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DROUGHT HAZARD, VULNERABILITY AND RISK ASSESSMENT OVER RAJASTHAN, INDIA

Divya Saini
Omvir Singh

Abstract

This study assesses the drought affected areas of Rajasthan at annual and monsoon season (June-September) time scales by applying hazard (Drought Hazard Index), vulnerability (Drought Vulnerability Index) and risk (Drought Risk Index) indices. For the computation of these indices, secondary data pertaining to several physical and socio-economic indicators have been collected and utilized. The results have revealed that extreme drought hazard prevails in most of the northern, eastern and southern parts of Rajasthan, whereas drought hazard is less severe in south-eastern and central parts of the state at both time scales. Similarly, more than 75 per cent area of Rajasthan has been found highly vulnerable to drought having maximum vulnerability in western, eastern, south-eastern and south-western parts. The area under drought risk has been found maximum under extreme drought category at annual (27 per cent) and monsoon season (36 per cent) time scales, spatially distributed in northern, eastern and southern parts of the state. The outcomes of this study can be helpful for the farmers, scientists, policymakers, and water resource managers to mitigate the effects of droughts over Rajasthan.

Keywords: Drought, Standardized Precipitation Index (SPI), Hazard, Vulnerability, Risk

Introduction

Drought, a challenging climatic phenomenon, is defined as a prolonged period of insufficient rainfall. Recently, several studies have predicted a significant rise in their frequency, severity and intensity due to an increase in the levels of carbon emission, human activities, and changing climatic conditions (Trenberth et al., 2014; Suárez-Amiñana et al., 2017; Wang et al., 2019). The prolonged occurrence of drought poses serious threats to agriculture, water resources, tourism, health, food productivity, and ecosystem services (Mishra and Singh, 2010; Zhang et al., 2011; Yu et al., 2014; Rahman and Lateh, 2016; Dabanli, 2018). Also, their occurrence results in huge economic losses due to slow onset and termination process of drought (Sheffield et al., 2014). Globally, drought events have caused annual economic losses of approximately $ 6-8 billion, surpassing those of any other climatic disaster (Pandey et al., 2010; Pei et al., 2019).

A comprehensive risk of drought can be calculated by combining both hazard and vulnerability (Chen et al., 2023). Several studies across different regions of the globe have used the concept of hazard and vulnerability for investigating the risk of drought. For instance, Shahid and Behrawan (2008) have identified a high risk of drought by using hazard and vulnerability indices in the northern and north-western parts of Bangladesh. Similarly, Dabanli (2018) and Singh et al. (2019) have detected a low to moderate and medium to high drought risk in Turkey and Krishna River basin of India, respectively. Likewise, Alamdarloo et al. (2020) have detected a high risk of drought by combining both hazard and vulnerability in central, north-eastern, south-eastern and western parts of Iran.

Drought hazard is a key component of drought risk and can be assessed by taking into account its frequency and probability of occurrence (Zhang and Zhang, 2016). Globally, drought hazard has been calculated by using the mathematical indices such as, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Precipitation Evapotranspiration Index (SPEI), Rainfall Anomaly Index (RAI), Precipitation Departure (PD), Effective Drought Index (EDI), Rainfall Deciles (RD), China-Z index (CZI), Z-score index (ZSI) etc. (Zargar et al., 2011; Beven et al., 2018; Mehr et al., 2019; Mallenahalli, 2020; Oikonomou et al., 2020; Pandzic et al., 2020; Yu et al., 2020). However, among all, the SPI technique has been extensively used due to its simple calculation, spatial consistency, probabilistic nature and ability to calculate drought at multiple time scales (Liu et al., 2012; Awchi and Kalyana, 2017; Baral et al., 2023). Therefore, SPI technique has also been advocated by the World Meteorological Organization (WMO) for drought assessment (Hayes et al., 2011; Zarch et al., 2015; Kwak et al., 2016; Bayissa et al., 2017; Juliani and Okawa, 2017; Lee and Dang, 2019).

Similarly, drought vulnerability is the second key indicator of drought risk after hazard having relationship with natural, social and economic conflicts (Birkmann, 2006). Drought vulnerability is estimated by using several physical and socio-economic indicators. For example, Shahid and Behrawan (2008) have identified a medium to high drought vulnerability by using physical and socio-economic indicators, such as soil water holding capacity, irrigated area, population density and sex ratio in Bangladesh. Likewise, Jain et al. (2015) have detected a high vulnerability of drought in central India based on physiographic, climatic and hydrologic factors. Recently, Dabanli (2018) and Reis et al. (2020) have revealed high and extreme drought vulnerability in Turkey and Brazil, respectively by using both physical and socio-economic indicators.

Droughts have occurred frequently in India, and more than 60 per cent of the total geographical area and population has been affected (Mishra et al., 2007; Pandey et al., 2012; Murthy et al., 2015; Amrit et al., 2017; Choudhary, 2024). Within India, Rajasthan province has the maximum probability of drought occurrence. Recently, several studies on drought characteristics (frequency, magnitude, intensity, duration, return period etc.) have been documented in literature over Rajasthan (Dhakar et al., 2013; Dutta and Chaudhuri, 2015; Singh et al., 2021). However, studies focusing on drought risk both by an integration of hazard and vulnerability are completely missing. Therefore, in this study, an effort has been made to assess the drought hazard, vulnerability and risk over Rajasthan both at annual and monsoon seasonal scales.

Objectives of Study

Major objectives of the study are:

- to identify drought affected areas by applying drought hazard index (DHI),
- to determine the level of vulnerability to drought by using the drought vulnerability index (DVI), and
- to assess drought risk by integrating hazard and vulnerability indices at annual and monsoon season (June-September) time scales over Rajasthan.

Area of Study

Rajasthan is the largest province of India that covers about 3,42,239 km² of area. Geographically, it is situated in north-western part of India and spreads between 23° 30′ to 30° 11′ N latitudes and 69° 29′ to 78° 17′ E longitudes (Fig. 1). The altitude ranges from 6 to 1698 m above mean sea level. Physiographically, it has a desert in the north-west, sandy plains in the north-east, hills in the middle and plateau in the south-east. The desert covers almost 70 per cent area of Rajasthan. It has a semi-arid to arid and semi-arid to sub-humid climate. The annual rainfall ranges from 100 to 400 mm in the west and 500 to 1000 mm in the east. June to September are the rainiest months and more than 90 per cent of the total rainfall occurs in these months. The average temperature varies from 26º C to 46 ºC (summer) and 8 ºC to 28 ºC (winter). Besides, unequal distribution of rainfall, the state has high variations in temperature, evaporation rate, inadequacy of vegetation and scarcity of perennial rivers. About 70 per cent of the total population earn

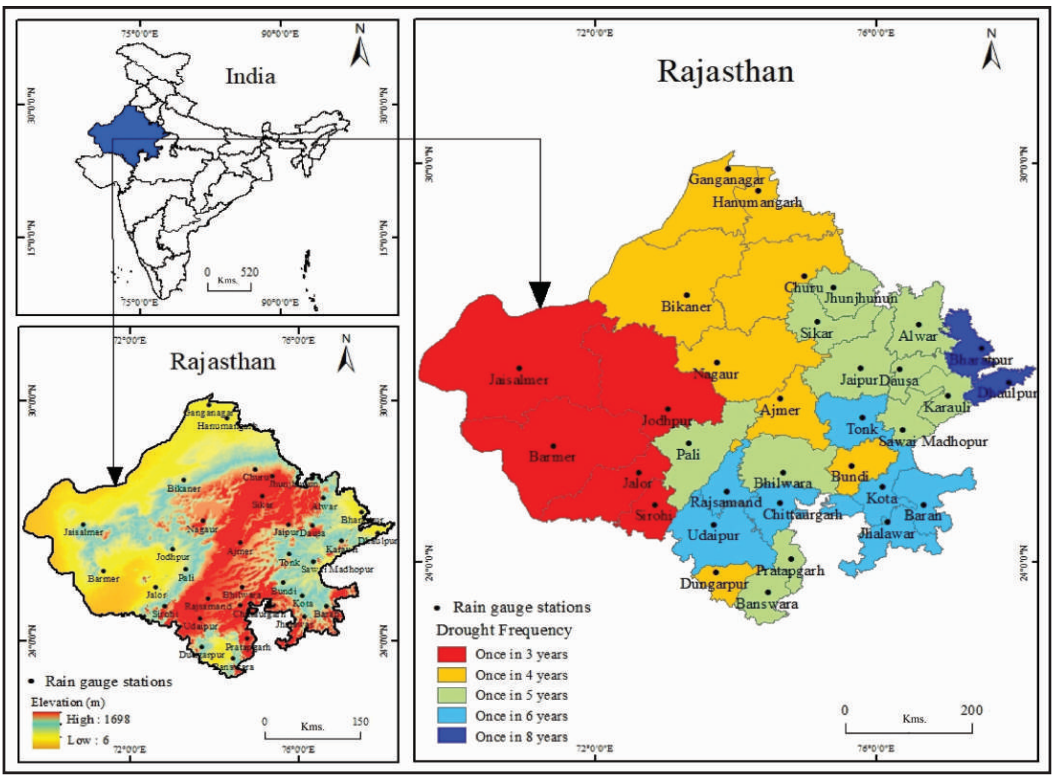


Fig. 1

their livelihood from agriculture, particularly during kharif (June-October) and rabi (November-March) cropping seasons.

Database and Methodology

This study is primarily focused on the assessment of drought risk, based on the study of drought hazard and drought vulnerability. For the assessment of drought hazard, daily rainfall data from 33 rain gauge stations covering the period 1961-2017 have been collected from Water Resources Department, Government of Rajasthan. The diurnal rainfall data have been converted into monthly and annual scales for drought hazard assessment by using SPI. Meanwhile, drought vulnerability has been examined using several physical and socio-economic indicators (Table 1). The data related to these indicators have been acquired from different secondary sources, which have also been mentioned in Table 1.

Drought risk is the likelihood of anticipated losses due to the interactions of hazard and vulnerability in a region. It is determined by combining the physical impacts and the degree of vulnerable population (Thomas et al., 2022). This study has adopted an integrated framework to assess the drought risk by combining meteorological drought hazard as well as physical and socio-economic drought vulnerability. A detailed procedure towards the computation of drought hazard, vulnerability and risk have been explained in the following sub-sections:

Computation of Drought Hazard Index (DHI)

Drought hazard is the frequency or probability of drought occurrence, which is measured by assessing its characteristics (frequency, severity etc.). In this study, drought frequency has been calculated by using SPI at annual (SPI-12) and monsoon season (SPI-4) time scales. The SPI-4 (short-term) has been selected, because maximum rainfall occurs during June-September (monsoon season) months, which helps in the assessment of soil moisture and drought conditions related to agriculture. However, SPI-12 (long-term) helps in the assessment of water supply, groundwater, stream flow and socio-economic impacts of drought (Ji and Peters, 2003; Potop et al., 2014). For the calculation of SPI, the long-term rainfall data from 33 rain gauge stations has been selected and fitted into gamma probability distribution function by utilizing the following mathematical equation:

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

where $\alpha > 0$ and $\beta > 0$ are the shape and scale, respectively and $x > 0$ is the quantity of rainfall. The values of α and β parameters have been computed by using the gamma probability distribution by applying following equation:

$$\hat{\alpha} = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{44}{3}}\right] \qquad (2)$$

$$\hat{\beta} = \frac{\overline{X}}{\hat{\alpha}} \qquad (3)$$

whereas for n observations,

$$A = In(\bar{x}) - \frac{\sum In(x)}{n} \qquad (4)$$

The values of both the parameters have been effectively used for the assessment of rainfall distribution at each rain gauge station by using cumulative probability distribution function:

$$G(x) = \int_0^x g(x)\,dx = \frac{1}{\beta^{\alpha}\gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta}\,dx \quad (5)$$

Table 1

Rajasthan: Types of Data Sets, their Sources and Time Period

Indicators	Data Layers	Data Type	Data Source	Period
Physical Indicators	Annual rainfall	Rainfall data (daily)	Water Resources Department, Government of Rajasthan (www.waterresources.rajasthan. gov.in)	1961-2017
	Annual temperature	Temperature data	Directorate of Economics and Statistics, Government of Rajasthan	1957-2002
	Annual evapotranspiration	Evapotranspiration data	Directorate of Economics and Statistics, Government of Rajasthan	1957-2002
	Groundwater level	Depth of groundwater level (m)	Groundwater Level Scenario in Rajasthan	2018
	Groundwater development	Stages of ground water development (percent)	Dynamic Ground Water Resources of Rajasthan	2013
	Elevation	Digital elevation model (90m)	Shuttle Radar Topographic Mission	2014
Socio - economic Indicators	Population density	Number of persons/km^2	Census of India (www.censusindia.gov.in)	2011
	Sex ratio	Number of females to one thousand males	Census of India (www.censusindia.gov.in)	2011
	Irrigated area	Percentage of irrigated area to total land	Year book of Agriculture Statistics	2016-2017
	Deep tube wells	Percentage of area irrigated by deep tube wells	Minor Irrigation Census, Rajasthan	2013-2014
	Agriculture dependent population	Percentage of people depending on agriculture	Census of India (www.censusindia.gov.in)	2011

Source: Compiled by Authors.

Table 2
Rajasthan: SPI Based Drought Categories and their Probability of Occurrence

SPI Values	Drought Category	Probability of Occurrence (per cent)
-2.00 and less	Extreme Drought	1.00
-1.50 to -1.99	Severe Drought	3.00
-1.00 to -1.49	Moderate Drought	12.00
0 to -0.99	Mild Drought	38.00

Source: Compiled by Authors.

However, the gamma function has not been explained for x = 0, then precipitation cumulative distribution becomes:

$$H(x) = q + (1-q)\, G(x) \qquad (6)$$

where q shows the zero probability and $H(x)$ is the cumulative standard normal distribution function. Further, the probability of occurrence of each SPI drought categories (mild, moderate, severe and extreme) has been calculated (Table 2). Also, the drought hazard (drought frequency) has been computed as the ratio of drought occurrences in each category to the total number of drought occurrences in different categories (Sonmez et al., 2005). Meanwhile, the weights and rating (1 to 4) have been assigned to all drought categories based on their severity and probability of occurrences (Table 3). Mathematically, the drought hazard index *(DHI)* has been calculated as under:

$$DHI = (MID_r \times MID_w) + (MD_r \times MD_w) + (SD_r \times SD_w) + (ED_r \times ED_w) \qquad (7)$$

where MID_r and MID_w are the ratings and weights assigned to mild drought, MD_r and MD_w are the ratings and weights of moderate drought, SD_r and SD_w are the ratings and weights allocated to severe drought, and ED_r and ED_w are the ratings and weights assigned to extreme drought categories (Table 3). Afterwards, the normalization technique has been applied and then drought hazard has been classified into 5 categories namely, nil drought (0.0), mild (0.0-0.25), moderate (0.25-0.50), severe (0.50-0.75) and extreme (0.75-1.0) on the basis of its severity.

Computation of Drought Vulnerability Index (DVI)

A comprehensive drought vulnerability index should consider ecological, socio-economic and production indicators. However, these indicators are not easily accessible for Rajasthan. Therefore, after a thorough scan of the accessible indicators, six physical and five socio-economic indicators have been identified (Table 1). The assumptions related to drought vulnerability of above stated indicators are outlined below.

Physical Indicators

Rainfall

The distribution of rainfall is the major drought controlling factor in any region of the world. A decrease or increase in the quantity of rainfall will directly affect the drought vulnerability. Therefore, the areas with greater rainfall deficiency are more vulnerable to drought, and vice versa (Pandey et al., 2012; Jain et al., 2015; Wu et al., 2017; Hoque et al., 2019).

Table 3
Rajasthan: Weights and Ratings Assigned to Different Drought Categories Based on their Percentage of Occurrence

Drought Severity	Weight	Percentage of Occurrence	Rating
Mild	1	≤31.0	1
		31.1-35.5	2
		35.6-42.0	3
		≥ 42.1	4
Moderate	2	≤ 7.0	1
		7.1-10.0	2
		10.1-13.0	3
		≥ 13.1	4
Severe	3	≤ 3.5	1
		3.6-4.5	2
		4.6-5.5	3
		≥ 5.6	4
Extreme	4	≤ 1.0	1
		1.1-2.0	2
		2.1-3.0	3
		3.1	4

Source: Compiled by Authors.

Temperature

Temperature is the second most significant indicator in the onset of drought. It is inversely proportional to the precipitation of a region. Recently, Hoque et al. (2019) have found a high drought vulnerability associated with high temperature.

Evapotranspiration

Similar to temperature, evapotranspiration also shows the direct correlation with drought. The areas receiving high temperature will have high rates of evapotranspiration, therefore, increases the chances of drought vulnerability (Wu et al., 2017; Hoque et al., 2019).

Groundwater Level

Groundwater level is also considered as an important indicator of drought vulnerability. The areas with deeper groundwater levels are more vulnerable to drought vis-à-vis to shallow groundwater levels. The shallow groundwater levels help in maintaining the water holding capacity of soil during the water scarcity period (Wu et al., 2017).

Stages of Groundwater Development

The stages of groundwater development have been divided into different zones (safe to over-exploited). The zones with over-exploitation of groundwater are considered more vulnerable to drought than the safer ones.

Elevation

The areas having high undulating topography receive greater amount of water in the lower areas as the water flows down with the slope (Nasrollahi et al., 2018; Hoque et al., 2019). As a result, areas with higher elevation are more vulnerable to drought than those at lower elevations.

Socio-economic Indicators

Population Density

Population density is an important component of social drought vulnerability, which is defined as the number of persons/km². Generally, the amount of calamity has been found highest in the areas having high density of population. Therefore, areas having high density of population are more vulnerable to drought (Jain et al., 2015; Dabanli, 2018; Hoque et al., 2019).

Sex Ratio

It is the ratio of number of females to one thousand males. The areas having high sex ratio are more vulnerable to drought because the coping ability of females is always lesser than the males (Singh et al., 2019).

Irrigated Area

Generally, most of the irrigation water comes from groundwater and its availability is directly related to rainfall. Therefore, a region with high irrigated area is more vulnerable to drought as a rainfall deficit causes a decline in the groundwater levels (Kim et al., 2013; Dabanli, 2018).

Deep Tubewells

The number of deep tubewells is directly related to groundwater depth. Therefore, the regions having high percentage of deep tubewells will significantly deplete the groundwater levels, thus making it more vulnerable to drought.

Agriculture Dependent Population

It is the percentage of population dependent on agriculture, including farmers and agricultural workers. Globally, the most affected sector by drought is agriculture. Therefore, areas having high agriculture dependent population are more vulnerable vis-à-vis to others (Singh et al., 2019).

Further, to ensure comparability among above indicators with different units and scales, the Min-Max normalization technique has been applied. This method transforms all indicator values to a standardized range between 0 and 1, where 0 shows nil vulnerability and 1 represents the extreme conditions of drought vulnerability (Reis et al., 2020). Mathematically, it is calculated as:

$$X_{normalised} = \frac{X - X_{min}}{X_{max} - X_{min}} \qquad (8)$$

where, X is the original value of indicator and X_{max}, X_{min} are the maximum and minimum values of the indicators across the study area, respectively. This approach has been chosen for its simplicity, effectiveness in preserving relative differences between values, and widely used in socio-economic vulnerability assessments. Mathematically, drought vulnerability index (DVI) is expressed as:

$$DVI = \frac{RF_r + TEM_r + EVP_r + ELV_r + GL_r + SGD_r + PD_r + SR_r + IL_r + DT_r + AD_r}{Total\ Number\ of\ Indicators} \qquad (9)$$

where RF_r, TEM_r, EVP_r, ELV_r, GL_r, SGD_r, PD_r, SR_r, IL_r, DT_r, and AD_r are the ratings assigned to rainfall, temperature, evapotranspiration, groundwater level, stages of groundwater development, elevation, population density, sex ratio, irrigated area, deep tubewells and agriculture dependent population.

Computation of Drought Risk Index (DRI)

Drought risk areas have been recognized and mapped following the formula proposed by Downing and Bakker (2000) and Wilhite (2000), which is mathematically expressed as:

$$DHI = DHI \times DVI \tag{10}$$

where *DRI* is drought risk index, *DHI* is drought hazard index, and *DVI* is drought vulnerability index. Thus, the drought risk index (*DRI*) has been generated based on meteorological and socio-economic indicators by multiplying drought hazard index (*DHI*) and drought vulnerability index (*DVI*). If one of the *DHI* or *DVI* has *"0"*, the resulting *DRI* will become *"0"*, which means there is nil drought risk. The higher the value of *DHI* or *DVI*, the higher will be the *DRI*.

The spatial pattern of drought hazard, vulnerability and risk have been shown by using the Inverse Distance Weighting (IDW) interpolation technique. IDW is a widely applied method that estimates values at unsampled locations based on the weighted average of nearby observations, assigning greater weight to closer points. This technique assumes that the influence of a data point decreases with distance and has been implemented using ArcGIS 10.2. For better understanding, detailed methodology used for the

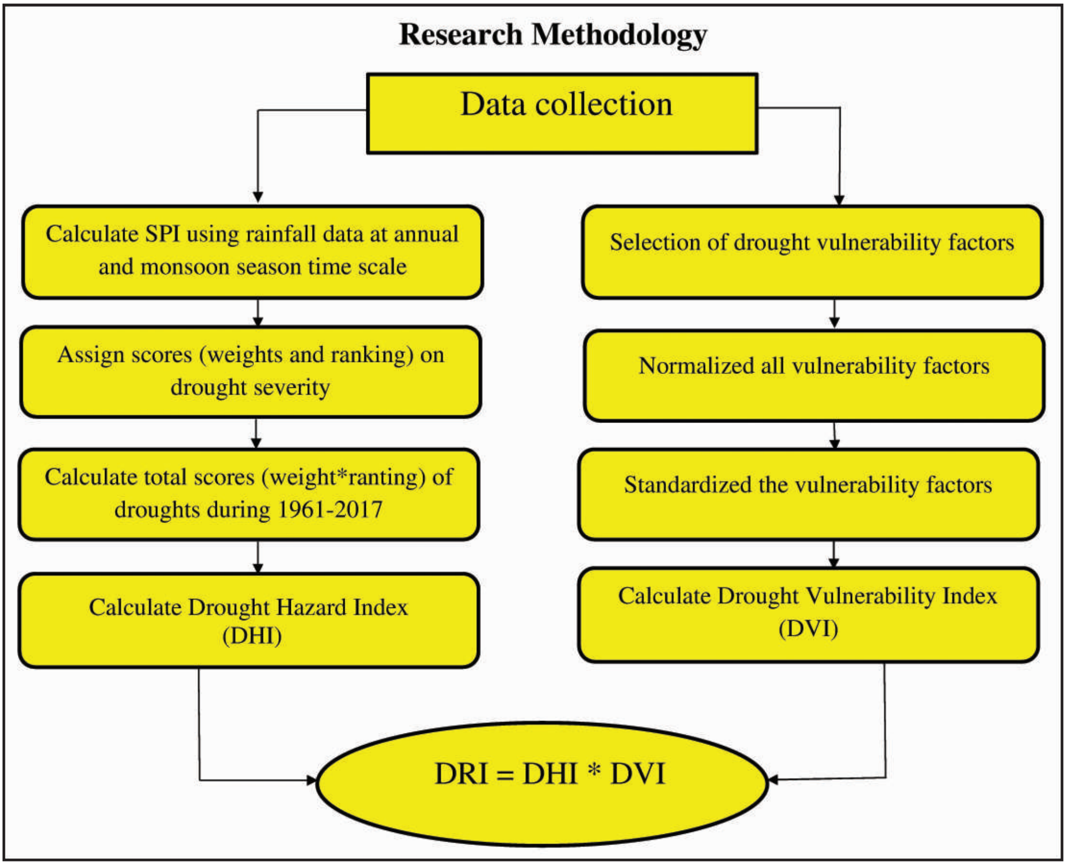


Fig. 2

assessment of drought hazard, vulnerability and risk has been presented in Fig. 2.

Results and Discussion

Drought Hazard Assessment

SPI based dry/wet events for different stations at both time scales (12- and 4-month) have been shown in Figs. 3 and 4, respectively. In these figures, the different categories of SPI i.e., nil drought/wet, mild, moderate, severe and extreme have been shown with dotted lines of different colors. The severity of dry/wet events has varied both at spatial (station to station) and temporal (year to year) scales. The results have revealed a high frequency of drought at Barmer station (35 events), while the lowest frequency has been detected at Bharatpur station (26 events) at annual time scale (Fig. 3). A similar pattern of drought frequency has been detected at monsoon season time scale with small fluctuations in the number of drought events (Fig. 4). Interestingly, mild (38 per cent) and moderate (12 per cent) drought events have occurred frequently, while the severe (3 per cent) and extreme (1 per cent) drought events have occurred rarely (Table 2). These results are in correspondence with Degefu and Bewket (2015) and Singh et al. (2021). Further, spatial distribution of percentage of drought occurrence of different drought categories at annual time scale has been shown in Fig. 5. The percentage of mild drought occurrence has been found highest in western, south-eastern and some pockets of eastern Rajasthan, while the lowest drought occurrence has been detected in northern, southern and north-eastern parts of the state (Fig. 5a). Fig. 5b shows the percentage of moderate drought occurrence, which has been noticed highest in most of the western Rajasthan and some pockets in south and north-eastern parts of the state. However, the eastern and south-eastern parts of Rajasthan have witnessed the lowest percentage of moderate drought occurrence. Remarkably, the percentage of severe and extreme drought occurrences have been found to be the lowest over Rajasthan vis-à-vis to mild and moderate drought occurrence, which are in tune with Mundetia and Sharma (2014) and Degefu and Bewket (2015). Spatially, the percentage of severe drought occurrence has been recorded highest in north-eastern and south-central parts (Fig. 5c), while the percentage of extreme drought occurrence has been detected only in few pockets of eastern and south-western Rajasthan (Fig. 5d).

The spatial distribution of percentage of drought occurrence at SPI-4 time scale has been shown in Fig. 6. The percentage occurrence of mild drought has been detected highest in the western, central and south-eastern parts of the state (Fig. 6a). Whereas, the percentage of moderate drought occurrence has been recorded maximum in northern, western and southern parts of the state (Fig. 6b). Noticeably, there is a large difference between the percentage of mild and moderate drought occurrences both at SPI-12 and SPI-4 time scales (Figs. 6a-b). Further, Figs. 6c-d show the percentage of severe and extreme drought occurrences, which reveals the highest percentage of severe drought occurrence in eastern, northern and southern parts of the state. Interestingly, except for a few pockets over eastern and north-western parts, the occurrence of extreme drought has been found to be absent over Rajasthan (Fig. 6d).

The spatial distribution of drought hazard both at annual and monsoon season time scales reveals the maximum drought in northern, eastern and southern parts, while the

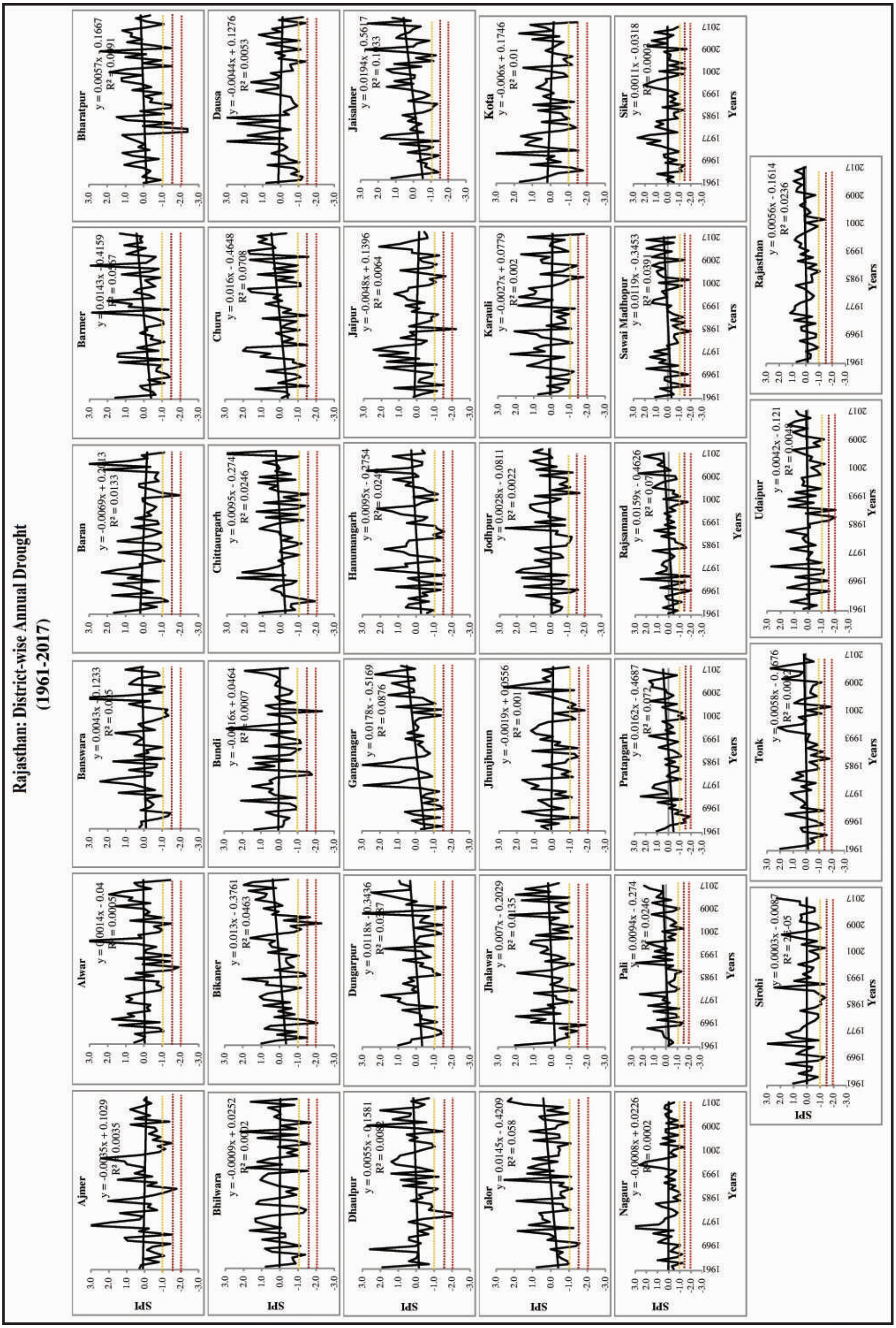

Rajasthan: District-wise Annual Drought
(1961-2017)
Ajmer
Alwar
Banswara
Baran
Barmer
Bharatpur
Bhilwara
Bikaner
Bundi
Chittaurgarh
Churu
Dausa
Dhaulpur
Dungarpur
Ganganagar
Hanumangarh
Jaipur
Jaisalmer
Jalor
Jhalawar
Jhunjhunun
Jodhpur
Karauli
Kota
Nagaur
Pali
Pratapgarh
Rajsamand
Sawai Madhopur
Sikar
Sirohi
Tonk
Udaipur
Rajasthan
SPI
Years

Fig. 3

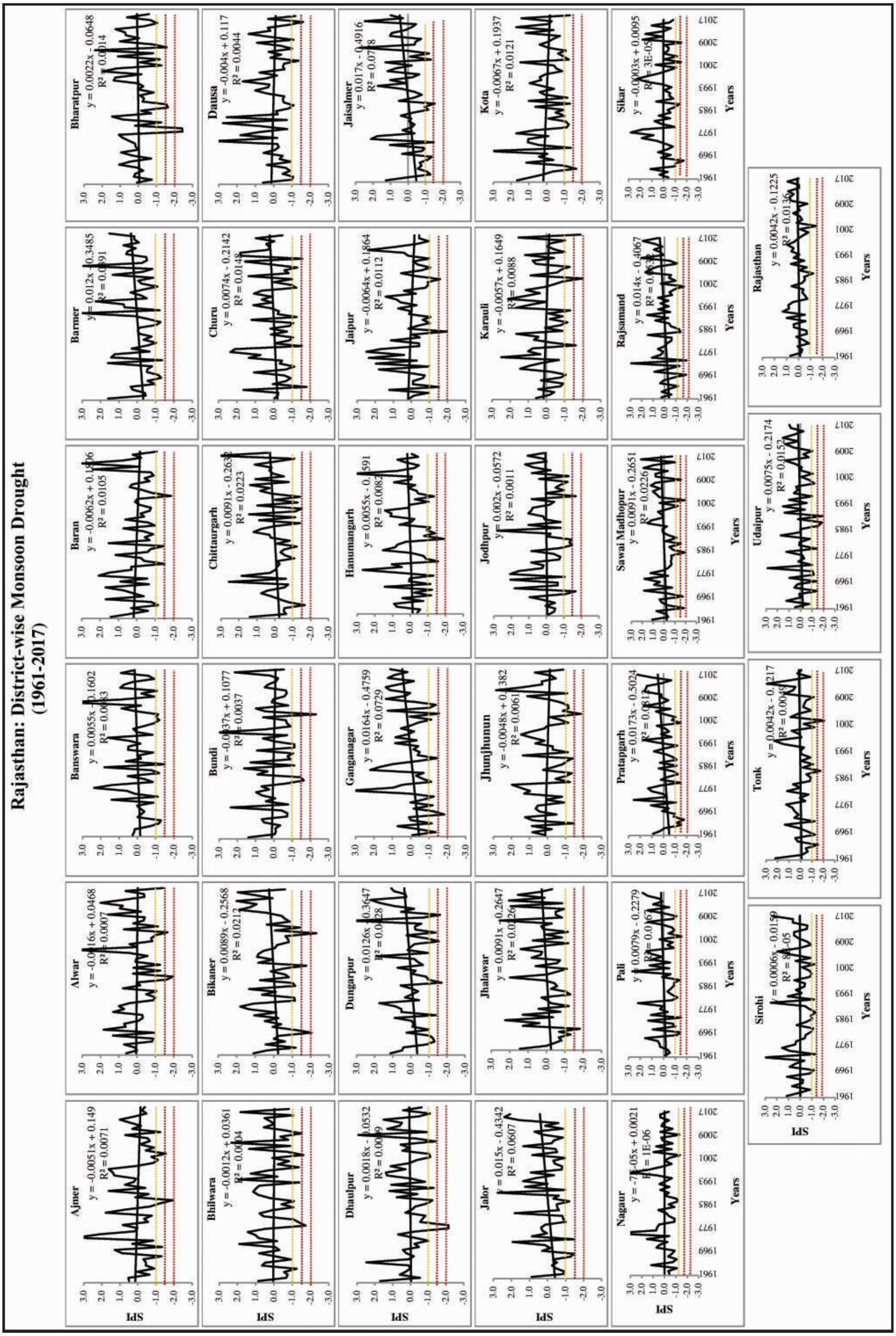

Rajasthan: District-wise Monsoon Drought
(1961-2017)
Ajmer
Alwar
Banswara
Baran
Barmer
Bharatpur
Bhilwara
Bikaner
Bundi
Chittaurgarh
Churu
Dausa
Dhaulpur
Dungarpur
Ganganagar
Hanumangarh
Jaipur
Jaisalmer
Jalor
Jhalawar
Jhunjhunun
Jodhpur
Karauli
Kota
Nagaur
Pali
Pratapgarh
Sawai Madhopur
Rajsamand
Sikar
Sirohi
Tonk
Udaipur
Rajasthan
SPI
Years

Fig. 4

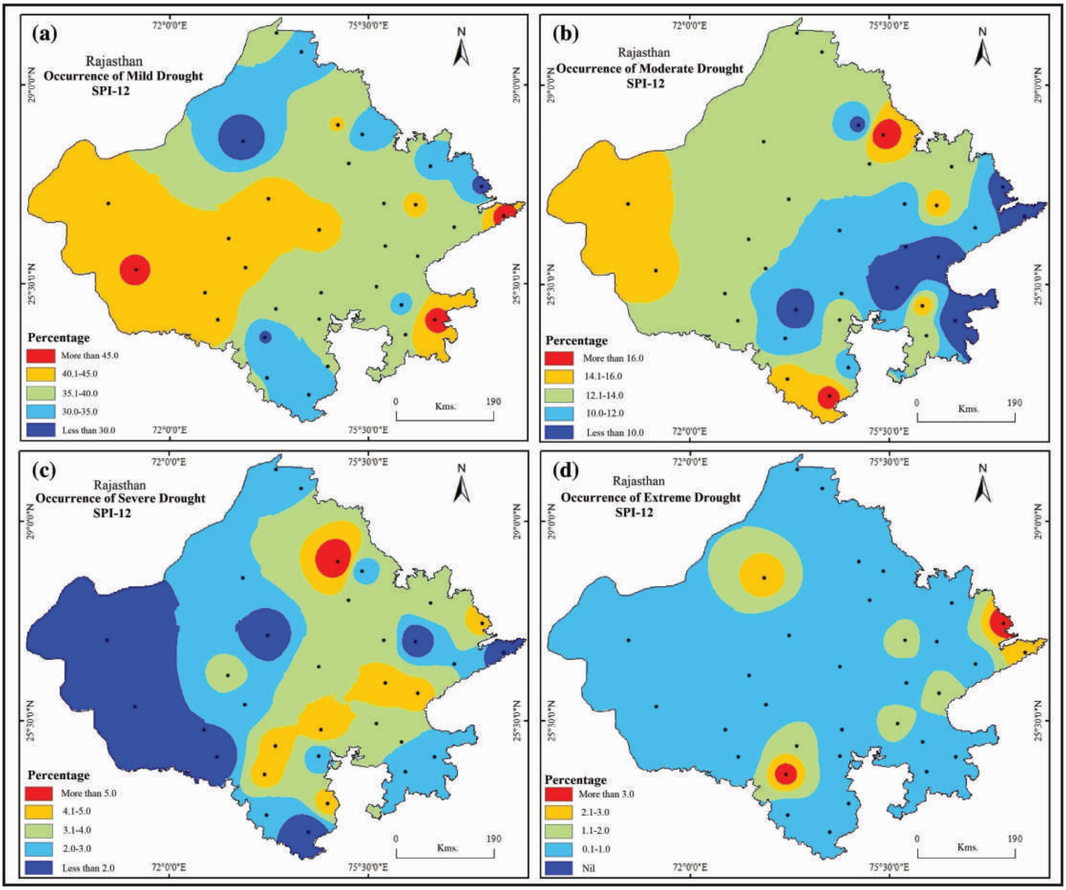


Fig. 5

lowest has been observed in south-eastern and central parts of the state (Fig. 7). At annual time scale, the drought hazard has been found highest in moderate category (42 per cent), followed by mild (36 per cent) and severe (12 per cent). Remarkably, Udaipur and Bharatpur districts have been found to be inflicted with extreme drought hazard, whereas this event has been found completely absent in south-east Baran district of the state (Fig. 7a). These results can be attributed to rainfall irregularity, seasonal deficits, and long-term inter-annual variability influenced by shifting monsoonal patterns. The Aravalli Hills in Rajasthan act as a climatic barrier, diverting monsoon currents and causing rain shadow effects on the western side, leading to a higher probability of drought occurrences. Additionally, at monsoon season time scale, the drought hazard has been detected maximum in moderate category (51 per cent), followed by mild (21 per cent), and severe (15 per cent) (Fig. 7b). Interestingly, during this season, extreme drought conditions have been detected in Bikaner, Dholpur and Bharatpur districts which suggest the failure of seasonal rainfall, rather than the annual deficit. The failure of monsoon season rainfall plays a dominant role in shaping the short-term

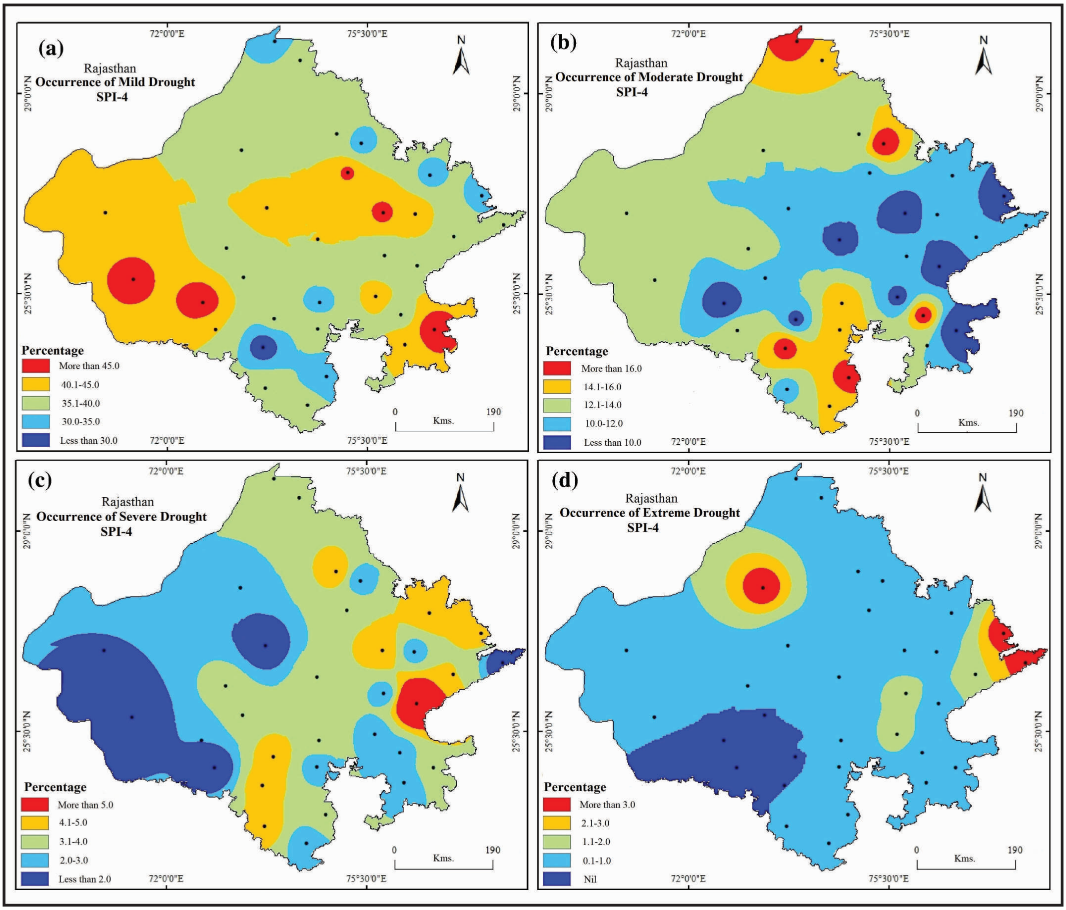
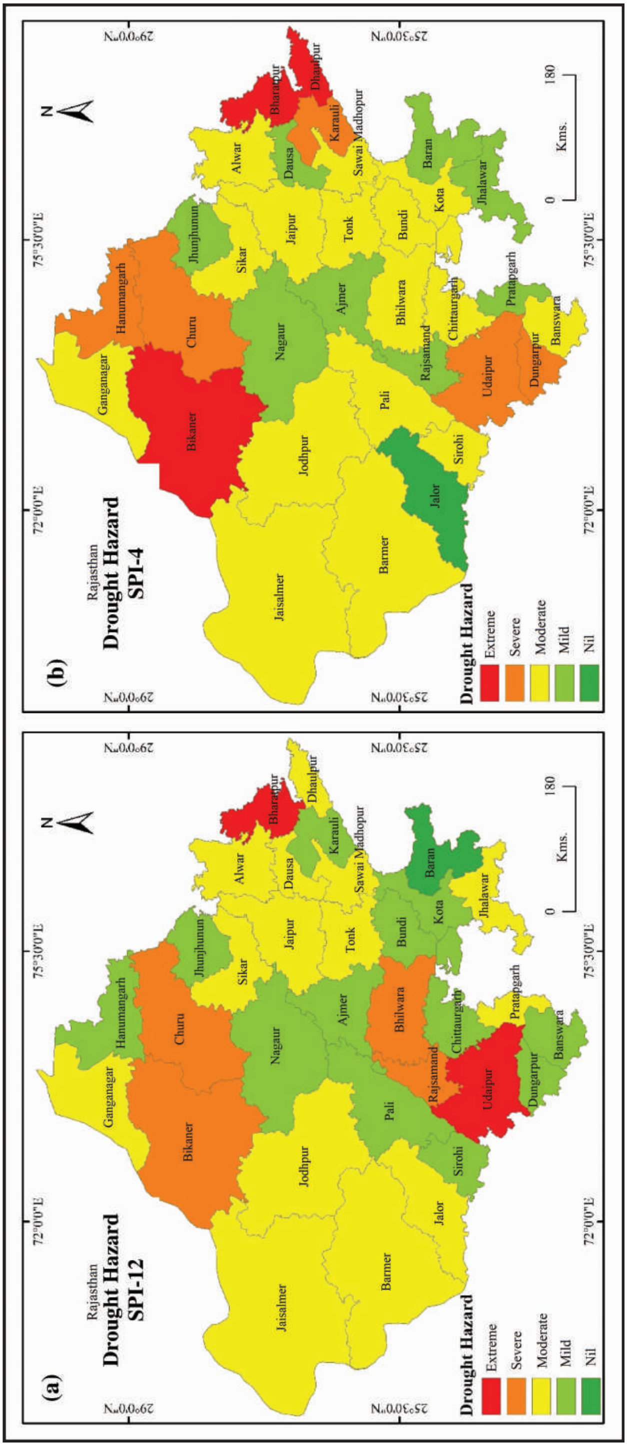


Fig. 6

agricultural stress in kharif crops (Jowar, Bajra, Cotton etc.) which directly translates to economic loss, food insecurity, and heightened livelihood vulnerability.

Drought Vulnerability Assessment

The drought vulnerability based on physical indicators, namely rainfall, temperature and evapotranspiration has been found to be the highest in the western and north-western parts, while the lowest has been detected in eastern and south-eastern parts of the state (Fig. 8a-c). The highest drought vulnerability in western and north-western parts can be ascribed to the existence of Aravalli Hills, which run parallel to the direction of South-West monsoon winds. These winds hit the eastern slopes of the Aravalli Hills, therefore, the south-eastern part receives enough rainfall, whereas the western and north-western parts remain dry, thus making these areas extremely vulnerable to drought. The remaining physical indicators, namely groundwater level, stages of groundwater development and elevation have been found to be the highest in the northern, north-eastern, north-western and south-western parts, whereas the lowest has been detected in small pockets over the northern and


(a)
Rajasthan
Drought Hazard
SPI-12
(b)
Rajasthan
Drought Hazard
SPI-4
Drought Hazard
Extreme
Severe
Moderate
Mild
Nil
72°0'0"E
75°30'0"E
29°0'0"N
25°30'0"N
0
180
Kms.
N
Ganganagar
Hanumangarh
Bikaner
Churu
Jhunjhunun
Sikar
Alwar
Bharatpur
Dhaulpur
Karauli
Dausa
Jaipur
Sawai Madhopur
Tonk
Jaisalmer
Jodhpur
Nagaur
Ajmer
Barmer
Jalor
Pali
Sirohi
Rajsamand
Bhilwara
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Baran
Jhalawar
Chittaurgarh
Pratapgarh
Udaipur
Dungarpur
Banswara

Fig. 7

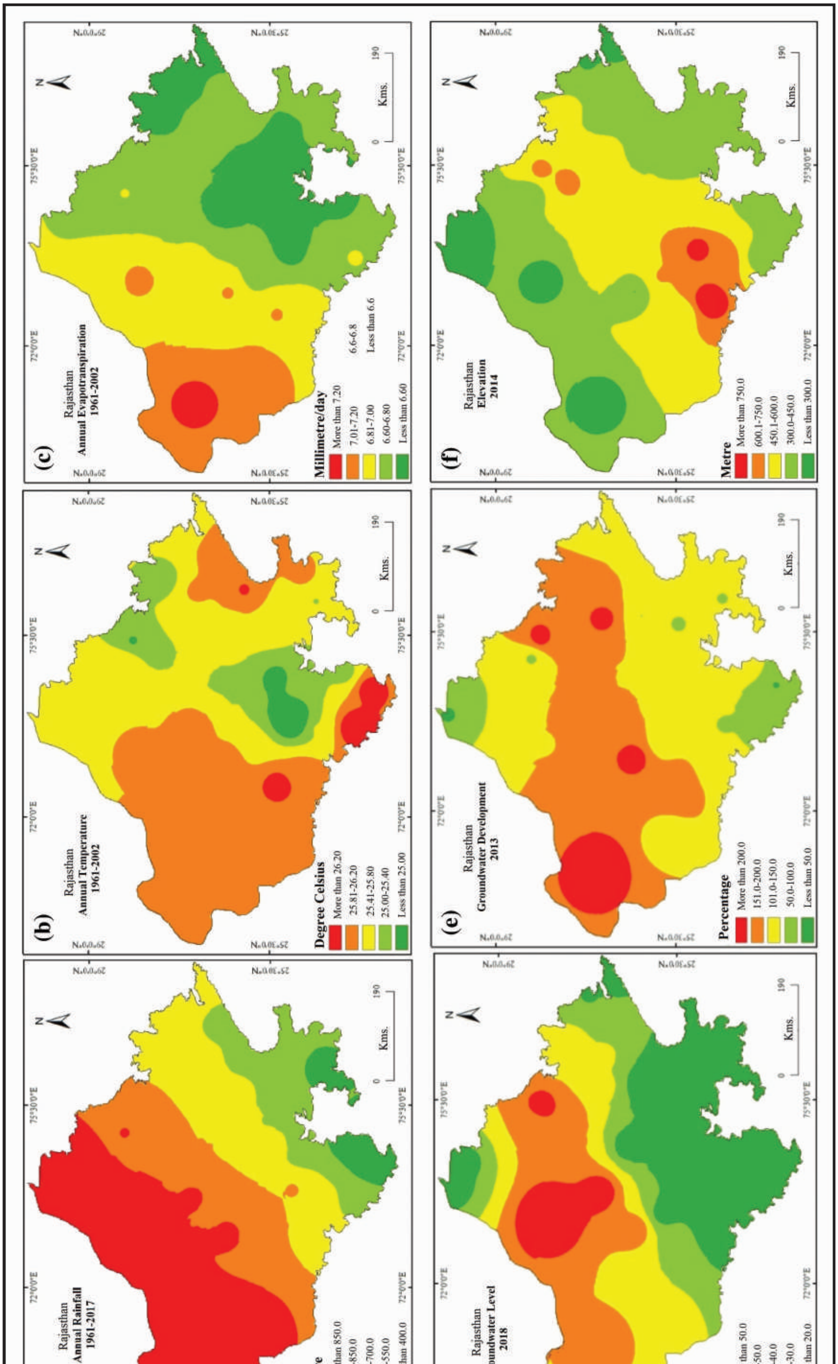
(a)
Rajasthan
Annual Rainfall
1961-2017
Millimetre
More than 850.0
700.1-850.0
550.1-700.0
400.0-550.0
Less than 400.0
(b)
Rajasthan
Annual Temperature
1961-2002
Degree Celsius
More than 26.20
25.81-26.20
25.41-25.80
25.00-25.40
Less than 25.00
(c)
Rajasthan
Annual Evapotranspiration
1961-2002
Millimetre/day
More than 7.20
7.01-7.20
6.81-7.00
6.60-6.80
Less than 6.60
6.6-6.8
Less than 6.6
(d)
Rajasthan
Groundwater Level
2018
Metre
More than 50.0
40.1-50.0
30.1-40.0
20.0-30.0
Less than 20.0
(e)
Rajasthan
Groundwater Development
2013
Percentage
More than 200.0
151.0-200.0
101.0-150.0
50.0-100.0
Less than 50.0
(f)
Rajasthan
Elevation
2014
Metre
More than 750.0
600.1-750.0
450.1-600.0
300.0-450.0
Less than 300.0
Kms.
0
190

Fig. 8

southern parts of the state (Fig. 8d-f). The high drought vulnerability in northern, north-eastern, north-western and south-western parts of the state is attributed to greater elevations, deep groundwater levels and over-exploitation of groundwater resources. These results have been found consistent with other studies in arid and semi-arid regions (Shahid and Behrawan, 2008; Pandey et al., 2012; Jain et al., 2015).

Further, the socio-economic drought vulnerability is directly or indirectly associated with the social, economic and livelihood conditions of the people. The socio-economic indicators, namely, population density and sex ratio have been found to be the highest (vulnerable) in the eastern, central, southern and western parts of the state due to higher density of population and more female to male ratio (Fig. 9a-b). The area under irrigation and deep tubewells has been found to be highly vulnerable in most of the eastern, northern and western parts of the state (Fig. 9c-d), whereas the agriculture dependent population has been found to be the highest vulnerable in northern and eastern parts of the state (Fig. 9e). Thus, moderate to extreme drought vulnerability in above stated parts of Rajasthan can be attributed to low rainfall, high evapotranspiration, deep groundwater tables and over-exploitation of aquifers. These areas rely heavily on tube wells for irrigation, which are unsustainable during repeated drought cycles. In contrast, eastern and southern districts, despite receiving more rainfall, show high drought vulnerability due to high population density, greater reliance on agriculture, and limited adaptive capacity. For instance, high sex ratio and a larger share of population engaged in farming suggest reduced coping mechanisms, making these communities more prone to adverse impacts of drought. This shows that drought vulnerability is not merely a function of climate but is also deeply rooted in socio-economic structures of the areas, reflecting inequalities in access to resources, infrastructure, and livelihood security. These findings of this study, are well in alignment with Mohmmed et al. (2017).

Drought vulnerability calculated by integrating physical and socio-economic indicators, clearly shows that most of the western, eastern, south-eastern and small pockets of south-western Rajasthan suffer from extreme to severe drought vulnerability (Fig. 10). Interestingly, 75 per cent area of Rajasthan has been found suffering from high drought vulnerability (extreme to moderate), while remaining areas have been found affected with nil to mild drought vulnerability. Besides, a high drought vulnerability has been detected in most of the north-western and north-eastern parts of the state due to high variability in rainfall, temperature, and evapotranspiration. These are the areas of Rajasthan, where most of the population is directly dependent on agriculture, hence drought vulnerability is very high.

Drought Risk Assessment

At annual scale, drought poses highest risk to north-western and north-eastern parts of the state (Fig. 11a). However, western and eastern parts of the state are exposed to moderate drought risk, while the areas facing less risk to drought are scattered all over the Rajasthan. Interestingly, the pattern of monsoon season drought risk is more or less analogous with annual drought risk (Fig. 11b). Like annual time scale, high risk zones of monsoon season drought are also concentrated in north-eastern and north-western parts of the state. Drought of monsoon season causes less

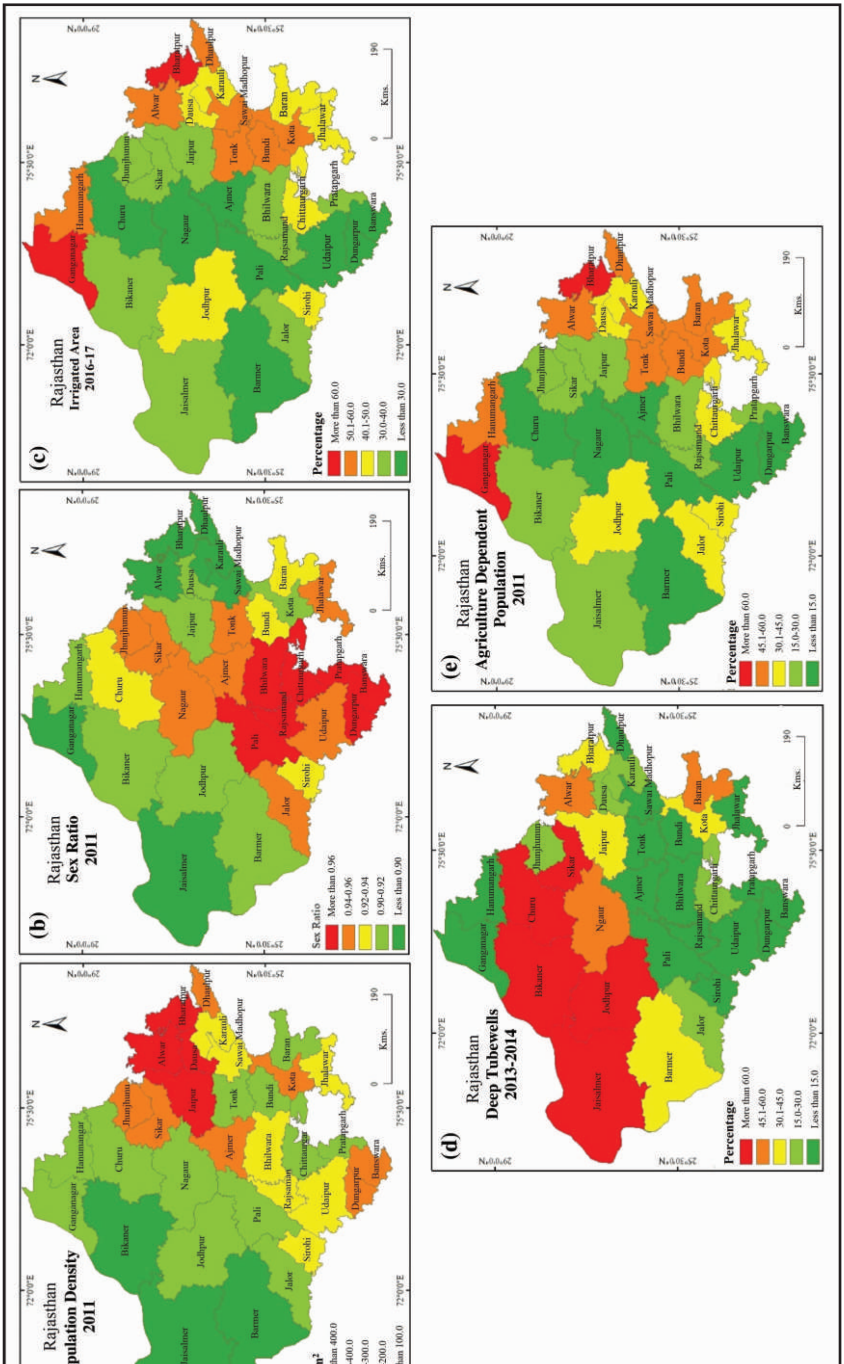
(a)
Rajasthan
Population Density
2011
Persons/km²
More than 400.0
300.1-400.0
200.1-300.0
100.0-200.0
Less than 100.0
(b)
Rajasthan
Sex Ratio
2011
Sex Ratio
More than 0.96
0.94-0.96
0.92-0.94
0.90-0.92
Less than 0.90
(c)
Rajasthan
Irrigated Area
2016-17
Percentage
More than 60.0
50.1-60.0
40.1-50.0
30.0-40.0
Less than 30.0
(d)
Rajasthan
Deep Tubewells
2013-2014
Percentage
More than 60.0
45.1-60.0
30.1-45.0
15.0-30.0
Less than 15.0
(e)
Rajasthan
Agriculture Dependent
Population
2011
Percentage
More than 60.0
45.1-60.0
30.1-45.0
15.0-30.0
Less than 15.0
Kms.

Fig. 9

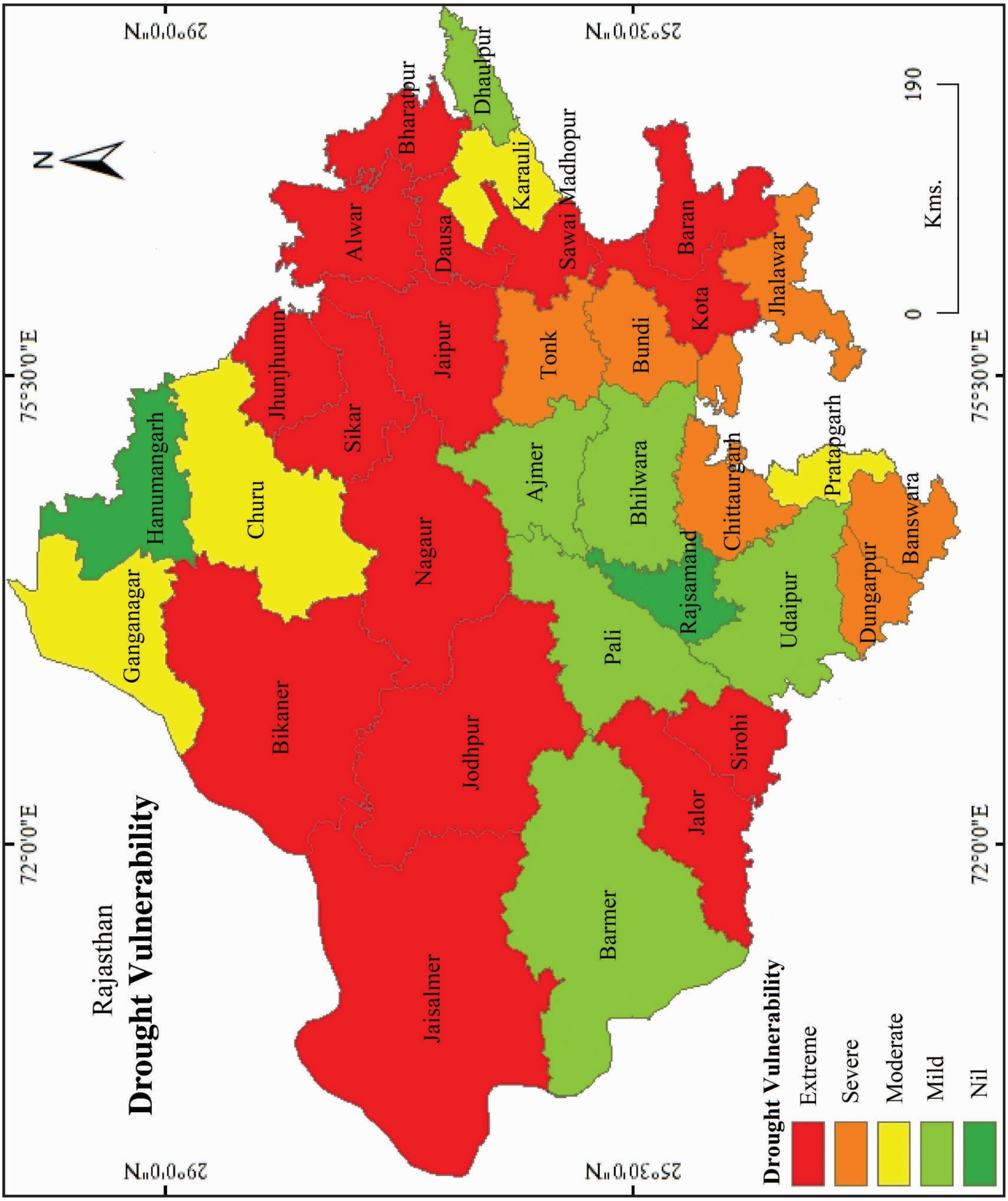
Rajasthan
Drought Vulnerability
N
Ganganagar
Hanumangarh
Churu
Jhunjhunun
Sikar
Alwar
Bharatpur
Dhaulpur
Karauli
Dausa
Jaipur
Sawai Madhopur
Bikaner
Nagaur
Jaisalmer
Jodhpur
Barmer
Ajmer
Tonk
Bundi
Baran
Kota
Jhalawar
Bhilwara
Chittaurgarh
Pratapgarh
Banswara
Dungarpur
Udaipur
Rajsamand
Pali
Sirohi
Jalor
Drought Vulnerability
Extreme
Severe
Moderate
Mild
Nil
0
190
Kms.
29°0'0"N
25°30'0"N
72°0'0"E
75°30'0"E

Fig. 10

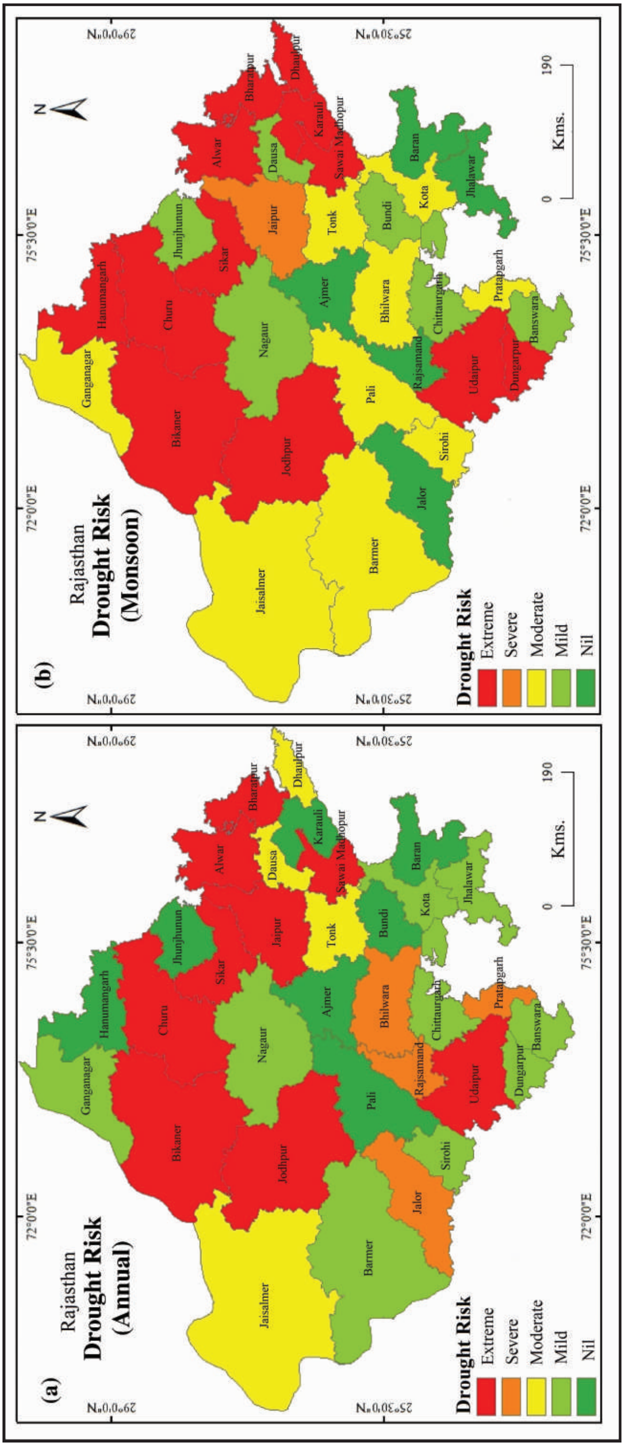
(a)
Rajasthan
Drought Risk
(Annual)
(b)
Rajasthan
Drought Risk
(Monsoon)
Drought Risk
Extreme
Severe
Moderate
Mild
Nil
Kms.
0
190
72°0'0"E
75°30'0"E
25°30'0"N
29°0'0"N
Ganganagar
Hanumangarh
Bikaner
Churu
Jhunjhunun
Sikar
Nagaur
Jaisalmer
Jodhpur
Barmer
Jalor
Sirohi
Pali
Ajmer
Jaipur
Alwar
Bharatpur
Dhaulpur
Karauli
Dausa
Sawai Madhopur
Tonk
Bundi
Kota
Baran
Jhalawar
Bhilwara
Rajsamand
Chittaurgarh
Udaipur
Pratapgarh
Dungarpur
Banswara

Fig. 11

Table 4
Rajasthan: Area under Different Drought Risk Classes at Annual and Monsoon Season Time Scales

Drought Risk Class	Area (per cent)	
	Annual	Monsoon
Extreme risk	27.50	33.40
Severe risk	12.10	03.00
Moderate risk	12.10	27.30
Mild risk	27.20	21.20
Nil risk	21.10	15.10

Source: Compiled by Authors.

risk to several central and south-eastern areas. Remarkably, moderately risky areas to drought have been found in most of the parts of Rajasthan. Further, areas (northern and eastern districts) with moderate drought hazard and high drought vulnerability face disproportionately high drought risk (Fig. 11). These results contradict the general assumptions that only low-rainfall areas are at higher drought risk. Interestingly, this study reveals that drought risk is more pronounced in those areas (eastern part) where a higher average annual rainfall is received vis-à-vis to low rainfall areas (western part) of the state. These results are not a manifestation of precipitation and temperature only, but also rely on several other parameters such as surface water, soil moisture, streamflow, groundwater, crop stress, vegetation condition and land use/land cover of a region, which are in tune with (Shahid and Behrawan, 2008; Mohmmed et al., 2017; Amin et al., 2020; Durowoju et al., 2022). For example, eastern districts with intensive agriculture, high groundwater dependency, and limited economic diversification demonstrate how drought hazard and drought vulnerability magnify the drought risk, even in the areas receiving relatively higher amount of rainfall. Furthermore, at annual time scale, 28 per cent area of the state is exposed to extreme drought risk, followed by mild (27 per cent), and no drought risk (21 per cent) (Table 4). Conversely, 33 per cent area is exposed to extreme drought risk, followed by moderate (27 per cent), and mild (21 per cent) at monsoon season time scale.

Conclusions

This study has assessed the drought hazard, drought vulnerability and drought risk at annual and monsoon season time scales over Rajasthan, India. The drought hazard has been assessed by applying SPI, whereas drought vulnerability has been identified by using various physical and socio-economic indicators. Likewise, drought risk has been assessed by integrating both the drought hazard and drought vulnerability. The drought hazard has been found maximum in moderate category (42 and 51 per cent), followed by mild (36 and 21 per cent), and severe (12 and 15 per cent) at both time scales (annual and monsoon), respectively. Spatially, drought hazard has been detected maximum in northern, eastern and southern parts, while the lowest has been witnessed in south-eastern and central parts of the state. Drought vulnerability assessment reveals that most of the western, eastern, south-eastern and few pockets of south-western Rajasthan suffers from extreme to severe drought vulnerability. Interestingly, 75 per cent area of Rajasthan has been found suffering from high drought vulnerability (extreme to moderate), while the remaining parts have low to mild drought vulnerability. Drought poses highest risk to north-western and north-eastern parts of the state. These results are opposite to the general perception that the western part of Rajasthan is highly susceptible to drought. Annually, 28 per cent area of Rajasthan is exposed to extreme drought, followed by mild (27 per cent), and nil risk (21 per cent). Conversely, 33 per cent area is vulnerable to extreme drought risk, followed by moderate (27 per cent), and mild (21 per cent) at monsoon season time scale.

This study is entirely based on secondary data sources, and the selected indicators datasets that have been available only at the district level, which have limited spatial precision. These limitations can be addressed by incorporating higher-resolution datasets, remote sensing-based indicators, and advanced modeling techniques such as machine learning or dynamic risk modeling. However, the methodology adopted in this study for drought risk assessment can be extended and validated in other drought-prone regions of India to take it as a decision-making tool for formulating drought mitigation policies.

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Divya Saini, Research Scholar,

Dr. Omvir Singh, Professor,
Email: ovshome@yahoo.com
(Author for Correspondence)
Department of Geography,
Kurukshetra University,
Kurukshetra (Haryana).

punjab
geographer