An analysis of rainfall variability and drought over Barmer District of Rajasthan, Northwest India

Darshan Mehta and S. M. Yadav

ABSTRACT

Climate variability, mainly the annual air temperature and precipitation, have received great attention worldwide. The magnitude of this climate variability changes with variation in location. Rajasthan comes under the arid and semi-arid zone of India in which monsoon is a principal element of water resource. Due to erratic and scanty rainfall in this zone, agriculture is totally dependent on the monsoon. The objective of the present study is to assess the meteorological drought characteristics using Drought Indices Calculator DrinC from the historical rainfall records of the Barmer District of Rajasthan State by employing the criterion of percentage departure (D%), rainfall anomaly index (RAI) and standardized precipitation index (SPI). Trend analysis of seasonal and extreme annual monthly rainfall was carried out for the Barmer District of Rajasthan State using the data period between 1901 and 2002 at the 5% level of significance. Sen's slope estimator was also applied to identify the trend. Temporal analysis is useful to predict and identify the possible drought severity and its duration in the study region. It also helps in understanding its effect on groundwater recharge and increasing the risk of water shortage. Trend analysis of rainfall over 102 years shows an increasing trend in pre-monsoon, post-monsoon, southwest monsoon and annual rainfall and a decreasing trend in winter rainfall. Through this study, policy makers and local administrators will be benefitted, which will help them in taking proactive drought relief decisions in the drought-hit regions.

Key words | Barmer district, drought indices, percentage departure, rainfall anomaly index, standardized precipitation index

Darshan Mehta (corresponding author)
S. M. Yadav
Department of Civil Engineering,
Sardar Vallabhbhai National Institute of Technology,
Surat 395007,
Gujarat,
India
E-mail: *darshanmehta2490@gmail.com*

HIGHLIGHTS

- To identify possible drought severity and duration in the study region.
- It will also provide an intermediate and long-term assessment of meteorological droughts.
- The study also deals with identification of drought patterns, and changes with the 102 years of the time span.
- Trend analysis is carried out using Mann–Kendall test to quantify the rainfall pattern.
- Magnitude of trend is carried out using Sen's slope.

INTRODUCTION

Climate change is gaining more attention around the globe when it comes to weather and extreme events. Climate may vary in different ways, over different time scales and geographical scales (Zarch *et al.* 2011). Rainfall is a significant part of the hydrological cycle, and its temporal and spatial variability is of key importance considering both perspectives i.e., scientific and socioeconomic (Ramkar & Yadav 2019). Environment and societies have always been vulnerable to extreme weather and drastic shifts in the

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distribution of weather patterns. But over the last few decades, the evidence is intensifying that the distribution of weather patterns is vulnerable to anthropogenic factors as well (Devi *et al.* 2005).

Regular availability of water does not affect the food, energy, farming, and health sectors. Climate change influences the trend of long-term rainfall that contributes to severe hazards like drought and flooding (Surendran *et al.* 2017). Because of the unequal rainfall distribution and the mismatch between water demand and its availability, storage structures are essential for controlling the natural flow to meet the requirements for water (Mondal *et al.* 2015). As per the Intergovernmental Panel on Climate Change (IPCC 2007), various research works were carried out to assess climate change and its effect on different sectors, endorsing the immediate effects of climate change on agriculture, problems due to scarcity of water, glaciers, and decrease in the flow of rivers. Because of climate change, the supply of freshwater is likely to decrease in many river basins (Gosain *et al.* 2006).

An increase in population and living-standard growth will adversely affect many people in India by the 2050s. To redistribute natural streamflow, large storage reservoirs may be required in compliance with the requirements of a particular area, under the conditions of distorted water supply and its mismatch with demand (Mondal *et al.* 2015). Due to global warming, rainfall pattern changes, which affects the cycle of hydrology. Hence, an audit is required for the design of reservoirs and water science and technology practices by considering climate variation and its unpredictability in India.

The atmospheric concentration of CO_2 has increased in 2014 to a value of 400 ppm from 280 ppm during pre-industrial times. The atmospheric concentration of CH_4, NO, and other essential GHGs has also increased significantly (Swain *et al.* 2007). Different anthropogenic actions impact the Earth's climate framework, which result in an increase in greenhouse gases within the atmosphere leading to global climate change. According to the 4th (Fourth) Assessment Report (AR4), an increase in observed surface temperature has occurred since the mid-20th century (Kundzewicz *et al.* 2008).

For understanding the changing pattern of rainfall and temperature, climate change and climate variability are a wide field of research work (Dore 2005). To know the issues related to flooding, droughts, and several uses of water, rainfall trend detection for the long term is needed which will lead to a better result against the future climate scenarios (Edossa *et al.* 2010). To reflect the process of energy exchange over the Earth's surface with reasonable accuracy, the air temperature is considered as a good indicator of the climate state. As a result of global warming, even with relatively minor average temperature increases, catastrophic events, such as tropical cyclones (including hurricanes and typhoons), flooding, droughts and severe rainfall are predicted to escalate in frequency and severity (Thomas & Prasannakumar 2016). Changes in extreme and severe events such as heat waves and heavy precipitation events have been observed in the past.

Severe events have many effects on socio-economic sectors, namely, water supply and its resources, agriculture, human strength, terrestrial environments, coastal zones and biodiversity (Serrano *et al.* 1999).

Due to global warming, changes in rainfall will influence hydrology and creek flows and demand, which requires a quick review of hydrological design and its parameters (Mundetia & Sharma 2015). The above study attempted to assess the drought indices for the study area. Temporal and rainfall changes will impact various hydraulic and hydrological processes (Basistha *et al.* 2008). Past researchers have stressed that change in climate can cause extreme events like floods and droughts. Hence it is important to consider the areas mainly that depend on rainfall. The current study focuses on the southwest region of Rajasthan State. Drought analysis is carried out to analyze the drought characteristics in the study area. Very few studies have been carried out in the mentioned arid region, which motivates the research work to study the drought phenomenon in such a region. This study also deals with the identification of drought patterns, and with changes in the 102-year time span.

OBJECTIVE OF STUDY

The objective of the study is:

- To analyze the variability and trend analysis of rainfall for Barmer District in the southwest region of Rajasthan using the Mann–Kendall test.

- To assess the trend magnitude using Sen's slope estimator over the study region.
- To carry out temporal analysis of drought characteristics based on rainfall data.

STUDY AREA

The Barmer District is a part of the Thar Desert, within the western part of the state of Rajasthan in India. Barmer is the third largest district in Rajasthan, occupying an area of 28,387 km^2, and is India's fifth largest district. The district is situated between latitudes 24° 58′ and 26° 32′N and longitudes 70° 05′ and 72° 52′E as shown in Figure 1. The longest river in the district is the Luni, which is 480 km long and flows into the Gulf of Kutch from Jalore.

Geographically, the whole region is an integral part of the Great Indian Desert. The surface elevation ranges from 70 m above mean sea level (MSL) at Sindhari to 457 m above mean sea level (MSL) at the village of Ghonia. Barmer District faces an arid type of climate. The district's average annual rainfall (1971–2005) is 281.8 mm, while normal rainfall (1901–1971) is 277.5 mm, which is less than the average rainfall. During the southwest monsoon, from the first week of July until mid-September, nearly 90% of the total annual rainfall is received in the study area. This shows that it experiences extremes of heat in summer and cold in winter as the area is in the desert region. Temperature also rises during day and night-time but gradually reaches the maximum value in the months of May and June. The range of temperature is from 48°C in summer to 2°C in winter. Even during the monsoon period, the atmosphere is generally dry. With a mean daily relative humidity of 43%, humidity is at its peak in the month of August. The district's annual maximum evapotranspiration potential is 1,850 mm which is highest in the month of May and 77 mm which is lowest in the month of December (Ground Water Information Barmer District 2013).

DATA COLLECTION AND ANALYSIS

India is divided into 36 sub-divisions according to IMD (Indian Meteorological Department). In the above study, drought analysis is done using drought indices calculator i.e., DrinC for Barmer District, a southwest region of Rajasthan State of India. Data for this district was collected from the IITM (Indian Institute of Tropical Meteorology, Pune). Homogeneous monthly rainfall (mm) data was collected for 1901 to 2002 (102 years). The study area

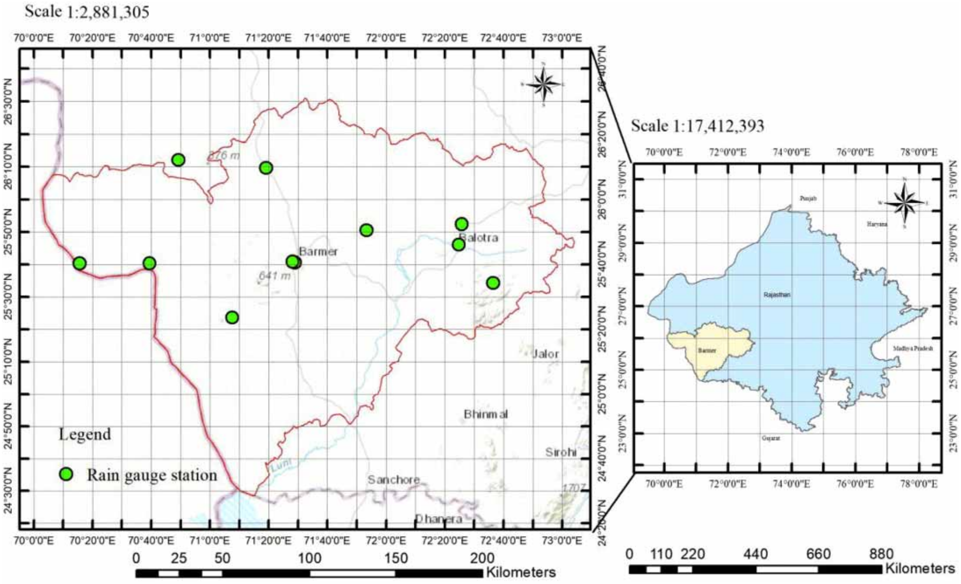

Figure 1 | Map of study area and location of meteorological stations.

consists of 11 gauging stations across Barmer for which rainfall data are available from 1901 to 2002.

METHODOLOGY

In the present study, trend analysis of rainfall is carried out in the first part, and in the second part meteorological drought analysis is carried out based on rainfall. For meteorological drought analysis, four climatic seasons are considered as per IMD (Indian Meteorological Department), namely southwest monsoon (June to October), post-monsoon (November–December), winter (January–February), and pre-monsoon (March–May). Data analysis from 1901 to 2002 was carried out for seasonal rainfall as well as for annual rainfall. The concept of meteorological drought is based on the degree of dryness and dry period duration as per the National Drought Mitigation Center (NDMC). Although numerous studies on rainfall characteristics on various spatial and temporal scales exist, none are intended to understand the trends in the concentration of precipitation as well as the drought scenario over the State of Rajasthan. Therefore, different techniques and methods for climate data and drought analysis have been used to analyze the temporal variation of rainfall as well as the drought scenario (Thomas *et al.* 2016).

Rainfall characteristics

In the present study, rainfall data was aggregated to prepare monthly, seasonal and annual time series for the study region. Statistical parameters like mean, standard deviation, coefficient of variation, maximum and minimum were computed for monthly, seasonal, and annual time series of rainfall data. The southwest region is an arid and semi-arid of Rajasthan State where monsoon is the only element that contributes to climate seasonality. Thus, the rainfall is taken into consideration for climate change analysis as per the hydrological year (June–May).

Trend analysis

To analyze the trend of rainfall and temperature, the rank-based non-parametric Mann–Kendall (MK) test and slope-based Sen's slope (SS) estimator were conducted on rainfall and temperature time series of 102 years. The Mann–Kendall (MK) test and Sen's slope (SS) estimator were performed by using XLSTAT 2016. Both these methods assume a linear trend in the time series. Regression analysis is conducted with time as the independent variable and rainfall/temperature as the dependent variable.

The Mann–Kendall (MK) test follows a computational procedure in which n is the number of data points in the time series and x_j and x_i are two sequential data sets of time series. Each data value of the time series is compared with another subsequent data value. If the data value of the later time period is higher than the earlier data value then the statistics S is incremented by 1, and if the value is lower than the earlier data value then the statistic S is decreased by 1. The final result for statistics S is calculated by the net result of these two increment and decrement data values. The positive value of S indicates an increasing (upward) trend while the negative value suggests a decreasing (downward) trend. The statistic S of the Mann–Kendall (MK) test is calculated by the given Equations (1) and (2):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}\,(x_j - x_i) \tag{1}$$

$$\text{sign}\,(x_i - x_j) = \begin{cases} -1; & (x_j - x_i) < 0 \\ 0; & (x_j - x_i) = 0 \\ 1; & (x_j - x_i) > 0 \end{cases} \tag{2}$$

where x_j and x_i are the data values in years j and i respectively.

The MK tests adopt the two-hypothesis null hypothesis (H_0) and the alternative hypothesis (H_a), in which the null hypothesis assumes that there is no trend in the time series or in other words the data values are independent and randomly ordered, while the alternative hypothesis assumes that there is a trend in the time series. This statistic of the Mann–Kendall test is used to test the null hypothesis H_0. If the value of the statistic is greater than the significance level (α) then the null hypothesis cannot be rejected from the time series, indicating that the test is statistically insignificant, and on the other hand if the value of the statistic is less than the significance level (α) then the null hypothesis is rejected and an alternative hypothesis is accepted, implying that the test is statistically significant. By performing trend analysis by XLSTAT 2016 the value of the MK statistic is denoted by value p. A two-tailed test was performed at 95% confidence level for both time series of rainfall and temperature (minimum, maximum).

The slope-based test for trend detection used in this paper was Sen's slope (SS) estimator. The method used for the analysis of trend was Sen (1968) which measures the magnitude of a trend as follows:

$$\text{Sen's slope} = \text{median}\left[\frac{Y_i - Y_j}{(i-j)}\right];\ j < i \tag{3}$$

where Y_i and Y_j are the data values at time periods i and j. A positive value of SS indicates an increasing trend while a negative value suggests a decreasing trend.

Another statistic obtained on running the Mann–Kendall test is Kendall's tau, which is a measure of correlation and therefore measures the strength of the relationship between the two variables. Like Spearman's rank correlation, Kendall's tau is carried out on the ranks of the data. That is, for each variable separately, the values are put in order and numbered, 1 for the lowest value, 2 for the next lowest, and so on. In common with other measures of correlation, Kendall's tau will take values between -1 and $+1$, with a positive correlation indicating that the ranks of both variables increase together whilst a negative correlation indicates that as the rank of one variable increases, the other decreases.

In time series analysis it is essential to consider autocorrelation or serial correlation, defined as the correlation of a variable with itself over successive time intervals, prior to testing for trends. Autocorrelation increases the chances of detecting significant trends even if they are absent and vice versa.

Drought analysis on basis of rainfall

The concept of meteorological drought is based on the degree of dryness and dry period duration as per the National Drought Mitigation Center (NDMC). For drought analysis of rainfall, the departure analysis of rainfall (D%), rainfall anomaly index (RAI) and standardized precipitation index (SPI) methods are generally used by researchers (Thomas *et al.* 2016).

Percentage departure (D%) of rainfall analysis

To assessing the various drought years, percentage departure of annual rainfall (D%) is used and calculated by using Equation (4):

$$D\% = \left(\frac{X_\text{i} - X_\text{m}}{X_\text{m}}\right)100 \tag{4}$$

where X_m – mean annual rainfall and X_i – annual rainfall series.

Steps for calculation of rainfall departure:

- Calculate mean of annual rainfall data from observed annual rainfall data for the station.
- For calculating departure, subtract the annual rainfall of the year from the mean rainfall of the year.
- Find out 75% of mean rainfall and calculate a drought year. If the value of annual rainfall of the year is less than 75% of mean rainfall, then it is called a drought year.
- After calculating a drought year, we have to calculate departure from mean rainfall.

According to IMD (Indian Meteorological Department) in India, meteorological drought over an area means that 'less than 75 percent of regular rainfall is the seasonal rainfall received over the region' (Thomas *et al.* 2015). Moderate drought means the deficit in rainfall varies from 26 to 50 percent and severe drought means the shortage in rainfall exceeds 50 percent of regular rainfall. Mild drought means the rainfall deficit is ranges from 20 to 25 percent. According to IMD, the rainfall distribution can be done on the basis of the percentage departure decision range as given in Table 1.

Table 1 | Regional rainfall distribution based on percentage departure

Type of distribution	Decision range
Excess rainfall	+20% or more
Normal rainfall	Between – 19% and +19%
Deficit rainfall	Between −20% and −59%
Scanty rainfall	Between −60% and −99%
No rainfall	Less than −100%

Source: (Kanellopoulou 2002).

RAI – rainfall anomaly index

Van Rooy (1965) provides a rating system for assigning magnitudes to positive and negative rainfall anomalies in the rainfall measured by using Equation (5):

$$RAI = \pm 3 \frac{P - \bar{P}}{\bar{E} - \bar{P}} \tag{5}$$

where P = measured precipitation, $\bar{P}$ = mean precipitation, and $\bar{E}$ = average of ten extremes (mean of ten highest precipitation records in the period). The values of RAI are categorized into nine regimes, as mentioned in Table 2 below.

Standardized precipitation index (SPI)

SPI is the most common meteorological drought index among the various drought indices, and is evaluated on the basis of long-term rainfall records for selected durations, namely three months, six months, nine months and 12 months. Due to its statistical precision and inherent probabilistic nature, SPI has gained worldwide applicability, the ability to define short-term as well as long-term impact of droughts across the different time scales and the suitability to compare the conditions of drought between areas having different time periods and climatic conditions (Mohammed & Scholz 2019). It is used to predict the parameters of drought for multiple series of time that indicate the effect of drought on the availability of water resources (McKee *et al.* 1993). To derive different drought parameters SPI can be computed on a variety of time scales and for different water variables such as soil moisture, groundwater, etc. (Shah *et al.* 2015).

Table 2 | Rainfall regime based on standard ranges of RAI

RAI values	Rainfall regime
≥3	Extremely wet
2.0–2.99	Very wet
1.0–1.99	Moderately wet
0.50–0.99	Slightly wet
0.49 to −0.49	Near normal
−0.50 to −0.99	Slightly dry
−1 to −1.99	Moderately dry
−2 to −2.99	Very dry
≤−3	Extremely dry

Source: (Van Rooy 1965).

Results obtained by using the above steps are then used to evaluate the cumulative probability of an observed time scale and precipitation events for the given month. The resulting cumulative probability is then converted into the standard normal random variable, Z variable with a mean of zero and a single value of SPI (Abramowitz & Stegun 1965). When the values of SPI are consistently negative or less than (−1) then it is said that drought has occurred and it ends when the SPI value is positive. The overall positive summary of the SPI is known as the magnitude of drought for all months during a drought event. The assessment of the ratio of the magnitude of the drought to its duration results in the intensity of drought, and the severity of the drought can be obtained using Table 3 (Hayes *et al.* 1999). In this study, DrinC (Drought Indices Calculator) software is used for calculating SPI & RAI. In order to calculate these indices, DrinC software is suitable for meteorological, hydrological and agricultural drought analysis. These indices have relatively small data requirements, while their outcomes can be easily interpreted and used in strategic development and operational applications.

RESULTS AND DISCUSSION

Rainfall characteristics over Barmer District

Descriptive statistics of rainfall were prepared on a monthly, seasonal, and annual scale for 1901–2002 (102 years).

Table 3 | Classification of rainfall regime based on standard ranges of SPI

SPI values	Rainfall regime
≥2.00	Extremely wet
1.50–1.99	Very wet
1.00–1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.00 to −1.49	Moderately dry
−1.50 to −1.99	Severely dry
≤−2.00	Extremely dry

Source: (Hayes *et al.* 1999).

Annual mean rainfall (1901 to 2002) is 291.3 mm with SD equal to 134.27. During the entire period of 102 years, annual minimum and maximum rainfall are 73.8 mm and 697.4 mm. Annual coefficient of variance (CV) is 46.1%, which implies a very high inter-annual variability of annual rainfall over Barmer District. During the 102 years, July and August months contribute the maximum percentage of rainfall (99.1 mm and 92.8 mm) to the annual rainfall. The winter months (January–February) and pre-monsoon months (March, April, and May) together contribute 0.7% and 1.1% rainfall to the annual budget, while the post-monsoon months (October–December) contribute 1.3% rainfall to the annual budget. On average January and February receive 1.12 mm and 2.68 mm mean rainfall, while March, April, and May receive 3.43 mm, 2.66 mm and 3.95 mm rainfall respectively. The degree of variability of rainfall events as per coefficient of variance is considered as per Table 4.

The coefficient of variance (CV) of all months except July is more than 70%, hence all the months excluding July have extremely high variability of rainfall. The month of July has a CV of 63.2%, implying very high inter-annual variability. Rainfall characteristics for seasonal rainfall show that the maximum share of annual rainfall greater than 90% is received in one spell of the southwest monsoon (265.7 mm) contributing 91.2% to annual rainfall (Table 5). The post-monsoon season also receives normal rainfall of about 11.8 mm, which contributes 4% of rainfall to the annual budget. The CV of the southwest monsoon is 46.1%, which indicates the very high inter-annual rainfall variability.

Table 4 | Classification of rainfall event based on coefficient of variance (CV)

CV values	Rainfall event
<20	Less
20–30	Moderate
30–40	High
40–70	Very high
>70	Extremely high

Source: (Thomas *et al.* 2016).

Table 5 | Statistics of monthly seasonal and annual rainfall over Barmer District for 102 years

	Rainfall (mm) for Barmer District					
Month	Mean	SD	CV (%)	% Contribution to annual	Minimum	Maximum
Jan	1.12	1.58	141.3	0.4	0.0	7.2
Feb	2.68	5.35	199.9	0.9	0.0	37.5
Mar	3.43	8.54	249.2	1.2	0.0	51.0
Apr	2.66	4.80	180.3	0.9	0.0	21.8
May	3.95	6.20	157.1	1.4	0.0	34.7
Jun	27.62	27.56	99.8	9.5	0.3	128.1
Jul	99.05	62.61	63.2	34.0	1.1	308.8
Aug	92.79	72.73	78.4	31.9	1.4	509.0
Sep	46.22	56.99	123.3	15.9	0.0	299.4
Oct	5.47	9.58	175.2	1.9	0.0	37.6
Nov	5.03	11.34	225.5	1.7	0.0	57.5
Dec	1.27	2.26	177.5	0.4	0.0	12.6
Annual	291.3	134.265	46.1	100.0	73.8	697.4
Pre-monsoon	10.0	11.479	114.3	3.4	0.0	51.1
SW monsoon	265.7	129.405	48.7	91.2	54.7	656.3
Post-monsoon	11.8	15.8816	134.9	4.0	0.0	85.3
Winter	3.8	5.42771	143.2	1.3	0.0	37.5

Rainfall trend analysis over Barmer District

By performing trend analysis, the results show that the monthly rainfall of July shows an insignificant increasing trend ($p = 0.664$), while the month of September shows an insignificant decreasing trend ($p = -0.038$). Annual rainfall shows an insignificant increasing trend ($p = 0.657$). Trend analysis for seasonal rainfall shows an increasing trend for pre-monsoon, southwest monsoon and post-monsoon while winter shows an insignificant decreasing trend ($p = 0.493$) (Table 6). Rainfall time series plots on annual and seasonal scales are presented in Figures 2 and 3 with a dotted line for the mean value.

Table 6 | Summary of the Mann–Kendall test for rainfall trend data 1901 to 2002 over Barmer District

Rainfall period	Kendall's tau	Trend interpretation	Mann–Kendall test *p*-value (two-tailed test)	Sen's slope	Test interpretation
January	– 0.074	Falling	0.262	– 0.00007	Insignificant decreasing trend
February	0.002	Rising	0.979	0	No trend
March	– 0.039	Falling	0.564	0	No trend
April	– 0.016	Falling	0.811	0	No trend
May	0.068	Rising	0.302	0.003	Insignificant increasing trend
June	0.086	Rising	0.185	0.07	Insignificant increasing trend
July	0.028	Rising	0.664	0.076	Insignificant increasing trend
August	0.025	Rising	0.706	0.072	Insignificant increasing trend
September	– 0.055	Falling	0.395	– 0.038	Insignificant decreasing trend
October	0.048	Rising	0.476	0	No trend
November	0.022	Rising	0.754	0	No trend
December	– 0.088	Falling	0.194	0	No trend
Winter	– 0.045	Falling	0.493	– 0.002	Insignificant decreasing trend
Pre-monsoon	0.026	Rising	0.687	0.007	Insignificant increasing trend
SW monsoon	0.023	Rising	0.725	0.153	Insignificant increasing trend
Post-monsoon	0.056	Rising	0.388	0.012	Insignificant increasing trend
Annual	0.029	Rising	0.657	0.187	Insignificant increasing trend

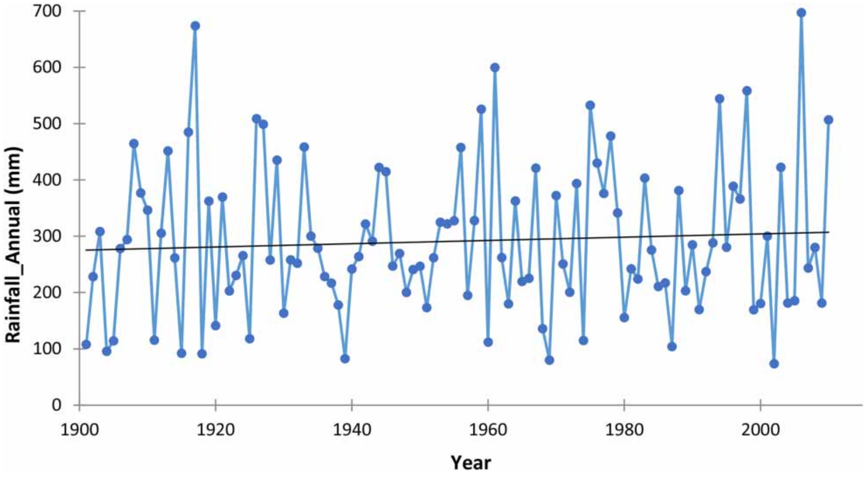

Figure 2 | Time series of annual rainfall (1901–2002) over Barmer District.

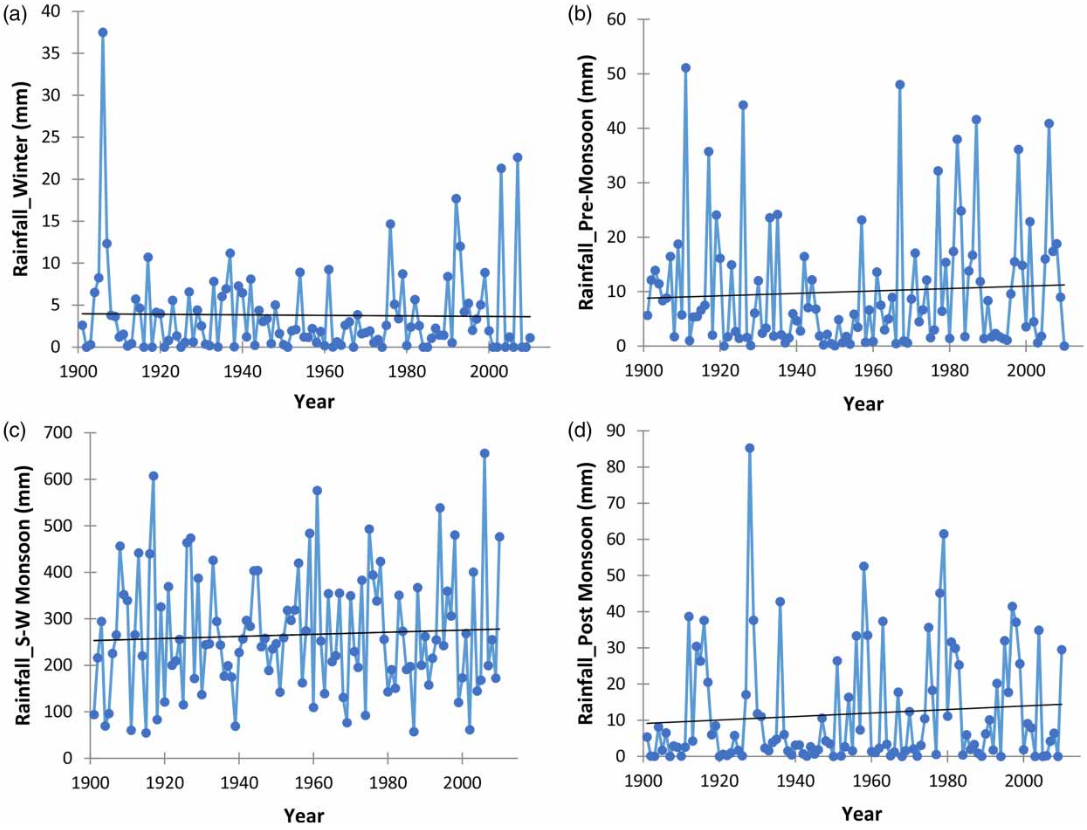

Figure 3 | Time series of rainfall during (a) winter, (b) pre-monsoon, (c) southwest monsoon and (d) post-monsoon for 1901–2002 over Barmer District.

Drought analysis based on rainfall

The drought characteristics of the study area were analyzed based on drought indices such as percentage departure of rainfall (D%), rainfall anomaly index (RAI), and standardized precipitation index (SPI). Departure analysis of rainfall during the entire study period of 102 years was computed on a seasonal and annual scale. A drought year in the present study was defined by two methods:

(i) Classification of drought as per IMD (Attri & Tyagi 2010), and
(ii) rainfall distribution and its classification on the basis of departure percentage as per Table 1.

Rainfall departure analysis (D%) for Barmer District

The annual rainfall departure analysis reveals that hardly any severe drought occurred during the period. The regional rainfall distribution classification based on D% (after IMD) is given in Table 1. Decade-wise percentage departure of annual and seasonal rainfall and number of years with excess, deficit, and scanty rainfall were examined by following the scheme. The seasonal rainfall departure analysis also shows that the departure of rainfall during the post-monsoon, winter and pre-monsoon seasons shows significantly greater inter-decadal variability compared with annual or southwestern monsoon-rainfall. On a time, series of D% values of varying scales for each year, the Mann–Kendall test applied (Table 7) indicates a significantly increasing trend of D% of the post-monsoon rainfall, reflecting the increasing trend of post-monsoon rainfall. In addition, a significant causative relationship with D% of southwest monsoon, post-monsoon and pre-monsoon rainfall is shown by D% of annual rainfall ($p < 0.05$) as shown in Figure 4.

Rainfall anomaly index (RAI)

The rainfall anomaly index was computed and classified on annual rainfall (Van Rooy 1965; refer to Table 2). As per the

Table 7 | Results of the Mann–Kendall test for percentage departure trends (D%) of various scales (1901 to 2002) for Barmer District

Percentage departure	Mann–Kendall test *p*-value (two-tailed test)	Sen's slope
Annual	0.657	0.064
Southwest monsoon	0.725	0.058
Post-monsoon	0.388	0.099
Winter	0.493	−0.048
Pre-monsoon	0.687	0.066

classification of rainfall regime, there is no extremely dry (Figure 5) year during the entire study period (1901 to 2002) of 102 years.

From the current study, overall 37 years are classified as drought years from the 102 years using the RAI index. Years with slightly dry, moderately dry and very dry regime are presented in Table 8.

Standard precipitation index (SPI)

SPI was calculated for four different time scales viz., three, six, nine and 12 month. Here, three-month SPI was used to represent a short-term drought event, six-month and nine-month SPI were used to represent intermediate drought events and twelve-month SPI was used for analyzing drought for a long-term period. Calculation of SPI was carried out using DrinC software (Drought Indices

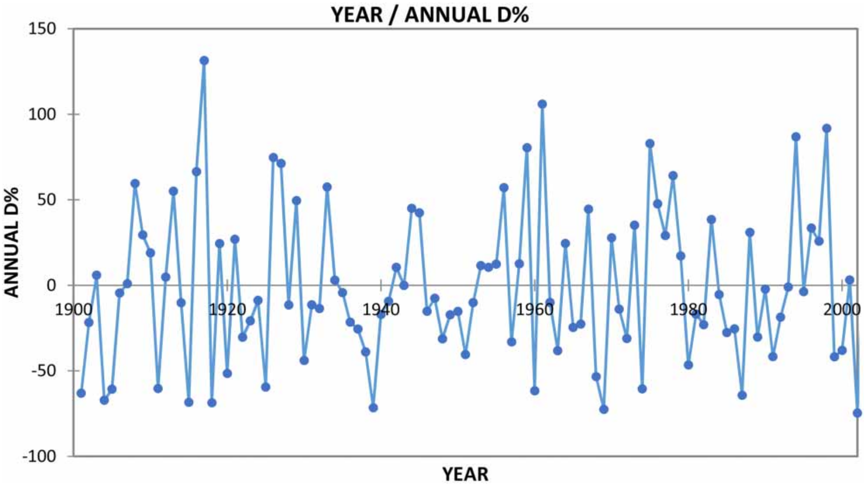

Figure 4 | Rainfall departure analysis (D%) for Barmer District.

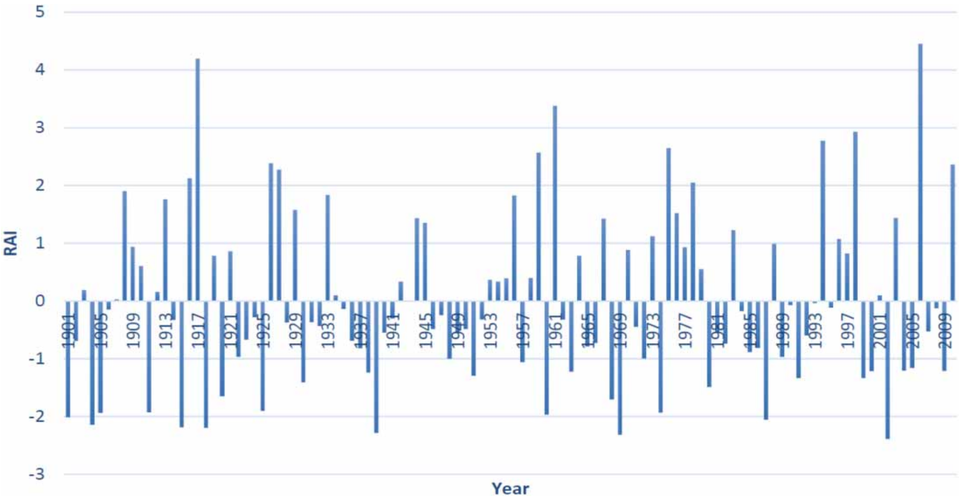

Figure 5 | Rainfall anomaly index for Barmer District from the year 1901 to 2002.

Table 8 | Rainfall regime over Barmer District from the year 1901 to 2002

	Total number of years		
Sr. no	**Very dry rainfall regime 7**	**Moderate dry rainfall regime 16**	**Slightly dry rainfall regime 14**
1	1901	1905	1902
2	1904	1911	1922
3	1915	1920	1923
4	1939	1925	1936
5	1969	1930	1937
6	1987	1938	1940
7	2002	1951	1949
8		1957	1965
9		1960	1966
10		1963	1981
11		1968	1982
12		1974	1985
13		1980	1986
14		1991	1992
15		1999	
16		2000	

Calculator) for the hydrological year October–September, and three-month SPI for the months October–December, January–March, April–June, and July–September were considered for the calculation. Figure 6 shows the time series of three-month SPI for all four time frames. SPI of all the years shows that a total of 70 drought events were found during all four time frames (October–December, January–March, April–June and July–September). Out of 70 years of drought events, 51 years are recorded with moderately dry, eight years with severely dry and 11 years with extremely dry rainfall regime. The six-month and nine-month SPI were analyzed for intermediate drought events.

Six-month SPI for the months of October to March and April to September were considered for the calculation. Figure 7 shows the time series of six-month SPI for two time frames. According to the classification of rainfall regime based on SPI (refer to Table 3), out of 45 years of drought events, 26 years are recorded with moderately dry, 12 years with severely dry and seven years with extremely dry rainfall regime.

The calculation for the nine-month SPI time frame of October–June was considered as shown in Figure 8. According to the classification of rainfall regime based on SPI (refer to Table 3), out of 25 years of drought events, 13 years are recorded with moderately dry, seven years with severely dry and five years with extremely dry rainfall regime. Temporal variation of long-term drought event for 12-month SPI (October–September) and its drought characteristics are given in Figure 9. Out of 20 drought events, ten years are recorded with moderately dry years, five years with severely dry and five years with extremely dry events as per the classification (refer Table 3).

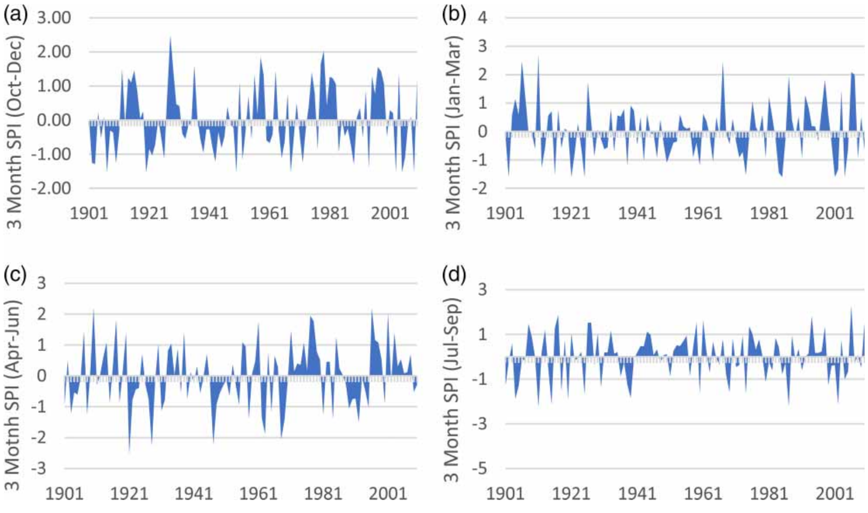

Figure 6 | SPI of three months for (a) Oct–Dec, (b) Jan–Mar, (c) Apr–Jun and (d) Jul–Sep over Barmer District.

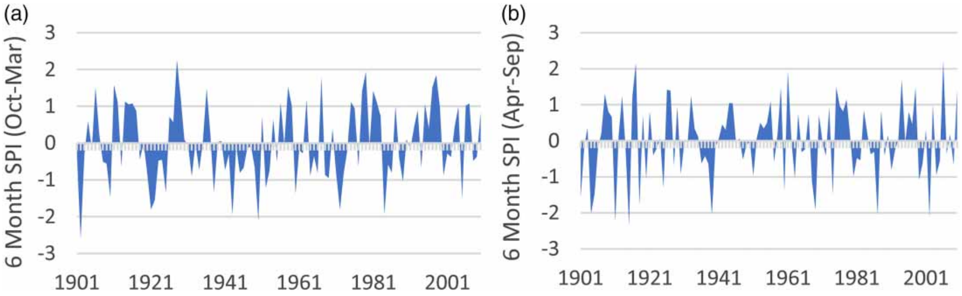

Figure 7 | SPI of six months for (a) Oct–Mar and (b) Apr–Sep over Barmer District.

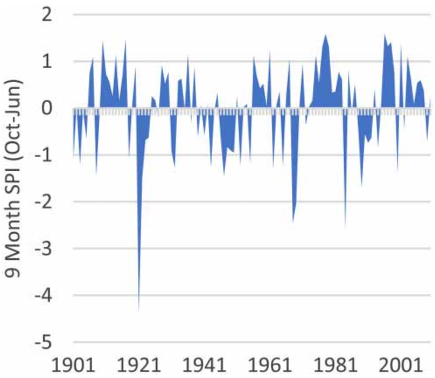

Figure 8 | SPI for nine months (Oct–June) for Barmer District.

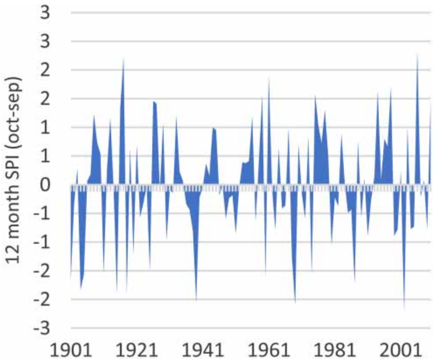

Figure 9 | SPI for 12 months (Oct–Sept) for Barmer District.

CONCLUSION

The rainfall analysis over the Barmer District (1901 to 2002) implies a decreasing winter trend while pre-monsoon, post-monsoon and southwest monsoon trends are increasing. The annual and seasonal rainfall within 5–10 years shows inconsistent frequency, which aligns with the periodicity of ENSO (El Niño Southern Oscillation). There have been 11 instances of drought years in the Barmer District with 28.1% to 40% below the average annual rainfall in the area. Four severe drought years were observed with 68.8% to 82.9% below the average annual rainfall in the area. The probability of moderate drought in this region is found to vary from 17% to 24% and for severe drought it is found to be between 2% and 14%. The recurrence period of once in three years is observed for the Barmer district which reflects a greater probability of frequent drought. From the above results of different indices for different time scales (i.e., three months, six months, nine months, and 12 months), it is clearly observed that near-normal droughts occurred most frequently, and severe drought events occurred least frequently. In planning the proposed mitigation measures to minimize the effects of drought, the conclusion drawn from this work may be very beneficial. The forecasts for SPI 12 and RAI are even better and can be utilized as long-term planning tools for water resource managers within the country.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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