Recent Rainfall Variability Over a Dryland Ecosystem of North Western India

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Research Article

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Abstract

In this study, an attempt has been made to examine the recent rainfall variability by means of daily rainfall data of 33 well spread stations over dryland ecosystem of Rajasthan in north western India during 1961-2017. For trend analysis, Mann-Kendall, Sen's slope estimator and simple linear regression test have been used (at 95% confidence level). The results have shown a high interannual variability in rainfall occurrence varying from 277 mm (in year 2002) to 839 mm (in year 1975) with mean of 583 mm over this dryland ecosystem. Most of the rainfall deficit years have occurred with El-Nino years. The mean annual rainfall has shown a marginal non-significant upward trend over the ecosystem. The station-wise mean annual rainfall has revealed a significant rising trend over Barmer, Churu, Ganganagar, Jaisalmer and Pratapgarh stations. Interestingly, three year running average has shown a cyclic pattern of rainfall over dryland ecosystem under the changing climatic conditions. The spatial pattern has exhibited that the mean annual rainfall decreases from east and south east (more than 850 mm) to west and north west (less than 400 mm), which is mainly associated with the presence of Aravalli Mountains spreading north east to south west in central Rajasthan. Remarkably, majority of stations positioned in western parts of dryland ecosystem have shown increasing rainfall trends, whereas some stations located in eastern parts have recorded a non-significant declining trend. The magnitude of significant rising trend has varied from 5.34 mm/year (Pratapgarh station) to 2.17 mm/year (Jaisalmer station). Also, the frequency of heavy rainfall events has shown a positive trend with significant increasing trends over Bharatpur, Jaisalmer and Pratapgarh stations, whereas Bundi station has shown significant decreasing trend.

1 Introduction

Rainfall and temperature are vital climatic parameters, which have been frequently used to identify the alterations in global climatic conditions (Mayowa et al. 2015; Sa'adi et al. 2019). Global ocean's and land surface temperature trend has revealed a warming of 0.85°C (ranging between 0.65°-1.06°C) during 1880–2012 (IPCC 2014). This rise in the surface temperature could result in changing rainfall patterns globally (Wang et al. 2016). For instance, Trenberth et al. (2007) have observed a rising trend in rainfall over Asia, Australia, northern Europe, North and South America, whereas decreasing trend over the Mediterranean area, southern Asia, Sahel, western and southern Africa. Likewise, Longobardi and Villani (2010) and Altava-Ortiz et al. (2011) have shown a decreasing trend in average annual precipitation over Mediterranean basin and nearby regions. More recently, Adler et al. (2017) have not detected any significant trend in the global mean precipitation, however, a rising trend over tropical oceans and a declining trend over certain mid-latitudes areas has been detected. Nicholson et al. (2018) and Caloiero et al. (2018) have detected a significant downward trend in annual rainfall over West Africa, North Africa, and eastern Mediterranean. Besides, several other attempts have been made to examine the possible influences of changing climate on spatial and temporal rainfall trends (Loo et al. 2015; Mayowa et al. 2015; Xiao et al. 2016; Hu et al. 2017; Sein et al. 2018; Biasutti 2019; Haag et al. 2019; Sa'adi et al. 2019; Gebrechorkos et al. 2019).

Additionally, it has been well-recognized that the warming environment has enhanced the intensity of extreme precipitation more rapidly than mean precipitation (Kharin et al. 2013; Boucher 2013; Berg 2013; Fischer and Knutti 2016; Myhre et al. 2019). Hartmann et al. (2013) have observed that the occurrence of extreme precipitation events has increased over larger land areas than it has decreased in the second half of 20th century. Therefore, extreme precipitation has increasingly become an illuminating subject of research during the period of changing climate (Cammarano and Tian 2018, Dahal et al 2018). Researchers have continuously made efforts to examine the extreme precipitation trends in relation to changing climate (Dore 2005; Alexander et al. 2006; Fischer and Knutti 2014; Asadieh and Krakauer 2015; Westra et al. 2013). Apart from this, increasing trends in extreme rainfall events have been detected over different parts of the world, for example, Europe (van den Besselaar et al. 2013), North America (Villarini and Vecchi 2012; Donat et al. 2013; Easterling et al. 2017), South America (Donat et al. 2013, Skansi et al. 2013), south eastern South America (Wu Y and Polvani 2017), Australia (Laz et al. 2014; Herath et al. 2017), South Asia (Sheikh et al. 2015) and south east Asia (Ge et al. 2019). Interestingly, most of the land areas have observed a rise in extreme rainfall events in summer season excluding Europe, which showed an increase during winters (Hartmann et al. 2013; Pinskiwar et al. 2019).

In India, a number of efforts have been made to investigate the spatial and temporal trends in rainfall and related extremes. For instance, Guhathakurta and Rajeevan (2006) have not observed any trend in south west monsoon season rainfall over Indian region, but noticed substantial regional differences. Naidu et al. (2009) have 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 has not shown any trend (Kumar et al., 2010; Jain and Kumar, 2012), while Ghosh et al. (2009) have shown mixed trends in rainfall occurrence over different regions in India. Kumar et al. (2010) have shown a decline in annual and monsoon rainfall, while a rise in winter, pre- and post-monsoon seasons for India as a whole. However, these trends are statistically insignificant. Jain et al. (2013) have not detected any significant trend in annual rainfall occurrence over north east India, although seasonal trends have been detected. However, several researchers have shown a substantial rise in number and magnitude of extreme rainfall events over the Indian region (Goswami et al. 2006; Joshi and Rajeevan 2006; Krishnamurthy et al. 2009; Pattanaik and Rajeevan 2010). Conversely, Guhathakurta et al. (2011) have 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. (2017) have noticed a significant rising trend in number of extreme rainfall events and ascribed it to increasing anthropogenic warming. Apart from this, numerous efforts have been done on the spatial and temporal pattern of rainfall and related extreme events for different states of India in recent times such as Kerala (Krishnakumar et al. 2009; Pal and Al-Tabbaa 2009; Pal and Al-Tabbaa 2011; Nair et al. 2014; Thomas and Prasannakumar 2016), West Bengal (Chatterjee et al. 2016; Ghosh

2018; Kundu and Mondal 2019), Andhra Pradesh (Rao et al. 2009; Patakamuri et al. 2020), Madhya Pradesh (Duhan and Pandey 2013; Jana et al. 2017); Orissa (Patra et al. 2012), Uttarakhand (Kotal et al. 2014; Nandargi et al. 2016), Jammu and Kashmir (Kumar et al. 2009), Punjab (Gill et al. 2013), Assam (Deka et al. 2013), Gujarat (Lunagaria et al. 2015; Dave and James 2017; Dave et al. 2017), and Maharashtra (Ratna 2012; Sonar 2014; Ingle 2018).

The above review exhibits that researchers have extensively examined the trends and pattern of rainfall and related extreme events for the different parts of globe, including India. However, studies on trends and pattern of rainfall and related extreme events pertaining to the dryland ecosystem of India i.e., for Rajasthan state are less in number. Climate of the Rajasthan state is of monsoon type and receives the major part of annual rainfall during the south west monsoon. The insufficient and erratic rainfall in many parts of the state constitutes a threat to agriculture. The distribution of rainfall in dryland ecosystem of Rajasthan is highly uneven and changes significantly from region to region and year to year (Pingale et al. 2014). Also, the state has been characterized by highest chances of rainfall deficiencies and drought occurrence (Rathore 2005). The region is highly dependent upon rainfall as it is an important source of groundwater recharge. The long-term climatic changes related to rainfall may affect the agriculture and water resources of the state (Yadav et al. 2018). For that reason, some investigations have been attempted to examine the rainfall and related extreme events for this state (Rao et al. 2011, 2014; Singh et al. 2012; Pingale et al. 2014; Poonia et al. 2014; Machiwal and Jha 2017; Srivastava 2018; Meena et al. 2019). However, these studies are restricted to the analyses of a particular rainfall event, district, western arid region and short period of data. No study has presented a comprehensive examination of rainfall and heavy rainfall events over entire dryland ecosystem of Rajasthan state in north western India. Therefore, a detailed analysis of recent rainfall variability for this dryland ecosystem is required. In the light of these facts, the main objective of this study is to examine recent rainfall variability over dryland ecosystem of Rajasthan state in north western India.

2 Study Area

The Rajasthan state, situated in north western part of India, is the largest state of country. It covers a widespread area of 3,42,239 km² occupying about 10.4 percent of the India's geographical extent. Geographically, the state extends between latitudes 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 amsl. The state has a variety of 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 south eastern plateau. The Thar Desert is India's largest desert, which covers approximately 70 percent area of the state.

The state has matchless climatological characteristics in the form of low, highly variable, erratic and ill-distributed rainfall, low humidity, high wind speed, high evaporation losses, and extremes of diurnal, seasonal and annual temperatures. The Aravalli Hills play a major role in the climatic pattern of Rajasthan due to its parallel running along the direction of the south west monsoon. The Arabian Sea branch of monsoon winds hit the eastern slope of these hills and the south eastern part gets sufficient rainfall, whereas the north western part remains dry (arid and semi-arid). However, the south eastern parts of the state are characterized by humid to very humid climatic conditions (Fig. 1).

The state is characterized by frequent droughts, lack of perennial rivers, scarce vegetal cover, nomadic population and dependency of human on animal rearing. Further, the state of Rajasthan has a predominantly agrarian society with agro-pastoral economy. Of the total cultivated area (approximately 20 million hectares), only 20 percent area is irrigated due to 1 percent of the country's total water resources availability in the state. The onset and duration of monsoon significantly controls the performance of rain fed *kharif* crops. The yields of crops are sensitive to rainfall and wetter years are associated with higher yields.

3 Data And Methods

3.1 Data collection and database preparation

In the present study, daily rainfall data of 33 stations has been used for 57-years period (1961–2017), which are well spread over the Rajasthan state (Fig. 1). The data has been acquired from the online portal of Department of Water Resources, Government of Rajasthan, Rajasthan, India (www.waterresources.rajabasthan.gov.in). Apart from this, annual temperature data of 26 stations have been obtained from the Department of Agriculture, Government of Rajasthan, Rajasthan, India for the period 1979–2014. The geographical position (latitude and longitude) and elevation details of these stations have been given in Table 1. The major problem with the rainfall analyses' is the missing records. For that reason, out of more than 400 stations, only 33 stations that have smaller number of missing values, has been selected for this investigation. Further, in above dataset, the daily rainfall data is available from the year 1957; however, the year 1961 has been considered as base year, because the data has been found consistent for the selected 33 stations only after 1961. Few stations have missing rainfall observations which are filled-in before undertaking further analysis. The normal ratio method has been executed to estimate the missing values by choosing the rainfall amounts of three nearest stations. Distance matrix is structured for all stations based on their geographical positions to evaluate closeness of stations with each other.

Table 1

Basic information of selected stations and station-wise rainfall characteristics over dryland ecosystem of north western India (1961–2017).

Stations	Latitude	Longitude	Elevation (m)	Mean rainfall (mm)	Maximum rainfall (mm)	Year	Minimum rainfall (mm)	Year	SD (mm)	C _V	C _K	C _S
Ajmer	26°27'	74°37'	529	551.0	1163.0	1975	205.3	1987	194.7	35.34	1.07	0.85
Alwar	27°34'	76°36'	282	662.8	1445.1	1996	223.8	1987	230.7	34.80	1.12	0.62
Banswara	23°33'	74°27'	229	1070.1	2591.0	2006	509.8	1966	385.6	36.03	3.28	1.33
Baran	24°52'	76°40'	290	850.2	1739.0	2013	254.0	2002	300.3	35.32	0.66	0.93
Barmer	25°45'	71°24'	189	275.9	759.0	2006	37.1	1968	165.7	60.06	0.89	1.01
Bharatpur	27°13'	77°30'	181	631.2	1041.0	2005	218.5	1978	172.7	27.36	0.06	-0.26
Bhilwara	25°44'	74°20'	417	664.8	1120.0	2006	307.0	2009	210.1	31.61	-0.96	0.19
Bikaner	28°01'	73°18'	235	271.8	482.2	1983	32.0	2002	104.6	38.51	-0.45	0.16
Bundi	25°27'	75°38'	345	710.7	1245.4	1996	275.5	2002	186.9	26.30	0.41	0.41
Chittaurgarh	24°53'	74°38'	401	805.7	1556.5	2016	389.7	1965	216.5	26.88	1.78	0.95
Churu	28°18'	74°58'	294	396.9	690.2	1977	165.0	1965	146.7	36.96	-0.88	0.32
Dausa	26°54'	76°20'	337	632.2	1363.2	1975	300.0	2002	238.9	37.79	1.82	1.25
Dhaulpur	26°42'	77°53'	174	659.8	1319.6	2008	171.8	1978	241.8	36.65	0.65	0.62
Dungarpur	23°51'	73°43'	293	767.8	1611.0	2006	319.0	2008	270.3	35.21	0.87	0.73
Ganganagar	29°55'	73°53'	178	281.3	666.0	1983	78.6	1968	130.2	46.28	1.30	0.93
Hanumangarh	29°35'	74°19'	182	248.6	547.0	2010	75.5	1974	108.6	43.68	0.16	0.53
Jaipur	26°55'	76°50'	428	596.0	1155.8	1977	85.0	1984	230.1	38.62	-0.04	0.41
Jaisalmer	26°55'	70°55'	229	196.8	512.8	2006	26.4	1969	115.9	58.93	1.17	0.70
Jalor	25°21'	72°37'	161	433.5	1047.4	1990	51.3	1969	242.1	55.86	-0.07	0.81
Jhalawar	24°36'	76°09'	317	936.1	1614.5	2006	375.0	1968	292.2	31.22	-0.26	0.60
Jhunjhunun	28°08'	75°23'	347	406.5	828.0	2010	123.0	2002	155.0	38.12	-0.48	0.27
Jodhpur	26°18'	73°02'	254	374.1	815.0	1990	91.0	2002	166.3	44.48	-0.46	0.49
Karauli	26°30'	76°01'	281	740.7	1329.4	1975	275.5	2017	256.4	34.63	-0.56	0.35
Kota	25°08'	76°05'	269	737.7	1475.5	1971	325.0	1965	231.2	31.35	0.48	0.57
Nagaur	27°12'	74°45'	314	388.4	1259.0	1975	110.0	2009	200.8	51.71	5.66	1.82
Pali	25°47'	73°20'	218	329.3	1018.6	1979	90.0	1972	432.9	52.01	-0.26	0.68
Pratapgarh	24°03'	74°47'	508	936.5	1668.7	1973	359.7	1966	298.7	31.90	-0.30	0.43
Rajsamand	25°45'	74°05'	552	553.0	1039.0	2010	190.0	1969	179.9	32.55	0.55	0.44
Sawai Madhopur	25°59'	76°22'	360	790.3	1249.0	2016	295.0	1984	245.0	31.00	-0.57	-0.06
Sikar	27°37'	75°09'	433	497.1	1090.0	1977	124.0	2009	225.5	45.38	-0.26	0.52
Sirohi	24°36'	72°43'	299	630.5	1577.6	1973	190.9	1987	320.5	50.83	0.63	0.94
Tonk	26°10'	75°48'	281	631.3	1200.0	2013	221.3	2002	207.9	32.94	0.25	0.45
Udaipur	24°11'	73°55'	591	594.5	1095.5	1973	215.1	1989	186.0	31.29	-0.15	0.11
SD = Standard deviation, C _V = coefficient of variation, C _K = kurtosis, C _S = skewness												

Further, data quality check is essential before the investigation, as outliers can extremely affect the rainfall trends and patterns (You et al. 2008; Shahid et al. 2016). To ensure the homogeneity, subjective double mass curve method and objective student's t-test have been performed for

rainfall time-series. The double mass curves of all stations have not shown any breakpoint and displayed more or less a straight line which indicates the homogeneity in the data. Similarly, student's t test has not revealed any break point or statistically significant difference in the rainfall time series at 95% confidence level. Apart from this, the daily rainfall data has been summed up to obtain monthly, seasonal and annual values. Seasonal analysis has been done for four seasons namely (a) winter (January-February), (b) pre-monsoon (March-May), (c) Monsoon (June-September) and (d) post-monsoon (October-December), as per categorization of India Meteorological Department (IMD).

3.2 Methods

After preparation of complete dataset, suitable statistical analysis such as sum, frequencies, percentage, mean, standard deviation (SD), coefficient of variation (CV), skewness (C_s) and kurtosis (C_k) have been performed for each station for the period 1961–2017. Then, the excess and deficit rainfall years and heavy rainy days have been identified as follows:

3.2.1 Identification of Excess and Deficit Rainfall Years

In this study, a year has been identified as an excess (deficit) rainfall year, if rainfall is more (less) than one SD from mean (Pant and Rupa Kumar 1997). Statistically, an excess rainfall year can be expressed as:

$$R_i \geq R_m + S_d$$

1

and a deficit year can be expressed as:

$$R_i \leq R_m - S_d$$

2

where, R_i = rainfall amount in a year i , R_m = mean rainfall and S_d = SD of rainfall.

3.2.2 Identification of Heavy Rainfall Events

In this study, an event is considered as heavy rainfall event if rainfall occurs > 65 mm in 24 hours (Kumar and Singh 2018). The total heavy rainfall events recorded at a particular station have been summed up to obtain monthly, seasonal and annual events. The total number of heavy rainfall events recorded at different stations have been averaged to represent their frequency.

3.2.3 Trend Detection Methods

The non-parametric Mann-Kendall (MK) (Mann 1945; Kendall 1948) has been used to detect the trend in rainfall. This MK test has been 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 has used to detect the trend and its significance level. The positive (negative) values of Z show rising (declining) trend in the time-series. In this study, the existence of statistically significant positive or negative trend has been considered at 95% confidence level. The MK test is a rank-based test, which have been used extensively for the verification of autocorrelation in the data series (Duhan and Pandey 2013). The test shows that if the lag-1 serial coefficients of the data are not statistically significant, then the MK test has been 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 an autocorrelation can increase the probability of detecting a significant trend (Bayazit and Onoz 2008). Therefore, in the present study, MK test has been 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 non-parametric Sen's Slope estimator (Sen 1968) has been used to detect the magnitude of the trend. It is closely associated to the MK test (Gilbert 1987) and provides a robust estimation of trend (Yue et al. 2002). Additionally, the parametric simple linear regression has also been used to detect the trend in time-series in this study. These three methods have been used widely for this purpose in the hydro-meteorological studies. A detailed discussion about 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). These tests have been performed by means of XLSTAT 2017 software.

3.2.4 Spatial Interpolation

To examine the spatial pattern of rainfall characteristics, the inverse distance weighting (IDW) interpolation technique has been used in this study. The IDW technique is a simple and widely used interpolation technique. This spatial interpolation technique considers the role of each input point by a standardized inverse of the distance from the control point to the interpolated point. This technique assumes that each input point has a local impact that diminishes with increase in remoteness. It weighs more on points nearer to the processing points, than those of far away. It means a rainfall or its derived quantity at any desired location is interpolated from the given data using weights that are based on the distance from each rainfall station and the desired location (Burrough and McDonnell, 1998). This technique gives a smooth pattern of rainfall along with undesirable troughs and peaks. The interpolation of rainfall characteristic using IDW technique has been done by ArcGIS 10.2 software.

4 Results And Discussion

4.1 Temporal Variations

4.1.1 Annual Variations

The mean annual rainfall over dryland ecosystem of Rajasthan during 1961–2017 has been demonstrated in Fig. 2. The time-series has exhibited a high interannual variability in mean annual rainfall (SD = 221.10, CV = 37.90) varying from 277 mm (in year 2002) to 839 mm (in year 1975) with a mean of about 583 mm (Fig. 2; Table 2). The lowest (highest) rainfall in the year 2002 (1975) may be attributed to the prevalence of strong El-Nino (La-Nina) conditions (Mahala et al. 2015; Bhardwaj et al. 2019). Similarly, C_k and C_s are the measures of data peakedness, flatness and symmetry and their values for normal data distribution is zero or near zero. The positive values of C_k reveal the peaked distribution and vice versa. In the study area, Banswara (very humid) and Nagaur (semi-arid) stations have high C_k , whereas Bhilwara (humid) and Churu (semi-arid) have low C_k . All the stations except Bharatpur and Sawai Madhopur (humid region) have positive C_s , which suggests that there is an increment in the amount of rainfall than normal in all over the study area. It has been observed from the analysis that most of the rainfall deficit years such as 1965, 1969, 1972, 1987, 2002 and 2009 have occurred with El-Nino years (Table 3) (Mahala et al. 2015; Bhardwaj et al. 2019). The El-Nino years have disturbed the Indian monsoon badly and affected the agriculture system specifically in the Rajasthan state which is completely dependent on south west monsoon for arrival of rainfall. However, the mean annual rainfall has shown a marginal non-significant upward trend over the dryland ecosystem. Interestingly, three years running average has shown a cyclic pattern of mean annual rainfall under the changing climatic conditions. The mean annual rainfall has revealed a significant rising trend in arid and semi-arid regions except Pratapgarh stations situated in the very humid region of the state, which has been found consistent with Singh et al. (2001) (Fig. 3). Apart from this, most of the stations located in semi-arid, sub-humid and humid regions have shown increasing non-significant trends, whereas eastern and south eastern parts have shown non-significant decreasing trends. Rest of the regions have shown almost constant trends in the mean annual rainfall.

Table 2
Mean (M), standard deviation (SD), coefficient of variation (CV), kurtosis (CK), skewness (CS), Mann Kendall Test (Z), Sen's Slope estimator (β) and regression (R) of monthly, seasonal and annual rainfall over dryland ecosystem of north western India (1961–2017)

β									
Time	M	SD	C_v	C_k	C_s	% of Annual	Z	β	R
	(mm)	(mm)							
January	4.69	6.08	129.66	3.96	2.00	0.80	0.39	0.01	0.39
February	6.16	8.46	137.35	2.23	1.76	1.05	0.17	0.00	0.30
March	5.06	10.46	206.63	19.38	4.23	0.86	0.88	0.01	0.61
April	4.19	6.33	151.03	10.93	2.91	0.71	2.51*	0.03*	0.14
May	12.60	10.83	85.94	-0.33	0.87	2.15	1.09	0.06	0.45
June	61.88	36.39	58.8	-0.07	0.54	10.55	1.87	0.55	0.08
July	195.90	64.07	32.71	0.10	-0.58	33.39	0.98	0.58	0.35
August	194.30	74.12	38.15	-0.86	0.22	33.12	0.08	0.08	0.80
September	80.85	53.02	65.58	1.96	0.95	13.78	-0.25	-0.11	0.39
October	12.13	17.74	146.28	3.25	1.99	2.07	-0.07	0.00	0.77
November	5.98	14.20	237.46	8.41	3.00	1.02	-0.70	0.00	0.74
December	2.88	6.06	210.27	16.99	3.77	0.49	0.24	0.00	0.36
Winter (January-February)	10.85	5.35	49.31	-0.58	0.50	1.85	1.23	0.07	0.18
Pre-monsoon (March-May)	21.86	7.98	36.51	-0.53	0.53	3.73	1.16	1.40	0.19
Monsoon (June-September)	532.93	213.53	40.07	-0.48	0.14	90.85	1.65+	0.15+	0.44
Post-monsoon (October- December)	21.00	9.61	45.74	-0.57	0.34	3.58	-0.42	-0.04	0.82
Annual	583.40	221.10	37.90	-0.61	0.09	100.00	1.30	1.60	0.39
Significant at 95% confidence level									

Table 3
Excess and deficient rainfall years over dryland ecosystem of north western India (1961–2017)

Annual		Winter		Pre-Monsoon		Monsoon		Post-Monsoon	
Excess	Deficit	Excess	Deficit	Excess	Deficit	Excess	Deficit	Excess	Deficit
1961	1965	1970	1967	1967	1972	1961	1965	1974	-
1973	1966	1979	1974	1982	1984	1973	1968	1976	-
1975	1968	1986	2000	1983	2010	1975	1974	1979	-
1976	1969	1990	2006	2001	-	1976	1979	1982	-
1977	1972	1995	-	2008	-	1977	1985	1985	-
1990	1980	2003	-	2014	-	1990	1987	1992	-
1996	1987	2007	-	2015	-	1994	1989	1997	-
2011	1989	2013	-	-	-	1996	2000	1998	-
2013	2000	2014	-	-	-	2006	2002	2010	-
2016	2002	-	-	-	-	2011	2009	-	-
-	2009	-	-	-	-	2013	-	-	-
-	-	-	-	-	-	2016	-	-	-

Temperature is an important meteorological variable after rainfall. A significant change in temperature can pose a serious threat to agriculture, vegetation, habitat and biodiversity of a place (Mishra 2018). Therefore, in this study, a temporal distribution of annual mean, maximum, and minimum temperature has been undertaken, which revealed a non-significant increasing trend in most parts of the state (Fig. 4). These results have been found consistent with that reported by Roy (2015), Sharma et al. (2017) and Mehta and Yadav (2019). Pingale et al. (2014) and Roy (2015) have attributed these warming trends to increasing anthropogenic activities, namely, land use/cover changes, industrialization and urbanization. Generally, a rise in temperature is directly associated with rising evapotranspiration rates which further results in increasing rainfall trends. Previously, several such studies have revealed similar results in different parts of India (Singh et al. 2008a, b; Jain et al. 2013; Pingale et al. 2014; Roy 2015). In a study over the dryland ecosystem, Mishra (2018) have concluded that a change in climatic conditions leads to a significant change in rainfall, temperature and evapotranspiration rates, which in turn adversely affects the physical as well as economic landscapes of an area.

4.1.2 Seasonal Variations

The mean seasonal rainfall during different seasons over dryland ecosystem of Rajasthan during 1961–2017 has been displayed in Table 2. Approximately, 90 percent of total annual rainfall over the dryland ecosystem has occurred during monsoon season. Remaining rainfall (less than 10 percent) has occurred in three seasons i.e. winter, pre-monsoon and post-monsoon. Winter season has accounted only about 2 percent rainfall. Pre- and post-monsoon seasons have accounted remaining 8 percent (4 percent each) rainfall. The values of SD have been found very small during winter (SD = 5.35), pre-monsoon (SD = 7.98) and post-monsoon (SD = 9.61) seasons due to very less amount of rainfall than monsoon season (SD = 213.53) (Table 2). Interestingly, the dryland ecosystem as a whole has shown a marginal non-significant increase in rainfall amounts during winter, pre-monsoon and monsoon seasons, whereas post-monsoon season has shown a marginal non-significant decrease (Fig. 5). Like annual pattern, three year running average has exhibited a clear cyclic pattern in rainfall occurrence during monsoon season over Rajasthan. Likewise, all the stations have shown positive trends in mean rainfall except three stations namely Jalor, Pratapgarh and Udaipur during pre-monsoon season. Further, the detected increasing or decreasing trend in the occurrence of rainfall during different seasons has not been found statistically significant.

4.1.3 Monthly Variations

The mean monthly rainfall over dryland ecosystem of Rajasthan during 1961–2017 has been shown in Table 2. Monthly rainfall has exhibited a wide variation in its occurrence. Remarkably, only two months (July and August) have accounted approximately two-third of total annual rainfall, whereas December month has accounted only about 0.49 percent rainfall. Further, the SD and CV values have been found high during the July and August as these two months have received huge amount of rainfall with very high variability, whereas rainfall occurrence has been observed very less in rest of the months (Table 2). Further, the mean rainfall occurrence has been noticed less in April month, however, a rising trend has been observed in this month (Fig. 6; Table 2). The months of June and July have also shown insignificant increasing trends, whereas September, October and November months have shown an insignificant decreasing trend. Rests of the months have shown almost constant trends.

4.2 Spatial Pattern

4.2.1 Annual Pattern

The spatial pattern of mean annual rainfall over dryland ecosystem in north western India during 1961–2017 has been displayed in Fig. 7a. The mean annual rainfall has exhibited an increasing rainfall gradient from arid and semi-arid to humid and very humid regions. The mean annual rainfall occurrence over entire arid and semi-arid regions has been found less than 400 mm, whereas it has been more than 850 mm over the south eastern parts located in the very humid regions. This decline in average annual rainfall from east to west is mainly associated with the presence of Aravalli Mountains spreading north east to south west in central Rajasthan (Yadav et al. 2012). The Arabian Sea branch of monsoon winds hit the eastern slope of these hills and the south eastern part receives ample rainfall, while north western parts remain dry (Dutta et al. 2015). The moisture loss of monsoonal winds with distance also reduces the rainfall amounts towards westward from south east. The lowest mean annual rainfall has occurred over Jaisalmer station (196.81 mm), whereas highest over Banswara station (1070.18 mm) during 57-years study period (Table 1). The spatial pattern of CV has exhibited almost opposite pattern to the mean annual rainfall (Fig. 7b). The higher (above 50 percent) values of CV have been noticed over the west and north west, whereas lower (below 35 percent) over east and south east. Exceptionally, the CV value has been found very high at Barmer station (about 60 percent), whereas it is just about 26 percent at Bundi station (Table 1). The higher CV values in the arid and semi-arid regions of the state have indicated high annual variability of rainfall. Conversely, the annual variability of rainfall has been observed relatively less in the areas of high rainfall. Hence, lack of rainfall and high variability are responsible for frequent occurrence of drought conditions (once in 2–3 years) over arid and semi-arid regions. These results are in correspondence with Narain et al. (2006) with respect to dryland ecosystem.

The spatial pattern of annual rainfall trends and magnitude during 1961–2017 detected by the MK test and Sen's slope estimator has been presented in Fig. 7c. Interestingly, majority of stations (23 stations; 70 percent) in the Rajasthan state have recorded positive trend in mean annual rainfall. Among these 23 stations, five stations namely Barmer, Churu, Ganganagar, Jaisalmer and Pratapgarh have observed statistically significant positive trends. These results have been found in agreement with previous studies (Pant and Hingane 1988; Singh et al. 2001). The magnitude of significant increasing trend has varied from 5.34 mm/year (Pratapgarh station) to 2.17 mm/year (Jaisalmer station). Majority of stations positioned in western parts of this dryland ecosystem have shown increasing trends, consistent with Kumar et al. (2010), Mondal et al. (2015) and Meena et al. (2019). Earlier, Lal et al. (2001) have also projected that the western arid region of India could receive higher than normal rainfall in warming climate. This rising trend in mean annual rainfall over western arid region, which is considered to be the most drought prone, could be extremely beneficial for agriculture as well as recharging of groundwater. However, these results are in contrast with Pingale et al. (2014) and Singh and Kumar (2015), who have shown a decline in mean annual rainfall over western parts of the state. Conversely, some stations located in the eastern parts of the state have recorded a non-significant decreasing trend, consistent with Kumar et al. (2010), Mondal et al. (2015) and Mundetia and Sharma (2015). However, no station has shown statistically significant declining trend in mean annual rainfall during 1961–2017. Additionally, the arid and semi-arid regions of the state have observed the maximum percent change in rainfall than humid and sub-humid regions (Fig. 7d). Jaisalmer station has shown the highest percent increase (63 percent) in mean annual rainfall during the study period 1961–2017.

4.2.2 Seasonal Pattern

The seasonal pattern of rainfall over dryland ecosystem in north western India during 1961–2017 has been displayed in Fig. 8. During winter season, the entire state has received less than 20 mm rainfall. The northern and north eastern parts have received rainfall between 10 to 20 mm and extreme western parts receive less than 5 mm during this season (Fig. 8a). During pre-monsoon season, the pattern of rainfall has appeared almost identical to the winter season, however, rainfall has slightly increased over all parts of the state (Fig. 8b). The northern parts receive approximately 30 mm mean rainfall during this season. During these two seasons, the northern and north eastern parts of the state have observed some amount of rainfall, which may be attributed to the western disturbances and associated thunderstorm activity over this region (Bhardwaj and Singh 2018; Singh and Bhardwaj 2019). The rainfall pattern during monsoon and post-monsoon seasons has been found almost similar, with higher concentration over the eastern to south eastern parts of the state and a consistent decrease towards westward and north westward (Fig. 8c-d). During monsoon season, rainfall amount has ranged from approximately 900 mm in south eastern parts to less than 300 mm over western and north western parts. The entire state has received the rainfall from the summer monsoonal winds during this season. As about 91 percent of total annual rainfall has occurred in this season, therefore, the rainfall pattern of monsoon season is almost similar to the pattern of mean annual rainfall. The moisture loss of monsoonal winds with distance and Aravalli Mountains reduces the rainfall occurrence towards westward from southeast. During post-monsoon season, less than 15 mm of rainfall has occurred in western parts and about 30 mm over south eastern parts. Further, the spatial pattern of CV for different seasons has shown opposite pattern to the mean seasonal rainfall (Figure not shown). The variability of rainfall occurrence has been found comparatively high over the parts of less rainfall and vice-versa. The values of CV have been observed very less over all parts during monsoon season, which may be accredited to the higher occurrence of rainfall with summer monsoon. The values of CV have been found very high over entire state during other three seasons namely winter, pre-monsoon and post-monsoon seasons due to very less and erratic rainfall.

The spatial pattern of seasonal rainfall trends and magnitude during 1961–2017 detected by the MK test and Sen's slope estimator has been shown in Fig. 9. During winter season, all the stations in the study area have shown non-significant positive trends in mean rainfall except Nagaur

(Fig. 9a). A significant increasing trend in rainfall has been detected in humid and semi-arid regions of the state during pre-monsoon season (Fig. 9b). The magnitude of increasing trend has varied from 0.60 mm/year (Churu station) to 0.12 mm/year (Pali station). During monsoon season, majority of stations located in arid region (western parts) of Rajasthan have shown increasing trends in rainfall (Fig. 9c). A significant rising trend has been detected for stations like Ganganagar, Pratapgarh and Jaisalmer during this season. The magnitude of increasing rainfall trend has differed from 5.57 mm/year (Pratapgarh station) to 2.02 mm/year (Jaisalmer station). These findings have been found consistent with previous studies like Basistha et al. (2007), Kharol et al. (2013), Mondal et al. (2015) and Meena et al. (2019), and in contrast with Pingale et al. (2014). During post-monsoon season, majority of stations have shown non-significant negative trends (Fig. 9d). Further, the spatial pattern of percent change in rainfall amount during different seasons for the study period 1961–2017 has been shown in Fig. 10. During winter season, humid and very humid regions of the state and only three stations in arid region (Ganganagar, Churu and Sikar) have observed a positive change of more than 25 percent (Fig. 10a). During pre-monsoon season, a substantial change in the pattern of percent change in rainfall has been observed (Fig. 10b). The northern and north eastern parts have observed a positive change of more than 60 percent for the period 1961–2017. During monsoon season, several stations located over eastern parts have shown a negative change in rainfall (Fig. 10c), consistent with Mundetia and Sharma (2015). However, no station has detected positive percent change in rainfall during post-monsoon season for a period of 57-years (Fig. 10d).

4.2.3 Monthly Variations

The spatial pattern of mean monthly rainfall over dryland ecosystem during 1961–2017 has been demonstrated in Fig. 11. In the months of January, February, March and April, the northern and north eastern parts have recorded the rainfall occurrence. However, the rainfall amount during these months has been found almost negligible. In the month of May, rainfall pattern has been found almost similar to April, but the amount of rainfall has increased. After the month of May, rainfall pattern has changed significantly. From the month June to August, rainfall has increased consistently over entire state. During these months, rainfall occurrence has been found comparatively higher over humid and very humid parts and a decrease towards westward and north westward. Then, the rainfall has started to lessen rapidly from September to December over all parts. Moreover, the spatial pattern of CV has exhibited the opposite pattern to mean monthly rainfall (Figure not shown). The values of CV have been found lowest over entire state in July month, whereas highest in December month.

4.3 Trends in heavy rainfall events

The annual maximum daily rainfall in Rajasthan during 1961–2017 has been displayed in (Fig. 12a). It has shown a non-significant positive trend, which signifies that the severity of the rainfall events has enhanced over dryland ecosystem in north western India. The maximum daily rainfall has been recorded highest in 1981 (550 mm) and lowest in 1989 (97 mm). The station-wise analysis of annual maximum daily rainfall has shown the mixed trends in rainfall without any significant rising or declining trend. The mean frequency of heavy rainfall events has been exhibited in Fig. 12b. The figure has revealed a positive trend in the frequency of heavy rainfall events over Rajasthan. The maximum number of heavy rainfall events have been observed in the years 1983 and 2006 (about 2.51 events), whereas lowest in the year 2002 (about 0.40 events). Additionally, the station-wise analysis of heavy rainfall events has shown almost constant trend except Bharatpur, Jaisalmer and Pratapgarh stations, which shows a significant rising trend, whereas Bundi station has shown significant decreasing trend (Figure not shown). The spatial pattern of heavy rainfall events over dryland ecosystem has been shown in Fig. 13. The pattern of heavy rainfall events has been found almost similar to the pattern of mean annual rainfall increasing from arid and semi-arid regions to humid and sub-humid regions. The mean frequency of heavy rainfall events has been noticed relatively higher over the humid and very humid parts (more than 2.50) and decreases towards arid and semi-arid parts (less than 1.0).

5 Conclusions

The distribution of rainfall over dryland ecosystem of Rajasthan is highly uneven due to its location and topography. Rainfall changes significantly from region to region and year to year having highest chances of deficiencies resulting occurrence of drought. But the studies pertaining to rainfall variability and trends over the dryland ecosystem are far less in number. To fill this research gap, an effort has been made in this study to examine the recent rainfall variability and trends for the period 1961–2017. The results of this study have revealed a significant rising trend over most of the arid and semi-arid regions except very humid region. The state has also recorded high interannual rainfall variability coupled with rainfall deficit years during El-Nino period. Remarkably, July and August months have accounted approximately two-third of total annual rainfall over the dryland ecosystem. Furthermore, the frequency of heavy rainfall events has shown a positive trend. The maximum number of heavy rainfall events have occurred in the years 1983 and 2006 (about 2.51 events), whereas lowest in the year 2002 (about 0.40 events). Apart from this, an increase in mean, minimum and maximum temperature has been detected in most parts of the state though statistically non-significant.

These above results show definite signs of change in rainfall and temperature over the state of Rajasthan, which can duly affect the climate as well as physical and economic landscapes. The overall increasing trends in rainfall may really be advantageous in the light of prevailing water scarcity problems over the dryland ecosystem. Interestingly, an increase in rainfall amount is anomalously due to increase in rainfall intensity, which produces large runoff volumes over a short period of time. Conversely, high rainfall variability may affect the net cultivated area. About

four million ha of culturable land has either been left uncultivated or has sowing been delayed during the year 2002 over the dryland ecosystem (Bhuiyan et al. 2006). Meanwhile, an increase in mean, maximum and minimum temperatures will lead to enhancement of aridity, which is most likely to affect the evapotranspiration, vegetation cover, crop growth and resultant agricultural productivity.

Furthermore, the findings of this study are important for water management as the water is key to human survival and all kinds of vegetative growth over the dryland ecosystem. Since the state holds only 1 percent of the total water resources of the country, the increasing trends of rainfall can hold good for recharging of groundwater resources. The increased availability of the rainwater resource will lessen the usual water-deficit scenario in arid and semi-arid regions due to statistically significant positive rainfall trends. Apart from this, the increasing trends in rainfall and temperature at most of the stations conspicuously reveal a changing climate over the dryland ecosystem. A persistence of climate change in future over the ecosystem may result in damages to both soil and water resources, leading to desertification and decrease in agricultural productivity. The changing climate may also result in crisis of drinking water along with the scarcity of water for irrigation. Finally, the outcome of this study may prove to be useful to policy makers, hydrologists and water resource managers dealing with climate change in the state of Rajasthan for sustainable development and planning of water resources.

Declarations

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Author contribution D. Saini, analyzed data, did literature review, and drafted the initial manuscript. P. Bhardwaj provided research direction, and assisted in writing and editing of the manuscript. O. Singh took lead in the supervision, guided research direction, and assisted in the writing and editing of the manuscript. The listed authors have made a significant contribution to warrant their being part of authorship and have approved the work.

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Figures

Figure 1

Map showing the position of study area in India and geographical location of selected rainfall and temperature stations.

Figure 2

Temporal distribution of mean annual rainfall over dryland ecosystem of north western India (1961-2017).

Figure 3

Station-wise mean annual rainfall over dryland ecosystem of north western India (1961-2017).

Figure 4

Station-wise annual mean, maximum and minimum temperature over dryland ecosystem of north western India (1979-2014).

Figure 5

Year-wise seasonal rainfall over dryland ecosystem of north western India (1961-2017). (a) Winter season, (b) Pre-Monsoon season, (c) Monsoon season and (d) Post-Monsoon season.

Figure 6

Year-wise monthly rainfall overdryland ecosystem of north western India (1961-2017).

Figure 8

Spatial distribution of seasonal rainfall over dryland ecosystem of north western India (1961-2017). (a) Winter season, (b) Pre-Monsoon season, (c) Monsoon season and (d) Post-Monsoon season

Figure 9
Spatial distribution of rainfall trends over dryland ecosystem of north western India (1961-2017) (a) Winter season, (b) Pre-Monsoon season, (c) Monsoon season and (d) Post-Monsoon season

Figure 10
Spatial distribution of percent change in rainfall over dryland ecosystem of north western India (1961-2017). (a) Winter season, (b) Pre-Monsoon season, (c) Monsoon season and (d) Post-Monsoon season

Figure 11

Spatial distribution of monthly rainfall over dryland ecosystem of north western India (1961-2017).

Figure 13

Spatial distribution of heavy rainfall events over dryland ecosystem of north western India (1961-2017).