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ORIGINAL ARTICLE

A simplistic approach for monitoring meteorological drought over arid regions: a case study of Rajasthan, India

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Abstract

The commonly used precipitation-based drought indices typically rely on probability distribution functions that can be suitable when the data exhibit minimal discrepancies. However, in arid and semi-arid regions, the precipitation data often display significant discrepancies due to highly irregular rainfall patterns. Consequently, imposing any probability distributions on the data for drought analysis in such regions may not be effective. To address this issue, this study employs a novel drought index called the Discrepancy Precipitation Index (DPI), specifically designed for arid regions. Unlike traditional methods, the DPI does not impose a probability distribution on the precipitation data; instead, it relies on the discrepancy between the data and the mean value. Drought severity classifications (i.e., Drought-I, Drought-II, and Drought-III) are proposed based on the DPI values. The DPI is used to characterize and assess the meteorological drought years based on annual and monsoonal precipitation over nineteen districts in Western Rajasthan, India, during 1901–2019. Additionally, a novel statistic called Discrepancy Measure (DM) is employed to assess the degree of discrepancy in the precipitation climatology of the districts for annual and monsoon precipitation time series. Based on annual precipitation, Jaisalmer district exhibited the highest number of historical drought years (35), whereas three districts, i.e., Jhunjhunu, Dausa, and Bhilwara exhibited the lowest number of drought years (11). Similarly, based on monsoon precipitation, Jaisalmer and Bhilwara encountered the highest (34) and the lowest (11) number of drought years, respectively. The return period of Drought-II is lower for monsoon precipitation-based DPI as compared to that of the annual precipitation-based DPI for all the districts. The DM and DPI-based total number of droughts are found to be strongly correlated for both annual and monsoon precipitation. The DM value is highest for Jaisalmer and lowest for Bhilwara district. The findings reveal DPI as an efficient tool for assessing drought years, particularly in arid climatic conditions. Moreover, as the DM value increases for a precipitation series, the DPI becomes more effective in capturing drought events.

Keywords Drought monitoring · Arid region · Discrepancy precipitation index · Discrepancy measure · Rajasthan

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Introduction

Droughts are natural disasters that can have severe socio-economic consequences, as seen in the cases of sub-Saharan and eastern Africa in the 1980s, which resulted in famine, starvation, mass migration, and millions of deaths (Hoque et al. 2021; Keyantash and Dracup 2002; Khalequzzaman et al. 2023; Mishra and Singh 2010; Razmi et al. 2022; Swain et al. 2017; Tayfur 2021; Wilhite et al. 2007). These events have become more frequent, especially in arid and semi-arid regions of the world, largely due to the impacts of climate change. The situation gets further worsened by water scarcity issues commonly associated with arid regions (Lotfirad et al. 2021; Swain et al. 2022c; Wu et al. 2007; Yacoub and Tayfur 2017, 2020). Drought and aridity, while both related to water scarcity, differ significantly. Drought is a temporary and abnormal condition marked by an unusual lack of water (primarily rainfall), whereas aridity is a fundamental and permanent climatic feature with low rainfall and high evaporation as the norm (Mishra and Singh 2010). It is important to understand that droughts in arid regions can be particularly dangerous as these areas already have limited water resources, and any further reduction in rainfall can quickly lead to severe water scarcity and exacerbate the challenges in sustaining agriculture, wildlife, and human populations. Moreover, the fragile ecosystems of arid regions may not be resilient to changes in water availability, making the impact of droughts more acute and damaging. In the Indian context, droughts occur frequently and can have severe impacts since agriculture plays a crucial role in the Indian economy, and a significant portion of the population relies on farming for their livelihood (Amrit et al. 2018a, 2018b; Madolli et al. 2022; Pandey 2023; Pandey and Khare 2018; Pandey et al. 2019, 2021; Sahoo et al. 2021; Swain et al. 2023). In recent years, climate change has caused more frequent and severe droughts in India, causing crop failures and water shortages. This may lead to serious implications, including food insecurity and economic instability (Fan et al. 2022; Rahman et al. 2023; Swain et al. 2021b, 2022a, 2022d). Therefore, it is crucial to develop various measures, such as robust drought monitoring and assessment systems, increasing irrigation efficiency, and water conservation programs to address the issue of droughts.

To effectively monitor and assess droughts, researchers have developed various drought indices (Mishra and Singh 2010; Mukherjee et al. 2018; Zargar et al. 2011). One of the conventional indices is the Palmer Drought Severity Index (PDSI; Palmer 1965), which was introduced in the 1960s. It calculates the standardized regional moisture supply with respect to local climatic norms (based on precipitation and temperature data). Another index, the Deciles index (Gibbs and Maher 1967) ranks precipitation records and divides them into ten equiprobable parts known as deciles. Lower deciles indicate drought conditions; however, this method is considered unreliable for assessing drought frequency. The Surface Water Supply Index (SWSI) developed by Shafer and Dezman (1982) can be analysed on a monthly basis and requires data on reservoir storage, streamflow, rainfall, and snow. A plethora of such indices exist in meteorological, hydrological, agricultural, socio-economic categories or their combinations (Mishra and Singh 2010, 2015; Montaseri and Amirataee 2017; Salimi et al. 2021). However, meteorological drought is considered to be the root cause of all other forms of drought (Mianabadi et al. 2022; Rossi et al. 1992; Swain et al. 2021a), and therefore, most drought research worldwide focuses on characterizing, monitoring, and assessing meteorological droughts.

The Standard Precipitation Index (SPI; McKee et al. 1993) is a practical and straightforward approach for evaluating meteorological drought characteristics. It is a univariate index that relies solely on precipitation data. It can be computed for different timescales and can be applicable to various climatic and topographic conditions (Ahmed et al. 2021; Dikshit et al. 2022). Further, it does not take moisture conditions into account, which makes it suitable for use in both summer and winter. To compute SPI, precipitation time-series are transformed into a standardized normal distribution (i.e., Z-distribution), i.e., converting the original data distribution into the normal distribution (Swain et al. 2022a, 2022b). Although normally distributed SPI is user-friendly and easy to use, it may not accurately identify regions that are more susceptible to drought than others. The gamma-SPI method, which is commonly used, is more effective in identifying drought-prone areas, but requires complex computations and parameter estimations (Guttman 1999). Other simplistic approaches that require only precipitation data as input include the maximum consecutive dry days, Percent Departure from Mean (PDM), Rainfall Departure (RD), Rainfall Anomaly Index (RAI), Percent of Normal Precipitation Index (PNPI), Simplified Rainfall Index (RI_S), among others (Mishra and Singh 2011; Swain et al. 2020, 2021a). The percent-deficit-based indices (e.g., PNPI, RD, PDM, RI_S) calculate monthly precipitation levels assuming a normal distribution and can be reliably used in a single season or region.

Based on the literature survey mentioned above, it can be inferred that numerous drought indices are available; however, some of these indices require complex computations and parameter estimations, while others rely on extensive hydrological and meteorological data that may not be easily accessible in all regions. Additionally, some indices are limited to specific time scales or regions, and others impose probability distribution functions that may not accurately represent the data, particularly in areas with sporadic rainfall like semi-arid and arid regions. To address these challenges, Tayfur (2021) proposed a novel drought index called the Discrepancy Precipitation Index (DPI). Unlike other indices, DPI does not impose any probability distribution function on the precipitation data, recognizing such distributions can be misleading in arid and semi-arid regions due to significant discrepancy and fluctuations of rainfall. Additionally, the DPI values facilitates a drought classifications system, where negative DPI values can be categorized into different severity levels, similar to the widely used Standardized Precipitation Index (SPI). Tayfur (2021) concluded that DPI can efficiently capture drought occurrences in regions with high rainfall fluctuations compared to the two-parameter SPI and therefore, recommended DPI for drought monitoring in arid regions.

Rajasthan, a state located in the northwestern India, is considered to be the most arid and water-scarce region of the country. The concerns regarding water availability and frequent rainfall discrepancies in rainfall are particularly severe in the western portions of the state. Therefore, this study aims to carry out characterization and assessment of meteorological droughts in an arid region of India using a novel index, i.e., DPI. The description of the study area, datasets, methods, results and key conclusions are discussed in detail in the subsequent sections.

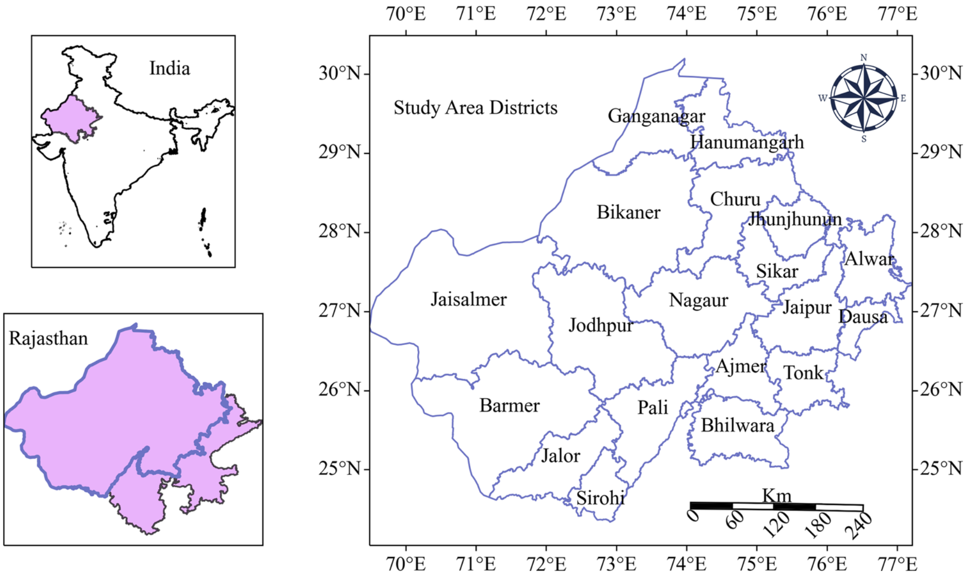
Study area and data description

Rajasthan spans over a geographical area of 34.22 million hectares, making it the largest state of India. The climate in this region is mostly semi-arid to arid with average annual rainfall ranging from 450 to 750 mm. The western portion of the state is predominantly an arid region, receiving lower rainfall values (around 150 mm). The months of April to June are the hottest times of the year, with temperatures ranging from 32 to 45 °C. In western Rajasthan, the air temperature can even reach up to 48 °C, accompanied by prevailing westerly winds that often result in dust storms. During the monsoon season, the region receives about 90% of its annual rainfall (Kharol et al. 2013). However, Rajasthan frequently experiences drought conditions due to inadequate and delayed monsoon rainfall, exceptionally high summer temperatures, and limited water resources (Chahal et al. 2021). Taking all these factors into consideration, 19 districts lying in Western Rajasthan State are chosen as the study area, whose locations are shown in Fig. 1. It is to mention that these 19 districts cover the four (out of seven) administrative divisions of the state, i.e., Jodhpur, Jaipur, Bikaner and Ajmer.

For this research, the daily precipitation data of 1901–2019 was obtained from the gridded (0.25° × 0.25°) observation dataset created by the India Meteorological Department (IMD). This dataset was developed by Pai et al. (2014) considering the dense network of rain gauges across the country and the dataset is freely available. The gridded data was converted to district-scale using the area-weighted method considering the portion of each grid inside a particular district. The daily precipitation was accumulated to form the year-wise monsoonal (June–September) and annual (January–December) time series for each district.

The spatial distribution of magnitude of average annual and monsoonal rainfall across various districts is presented in Fig. 2. Moreover, Table 1 presents the statistics, i.e., maximum, minimum, mean (μ), and standard deviation (σ) values for both annual and monsoonal rainfall across

Fig. 1 Location of study area, i.e., 19 districts of Rajasthan, India



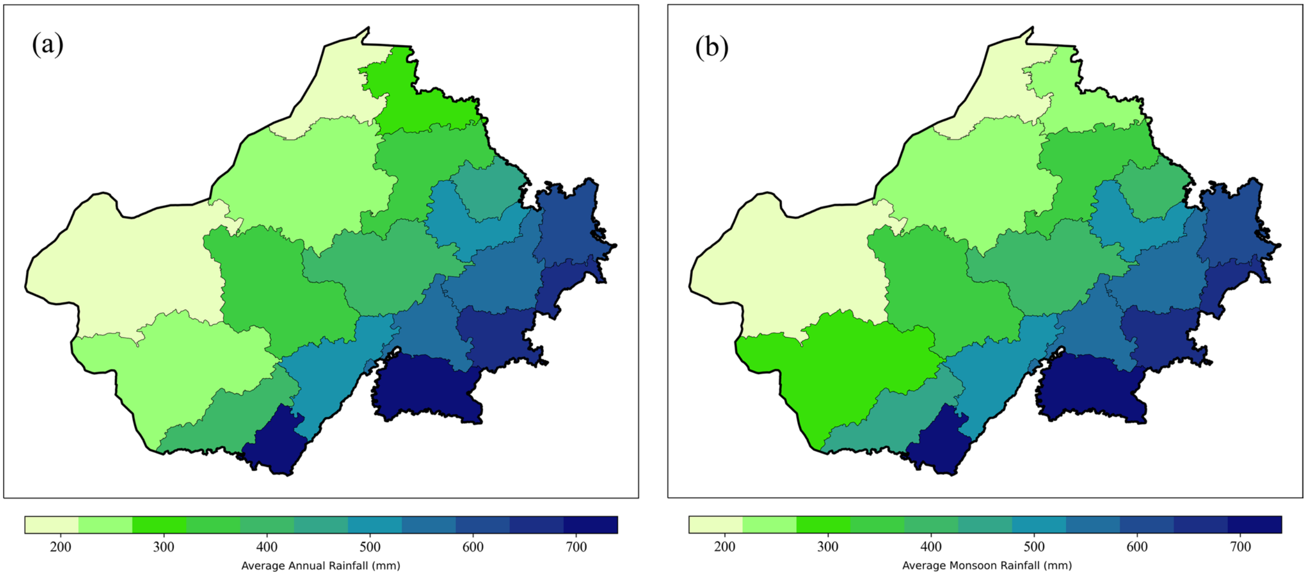


Fig. 2 The spatial distribution of magnitude of (**a**) average annual rainfall, and (**b**) average monsoonal rainfall

Table 1 The statistics of annual and monsoonal rainfall across the districts of the study area

Districts	Annual rainfall (mm)				Monsoonal rainfall (mm)			
	Max	Min	μ	σ	Max	Min	μ	σ
Tonk	1346	195	625	203	1174	171	576	194
Sirohi	1822	210	739	332	1756	170	697	326
Sikar	999	153	478	158	893	121	416	151
Pali	1236	111	494	191	1073	103	457	184
Nagaur	1083	90	397	158	1020	85	353	146
Jodhpur	846	44	306	127	678	43	273	118
Jhunjhunun	908	136	463	150	854	101	395	142
Jalor	1020	89	442	217	986	69	412	211
Jaisalmer	587	21	189	104	570	21	165	99
Jaipur	1245	134	570	187	1087	111	511	177
Hanumangarh	863	53	296	119	703	39	244	112
Ganganagar	582	55	225	93	508	25	183	88
Dausa	1430	176	626	201	1262	156	565	194
Churu	931	77	364	138	746	70	309	129
Bikaner	688	56	263	106	549	26	221	97
Bhilwara	1392	210	628	188	1223	196	584	181
Barmer	800	35	284	146	786	35	259	142
Alwar	1255	216	602	192	1101	172	529	182
Ajmer	1210	155	502	166	1065	148	459	156

Max., Min., μ, and σ represent Maximum, Minimum, Mean, and Standard deviation, respectively

various districts, highlighting significant variations in rainfall patterns. This data underscores the heterogeneity in rainfall distribution, which could be pivotal in understanding regional climatic variabilities. The annual (monsoonal) rainfall varies from 189 mm (165 mm) over Jaisalmer district to 739 mm (697 mm) over Sirohi district. The average annual/monsoonal rainfall shows an increasing gradient from west to east. The standard deviation value is high, especially considering the low values of average annual/monsoonal rainfall. This indicates that the study area experiences frequent and considerable flickering of annual/monsoonal rainfall.

Methodology

Discrepancy precipitation index (DPI)

In this study, the Discrepancy Precipitation Index (DPI) developed by Tayfur (2021) is used for identifying drought years and their characteristics. The assessment of drought characteristics is carried out by considering both the annual and monsoonal precipitation time series. DPI can be used as a metric for measuring the severity of drought conditions. DPI is given by,

$$DPI_i = log_{10}\left(\frac{P_i}{P_M}\right) \tag{1}$$

where, DPI_i represents the index value for the ith year, P_i is the precipitation for the ith year, and P_M is the long-term average value of the precipitation time series, given by

$$P_M = \frac{1}{n}\sum_{i=1}^{n} P_i \tag{2}$$

where, n is the total number of years (or the length of the time series). It is to mention that the procedure of computing DPI_i shall be the same for both annual and monsoonal precipitation; only the magnitudes/values of P_i and P_M for annual precipitation will be greater than or equal to those of the monsoonal precipitation.

From Eq. 1, it is clear that the value of DPI will be zero for $P_i = P_M$ and negative for $P_i < P_M$. Hence, a negative value of DPI can be interpreted as a dry condition with respect to the mean precipitation, whereas a positive DPI represents a wet condition. Tayfur (2021) recommended that a DPI value equal to or lower than –0.2 indicates a drought. Further, droughts can be categorized into different severity categories, i.e., Drought-I (–0.4 < DPI ≤ –0.2), Drought-II (–0.6 < DPI ≤ –0.4), and Drought-III (DPI ≤ –0.6) corresponding to moderate, severe, and extreme drought conditions, as presented in Table 2. This severity classification based on the DPI values is also similar to that of the widely used Standard Precipitation Index (SPI).

Table 2 DPI-based classification droughts into different categories

DPI	Category	Remarks
DPI > 0	Wet conditions	$P_i > P_M$
–0.2 < DPI ≤ 0	Near Normal dryness	$0.63P_M < P_i \le P_M$
–0.4 < DPI ≤ –0.2	Drought-I (Moderate)	$0.4P_M < P_i \le 0.63P_M$
–0.6 < DPI ≤ –0.4	Drought-II (Severe)	$0.25P_M < P_i \le 0.4P_M$
DPI ≤ –0.6	Drought-III (Extreme)	$P_i \le 0.25P_M$

P_i is the precipitation in the ith year, P_M is the long-term average precipitation

The DPI method does not impose any transformation or probability distribution function on the data. It does not require the assumption of normal distribution either. The computation of DPI is simple and straightforward, and it solely relies on long-term precipitation data, which is easily accessible across most parts of the world. Further, DPI effectively discerns the variability in drought frequencies across different sub-regions and hence, it serves as an instrumental tool in the technical identification of regions with a higher propensity for drought occurrences. The classification system of DPI, as presented in Table 2, reveals uniformity in transitioning from Drought-I to Drought-II, and Drought-II to Drought-III, which is similar to SPI and RI_S. From a practical standpoint, the simplicity of DPI facilitates its application, use, and communication with the public. Therefore, DPI can be an efficient tool for drought monitoring and assessment, particularly in arid regions.

Discrepancy measure (DM)

Tayfur (2021) proposed the DM, which is a statistic representing the degree of discrepancy in precipitation climatology of a particular region. DM is given by,

$$DM = \frac{1}{n}\sum_{i=1}^{n}\left|log_{10}\left(\frac{P_i}{P_M}\right)\right| \tag{3}$$

As DM is a measure of discrepancy associated with a precipitation time series, it can be interpreted as a proxy for evaluating aridity conditions. A high value of DM (> 0.15) indicates a highly arid region, whereas humid regions will exhibit a significantly lower value of DM (Mersin et al. 2022; Tayfur 2021). Therefore, DM can be used to categorize or rank the sub-regions for aridity conditions.

Results and discussion

The frequency of drought (or drought years) is an important characteristic. The drought years (i.e., DPI ≤ –0.2) are identified for each district during 1901–2019, considering the monsoonal and annual precipitation accumulations separately. The total number of droughts (or total droughts) in each district computed on the basis of annual rainfall and monsoonal rainfall are presented in Figs. 3 and 4, respectively, whereas the detailed information is also provided in Table 3. The result reveals that the number of droughts significantly varies across districts over the century-long period. On the basis of annual rainfall, the range spans from eleven to thirty-five droughts in different districts. This indicates that the frequency of drought occurrence varies between once every 3 to 10 years across the region. Notably, the westernmost districts of the study area

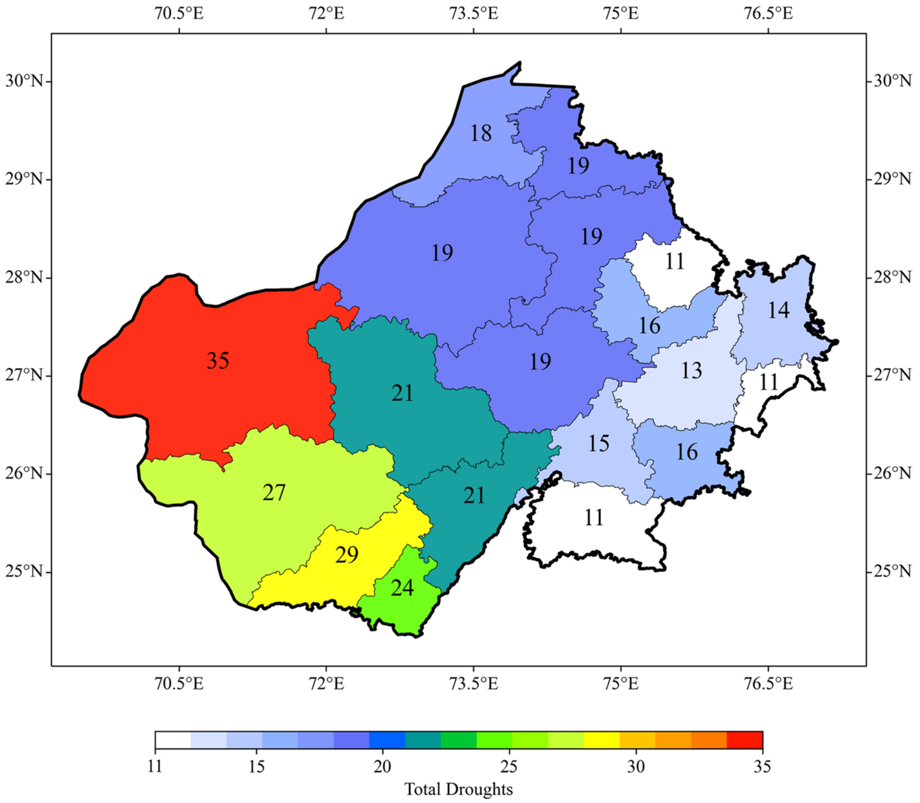


Fig. 3 The total number of droughts over each district during 1901–2019 through annual precipitation-based DPI

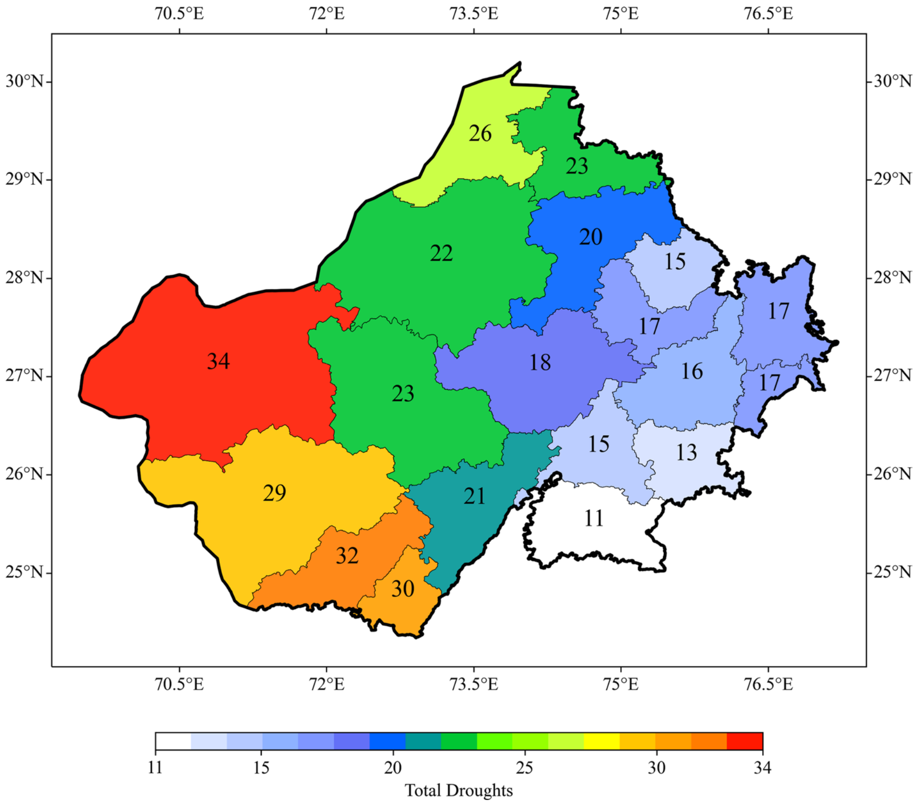


Fig. 4 The total number of droughts over each district during 1901–2019 through monsoonal precipitation-based DPI

Table 3 The detailed information on number of droughts on the basis of both annual rainfall-based DPI and monsoon rainfall-based DPI

District	Number of droughts (Annual Rainfall)				Number of droughts (Monsoon Rainfall)			
	Drought-I	Drought-II	Drought-III	Total Droughts	Drought-I	Drought-II	Drought-III	Total Droughts
Tonk	13	3	0	16	8	5	0	13
Sirohi	18	6	0	24	21	8	1	30
Sikar	13	3	0	16	12	5	0	17
Pali	17	3	1	21	16	4	1	21
Nagaur	16	2	1	19	11	6	1	18
Jodhpur	18	2	1	21	16	6	1	23
Jhunjhunu	8	3	0	11	11	4	0	15
Jalor	19	8	2	29	20	8	4	32
Jaisalmer	24	7	4	35	22	3	9	34
Jaipur	10	2	1	13	12	3	1	16
Hanumangarh	16	2	1	19	15	7	1	23
Ganganagar	12	5	1	18	17	7	2	26
Dausa	9	2	0	11	14	3	0	17
Churu	18	0	1	19	16	3	1	20
Bikaner	16	1	2	19	16	3	3	22
Bhilwara	9	2	0	11	8	3	0	11
Barmer	17	7	3	27	16	7	6	29
Alwar	13	1	0	14	15	2	0	17
Ajmer	11	4	0	15	10	5	0	15

face more frequent droughts (Fig. 3). Jaisalmer district has encountered the highest number of droughts (35), followed by Jalor and Barmer with 29 and 27 total droughts, respectively. Conversely, three districts, namely Jhunjhunu, Dausa, and Bhilwara, have experienced the lowest number of droughts (11), followed by the Jaipur district with 13 total droughts (Table 3). Six districts, namely Sirohi, Pali, Jodhpur, Jalor, Jaisalmer, and Barmer, have experienced more than 20 total droughts, whereas four districts (i.e., Nagaur, Hanumangarh, Churu, and Bikaner) have experienced 19 total droughts during the period of 1901–2019.

On the other hand, based on monsoonal rainfall, the range of total droughts spans from eleven to thirty-four in different districts (Fig. 4). Jaisalmer district has encountered the highest number of droughts (34), followed by Jalor and Sirohi with 32 and 30 total droughts, respectively. Conversely, Bhilwara has experienced the lowest number of droughts (11), followed by Tonk and Ajmer with 13 and 15 total droughts, respectively. Ten districts, namely Sirohi, Pali, Jodhpur, Jalor, Jaisalmer, Hanumangarh, Ganganagar, Churu, Bikaner, and Barmer, have experienced more than 20 total droughts during the period 1901–2019 (Table 3). It can be observed that the monsoonal rainfall-based results are quite similar to that of the annual rainfall-based results; however, the total droughts computed from monsoonal rainfall are relatively higher for most of the districts.

Merely considering the frequency of droughts may not provide a complete understanding of the rainfall fluctuations in a region. For example, two distinct districts with the same drought frequency can exhibit significant differences in drought severity. Therefore, it is important to analyse the frequency of droughts across different severity categories. Figure 5 illustrates the distribution of droughts, categorized as Drought-I ($-0.4 < \mathrm{DPI} \leq -0.2$), Drought-II ($-0.6 < \mathrm{DPI} \leq -0.4$), and Drought-III ($\mathrm{DPI} \leq -0.6$), for each district during the period 1901–2019 based onthe annual precipitation-based DPI. The severity category-wise distribution of droughts based on the monsoonal precipitation-based DPI is illustrated in Fig. 6. The detailed information on frequency of droughts in each severity category can be found in Table 3, whereas the district-wise return period of droughts in each severity category for both annual and monsoonal precipitation-based DPI can be found in Table 4.

Considering the annual precipitation-based DPI, the number of droughts in Drought-I category ranges from eight to twenty-four in different districts (Fig. 5). Jaisalmer district has encountered the highest frequency of Drought-I (24), followed by Jalor (19), Sirohi, Jodhpur and Churu (18 each). In contrast, Jhunjhunu district has encountered the lowest frequency of Drought-I (8), followed by Bhilwara and Dausa (9 each), as evident from Table 3. For Drought-II, the highest frequency is observed for Jalor (8), followed by Jaisalmer and Barmer (7 each), Sirohi (6), Ganganagar

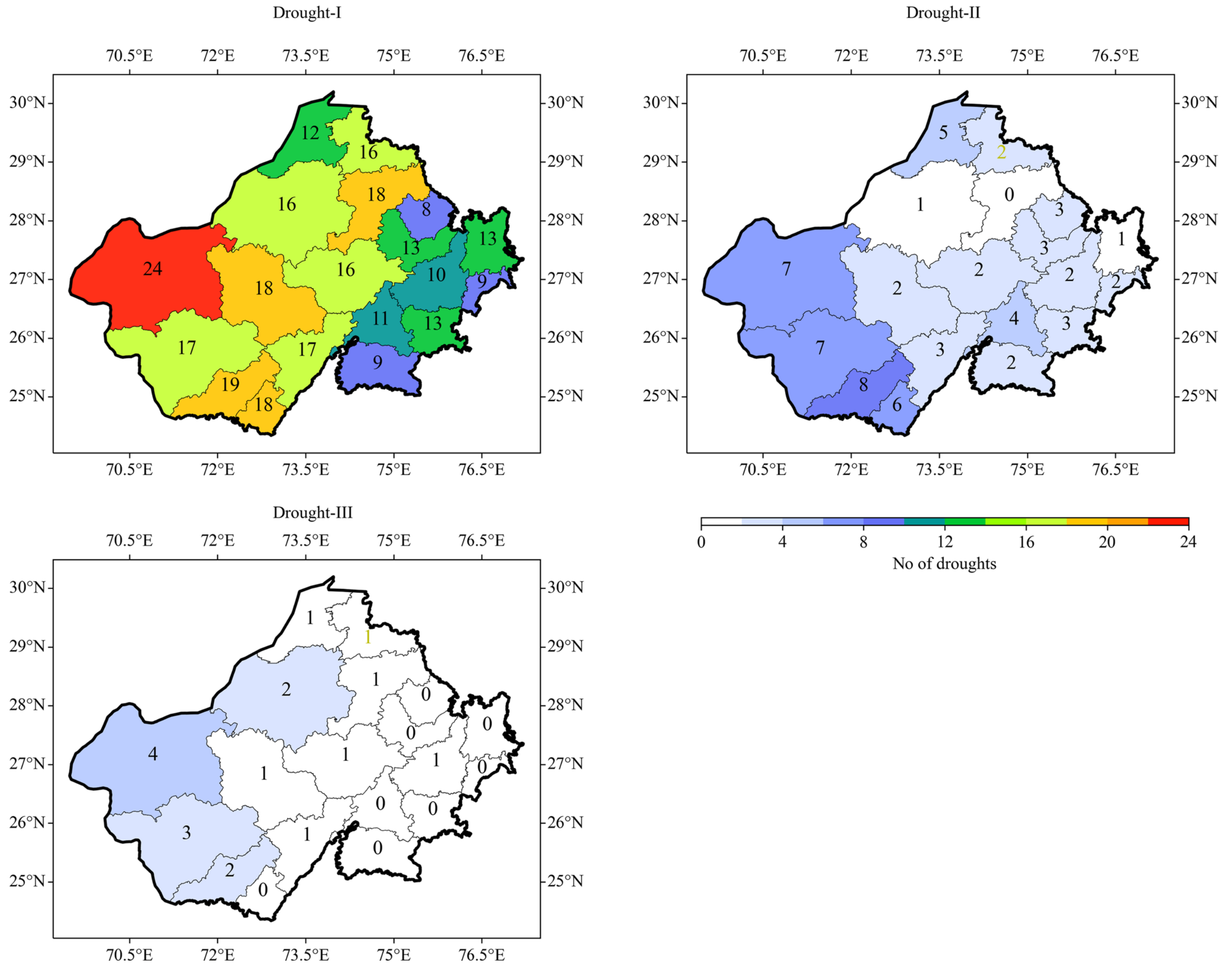


Fig. 5 The number of droughts in each category (i.e., Drought-I, Drought-II and Drought-III) over each district during 1901–2019 through annual precipitation-based DPI

(5) and Ajmer (4). Conversely, Churu is the only district that has never encountered a Drought-II, whereas Bikaner and Alwar have experienced it once during 1901–2019. Similarly, six and four districts have experienced Drought-II twice and thrice, respectively. For Drought-III, the highest frequency is observed for Jaisalmer (4), followed by Barmer (3), Jalor and Bikaner (2 each). Conversely, eight districts, viz., Tonk, Sirohi, Sikar, Jhunjhunu, Dausa, Bhilwara, Alwar, and Ajmer, have never encountered a Drought-III, whereas seven districts have experienced it only once. From Table 4, it is evident that the return period of Drought-I and Drought-II ranges from 3.4 to 10.8 years and 10.8 years to 119 years, respectively. It is worth mentioning that the 'return period' can be defined as the average time interval after which a drought of a given severity is equalled or exceeded. Therefore, for computing the return period of Drought-I for a particular district, the sum of the number of droughts in Drought-I, Drought-II and Drought-III categories are considered. Similarly, for computing the return period of Drought-II, the sum of the number of droughts in Drought-II and Drought-III categories are considered. For Drought-III, the return period ranges from 29.8 to 119 years in eleven out of nineteen districts, as the remaining eight districts have never encountered it.

Considering the monsoonal precipitation-based DPI, the number of droughts in the Drought-I category ranges from eight to twenty-two across different districts (Fig. 6). Jaisalmer district has encountered the highest frequency of Drought-I (22), followed by Sirohi (21) and Jalor (10). In contrast, Tonk and Bhilwara districts have encountered the lowest frequency of Drought-I (8 each), followed by Ajmer (10). For Drought-II, the highest frequency is observed for Sirohi and Jalor (8 each), followed by Hanumangarh, Ganganagar, and Barmer (7 each). Conversely,

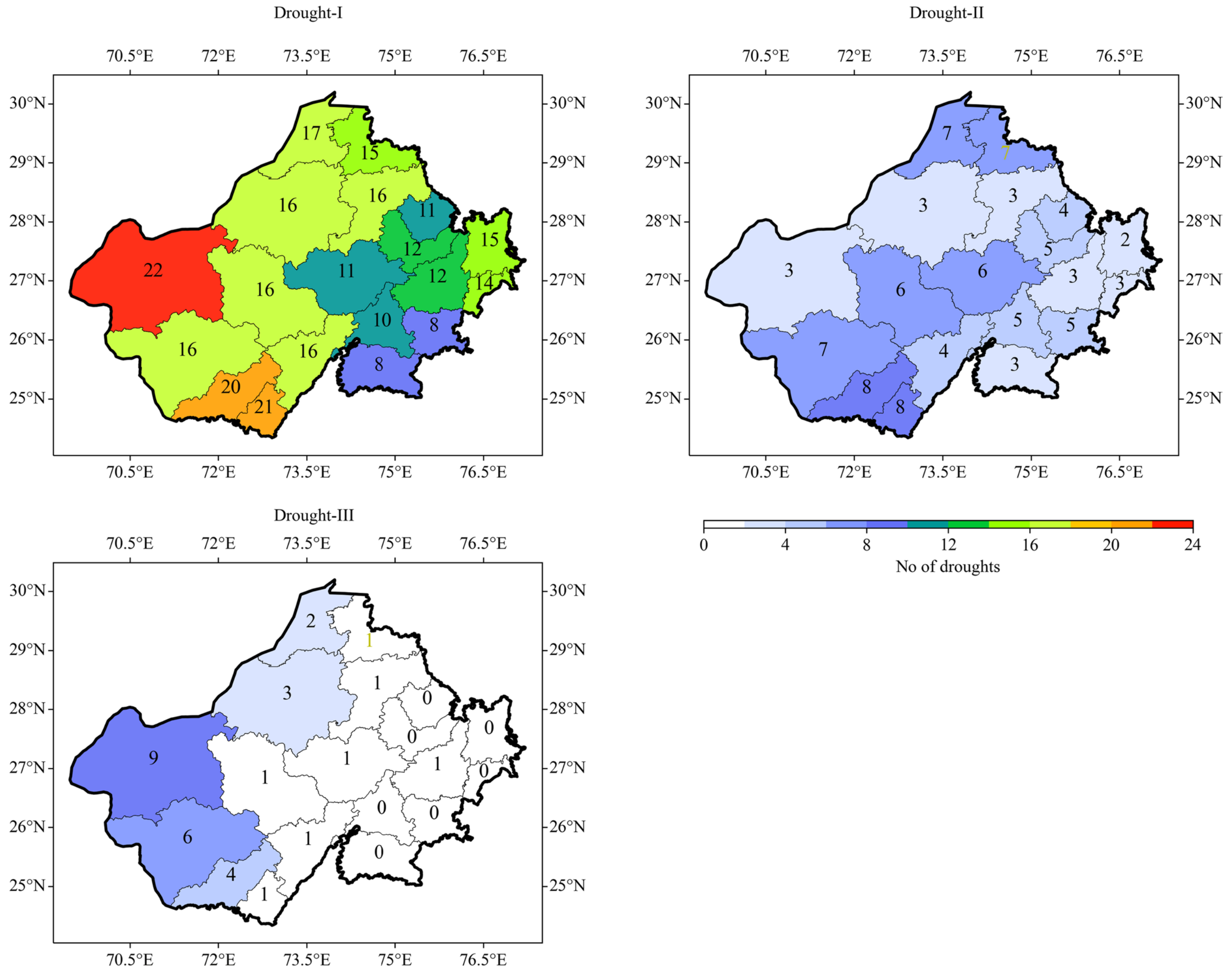


Fig. 6 The number of droughts in each category (i.e., Drought-I, Drought-II and Drought-III) over each district during 1901–2019 through monsoon precipitation-based DPI

the lowest frequency is observed in Alwar district with only two instances of Drought-II. Similarly, the number of occurrences of Drought-II has been three, four, five and six times over six, two, three and two districts, respectively. For Drought-III, the highest frequency is observed in Jaisalmer (9), followed by Barmer (6), Jalor (4), Bikaner (3), and Ganganagar (2). Conversely, seven districts, viz., Tonk, Sikar, Jhunjhunu, Dausa, Bhilwara, Alwar, and Ajmer, have never encountered a Drought-III, whereas the remaining seven districts have experienced it only once (Table 3). From Table 4, it is evident that the return period of Drought-I and Drought-II ranges from 3.5 to 10.8 years and 9.2 years to 59.5 years, respectively. For Drought-III, the return period ranges from 13.2 to 119 years across eleven out of nineteen districts, as the remaining eight districts have never encountered it. It can be observed that the return period of Drought-II is much lower for monsoon precipitation-based DPI compared to that of the annual precipitation-based DPI (Table 4). Hence, the high-deficit anomalies are relatively more frequent in monsoon rainfall.

The arid regions are expected to exhibit a higher Discrepancy Measure (DM). The study by Tayfur (2021) presented a significant relationship between the number of drought years and the DM value for each station. Therefore, in this study, the existence of such a relationship is also investigated. To this end, the DM value is computed considering annual precipitation and monsoonal precipitation for each district. Figure 7 presents the scatterplot of the DPI-based total droughts versus DM values for both annual and monsoonal precipitation, taking all nineteen districts into account. It can be observed that there is a remarkable interrelation between DM and total droughts, meaning that the higher the DM, the higher the number of droughts. The excellent agreement is also evident from the coefficient of determination (R^2),

Table 4 The district-wise return period of droughts in each category (i.e., Drought-I, Drought-II and Drought-III) on the basis of both annual rainfall-based DPI and monsoon rainfall-based DPI

District	Annual rainfall-based Return Period for drought (in years)			Monsoonal rainfall-based Return Period for drought (in years)		
	Drought-I	Drought-II	Drought-III	Drought-I	Drought-II	Drought-III
Tonk	7.4	39.7		9.2	23.8	
Sirohi	5.0	19.8		4.0	13.2	119.0
Sikar	7.4	39.7		7.0	23.8	
Pali	5.7	29.8	119.0	5.7	23.8	119.0
Nagaur	6.3	39.7	119.0	6.6	17.0	119.0
Jodhpur	5.7	39.7	119.0	5.2	17.0	119.0
Jhunjhunu	10.8	39.7		7.9	29.8	
Jalor	4.1	11.9	59.5	3.7	9.9	29.8
Jaisalmer	3.4	10.8	29.8	3.5	9.9	13.2
Jaipur	9.2	39.7	119.0	7.4	29.8	119.0
Hanumangarh	6.3	39.7	119.0	5.2	14.9	119.0
Ganganagar	6.6	19.8	119.0	4.6	13.2	59.5
Dausa	10.8	59.5		7.0	39.7	
Churu	6.3	119.0	119.0	6.0	29.8	119.0
Bikaner	6.3	39.7	59.5	5.4	19.8	39.7
Bhilwara	10.8	59.5		10.8	39.7	
Barmer	4.4	11.9	39.7	4.1	9.2	19.8
Alwar	8.5	119.0		7.0	59.5	
Ajmer	7.9	29.8		7.9	23.8	

The blank cells represent that the district has never encountered a Drought-III during 1901–2019

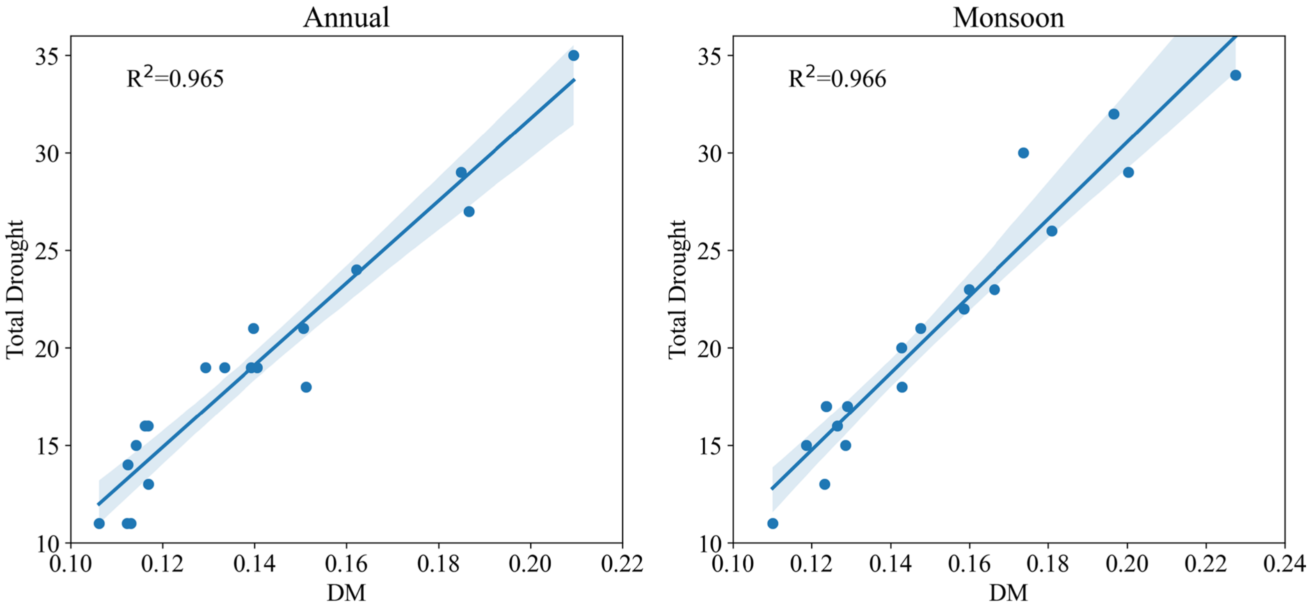


Fig. 7 Scatterplot of DPI-based total droughts vs DM for annual and monsoon precipitation

whose value is found to be 0.965 and 0.966 for annual and monsoonal precipitation, respectively. It should be noted that among two regions, it is possible that a region with higher DM can have a lower number of droughts; however, a region with higher DM typically indicates higher fluctuations from the mean, and therefore, the number of droughts is expected to be higher, which is evident from the very strong correlation as discussed above.

The DM values and the corresponding ranks for each district on the basis of both annual and monsoon precipitation can be found in Table 5. The spatial mapping of DM along with the district-wise ranks, is also presented in Fig. 8. The DM-based ranking will be useful in prioritizing districts for drought management, which can assist administrators and policymakers. It is worth mentioning that rank 1 refers to the highest magnitude of DM, indicating the maximum discrepancies in rainfall compared to the average value. It can be observed that Jaisalmer has the highest DM value, while Bhilwara has the lowest DM value for both annual and monsoonal precipitation. Additionally, seven districts (ranked from 1 to 7) namely Sirohi, Jodhpur, Jalor, Jaisalmer, Hanumangarh, Ganganagar, and Barmer, exhibit DM values of above 0.14 for annual precipitation and above 0.16 for monsoon precipitation. Therefore, these districts should be given top priority in implementing adaptation and mitigation measures to combat the pernicious impacts of droughts. Overall, the DM values are higher for monsoon precipitation compared to annual precipitation across all districts, indicating greater inter-annual fluctuations in monsoonal rainfall.

Overall, DPI is a simple and straightforward approach for drought characterization that does not require data transformations, probability distributions, or the assumption of normal distribution. Further, its classification system being similar to the widely used SPI, makes it particularly effective and user-friendly for practical applications, especially in arid regions. However, DPI has certain limitations. It may not accurately capture the statistical features of precipitation patterns, as it simplifies the complex rainfall distributions into basic logarithmic scales. Also, similar to other percent-deficit-based indices, DPI can be highly sensitive to the coefficient of variation in precipitation, i.e., assessment/classification of drought severity can be unduly influenced by fluctuations in rainfall intensity and frequency. Nevertheless, the application of DPI over Rajasthan showed its effectiveness in distinguishing more drought-prone districts and assessing the drought characteristics. The research findings indicate a high frequency and severity of droughts in the study area. This situation may be further worsened by the influence of climate change, leading to more frequent deviations from normal rainfall patterns. Further, anthropogenic activities are likely to aggravate the consequences of irregular rainfall patterns (Guptha et al. 2021, 2022). Additionally, the rapid growth of industries and excessive exploitation of natural resources can have negative impacts on both surface and groundwater quality (Li and Qian 2018; Li and Wu 2019; Swain et al. 2022e, 2022f, 2022g, 2022h). Given these circumstances, it becomes imperative to implement sustainable water resource management practices that address both quantity and quality concerns (Himanshu et al. 2021, 2023; Wilhite et al. 2014). Western Rajasthan is one of the most arid and water-scarce regions of India. Therefore, the findings of this study will be highly valuable for proactive planning for drought mitigation in the region. Moreover, the implications of this study extend beyond the specific area, as it encourages conducting similar investigations in other arid regions worldwide, where drought consequences often manifest in reduced crop yields, particularly in developing and underdeveloped nations. Moreover, research community across the world has been emphasizing on the fulfilment of Sustainable Development Goals (SDGs) (Nandi and Swain 2023; Nandi et al. 2024; Patel et al. 2022; Sahoo et al. 2022). The insights provided by this study will guide efforts to address escalating drought challenges, foster climate resilience, enhance food security, and inform decision-making processes to ensure sustainable water resource management and water security, particularly in arid regions like Western Rajasthan. Therefore, by addressing these challenges or targets, such research can pave the way for a more sustainable and prosperous future in the face of climate change and its associated risks, thereby contributing to multiple SDGs, i.e., SDG 2 (*Zero Hunger*), SDG 6 (*Clean Water and Sanitation*), and SDG 13 (*Climate Action*).

Table 5 The DM values and ranks of the districts of the study area based on both annual and monsoonal precipitation

District	Annual		Monsoon	
	DM	Rank	DM	Rank
Tonk	0.1162	14	0.1233	17
Sirohi	0.1622	4	0.1737	5
Sikar	0.1169	13	0.1291	12
Pali	0.1398	8	0.1476	9
Nagaur	0.1334	10	0.1429	10
Jodhpur	0.1507	6	0.1601	7
Jhunjhunu	0.1131	16	0.1286	13
Jalor	0.1849	3	0.1966	3
Jaisalmer	0.2094	1	0.2275	1
Jaipur	0.1169	12	0.1264	14
Hanumangarh	0.1406	7	0.1663	6
Ganganagar	0.1512	5	0.1809	4
Dausa	0.1123	18	0.1238	15
Churu	0.1293	11	0.1428	11
Bikaner	0.1393	9	0.1586	8
Bhilwara	0.1062	19	0.1101	19
Barmer	0.1866	2	0.2003	2
Alwar	0.1124	17	0.1237	16
Ajmer	0.1142	15	0.1186	18

Conclusions

This study evaluated the frequency and severity of droughts during 1901–2019 across the nineteen districts of Rajasthan State, India, using DPI based on annual and monsoonal precipitation. Additionally, the degree

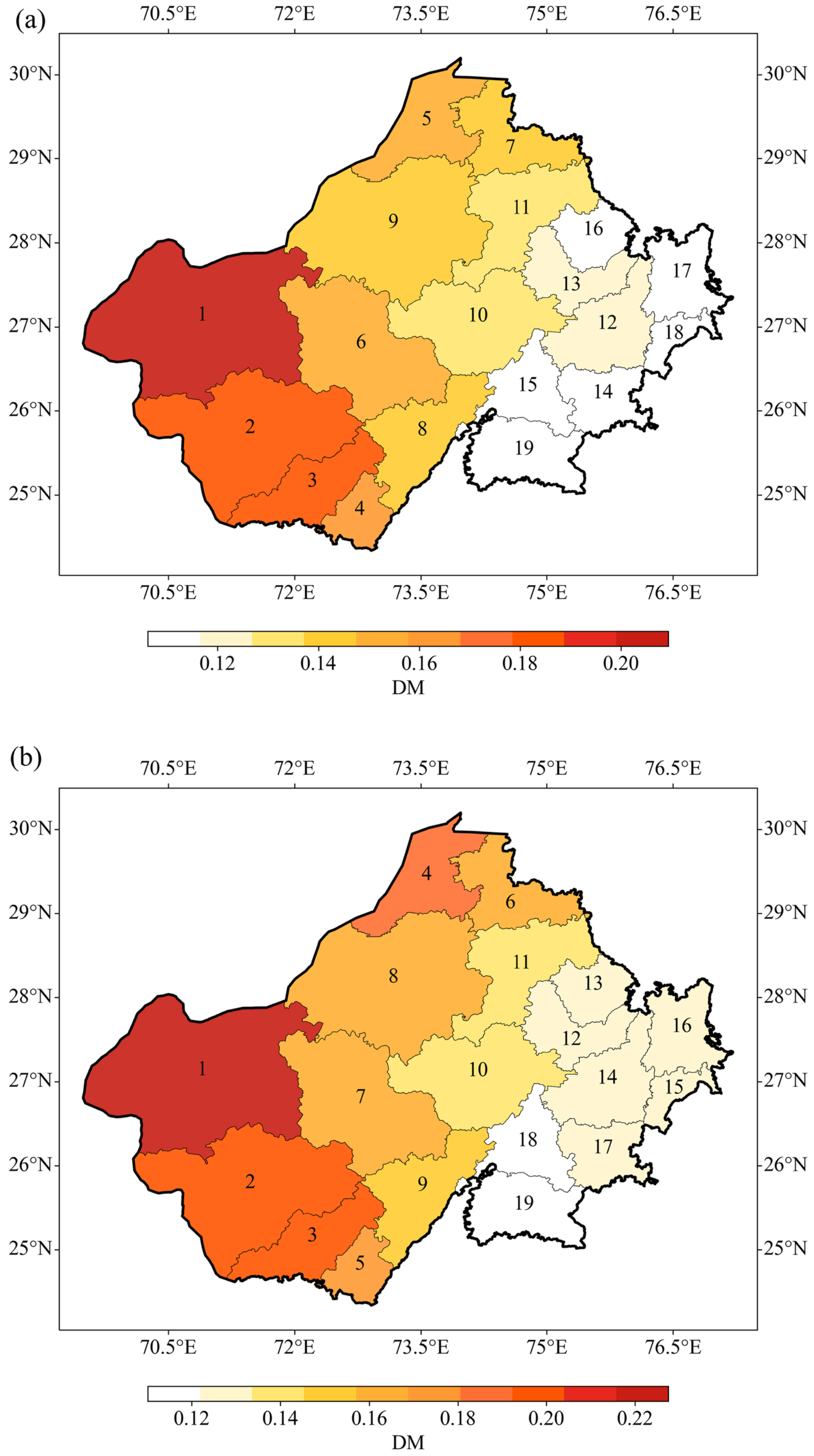


Fig. 8 The ranking of districts of the study area on the basis of DM computed using (**a**) annual precipitation, and (**b**) monsoonal precipitation

of discrepancy in precipitation climatology for each district's annual and monsoon precipitation time-series was assessed through DM. The key conclusions of this study are as follows:

1. DPI does not rely on a specific probability distribution for precipitation data; instead, it focuses on the deviation from the mean value. DPI is very simple to compute and can be an efficient tool for assessing drought years, particularly in arid climatic conditions.
2. Based on annual precipitation, Jaisalmer district has encountered the highest number of drought years (35), whereas three districts, i.e., Jhunjhunu, Dausa, and Bhilwara, had the lowest number of drought years (11). Similarly, based on monsoon precipitation, Jaisalmer and Bhilwara encountered the highest (34) and the lowest (11) number of droughts, respectively.
3. Drought severity classifications (i.e., Drought-I, Drought-II, and Drought-III) are proposed based on the DPI values and the return period of droughts in each severity category is assessed. The return period of Drought-II is lower for monsoon precipitation-based DPI compared to the annual precipitation-based DPI for all districts.
4. There is a strong correlation between DM and DPI-based total number of droughts for both annual and monsoon precipitation. As the DM values increase for a precipitation series, DPI becomes more effective in capturing drought events.
5. Jaisalmer district has the highest DM value, while Bhilwara has the lowest. The DM-based ranking can help prioritize districts for implementing drought mitigation measures. Across all districts, DM values are higher for monsoon precipitation compared to annual precipitation.

Overall, these findings provide valuable insights into the drought characteristics and their assessment in Rajasthan. The study highlights the importance of considering both frequency and severity of droughts and the relationship between DM and DPI. It also emphasizes the need for prioritizing drought mitigation efforts and recognizing the differences between annual and monsoonal precipitation patterns.

Author contributions S.S. (First author)—Conceptualization, methodology, formal analyses, figures, writing (original draft); S.N.—methodology, formal analyses, figures, writing (review); P.K.M.—writing (review); B.P.—writing (review); S.S. (Fifth author)—writing (review); N.A.A.—writing (review), open access funding.

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Data availability The gridded rainfall data from IMD is freely available all over India. The district-wise rainfall records over the study area are available from the first author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interest.

Code availability The Python library 'IMDLIB' (https://doi.org/https://doi.org/10.5281/zenodo.4405233) can be used to read and download the IMD gridded data. More details on IMDLIB can be found here: https://imdlib.readthedocs.io/en/latest/

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