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RAINFALL ANALYSIS FOR DROUGHT PRONENESS AT WESTERN RAJASTHAN, INDIA

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Abstract: The western Rajasthan region of India is in the grip of severe drought conditions due to deficit rainfall. To assess the drought proneness at this region, the most drought affected 9 districts such as Barmer, Bikaner, Churu, Ganganagar, Jaisalmer, Jalor, Jodhpur, Nagaur and Pali are selected. A total of 60 years of monthly rainfall series at each district has been analyzed. Of these, a total of 30 years are of historic period *i.e.*, from the year 1983 to 2012 and the remaining 30 years are of synthetic period *i.e.*, from the year 2013 to 2042 are considered for analysis. Synthetic monthly rainfall series were generated using widely used Thomas-Fiering model. In order to test how well the historic and synthetic rainfall data follow the normal distribution the Anderson-Darling test is conducted. The Confidence Interval (CI) for Mean and Standard Deviation (SD) is also estimated at different significance levels (*p*-values). Further, the present study highlights different widely used methods to assess the drought proneness of a region. On the basis of percentage departure of rainfall from the long term average annual rainfall the drought event is categorized in to various drought intensities such as 'no', 'mild', 'moderate', 'severe' and 'extreme' droughts in the study region. Investigation for normal, abnormal or wet and drought years both in historic and synthetic rainfall series is done in the study region. Furthermore, the normal, abnormal or wet and the drought months were also estimated based on the monthly rainfall variations with that of the average monthly rainfall for both the historic and synthetic periods separately in the study region.

Key Words: *Drought, Rainfall, Thomas-Fiering model, Anderson-Darling test, p-value, Confidence Interval.*

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1. INTRODUCTION

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) states that the world indeed has become more drought-prone during the past 25 years, and the climate projections for the 21st century indicate increased frequency of severe droughts in many parts of the world. Global warming will increase the risk of drought in some regions. Even in regions that may not see changes in rainfall, warmer temperatures can increase water demands and evaporation, putting greater stress on water supplies. When droughts do occur, warmer temperatures can amplify their impacts. Droughts can persist through a "positive feedback," where very dry soils and diminished plant cover can further suppress rainfall in an already dry area. Increased temperatures enhance evaporation from soils, making a periodic occurrence of drought worse than it would be under cooler conditions (Richard Tinker, 2015). Indeed, the studies on regional droughts using rainfall series are often interesting to the hydrological researchers. Droughts are destructive climatic extreme events that may cause significant damage both in natural environments and in human lives (Kim and Valdés, 2003). Many researchers in the recent past have assessed the droughts in the drought affected regions. Bennerji and Chhabra (1963), studied the condition of droughts in Telangana region of combined Andhara Pradesh in India. Banerji and Upadhyay (1975), have conducted a survey of drought and scarcity in Rajasthan state in India. Srikanthan and McMahon (1985) have examined the recurrence interval of drought events through stochastic analysis of rainfall and streamflow data of Eppalock catchment in north central Victoria, Australia. Suresh *et al.,* (1993), have performed the rainfall analysis for drought study at Pusa, a place situated in the state of Bihar in India. Kim and Valdés (2003), developed nonlinear model for drought forecasting based on conjunction of wavelet transforms and neural networks. The developed conjunction model was applied to forecast droughts in the Conchos River Basin in Mexico, which is the most important tributary of the lower Rio Grande/Bravo. Jhajharia *et al.,* (2007), carried out the historic rainfall analysis for drought proneness at Guwahati, a main city of Assam in India using the widely used IMD criteria as suggested by Bennerji and Chhabra (1963). Mosaad (2011) has done the water resources management of Ruhr river basin in Germany in the context of drought.

The recent "Big Dry" in the Australia was reviewed by Leblanc *et al.,* (2012). They have analyzed the historic and future hydrological changes in the Murray-Darling Basin. Jethoo *et al.*, (2012) performed the analysis for water resources crises during drought in Nagaur district of the western Rajasthan. Sayari *et al.,* (2013) used drought indices to assess climate change impacts on drought conditions of Kashafrood basin in the northeast of Iran. Ault *et al.,* (2014) assessed the risk of persistent drought using climate model simulations and paleoclimate data in the U.S. Southwest. Very recently, Mundetia and Sharma (2015) developed rainfall indices and performed Standardized Precipitation Index (SPI) drought analysis for Rajasthan state. Inline, an attempt has

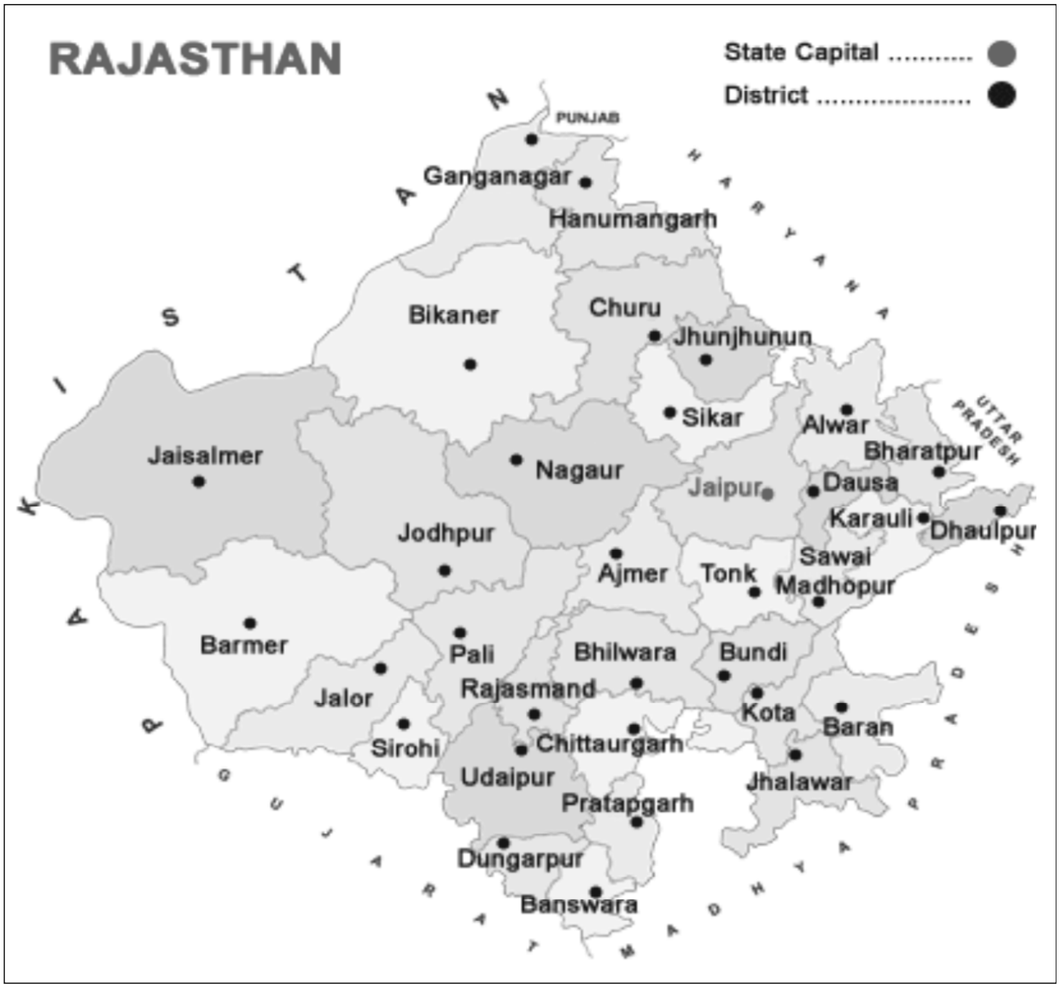


Figure 1: District map of Rajasthan

been made to assess the drought proneness of the selected 9 districts of the western Rajasthan region of India as this region is more prone to frequent droughts. The application of various widely used methods for the assessment of drought proneness of a region using rainfall analysis has been emphasized in the present study.

2. STUDY AREA

Drought occurs in many parts of India. Rajasthan is the most critical state in India with highest probabilities of drought occurrence and rainfall deficiencies (Mundetia and Sharma, 2015). As stated, the state of Rajasthan is prone to droughts particularly, over the western districts consisting of Thar Desert which often experience a number of successive years of drought Banerji and Upadhyay (1975). The annual rainfall is highly variable and it is most erratic in the western region of Rajasthan with frequent dry spells, punctuated occasionally by heavy downpour in some years associated with the passing low pressure systems over the region (Rathore, 2005). The selected 9 districts of western Rajasthan such as Barmer, Bikaner, Churu, Ganganagar, Jaisalmer, Jalor, Jodhpur, Nagaur and Pali (see Figure 1) are prone to severe droughts.

In order to assess the drought proneness at these selected 9 districts of western Rajasthan, a district wise rainfall analysis has been performed using a total of 60 years of rainfall series at each district. Of these, a total of 30 years of historic period from the year 1983 to 2012 rainfall series are collected from Water Resources Department (WRD, 2012), Government of Rajasthan, Rajasthan (India) and the remaining 30 years of synthetic period (predicted) from the year 2013 to 2042 rainfall series are generated using widely adopted Thomas-Fiering model at each district of the study region. The present study adopts the perception of the drought assessment which involves consideration of deviation of actual rainfall from normals (a meteorological concept of drought). Normal rainfall to a meteorologist is an average of the rainfall values over a 30 year period. Rainfall may very often be wither well above or well below the seasonal average, or normal.

3. DROUGHT ASSESSMENT USING RAINFALL SERIES

Drought assessment mainly involves analysis of spatial and temporal rainfall variations. Over the years, several methods and various indices were developed to assess the drought. The India Meteorological Department (IMD) method is a simple and widely used approach which gives a reliable information about the drought condition of an area. In this method, drought is assessed on the basis of percentage deviation of rainfall from the long term annual mean rainfall. According to IMD, a station is considered as drought-hit if it receives total rainfall < 75% of the normal rainfall (Jhajharia *et al.*, 2007). IMD adopted a normal practice that if annual co-efficient of variation (cv) is 30% or more, the rainfall is said to be erratic and the area is classified as drought prone. Further, IMD defined an area as drought prone if the annual rainfall < 75% of normal in 20% or more of the years examined. Furthermore, in order to characterize the droughts by their intensity which refers to magnitude to which the actual precipitation are lesser than the mean value and to identify the area as either drought prone or non-drought prone, IMD has suggested the following categorization of droughts as M_0 to M_4 based on the percentage deviation of rainfall from the normal rainfall as suggested by Bennerji and Chhabra (1963):

Departure of rainfall from normal (%)	*Drought Intensity*	*Code*
0.0 or above	No drought	M_0
0.0 to –25.00	Mild drought	M_1
–25.01 to –50.00	Moderate drought	M_2
–50.01 to –75.00	Severe drought	M_3
> –75.01	Extreme drought	M_4

Source: Jhajharia *et al.* (2007)

In an another criterion as adopted by Sharma *et al.*(1979; 1987) for investigating the drought reveal that, any year receiving rainfall $\leq(\overline{X}-SD)$, $\geq(\overline{X}+SD)$ and in the range $(\overline{X}\pm SD)$ of the average annual rainfall is identified as a drought year, abnormal year and a normal year, respectively (where, $\overline{X}$ is the mean and SD is the standard deviation). Further, as a threshold percentage the month receiving rainfall < 50%, > 200% and 50% to 200% of the average monthly rainfall is termed as drought, abnormal or wet and normal month, respectively. In order to assess the drought proneness at western Rajasthan region, the present study uses the IMD approach and the criteria as used by Sharma *et al.* (1979; 1987).

4. GENERATION OF SYNTHETIC RAINFALL SERIES USING THOMAS-FIERING MODEL

The method of Thomas and Fiering (1962) is of a Markovian nature with periodic parameters, namely, the monthly means, standard deviations and the lag-zero cross correlations between successive months (Mosaad, 2011). The method of Thomas and Fiering implicitly allows for the non-stationarity observed in monthly input data (Singhal, 1980). In its simplest form, the Thomas-Fiering model consists of twelve linear regression equations, one for each month (Goel, 2008). The characteristics of an observed flow records will be reproduced in a synthetic record generated from the observed record or historic data, statistically, the synthetic flow record is indistinguishable from the historical flow record (Pearson, 1968). In order to generate monthly rainfall series each year, the historic monthly rainfall series of each year have to be supplied as an input to the model. For the Thomas-Fiering model, synthetic monthly series is generated with the following recursive relationship:

$$p_{i+1}=\overline{p}_{j+1}+b_j\left(p_i-p_j\right)+z_i * S_{j+1} *\left(1-r_j^2\right)^{\frac{1}{2}} \tag{1}$$

In Equation (1), p_i and p_{i+1} are the monthly rainfall during the i^{th} and $(i+1)^{th}$ month respectively; $\overline{p}_j$ and $\overline{p}_{j+1}$ are the mean monthly rainfall during j^{th} and $(j+1)^{th}$ months respectively, within a repetitive annual cycle of 12 months; b_j is the regression coefficient for estimating the rainfall in the $(j+1)^{th}$ month from the j^{th} month and is given in Equation (2); z_i is a random normal deviate with zero mean and unit variance; S_j and S_{j+1} are the standard deviations of rainfall in the j^{th} and $(j+1)^{th}$ months and r_j is the correlation coefficient between rainfall in the j^{th} and $(j+1)^{th}$ months.

$$bj = r_j(S_{j+1}/S_j) \tag{2}$$

The sequence of the rainfall generated by Equation (1) possesses the same general statistical properties as those representing natural rainfall. The present study uses 30 years of the historical monthly rainfall data from the year 1983 to 2012 as an input to the Thomas-Fiering model to generate synthetic monthly rainfall series for next 30 years from the year 2013 to 2042 at each district. Further, the Thomas-Fiering model considers the noise in rainfall estimates follows a white noise or normal distribution. However, in the case of rainfall, it is hard to ensure the assumption of normality. Therefore, before doing the drought assessment using rainfall in the study region, a statistical analysis like Anderson-Darling test for normality is conducted.

5. STATISTICAL ANALYSIS OF RAINFALL AT WESTERN RAJASTHAN

In order to test how well the historic and synthetic rainfall data follow the normal distribution the Anderson-Darling test has been conducted as this test is a statistical test of whether a given data sample is drawn from a given probability distribution. The Anderson-Darling test for normality is designed to detect all departures from normality and also sometimes touted as the most powerful test than other available tests. The test rejects the hypothesis of normality when the p-value < 0.05, where p-value is also known as significance level (comes from significance test or tests of fit). Failing the normality test allows to state with 95% (p-value = 0.05) confidence the data does not fit the normal distribution. Passing the normality test (p-value > 0.05) only allows to state significant departure from normality is found. The p-value of 0.05 would indicate that the chance of the observed data is low due to variation alone. This is good evidence that the data was not generated under the hypothesized condition. The hypothesized condition is rejected if the p-value is 0.05 or below. This provides 95% confidence the hypothesized condition is not true, *i.e.*, the data does not fit the selected distribution or the means are not the equal. The smaller the p-value, the greater the evidence that the sample data did not come from the selected distribution. For tests of fit the confidence level can also be calculated from the p-value as 100*(1-p-value). Therefore, the calculated confidence levels say for example 99%, 95% and 90% which means that they are calculated using the p-values 0.01, 0.05 and 0.1, respectively.

The present study uses the Anderson-Darling test calculator, version 6.0 with excel interface (Kevin Otto, 2005) to test the normality in the rainfall data. Figure 2 depicts the calculated p-values for each district for both historic and synthetic rainfall data along with the p-value for all 9 districts as a whole. Similarly, Figure 3 show the confidence level values corresponding to the calculated p-values pertaining to each district and for all 9 districts as a whole.

It is seen from Figures 2 and 3 that both for historic and synthetic rainfall data the calculated p-values and their corresponding confidence level values are 0.22363 (confidence level = 77.637% < 95%) and 0.27282 (confidence level = 72.718% < 95%), respectively, when considered all the 9 districts as a whole. These results also reveal that, the calculated p-values showing > 0.05 (*i.e.*, confidence level < 95%) for both the historic and synthetic periods. The hypothesis condition is not rejected. Hence, both the historic and synthetic sample data are from the normal distribution when considered the region as a whole. This provides only 77.637% and 72.718% confidence

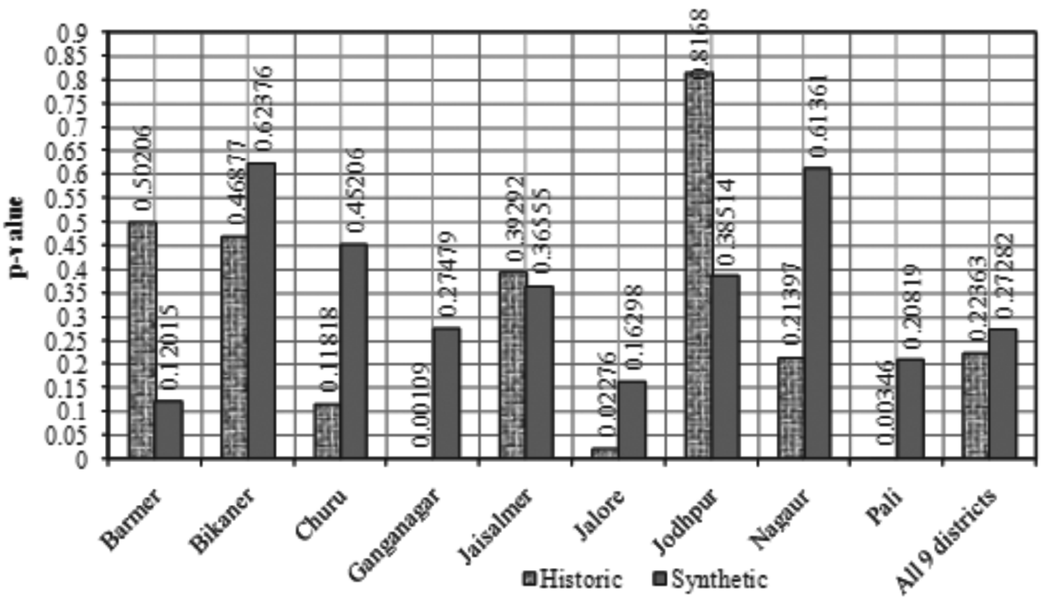


Figure 2: Showing calculated p-values for each district for both historic and synthetic rainfall data along with the p-value for all 9 districts as a whole.

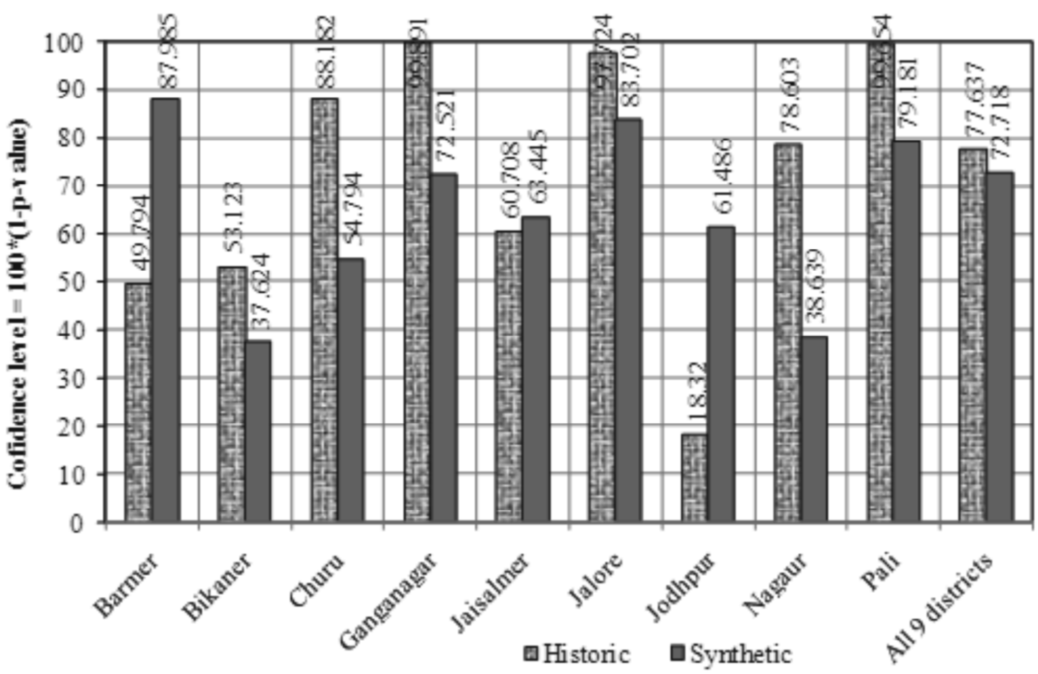


Figure 3: Showing confidence level values corresponding to the p-values pertaining to each district and all 9 districts as a whole.

the hypothesized condition is not true, *i.e.*, the data does not fit the selected distribution or the means are not the equal. However, as discussed the test rejects the hypothesis of normality when the p-value ≤ 0.05. This provides 95% confidence the hypothesized condition is not true, *i.e.*, the data does not fit the selected distribution or the means are not the equal. This condition is seen only in historic rainfall data for 3 districts such as Ganganagar (p-value = 0.00109 < 0.05, confidence level = 99.891% > 95%); Jalor (p-value = 0.02276 < 0.05, confidence level = 97.724% > 95%) and Pali (p-value = 0.00346 < 0.05, confidence level = 99.654% > 95%) indicating that the test rejects the hypothesis and the sample data did not come from the normal distribution. The data may come from another identifiable distribution or the presence of one or a few outliers (*i.e.*, either extreme or insignificant) might be causing the normality test to fail. There are many robust statistical tests available in the literature to detect the outliers from the sample data and also to identify the type of distribution from which the data has been drawn.

The present study directly uses the most common kind of data transformation approach *i.e.*, log transformation approach to test for normality in the rainfall data of these 3 districts. When used log transformed data, the revised results obtained for these 3 districts reveal that Ganganagar (p-value = 0.89848 > 0.05, confidence level = 10. 152% < 95%); Jalor (p-value = 0.8613 > 0.05, confidence level = 13.87% < 95%) and Pali (p-value = 0.36742 > 0.05, confidence level = 63.258% < 95%) indicating that the test does not rejects the hypothesis and the sample data come from the normal distribution. The problem from outliers is not seen in synthetic rainfall data as the Thomas-Fiering model inherently considers the noise in rainfall estimates follow a white noise or normal distribution. Figure 4 depict the normal probability variation

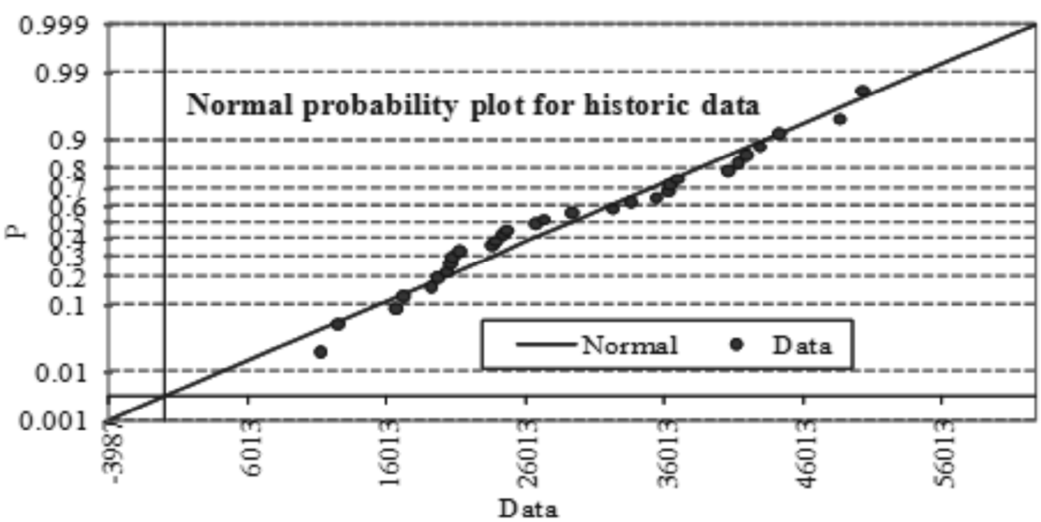


Figure 4: Depicting the normal probability variation for historic data developed only for all 9 districts as a whole in the study region.

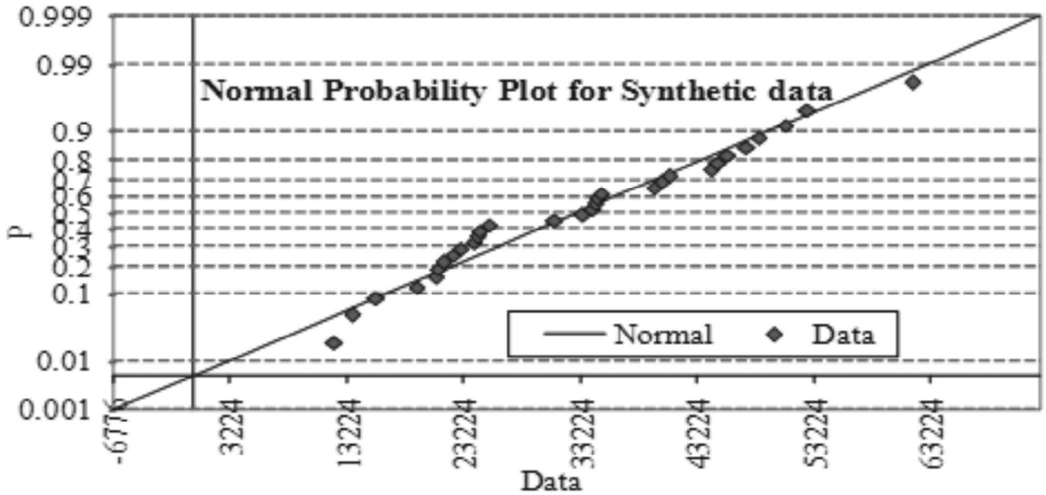


Figure 5: Depicting the normal probability variation for synthetic data developed only for all 9 districts as a whole in the study region.

for historic data developed only for all 9 districts as a whole in the study region. Similarly, Figure 5 depict the normal probability variation for synthetic data developed only for all 9 districts as a whole in the study region.

The district wise normal probability plots though they developed for both historic and synthetic rainfall data they are not presented herein. Further, the Confidence Interval (CI) for Mean as well as for Standard Deviation (SD) are also been estimated for both the historic and synthetic periods. The confidence intervals indicate the precision and uncertainty of the estimate. It is natural to interpret a 95% confidence interval as an interval with a 0.95 probability of containing the population mean or standard deviation. The present study estimates the 95% confidence intervals for both mean and standard deviations using simple and widely used Microsoft office excel worksheet calculations. The calculated confidence interval for mean of historic data show the bounds 25543.82 (lower limit) < 29411.18 (mean value) < 33278.55 (upper limit). There is good reason to be believe that the population mean *i.e.*, 29411.18 of historic data lies between these two bounds of 25543.82 and 33278.55 for a 95% confidence intervals contain the true mean. Similarly, the calculated confidence interval for mean of synthetic data show the bounds 28378.09 (lower limit) < 32981.90 (mean value) < 37585.72 (upper limit). This means that the population mean *i.e.*, 32981.90 of synthetic data lies between these two bounds of 28378.09 and 37585.72 for a 95% confidence interval contain the true mean. Further, the confidence limit for standard deviation (SD) of historic data show the bounds 8607.21 < 10807.56 < 14528.76, whereas for synthetic data shows 10246.26 < 12865.62 < 17295.44 indicating the standard deviations of both historic and synthetic data are well within the lower and upper bounds for a 95% confidence interval.

6. DROUGHT PRONENESS AT WESTERN RAJASTHAN

Figures 6, 7 and 8 demonstrates the district wise statistical parameters such as the mean annual rainfall, standard deviation and the coefficient of variance for both the historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series, respectively. Table 1 and 2 reveal the district wise mean monthly rainfall for the historic and synthetic periods, respectively. One of these statistical parameters such as the mean annual rainfall is the average of all the rainfall records about which the distribution is equally weighted.

It is seen from Figure 6 that, almost all the districts showing the mean annual rainfall falling < 3992.09 mm both in the historic and synthetic periods except in the case of Pali district as it is rarely gains high rainfall. The Pali district gains the mean annual rainfall of 8071.12 mm and 8764.34 mm both for the historic and synthetic periods, respectively (see Figure 6). Also note that, during the historic period the Pali district gains the higher estimates of mean monthly rainfall showing 2876.38 mm and 3053.09 mm (see Table 1) for the July and August months, respectively. And during synthetic period it is showing 3079.02 mm and 3211.45 mm (see Table 2) for the same July and August months, respectively.

The variability of rainfall is better represented by the statistical parameter called standard deviation. The higher is the value of the standard deviation, the larger is the spread of data from the mean. An unbiased estimate of standard deviation is computed

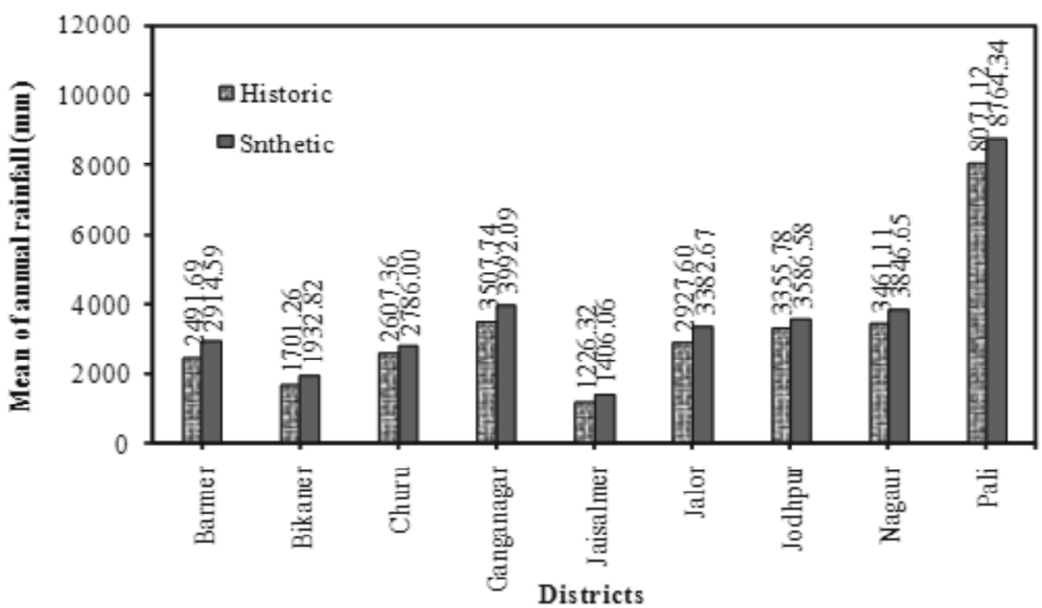


Figure 6: District wise mean annual rainfall estimate in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series.

Table 1
District wise mean monthly rainfall during historic period 1983 to 2012.

Month	*Barmer*	*Bikaner*	*Churu*	*Ganganagar*	*Jaisalmer*	*Jalor*	*Jodhpur*	*Nagaur*	*Pali*
JAN	8.53	20.91	32.64	65.76	6.18	10.54	16.28	20.85	17.30
FEB	22.07	56.93	63.87	135.56	23.18	24.23	30.34	61..38	34.51
MAR	14.82	42.10	49.52	65.55	13.20	8.55	10.37	24.08	11.60
APR	35.61	48.37	44.73	107.02	26.04	14.70	43.79	57.47	40.76
MAY	58.61	104.56	156.91	179.62	56.55	26.03	95.34	148.24	85.30
JUN	264.74	245.27	353.94	441.59	150.56	235.32	362.53	431.67	670.46
JUL	795.59	498.84	777.06	1174.21	370.36	1119.14	1227.67	1137.24	2876.38
AUG	830.72	409.35	682.65	810.41	364.84	934.20	1075.60	1113.91	3053.09
SEP	372.09	202.85	356.18	453.55	168.97	446.36	428.58	424.22	1148.71
OCT	69.78	54.66	69.11	49.67	35.82	69.67	49.33	83.91	86.78
NOV	14.02	3.67	5.58	8.37	3.38	31.59	9.41	10.03	38.00
DEC	5.11	13.75	15.17	16.43	7.24	7.27	6.54	9.49	8.23

Table 2
District wise mean monthly rainfall during synthetic period 2013 to 2042.

Month	*Barmer*	*Bikaner*	*Churu*	*Ganganagar*	*Jaisalmer*	*Jalor*	*Jodhpur*	*Nagaur*	*Pali*
JAN	15.12	27.42	39.92	93.77	8.59	18.99	24.43	28.10	27.11
FEB	31.46	70.71	76.41	153.81	29.56	43.91	38.41	76.83	48.52
MAR	25.75	50.27	61.19	84.95	21.90	15.92	17.77	39.15	22.16
APR	41.11	63.42	53.78	147.40	35.00	20.59	52.52	74.19	49.75
MAY	59.34	108.96	155.20	193.10	59.76	26.20	93.50	152.51	88.41
JUN	253.73	227.16	325.10	413.64	141.59	224.15	346.19	406.58	637.07
JUL	869.97	520.38	783.33	1322.69	396.78	1178.96	1259.59	1140.86	3079.02
AUG	1018.28	467.96	727.26	943.22	427.46	1120.41	1141.65	1252.98	3211.45
SEP	398.30	219.89	362.05	481.16	178.45	477.28	466.05	420.54	1287.82
OCT	163.90	152.32	169.99	125.08	90.46	166.98	116.72	218.05	214.53
NOV	30.42	6.64	11.01	13.40	5.99	78.27	21.78	21.29	87.04
DEC	7.22	17.69	20.76	19.87	10.52	11.01	7.97	15.57	11.46

for both the historic and synthetic rainfall series at all the selected nine districts of western Rajasthan. The Pali district showing the higher value of standard deviation 5279.01 mm and 4755.92 mm (see Figure 7) for historic and synthetic series, respectively, indicating the larger deviation from the mean, whereas, at other districts it is seen from Figure 7 that, a relatively lesser variation is observed in the standard deviation for both the historic and synthetic series.

The annual coefficient of variance (*cv*) is also estimated for the selected nine districts of western Rajasthan region and are shown in Figure 8. The normal practice as adopted by IMD, if $cv \geq 30\%$ the rainfall is said to be erratic and the area is classified as drought prone. The estimates of cv in historic rainfall series reveal that, the value of cv for all the districts showing > 30% (see Figure 8) indicating that the rainfall is erratic and all the selected nine districts of western Rajasthan region are drought prone. On the other hand, when observed in synthetic rainfall series the value of cv showing 27.22% and 27.72% (see Figure 8) which are slightly < 30% at two districts such as Churu and

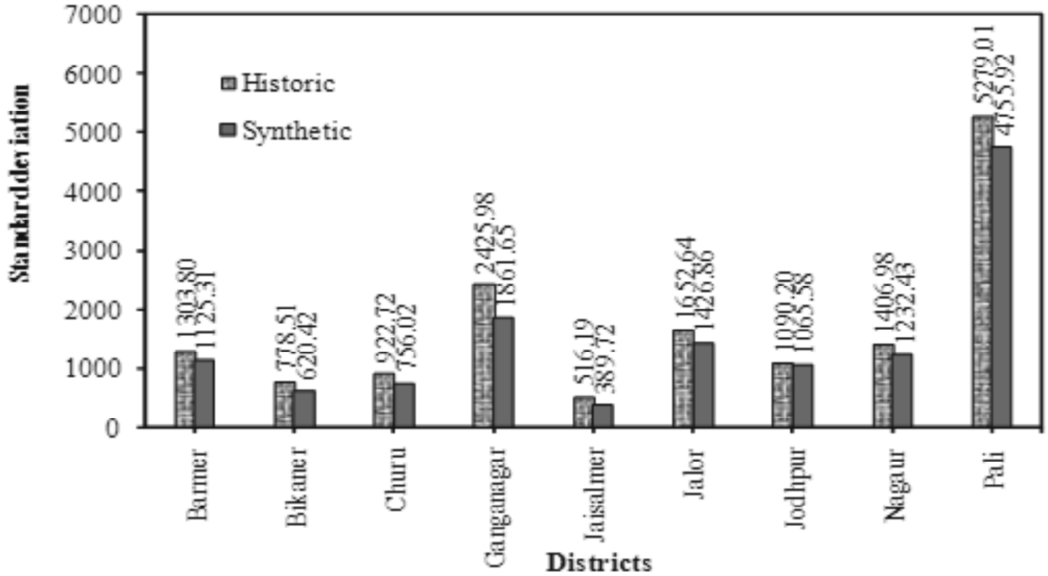


Figure 7: District wise standard deviation estimate in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series.

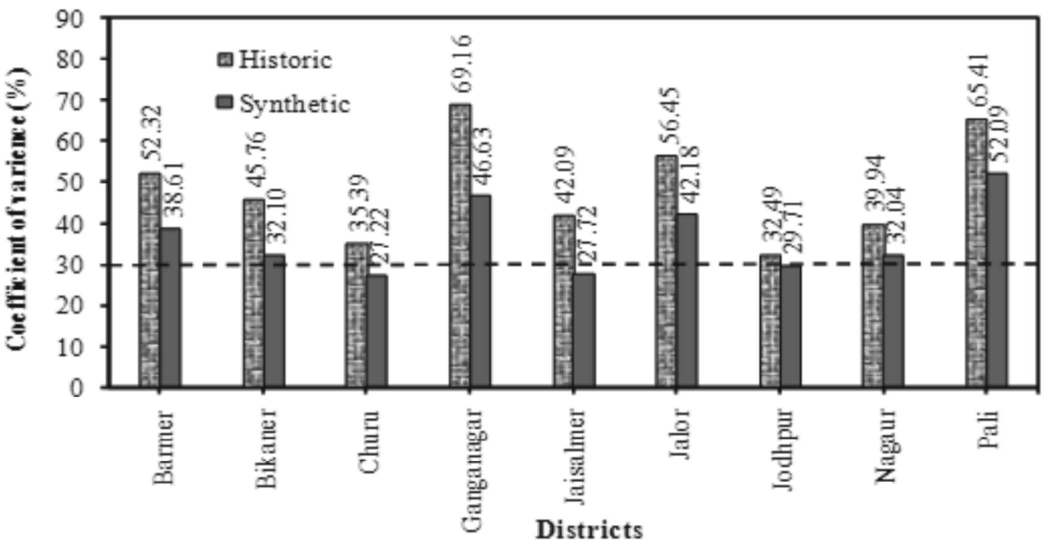
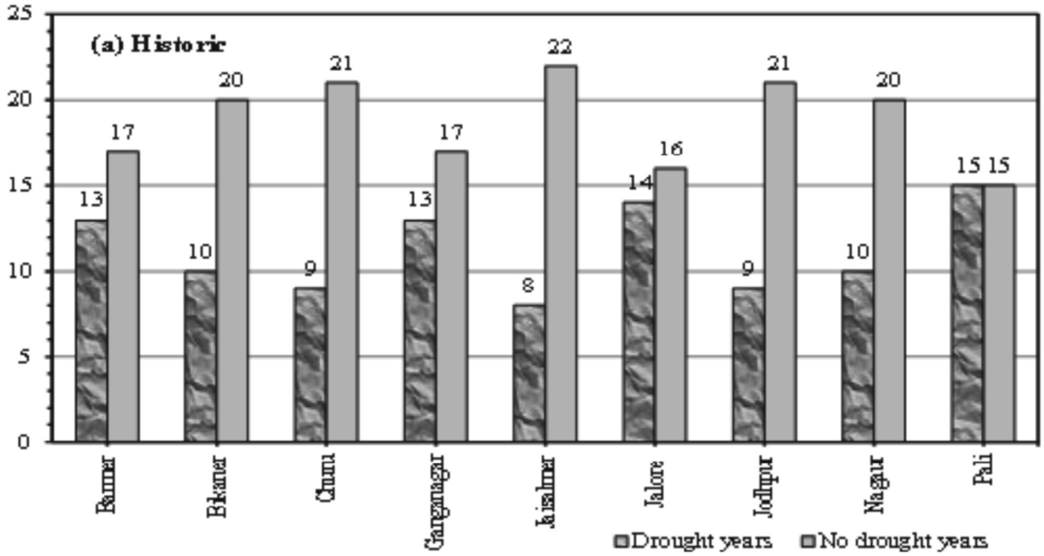
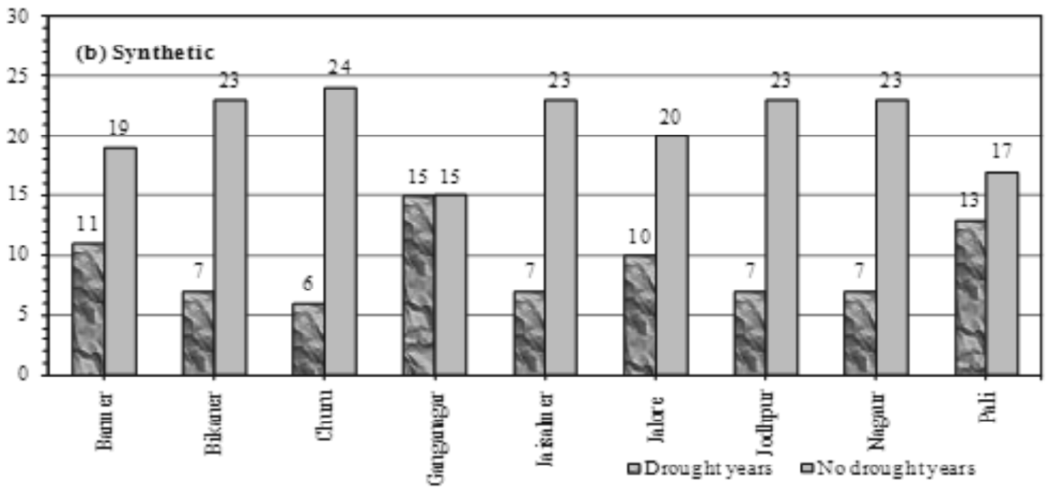


Figure 8: District wise coefficient variance (*cv*) estimate showing deviation from the value of *cv* = 30% both in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series.

Jaisalmer, respectively, and the rest of the districts showing > 30% indicating that the rainfall at these two districts is slightly non erratic and are non drought prone districts, whereas the other districts classified as drought prone areas and the rainfall is erratic.



(a)



(b)

Figure 9: District wise total number of drought and no drought years observed in (a) historic period (1983 to 2012) and (b) synthetic period (2013 to 2042) rainfall series as per the annual rainfall falling < 75% of normal rainfall computations.

In order to get the primary information of a region weather it is drought-hit or not, one can use an IMD criterion, *i.e.*, an area is said to be drought prone if the annual rainfall < 75% of normal in 20% or more of the years observed. The present study observes the sample length (*i.e.*, number of years of rainfall records) of 30 years in each historic and synthetic series which gives 6 years as the minimum number of years when worked out under 20% of the years observed. In this connection, Figure 9 (a and b) demonstrates the district wise total number of drought and no drought years observed in (a) historic period (1983 to 2012) and (b) synthetic period (2013 to 2042) rainfall series as per the annual rainfall falling < 75% of normal rainfall computations. It is inferred from Figure 9 (a, and b) that, all the selected 9 districts of western Rajasthan are in the grip of drought conditions as the annual rainfall falling < 75% of normal in 20% or more of the years observed (*i.e.*, 6 years) in the historic as well as in the synthetic (predicted) periods. Note that the droughts are persisting during the synthetic (predicted) period also in the study region. Recollecting the statement made by IPCC (2007) that, the future climate projections indicate the increased frequency of severe droughts in many parts of the world. Therefore, the present results revealed the statement made by IPCC (2007).

In order to characterize the droughts by their intensity as M_0 to M_4 based on the percentage deviation of rainfall from the normal rainfall as suggested by Bennerji and Chhabra (1963), an attempt has been made to analyze the rainfall of both the historic and synthetic series pertain to the study area. The estimates of percentage deviation of rainfall from the normal rainfall has been worked out at each district for all the considered 30 years separately for historic and synthetic rainfall series and the droughts were categorized as M_0 to M_4.

The total number of years of each category (*i.e.*, M_0 to M_4) are counted and the occurrence of the drought year with reference to drought intensity are given in Table 3. It is inferred from Table 3 that, based on the percentage departure of rainfall from the long term average annual rainfall the drought events were categorized in to various drought intensities such as no drought (M_0), mild drought (M_1), moderate drought (M_2), severe drought (M_3) and extreme drought (M_4) in the study region. The majority of M_0 type drought events were observed at the study region during the historic (1983 to 2012) and synthetic (2013 to 2042) periods. The Ganganagar district received the highest number (19) of M_0 type drought events for the historic period, whereas, the Pali district will be receiving the highest number (17) of the same M_0 type drought events but for the synthetic period out of each 30 years of rainfall series observed. Excluding the M_0 type drought events, a total of 125 (*i.e.*, 49 (M_1 type) + 31(M_2 type) + 25 (M_3 type) + 20 (M_4 type)) and 136 (*i.e.*, 64 (M_1 type) + 52 (M_2 type) + 12 (M_3 type) + 08 (M_4 type)) drought events corresponding to M_1 to M_4 type droughts were observed during the historic and synthetic periods, respectively, indicating that the total number of droughts are going to be increased in next 30 years in the study region (see Table 3). All most all the districts of west Rajasthan will be equally affected by droughts of M_0 to M_4 type drought events in the next 30 years. However, the results also reveal that, the Churu, Jaisalmer, Jodhpur and Nagaur districts will not receive any extreme (*i.e.*, M_4 type) drought events in next 30 years. The Barmer and Bikaner districts are going to be hit by one extreme drought event each in the 2036 year. The Ganganagar, Jalor and Pali districts are going to be hit by two extreme drought events each in the

Table 3
Pertinent characteristics of drought years at western Rajasthan in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series with reference to M_0 to M_4 computations.

		Historic series (1983 to 2012)			Synthetic series (2013 to 2042)		
Sl. No.	*Name of the district*	*Type of drought*	*Year(s)*	*No. of drought events*	*Type of drought*	*Year(s)*	*No. of drought events*
1.	Barmer	M_0	1983; 1984; 1985; 1986; 1987; 1988; 1989; 1991; 1996; 1999; 2002; 2004; 2005; 2007; 2009	15	M_0	2014; 2015; 2016; 2017; 2019; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2039; 2040	15
		M_1	1993; 1995; 1997; 2000; 2001; 2008	06	M_1	2027; 2032; 2035; 2037; 2041; 2042	06
		M_2	1992; 1994; 2012	03	M_2	2013; 2018; 2024; 2030; 2034; 2038	06
		M_3	1998; 2003; 2011	03	M_3	2028; 2029	02
		M_4	1990; 2006; 2010	03	M_4	2036	01
2.	Bikaner	M_0	1984; 1985; 1986; 1987; 1988; 1989; 1990; 1991; 1993; 1999; 2000; 2002; 2004; 2006; 2009	15	M_0	2014; 2015; 2016; 2017; 2019; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2037; 2039; 2040	15
		M_1	1992; 1994; 1996; 1998; 2001	05	M_1	2013; 2018; 2020; 2027; 2032; 2035; 2041; 2042	08
		M_2	1995; 2003; 2005; 2007	04	M_2	2024; 2028; 2029; 2030; 2034; 2038	06
		M_3	1983; 1997; 2008; 2011; 2012	05	M_3	–	00
		M_4	2010	01	M_4	2036	01
3.	Churu	M_0	1984; 1985; 1986; 1987; 1989; 1991; 1993; 1994; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007	17	M_0	2014; 2015; 2016; 2017; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2037; 2039; 2040	15
		M_1	1990; 1996; 2008; 2009; 2012	05	M_1	2013; 2018; 2019; 2024; 2027; 2032; 2035; 2041; 2042	09
		M_2	1992; 1995; 1998; 2010	04	M_2	2028; 2029; 2030; 2034; 2038	05
		M_3	1988; 1997; 2011	03	M_3	2036	01
		M_4	1983	01	M_4	—	00
4.	Ganganagar	M_0	1994; 1995; 1996; 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012	19	M_0	2014; 2015; 2016; 2017; 2018; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2039; 2040	15
		M_1	1987; 1989; 1991	03	M_1	2013; 2019; 2027; 2032; 2041; 2042	06
		M_2	1986; 1990; 1993	03	M_2	2024; 2028; 2030; 2034; 2035; 2037	06
		M_3	—	00	M_3	2029	01
		M_4	1983; 1984; 1985; 1988; 1992	05	M_4	2036; 2038	02

5.	Jaisalmer	M_0	1984; 1985; 1986; 1987; 1988; 1989; 1990; 1991; 2000; 2002; 2004; 2005; 2009	13	M_0	2014; 2016; 2017; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2039; 2040	13
		M_1	1993; 1995; 1997; 2001; 2003; 2007; 2008; 2012	08	M_1	2015; 2018; 2019; 2024; 2027; 2032; 2035; 2037; 2038; 2041; 2042	11
		M_2	1983; 1992; 1994; 1996; 1998; 2006	06	M_2	2013; 2028; 2029; 2030; 2034	05
		M_3	1999; 2011	02	M_3	2036	01
		M_4	2010	01	M_4	—	00
6.	Jalor	M_0	1984; 1985; 1986; 1987; 1988; 1989; 1991; 1993; 1995; 1996; 1998; 1999; 2000; 2001; 2002; 2004; 2009; 2012	18	M_0	2014; 2015; 2016; 2017; 2019; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2039; 2040	15
		M_1	1994; 2005; 2007; 2008	04	M_1	2013; 2030; 2035; 2037; 2041; 2042	06
		M_2	1983; 1997	02	M_2	2018; 2024; 2027; 2032; 2034; 2038	06
		M_3	1990; 1992; 2003	03	M_3	2028	01
		M_4	2006; 2010; 2011	03	M_4	2029; 2036	02
7.	Jodhpur	M_0	1984; 1985; 1986; 1987; 1989; 1991; 1993; 1998; 2002; 2004; 2005; 2006; 2009	13	M_0	2014; 2015; 2016; 2017; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2037; 2039; 2040	15
		M_1	1983; 1988; 1995; 1997; 1999; 2000; 2003; 2007; 2008	09	M_1	2018; 2019; 2027; 2032; 2035; 2041; 2042	07
		M_2	1992; 1994; 1996; 2001; 2011; 2012	06	M_2	2013; 2024; 2028; 2029; 2030; 2034; 2038	07
		M_3	1990; 2010	02	M_3	2036	01
		M_4	–	00	M_4	–	00
8.	Nagaur	M_0	1984; 1985; 1986; 1987; 1988; 1989; 1990; 1991; 1993; 1994; 1999; 2000; 2002; 2004; 2006; 2007; 2009	17	M_0	2014; 2015; 2016; 2017; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2037; 2039; 2040	14
		M_1	1992; 1995; 1998; 2001; 2005	05	M_1	2018; 2019; 2020; 2027; 2032; 2035; 2041; 2042	09
		M_2	2003; 2008; 2011	03	M_2	2013; 2024; 2028; 2029; 2030; 2038	06
		M_3	1983; 1996; 1997; 2010; 2012	05	M_3	2036	01
		M_4	–	00	M_4	–	00
9.	Pali	M_0	1983; 1984; 1985; 1986; 1987; 1989; 1990; 1991; 1993; 1994; 1995; 1996; 1997; 1998; 1999; 2000; 2002; 2009	18	M_0	2014; 2015; 2016; 2017; 2018; 2020; 2021; 2022; 2023; 2025; 2026; 2031; 2033; 2035; 2039; 2040; 2042	17
		M_1	1988; 2004; 2005; 2008	04	M_1	2019; 2037	02
		M_2	–	00	M_2	2027; 2030; 2032; 2034; 2041	05
		M_3	1992; 2003	02	M_3	2013; 2024; 2028; 2038	04
		M_4	2001; 2006; 2007; 2010; 2011; 2012	06	M_4	2029; 2036	02

years *viz*. 2036 and 2038 at Ganganagar district, and in the years *viz.* 2029 and 2036 at both the Jalor and Pali districts (see Table 3). Further it is also seen from Table 3 that, the Pali district going to be hit by 4 severe droughts (M_3 type) in the years *viz.* 2013; 2024; 2028; 2038 in the next 30 years period.

In an another criterion as adopted by Sharma *et al.*(1979; 1987) for investigating the drought years, abnormal or wet years and normal years at the study region, an analysis has also been done by verifying any year receiving rainfall $\leq (\overline{X} - SD)$, $\geq (\overline{X} + SD)$ and in the range $(\overline{X} \pm SD)$ of the average annual rainfall. Table 4 reveal the pertinent characteristics of drought years at western Rajasthan in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series with reference to the annual rainfall $\leq (\overline{X} - SD)$ computations. Table 5 presents the pertinent characteristics of abnormal or wet years at western Rajasthan in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series with reference to the annual rainfall $\geq (\overline{X} + SD)$ computations.

The pertinent characteristics of drought years at western Rajasthan in historic period (1983 to 2012) with reference to the annual rainfall $\leq (\overline{X} - SD)$ computations show that, more frequent drought years (events) occurred in almost all the districts except in Ganganagar district has only one drought event *viz.* in the year 2002 (see Table 4). Out of all these selected 9 districts of study region, the Jaisalmer district has received a maximum number of drought events (*i.e.*, 7 droughts) *viz.* 1985, 1986, 1987, 1991, 2002, 2004 and 2009 during historic period from 1983 to 2012 (see Table 4). The worst drought was experienced in the year 2002 due to 21.53% of the average annual rainfall and the year 1991 was the least severe drought as it receives 50.42% of the average annual rainfall among the seven drought years observed for the Jaisalmer district. Further, three consecutive drought years (events) *viz.* 1985, 1986 and 1987 at Jaisalmer and Pali districts, and 4 consecutive drought years *viz.* 1984, 1985, 1986 and 1987 at Jodhapur district has also been observed. Note that, all these observations has been made based on the annual rainfall $\leq (\overline{X} - SD)$ computations. The estimates of $\overline{X}$ (mean) and SD (standard deviation) were taken from their respective district rainfall series (see Figures 6 and 7).

In order to give more clarification on $\leq (\overline{X} - SD)$ computationsfor historic period, the Barmer district is considered as an example case. Figure 10 (a and b) reveal the comparison of annual rainfall, drought and abnormal events at Barmer district in a) historic period (1983 to 2012) and b) synthetic period (2013 to 2042) rainfall series. The average annual rainfall at Barmer district is 2491.69 mm with a standard deviation of 1303.80 mm during historic period (see Figures 6 and 7). Any year receiving rainfall ≤ 1187.89 mm, (*i.e.*, 2491.69 - 1303.80) would be the drought year. Consequently, there were 4 drought years *viz*. 1986, 1987, 1991 and 2002 occurred in the Barmer district during historic (1983 to 2012) period (see Table 4).

Table 4

Pertinent characteristics of drought years at western Rajasthan in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series with reference to the annual rainfall computations.

		Historic series (1983 to 2012)		*Synthetic series (2013 to 2042)*	
Sl. No.	Name of the district	Drought years and their respective pertinent characteristics	No. of drought events observed	Drought years and their respective pertinent characteristics	No. of drought events observed
1.	Barmer	1986 (691.50, 27.75, 11); 1987 (460.30, 18.47, 11); 1991 (839.30, 33.68, 10); 2002 (826.00, 33.15, 8)	04	2017 (1556.68, 53.41, 6); 2021 (1566.14, 53.73, 7); 2022 (1461.41, 50.14, 5); 2023 (1208.32, 41.46, 3); 2031 (1695.43, 58.17, 4); 2033 (1744.25, 59.85, 7)	06
2.	Bikaner	1984 (889.50, 52.29, 8); 1985 (663.30, 38.99, 9); 1987 (696.00, 40.91, 8); 1991 (584.10, 34.33, 8); 1993 (862.00, 50.67, 8); 2002 (486.60, 28.60, 7)	06	2021 (877.21, 45.39, 7); 2022 (1237.92, 64.05, 6); 2023 (997.88, 51.63, 5); 2025 (1294.16, 66.96, 6); 2026 (1197.18, 61.94, 9)	05
3.	Churu	1987 (1510.00, 57.91, 7); 2000 (1680.00, 64.43, 7); 2002 (973.00, 37.32, 7); 2009 (1589.00, 60.94, 6)	04	2021 (1591.06, 57.04, 8); 2022 (1774.19, 63.60, 3); 2023 (1633.65, 58.57, 4); 2025 (1922.09, 68.91, 5); 2026 (1809.23, 64.86, 6); 2033 (2020.31, 72.43, 4)	06
4.	Ganganagar	2002 (801.00, 22.84, 9)	01	2015 (1460.91, 36.59, 9); 2021 (1875.15, 46.97, 7); 2022 (1599.85, 40.07, 5); 2023 (1629.77, 40.82, 4); 2025 (1356.20, 33.97, 8)	05
5.	Jaisalmer	1985 (546.90, 46.07, 9); 1986 (590.80, 48.18, 9); 1987 (288.50, 23.53, 10); 1991 (618.30, 50.42, 7); 2002 (264.00, 21.53, 8); 2004 (477.30, 38.92, 8); 2009 (611.50, 49.87, 9)	07	2021 (747.35, 53.15, 7); 2022 (824.59, 58.64, 5); 2023 (989.13, 70.34, 2); 2026 (783.71, 55.73, 9); 2033 (881.67, 62.70, 6)	05
6.	Jalor	1986 (1226.20, 41.88, 9); 1987 (455.60, 15.56, 8); 1991 (1008.80, 34.46,10); 2002 (1178.30, 40.25, 8)	04	2017 (1664.12, 49.19, 5); 2021 (1913.90, 56.57, 7); 2022 (1838.40, 54.34, 4); 2023 (1109.09, 32.78, 5); 2025 (1829.49, 54.08, 6); 2031 (1578.56, 46.66, 5)	06
7.	Jodhpur	1984 (1757.40, 52.37, 10); 1985 (1984.80, 59.15, 7); 1986 (2200.80, 65.68, 8); 1987 (1358.20, 40.47, 7); 1991 (2158.00, 64.31, 8); 2009 (1573.60, 46.89, 9)	06	2021 (2101.05, 58.58, 8); 2022 (1902.47, 53.04, 4); 2023 (1566.05, 43.66, 3)	03

Contd. table 4

		Historic series (1983 to 2012)		*Synthetic series (2013 to 2042)*	
Sl. No.	*Name of the district*	*Drought years and their respective pertinent characteristics*	*No. of drought events observed*	*Drought years and their respective pertinent characteristics*	*No. of drought events observed*
8.	Nagaur	1984 (1871.10, 53.12, 10); 1986 (2053.40, 58.29, 8); 1987 (1325.20, 37.62, 8); 2004 (1443.30, 40.97, 7); 2009 (1939.00, 55.05, 6)	05	2021 (1697.28, 44.13, 8); 2022 (1976.72, 51.39, 5); 2023 (1657.94, 43.12, 4); 2026 (2425.55, 63.06, 8); 2033 (2494.73, 64.85, 5)	05
9.	Pali	1985 (1991.60, 24.68, 9); 1986 (2646.30, 32.79, 9); 1987 (1112.90, 13.79, 10)	03	2021 (3404.23, 37.28, 7); 2022 (1086.73, 11.90, 6); 2023 (1379.70, 15.11, 5); 2033 (3570.86, 39.10, 6)	04

Note: Values inside the bracket represents annual rainfall, % of average annual rainfall, and no. of drought months in the corresponding drought year, respectively.

Table 5

Pertinent characteristics of abnormal or wet years at western Rajasthan in historic period (1983 to 2012) and synthetic period (2013 to 2042) rainfall series with reference to the annual rainfall $\geq(\bar{X}+SD)$ computations.

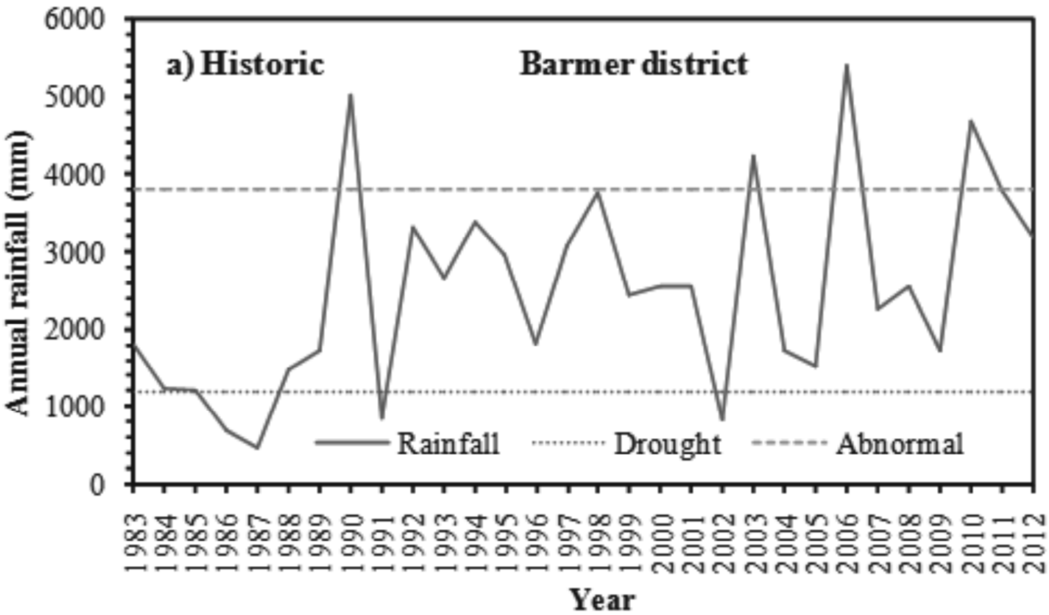
		Historic series (1983 to 2012)		*Synthetic series (2013 to 2042)*	
Sl. No.	*Name of the district*	*Abnormal years and their respective pertinent characteristics*	*No. of abnormal or wet events observed*	*Abnormal years and their respective pertinent characteristics*	*No. of abnormal or wet events observed*
1.	Barmer	1990 (5019.8, 201.46, 3); 2003 (4226.00, 169.60, 3); 2006 (5400.00, 216.72, 3); 2010 (4685.50, 188.05, 4)	04	2028 (4815.84, 165.23, 3); 2029 (4686.53, 160.80, 2); 2036 (5481.49, 188.07, 5)	03
2.	Bikaner	1983 (2565.70, 150.81, 2); 1997 (2941.00, 172.87, 5); 2008 (2805.00, 164.88, 4); 2010 (3414.00, 200.68, 5); 2011 (2725.00, 160.18, 2); 2012 (2682.00, 157.65, 3)	06	2024 (133.83, 133.83, 1); 2028 (2740.85, 137.39, 4); 2029 (3468.74, 141.81, 1); 2030 (2881.45, 149.08, 4); 2036 (3468.74, 179.47, 5); 2038 (2712.94, 140.36, 2)	06
3.	Churu	1983 (4693.40, 180.00, 4); 1988 (4117.90, 157.93, 2); 1992 (3598.50, 138.01, 2); 1997 (4179.00, 160.27, 3); 2010 (3897.00, 149.46, 3); 2011 (3962.00, 151.95, 1)	06	2029 (3805.95, 136.44, 2); 2030 (3816.14, 136.81, 3); 2031 (2486.69, 89.15, 3); 2034 (3635.93, 130.35, 0); 2036 (4390.97, 157.42, 1); 2038 (3593.31, 128.82, 0)	06
4.	Ganganagar	1983 (12089.50, 344.65, 6); 1984 (6606.50, 188.34, 4); 1985 (6843.20, 195.09, 5); 1988 (6761.00, 192.74, 2); 1992 (7109.80, 202.69, 4)	05	2024 (5873.24, 147.12, 1); 2029 (6895.20, 172.72, 4); 2034 (5880.39, 147.30, 1); 2036 (8546.84, 214.10, 6); 2038 (7179.92, 179.85, 3)	05

Contd. table 5

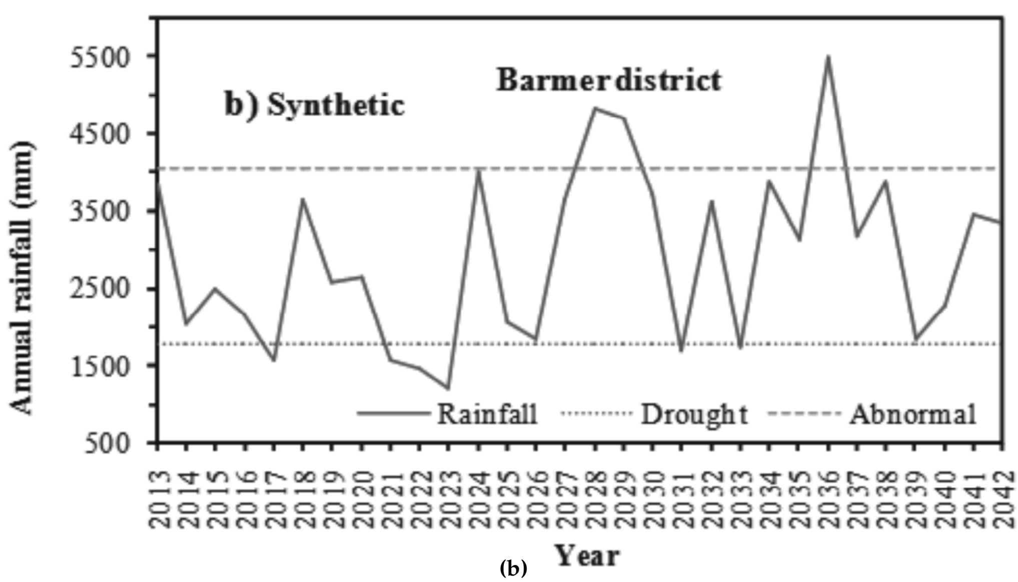
		Historic series (1983 to 2012)		Synthetic series (2013 to 2042)	
Sl. No.	*Name of the district*	*Abnormal years and their respective pertinent characteristics*	*No. of abnormal or wet events observed*	*Abnormal years and their respective pertinent characteristics*	*No. of abnormal or wet events observed*
5.	Jaisalmer	1983 (1822.30, 148.60, 2); 1998 (1792.10, 146.14, 3); 1999 (1883.90, 153.62, 3); 2010 (2252.50, 183.68, 3); 2011 (1849.00, 150.78, 3)	05	2013 (1893.88, 134.69, 1); 2028 (1976.04, 140.53, 3); 2029 (1846.68, 131.33, 1); 2030 (1879.21, 133.65, 3); 2034 (1838.35, 130.74, 0); 2036 (2158.1, 153.48, 6)	06
6.	Jalor	1990 (4829.00, 164.95, 2); 1992 (4844.00, 165.46, 3); 2003 (4729.50, 161.55, 3); 2006 (6682.20, 228.25, 2); 2010 (6678.40, 228.12, 5); 2011 (5843.00, 199.58, 2)	06	2024 (4820.41, 142.50, 2); 2028 (5741.30, 169.72, 3); 2029 (5933.94, 175.42, 2); 2036 (6830.14, 201.91, 6)	04
7.	Jodhpur	1990 (5250.10, 156.45, 2); 1992 (4952.10, 147.57, 2); 1994 (4497.60, 134.03, 2); 2010 (5209.70, 155.25, 2); 2011 (4715.50, 140.52, 3)	05	2029 (5157.73, 143.80, 2); 2030 (4531.83, 126.35,3); 2031 (2752.43, 76.74, 3); 2034 (4586.84, 127.88, 0); 2036 (5876.73, 163.85, 1); 2038 (4678.04, 130.43, 0)	06
8.	Nagaur	1983 (5482.20, 155.63, 2); 1996 (6124.50, 173.87, 1); 1997 (6024.80, 171.04, 5); 2003 (5165.30, 146.64, 3); 2010 (5854.30, 166.20, 4); 2012 (5506.50, 156.32, 3)	06	2013 (5342.43, 138.88, 1); 2024 (5277.66, 137.20, 0); 2028 (5436.49, 141.33, 5); 2029 (5208.15, 135.39, 2); 2030 (5666.45, 147.30, 4); 2036 (6282.02, 163.31, 1)	06
9.	Pali	2001 (14763.70, 182.92, 3); 2003 (13896.90, 172.18, 3); 2006 (18046.70, 223.60, 2); 2007 (15438.50, 191.28, 2); 2010 (15281.60, 189.34, 4); 2011 (17659.10, 218.79, 3); 2012 (17523.00, 217.11, 2)	07	2024 (15098.81, 165.35, 2); 2028 (15509.56, 169.85, 3); 2029 (16443.32, 180.08, 1); 2036 (18675.65, 204.52, 4); 2038 (15048.42, 164.80, 2)	05

Note: Values inside the bracket represents annual rainfall, % of average annual rainfall, and no. of abnormal months in the corresponding abnormal year, respectively.

The pertinent characteristics of drought years at western Rajasthan in synthetic period (2013 to 2042) with reference to the annual rainfall $\leq (\overline{X} - SD)$ computations reveal that, all the selected 9 districts of western Rajasthan region are going to be affected by droughts in future. It is predicted that, the total number of drought events such as 6, 5, 6, 5, 5, 6, 3, 5, and 4 will occur at each 9 selected districts such as at Barmer, Bikaner, Churu, Ganganagar, Jaisalmer, Jalor, Jodhpur, Nagaur and Pali, respectively (see Table 4). To be alarming, the years such as 2021, 2022 and 2023 will be the three consecutive drought years in all of the selected 9 districts of the region. The Jodhpur district will only gain less number of droughts, *i.e.*, 3 number of drought



(a)



(b)

Figure 10: Comparison of Annual rainfall, drought and abnormal events at Barmer district in (a) historic period (1983 to 2012) and (b) synthetic period (2013 to 2042) rainfall series.

events *viz.* 2021, 2022 and 2023 but again they are of consecutive drought events. Among all other districts in the study region, the Pali district will be affected by worst drought in the year 2022 as it is going to be received by 11.90% of the average annual rainfall with 6 drought months (months receiving rainfall < 50% of the average monthly rainfall) in it (see Table 4). The Churu district of the study region will be the least severe drought district as it receives 72.43% of average annual rainfall with 4 months of drought period in the year 2033 (see Table 4).

To give clarification on $\leq (\overline{X} - SD)$ computationsfor synthetic period, again the Barmer district is considered an example case. The average annual rainfall at Barmer district is 2914.59 mm with a standard deviation of 1125.31 mm during synthetic period (see Figures 6 and 7). Any year receiving rainfall ≤ 1789.28 mm, (*i.e.*, 2914.59 - 1125.31) would be the drought year. Consequently, there were 6 drought years *viz*. 2017, 2021, 2022, 2023, 2031 and 2033 (see Table 4) occurred at the Barmer district during synthetic period (2013 to 2042).

Further, the pertinent characteristics of drought years at western Rajasthan in historic period (1983-2012) rainfall series with reference to the annual rainfall $\geq (\overline{X} + SD)$ computations show that, abnormal or wet years are also frequent in the study region (see Table 5). The Pali district received a maximum number of abnormal or wet events (7 years) *viz.* 2001, 2003, 2006, 2007, 2010, 2011 and 2012 (see Table 5). Three consecutive abnormal or wet years *viz.* 2010, 2011 and 2012 at Bikaner and Pali districts, and 1983, 1984 and 1985 at Ganganagar district has been observed. The results of the Pali districts reveal that, it receives 223.60% of average annual rainfall with 2 abnormal months (months receiving rainfall > 200% of the average monthly rainfall) in the year 2006 and is identified as the most abnormal or wet year. The year 2003 is identified as the least wet year as it received 172.18% of average annual rainfall with 3 abnormal months in it (see Table 5). Note that, all these observations has been made based on the annual rainfall $\geq (\overline{X} + SD)$ computations.

To illustrate the $\leq (\overline{X} + SD)$ computations for the historic period, the Barmer district is again considered and the computations show that, any year receiving rainfall ≥ 3795.49 mm (*i.e.*, 2491.69 + 1303.80) would be the abnormal or wet year. Consequently, there were 4 abnormal or wet years *viz.* 1990, 2003, 2006 and 2010 (see Table 5) occurred in the Barmer district during historic period (1983 to 2012). The year receiving the rainfall in the range of 1187.89 mm to 3795.49 mm would be the normal year in the case of historic period at the Barmer district. Note that, the value 1187.89 mm was calculated based on the $\leq (\overline{X} - SD)$ computations as given above. Consequently, there were 22 normal years (*i.e.*, 30 total years - 04 drought years - 04 abnormal or wet years) observed during 1983 to 2012 at Barmer district (see Figure 10(a) and Tables 4 and 5).

Table 6
District wise number of monthly normal, abnormal and drought events during historic period (1983 to 2012).

	Barmer			*Bikaner*			*Churu*			*Ganganagar*			*Jaisalmer*			*Jalor*			*Jodhpur*			*Nagaur*			*Pali*		
Month	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*
JAN	6	3	21	9	6	15	13	5	12	6	5	19	6	5	19	5	4	21	6	4	20	5	6	19	2	7	21
FEB	3	5	22	10	4	16	7	4	19	8	7	15	4	6	20	3	3	24	4	5	21	4	6	20	4	5	21
MAR	3	4	23	8	6	16	11	4	15	11	3	16	6	3	21	2	4	24	8	2	20	7	3	20	2	3	25
APR	9	6	15	10	4	16	8	5	17	11	3	16	6	5	19	6	5	19	10	5	15	6	5	19	10	4	16
MAY	6	5	19	12	5	13	15	4	11	13	3	14	8	4	18	9	5	16	9	6	15	11	6	13	8	5	17
JUN	12	4	14	12	5	13	22	3	5	11	6	13	15	3	12	15	4	11	18	2	10	17	2	11	18	3	9
JUL	15	4	11	24	2	4	24	1	5	13	4	13	16	4	10	19	3	8	22	2	6	25	1	4	19	3	8
AUG	17	4	9	15	4	11	21	2	7	15	3	12	18	4	8	17	3	10	21	2	7	20	2	8	14	4	12
SEP	9	6	15	13	5	12	15	4	11	11	5	14	6	6	18	13	4	13	13	5	12	17	4	9	10	5	15
OCT	4	4	22	4	3	23	6	3	21	2	5	23	1	4	25	2	5	13	3	5	22	7	2	21	3	5	22
NOV	2	2	26	1	5	24	5	3	22	2	6	22	3	4	23	1	1	28	1	2	27	2	3	25	2	1	27
DEC	1	4	25	1	6	23	4	4	22	7	4	19	5	3	22	3	3	24	2	6	22	2	4	24	0	5	25

where, N = normal, A = abnormal, D = drought

Table 7
District wise number of monthly normal, abnormal and drought events during synthetic period (2013 to 2042).

	Barmer			*Bikaner*			*Churu*			*Ganganagar*			*Jaisalmer*			*Jalor*			*Jodhpur*			*Nagaur*			*Pali*		
Month	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*	*N*	*A*	*D*
JAN	10	7	13	18	4	8	19	3	8	14	4	12	12	5	13	10	7	13	12	5	13	15	4	11	11	7	12
FEB	14	5	11	11	6	13	16	5	9	18	3	9	12	6	12	8	6	16	12	6	12	12	6	12	11	6	13
MAR	10	5	15	15	4	11	14	5	11	12	5	13	13	5	12	9	6	15	11	5	14	11	6	13	10	5	15
APR	13	5	12	9	7	14	15	5	10	9	7	14	9	7	14	10	6	14	13	4	13	10	7	13	14	6	10
MAY	8	8	14	18	4	8	20	3	7	13	5	12	11	6	13	12	6	12	17	4	9	18	4	8	13	5	12
JUN	13	5	12	15	5	10	18	4	8	15	4	11	12	5	13	13	6	11	13	5	12	12	5	13	15	4	11
JUL	17	4	9	20	2	8	24	0	6	18	4	8	19	3	8	20	3	7	26	0	4	24	0	6	21	2	7
AUG	16	3	11	17	3	10	21	1	8	14	4	12	18	3	9	14	4	12	22	1	7	19	2	9	16	3	11
SEP	12	5	13	20	3	7	19	3	8	17	4	9	10	6	14	18	3	9	20	3	7	22	2	9	19	2	9
OCT	15	3	12	13	5	12	15	4	11	14	5	11	12	5	13	16	3	11	16	3	11	14	4	12	14	5	11
NOV	11	6	13	13	5	12	13	5	12	14	5	11	12	6	12	8	7	15	13	5	12	13	6	11	9	7	14
DEC	7	6	17	11	5	14	11	6	13	10	5	15	8	5	17	8	5	17	8	7	15	12	6	12	9	5	16

where, N = normal, A = abnormal, D = drought

The similar computations were also made for the synthetic period (2013 to 2042) with reference to $\leq (\overline{X} - SD)$ computations. Table 5 reveal that, all the selected 9 districts in the study region will be receiving frequent abnormal or wet years *viz.* 3, 6, 6, 5, 6, 4, 6, 6 and 5 at their respective selected 9 districts in the order as stated earlier. The Barmer district will only receive three abnormal or wet years *viz.* 2028, 2029 and 2036. Results also reveal that, the Ganganagar district received 214.10% of average annual rainfall in the year 2036 with 6 abnormal months in it and is identified as the most abnormal or wet year. The Jodhpur district will be the least wet year in 2031 year which will be receiving 76.74% of average annual rainfall with 3 abnormal months in it.

Again performing an example calculations at Barmer district by taking the average annual rainfall 2914.59 mm and the standard deviation of 1125.31 mm during synthetic period (see Figures 6 and 7). Any year receiving rainfall ≥ 4039.90 mm, (*i.e.*, 2914.59 + 1125.31) would be the abnormal year. Consequently, there were 3 abnormal or wet years *viz*. 2028, 2029, and 2036 (see Table 5) occurred in the Barmer district during synthetic period (2013 to 2042). The year receiving the rainfall in the range of 1789.28 mm to 4039.90 mm would be the normal year in the case of synthetic period at the Barmer district. Consequently, there were 21 normal years (*i.e.*, 30 total years - 06 drought years - 03 abnormal or wet years) observed during 2013 to 2042 at Barmer district (see Figure 10(b) and Tables 4 and 5). Corresponding to the criterion of Sharma *et al.* (1979; 1987), it is demonstrated from Table 4 that, a total of 40 and 45 number of drought events (years) has been observed during historic and synthetic periods, respectively, indicating that the increase of drought events in next 30 years in the study region. Note that, the same trend was observed using IMD method also. It is also observed from Table 5 that the total number of abnormal events are reduced from 50 to 47 in next 30 years period indicating the frequent failures of monsoon in the study region.

Further, in order to find the number of drought months, abnormal or wet months and normal months in the study region, an investigation has been made by checking the month receiving rainfall < 50% (drought), > 200% (abnormal or wet) and the range between 50% to 200% (normal) of the average monthly rainfall. Table 6 and 7 demonstrates the district wise total number of monthly normal, abnormal or wet and drought events during the historic period (1983 to 2012) and synthetic period (2013 to 2042) respectively.

It is observed that the month of November witnessed the highest number of drought events equal to 28, *i.e.*, 93.33% of the 30 rainfall events (see Table 6) during historic period from 1983 to 2012 at Jalor district. Further, it is predicted that, the month of December will be witnessing the highest number of drought events equal to 17, *i.e.*, 56.67% of the 30 rainfall events (see Table 7) during synthetic period from 2013 to 2042 at Barmer, Jaisalmer and Jalor districts. For simplicity, the highest number of monthly normal, abnormal and drought events were tinted (see Tables 6 and 7) in each column of the respective district demonstrating its month of occurrence. No abnormal rainfall events occurred in the month of July at Churu, Jodhpur and Nagaur districts (see Table 7) during synthetic period, but this type of situation is not present during historic period. In future ,the rainfall events of July month will be normal at the study region as this month is going to witness the highest number of monthly normal events which are shown tinted (see Table 7) at each district. About 26, *i.e.*, 86.67% of the total rainfall events of July month will be normal at Jodhpur district in future (see Table 7). The occurrence of drought events during the months of June to September were less at the study region as it is a monsoon season for both the historic and synthetic periods. But, the rest of the months likely to be drought hit in both the historic and synthetic periods at the study region.

7. CONCLUSIONS

Drought analysis on rainfall data collected from 9 selected districts of western Rajasthan in India for the period of 1983 to 2012 has been done. Future simulations of rainfall for the period 2013 to 2042 are obtained using Thomas-Fiering model and tried to categorize drought periods for future by using the simulated data. This idea is considerable as it is very important to know about future scenario of droughts in the study region for planning and management purpose. Further, an appraisal of various widely used drought assessment criterions based rainfall analysis are discussed with the field application to the selected 9 districts of the study region. The results reveal that, the selected 9 districts of western Rajasthan will become more drought-prone in the next 30 years with increased frequency of severe droughts in many parts of the study region. Hence, indeed the present study substantiate the statement made by the IPCC (2007) that the projections for the 21st century indicate the world is going to face severe droughts.

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