline in volume of rainfall, however, a decline in drought events were reported over the western zone on account of a drop in potential evapotranspiration. Additionally, rising drought conditions accompanied by prolonged duration and greater intensity were experienced over entire country apart from north western India, where a reduction in drought duration and intensity was witnessed. More importantly, Guhathakurta et al. (2017) detected an increasing trend in percentage area affected by droughts in eastern as well as north eastern India. Recently, Moradi et al. (2011) and Tabari et al. (2012) detected an intensification of meteorological droughts over eastern regions of Iran. Surprisingly, Sehgal and Dhakar (2016) reported an increasing drought vulnerability to cropped areas from eastern to western parts of dryland ecosystem and attributed this to lower water holding capacity of soils and percentage-irrigated area in the western zone.

6 Limitations of study and future work

First, the landscape of dryland ecosystem is very heterogeneous, therefore, drought forecasting based on station rainfall cannot be fully representative of the regional conditions. Secondly, the number of meteorological stations selected for analysis were limited and far from each other due to a poorly developed network of stations. Thirdly, the selected time span was also of short duration. Generally, longer records deliver more reliable results for computation of SPI. These two limitations cannot accurately explain the characteristics of droughts over the dryland ecosystem. Fourthly, drought forecasting administered entirely using the SPI may have much weakness in recognizing the complex drought processes across the geographical units, thus affecting its reliability as a drought index. Additionally, it examines the deficiency of rainfall, the principal cause of drought onset, however, it did not yield an account of major fallouts. At large, an area may not be under the influence of water-stress and might preserve usual foliage regardless of the negative SPI, and may not always be corresponding to drought. However, in future research, these shortcomings of the study can be improved first by considering gridded rainfall projections retrieved by merging rain gauge, satellite, and reanalysis data at a high spatial and temporal resolution. Second, an integrated drought considering the interconnectivity of hydrological and

agricultural drought with meteorological one need to be evaluated for the future forecasting of droughts by employing remote sensing and meteorological data. The use of high-resolution, satellite-oriented observations of foliage cover had an important role in spatially continuous, real-time monitoring of drought, advance warning and alleviating the fallout of droughts over large areas. Third, for a more detailed study of the drought situation, an inclusion of other hydro-climatic variables including temperature, evaporation, transpiration, soil water content, etc. is essential for an all-inclusive perspective of the drought. Fourth, future studies on the quantification of drought impacts on different sections of economy need to be undertaken. Finally, an estimation of drought characteristics in relation to livelihood zones is also indispensable for management of drought hazard, advance warning reactions, regional planning and safety of food.

7 Conclusions

In this investigation, characteristics of meteorological drought over a dryland ecosystem of north western India were examined using SPI. Accordingly, diurnal rainfall statistics of 33 stations were used for the period 1961 to 2017. The analyses revealed that the meteorological drought characteristics changed with time and a mixture of wet and dry periods were detected. During study period, nearly half of the years experienced a drought at all-time scales. Fascinatingly, more than 90 percent of them were mild droughts. In the year 1987 and 2002 moderate droughts were witnessed all over the dryland ecosystem, with SPI records of -1.45 and -1.08 , respectively. Surprisingly, during the year 2002, all stations of the dryland ecosystem experienced a mix of mild, moderate, severe and extreme droughts. Conversely, an absence of severely dry and extremely dry episodes of drought was detected at all-time scales. However, the most extreme drought episodes were witnessed in the years 1978 and 1979 at Bharatpur (SPI = -2.39 ; return period 34.5-years) and Dhaulpur (SPI = -2.02 ; return period 17.2-years) stations. Drought severity for most stations (60 percent) at all-time spans except the late season is ≤ -0.70 but never crossed the mild drought cut off i.e., 0.00 to -0.99 . At spatial level, this study illustrated a distinct but logical spatial difference in severity of droughts at different time scales. The severity of drought at annual time scale showed that the eastern parts (moderately to highly elevated) were more drought prone than the western parts (low elevated).

The drought frequency followed an order of mid-season > whole *kharif* season > early season > late season > annual. Apart from this, mild droughts occurred frequently, whereas extreme droughts were unusual. The annual spatial pattern of mild, moderate, severe and extreme drought frequency was almost opposite to the pattern of annual rainfall, which increased from north west (low elevated) to south east (highly elevated). The maximum drought magnitude of 643 mm was detected at Banswara station, whereas the minimum magnitude of 157 mm was observed at Bikaner station. The average drought duration at different time spans for most stations (more than 75 percent) was 2–4 decades, which may be alarming for agriculture practices and environmental issues. The return periods for mild and moderate drought conditions were found smaller, whereas longer for severe and extreme droughts. The western, northern and southern (low to moderately elevated) parts experienced wetter conditions (significant at 95% confidence level), whereas north eastern, eastern and south eastern regions (moderately to highly elevated) witnessed increased drier situations, though statistically it was found non-significant. To sum up, the analysis of the whole *kharif* season and annual SPI for dryland ecosystem yielded similar results. This

suggests that the occurrence of drought during a year is generally determined by the rainfall pattern from June to October. June to September is monsoon months and an investigation of drought during these months is meaningful from an agricultural viewpoint. Finally, SPI, which is largely about the past performance of rainfall, was successfully employed for the characterization of meteorological droughts over the dryland ecosystem. The analysis of various meteorological drought characteristics suitably validated conception as well as perception and will favor the local stakeholders and policy makers in planning of meteorological drought management across the dryland ecosystem of north western India.

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