

Drought indicators-based integrated assessment of drought vulnerability: a case study of Bundelkhand droughts in central India

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Abstract Decision makers face multifaceted challenge in characterizing drought climatology for appropriate water resources-related drought management strategies. This paper focuses on understanding and quantifying the drought vulnerability of Bearma basin in the Bundelkhand region of central India, which is one of the prominent climate extremes that the region is affected by frequently. Regular drought conditions have been prevailing in the region in the last decade with continuous drought from 2004 to 2007. An integrated approach using multiple indicators has been developed to spatially identify the vulnerable regions. The Bearma basin has been selected as a pilot basin to develop a methodology for integrated drought vulnerability assessment adopting spatially and temporally varying drought characteristics represented by drought indicators. The temporally varying indicators include standardized precipitation index (SPI), surface water drought index and groundwater drought index. The spatial information of the indicators was categorized in layers prepared in the spatial domain using a geographic information system, and integrated values of weights of various indicators have been computed on a 50 × 50 m grid scale. The SPI has been applied to quantify monthly precipitation deficit anomalies on multiple time scales (1, 3, 6 and 12 months). The drought characteristics including frequency, duration and intensity and magnitude have been calculated with the estimated SPI. The multiple indicator approach has been used for arriving at the drought vulnerable zones. The highly vulnerable areas are located in the southern and northern regions of the Bearma basin. It has been observed that more than 26 % of the basin lies in the highly and critically

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vulnerable classes and consequently has greater drought-related negative impacts. Results show that the proposed method is highly effective in representing assessments of drought vulnerability.

Keywords Drought analysis · Drought vulnerability · Standardized precipitation index · Surface water drought index · Groundwater drought index

1 Introduction

The growing interest in the development of methodologies for analysis and policies for adaptation in the context of climate change is making the drought vulnerability assessment a very active area of research. The Intergovernmental Panel on Climate Change (IPCC 2001) assessments warn of potential increases in the vulnerability and impacts of extreme drought conditions and extreme heat events (Bernstein et al. 2007). Drought, an unavoidable part of Earth's climate, commonly develops with no clear warning and without identifiable borders and leads to agriculture losses of billions of dollars annually (Kogan 2000). Drought affects virtually all climatic regions (Wilhite 2000), and more than one-half of the earth is susceptible to drought each year (Kogan 1997). Hewitt (1997) reported that, throughout the world, drought ranks first among the natural disasters in numbers of persons directly affected. Droughts occur in both high and low rainfall areas, and virtually all climate regimes and its impacts are critical and costly affecting more people than any other type of natural disaster universally (Keyantash and Dracup 2002). The impacts of droughts vary depending on the state of development and coping capabilities of regions and countries in a manner that it affects the livelihoods and economy of the developing countries, whereas in developed countries commerce and trade of private and public enterprises are affected. In India, apart from the other major disasters including floods and cyclones, droughts are considered to be impact the Indian economy as some or the other region suffers from regular droughts.

Globally, droughts are the second most geographically extensive hazard after floods. The percentage of Earth's land area stricken by serious drought more than doubled from the 1970s to the early 2000s, according to a new analysis by National Centre for Atmospheric Research (NCAR). Dai et al. (2004) found that the fraction of global land experiencing very dry conditions (defined as -3 or less on the Palmer Drought Severity Index) rose from about 10–15 percent in the early 1970s to about 30 percent by 2002. The high economic costs and social vulnerability issues related to drought have led to increasing attention to drought vulnerability (Wilhite 1993, 2000; Keenan and Krannich 1997; Downing and Bakker 2000). Drought vulnerability depends on the reliability of the water resources system and its ability to respond effectively and may increase as population expands, various water demands increase and competing demand on water resources intensify.

The assessment of drought vulnerability is a new paradigm in disaster management which benefits the decision makers to prepare for droughts, allocate resources and reduce impacts. The abundant literature on vulnerability and adaptation contains many terms viz., vulnerability, sensitivity, resilience, adaptation, adaptive capacity, risk, hazard, coping range, adaptation baseline and so on (IPCC 2001; Adger et al. 2002; Burton et al. 2002). The drought vulnerability of a region basically depends on the degree of exposure to

drought and the regions' impact coping abilities, and underdeveloped regions with lower coping abilities and higher exposure are subject to highest risk. Vulnerability has dimensions of time and space as it changes constantly due to changes in technology, population behavior, practices and policies (Downing and Bakker 2000; Wilhite 2000).

The vulnerability is manifest in specific places at specific times which indicate that it is context specific, place specific, time specific and specific to the perspective of those assessing it (Adger 2006). The context-specific nature of vulnerability means that there can be no single, unified or general approach to conceptualizing it. Ionescu et al. (2005) suggested that vulnerability should ideally be conceptualized to comprise of three primitives viz., (1) the entity that is vulnerable, (2) the stimulus to which it is vulnerable and (3) the preference criteria to evaluate the outcome of the interaction between the entity and the stimulus.

Several studies on vulnerability assessment have been carried out in various disciplines including geography, agricultural science, water resources, climate research and social science sectors (Baethgen 1997; Eakin and Conley 2002; Wilhelmi and Wilhite 2002; Descroix et al. 2003). Some analysts have conceptualized the nature of vulnerability from various theoretical perspectives (Cutter 1996; Villa and McLeod 2002; Turner et al. 2003), while others have attempted to develop some quantitative measures of vulnerability (Gogu and Dassargues 2000; Cutter et al. 2003). Because of the complexity of the systems under analysis and the fact that vulnerability is not a directly observable phenomenon, it has been proved difficult to develop measures for quantifying vulnerability (Downing et al. 2001a, b; Luers et al. 2003). However, a detailed vulnerability assessment is essential as it can assist in developing targeted drought mitigation and response strategies.

Wilhelmi et al. (2002) developed a numerical weighting scheme to evaluate the agricultural drought potential and concluded that the most vulnerable areas to agricultural drought were non-irrigated cropland and range land on sandy soils. Lilibeth et al. (2006) used the security diagram concept for measuring the vulnerability to drought in India under climatic stress, wherein environmental stress was derived using indicators of water stress generated from the WaterGap model. The World Meteorological Organization (WMO) recommended the use of the standardized precipitation index (SPI) (McKee et al. 1993) as the global standard hazard index to measure droughts via the 'Lincoln Declaration on Drought Indices' (Hayes et al. 2010) which has been used by several researchers as a drought vulnerability assessment indicator. Dougil et al. (2010) applied dynamic system modeling tools to investigate food system vulnerability to both climate change and land degradation, with a focus on drought sensitivity in the pastoral Kalahari region of Botswana. An overview of the vulnerability to climate change in coupled social ecological systems was provided by Fraser et al. (2011).

Zarafshani et al. (2012) assessed the drought vulnerability across three drought intensities viz., very high, extremely high and critical areas for the wheat farmers in Western Iran and concluded that the farmer's vulnerability is influenced mainly by economic, sociocultural, psychological, technical and infrastructural factors. Khoshnodifar et al. (2012) identified and measured the drought vulnerability indicators including economic, social and technical indicators among the wheat farmers in Mashhad County, Iran. Me-Bar and Valdes formula was applied to measure the drought vulnerability, and they concluded that results of this study may have implications for reconsidering priority of government supporting credits allocation and planning for agricultural extension-education programs. Babaei et al. (2013) developed a new highly effective method for spatial assessment of drought vulnerability for Zayandeh-Rood river basin in Iran using multi-attribute decision-making methods (MADM) based on a set of preferences, criteria and multiple indicators.

Naumann et al. (2014) conducted an indicator-based analysis for exploring drought vulnerability in Africa for early warning systems and developed a drought vulnerability indicator (DVI) that reflects different aspects of drought vulnerability evaluated at Pan-African level based on renewable natural capital, the economic capacity, the human and civic resources, and infrastructure and technology.

This major objective of the paper is to develop a novel approach to measuring the vulnerability to drought particularly for the temporally varying factors that are responsible for the vulnerability of a region during drought. The analysis focuses on understanding and quantifying the drought vulnerability of Bearma basin in the Bundelkhand region of central

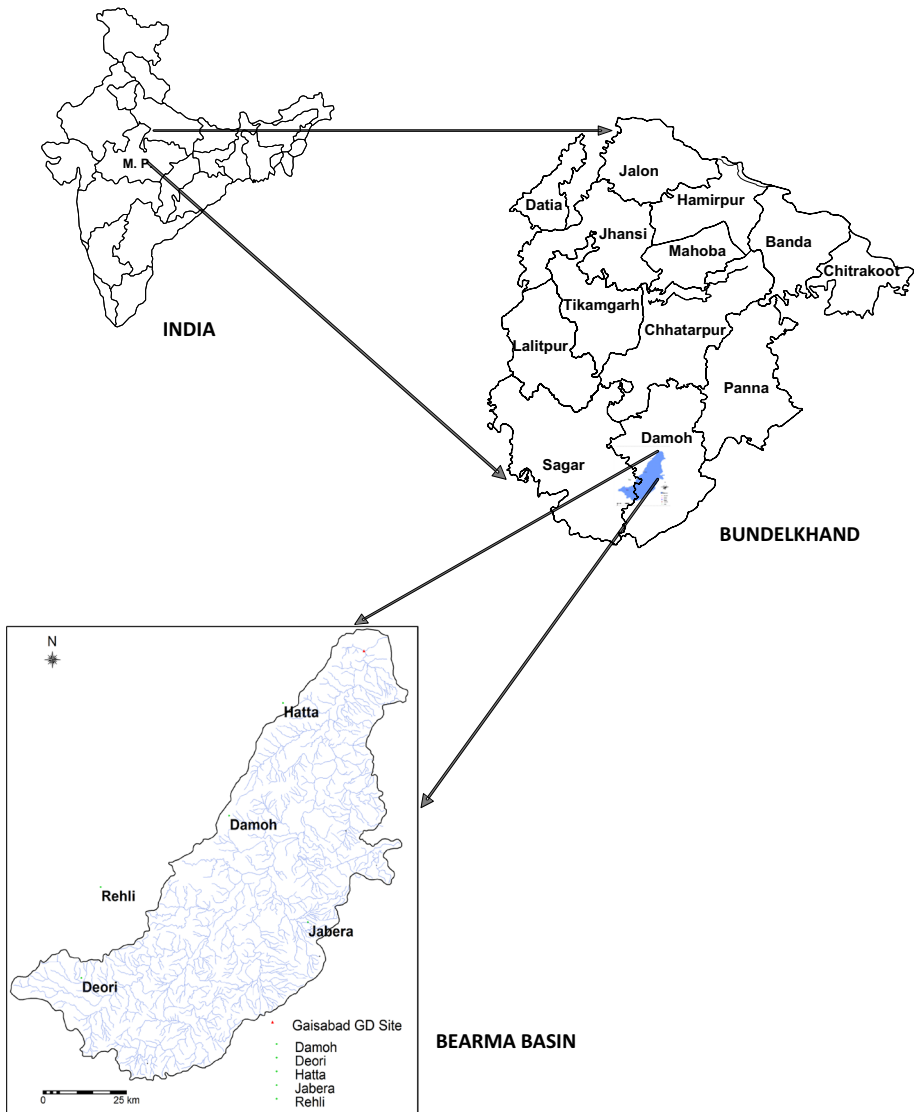


Fig. 1 Index map of Bearma basin in Bundelkhand region of central India

India, which is one of the prominent climate extremes that the region is affected by frequently. This paper is organized as follows: After the introduction, a brief overview of the study area and data are discussed. The deficit water scenario pertaining to soil moisture, surface water and ground water are presented in the subsequent section on the basis on the drought indices, namely SPI, SDI and GDI, considering its spatial and temporal variations. The interrelationships developed between these indices are discussed and presented in analysis, results and discussion section.

2 Study area details

The river Bearma is one of the important tributaries of Ken river system located between 23°07' and 24°18' N latitudes and 78°54' and 80°00 E longitudes, and parts of Sagar, Damoh, and Panna districts of Madhya Pradesh (M.P.) state in India are drained by it. Ken river is one of the major tributaries of River Yamuna joining from its south river-bank. Bearma basin is a leaf-shaped elongated basin with a catchment area of 5890 km² up to Gaisabad gauge-discharge site. Some of the important tributaries of river Bearma are Lamti, Sun, Bamner, Guraiya, Godhar and Mala. The index map showing the Bearma River system up to Gaisabad is given in Fig. 1. The upper reaches of the basin lie in a very undulating plateau, with steeply sloping hills at few places. As per the reports of the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), about 40 % of the area is comprised of undulating plateau.

The Bearma basin belongs to dry sub-humid climate with a single rainy season (June–September) followed by dry winter and a dry summer. During winter season, the nights are cool, but the day temperature is comfortable. The average maximum and minimum temperature varies from 41.5° C in May and 11.5° C in January, respectively. Rainfall occurs mostly due to the southwest monsoon (June–September) with very few winter showers in the region. The mean annual rainfall in the basin is 1186.9 mm. The rainfall over the basin is unevenly distributed and highly variable with very high coefficient of variation ranging between 25 and 31 %. The five rain gauge stations viz., Deori, Rehli, Damoh, Jaber and Hatta influence rainfall in the basin.

The geological formation comprises of Vindhyan system, Lameta beds, Deccan traps and alluvial soils. Soils found on hill and ridges are fine loamy to coarse loamy in texture and grayish brown to dark reddish brown in color with shallow depth and low nutrient status. These soils are highly erodible, excessively drained, with low organic matter content and have poor water retentive capacity. Yellowish brown to dark brown soils are found in plain to gently undulating terrains. Soils of flood plains comprise of well to moderately well-drained, deep, fine loamy soils.

The Bearma basin is covered to a large extent by forests shrubs and grasslands. About 36 % of the geographic area is covered by forests, 37 % area comprises of agricultural land, 5 % is barren, and the remaining area is under permanent pastures, miscellaneous crops and wastelands. The predominant crops grown in the basin are soyabean, wheat, paddy, jowar, arhar, groundnut, oil seeds, pulses and grams. Mostly rainfed agriculture is practiced in the catchment, resulting in poor agricultural yields. About 3 % of the total area is irrigated by surface water and 2 % by ground water. Soyabean is the predominant crop during kharif season, whereas wheat is the major crop grown during the Rabi season. Perennial and summer crops are rarely grown. In a major portion of the basin, single crop is practiced due to poor groundwater availability and lack of irrigation facilities.

3 Methodology

In the current investigation, the methodology adopted to classify the drought vulnerable zones considers both the spatially varying and temporally varying factors, identified using the various drought indicators and their interrelationships. The spatial indicators include user water demand, topographic characteristics including the river basin reaches and watershed slope, land use, and soil-type information. The temporal indicators include rainfall departure from normal, groundwater drought index (GDI), soil moisture availability, and surface water availability and their relationship. Prior to identification of vulnerable zone, different tests have been carried out. Initially, statistical analysis of rainfall and runoff data has been adopted. Standardized precipitation index (SPI), surface water drought index (SDI) and ground water drought index (GDI) are used as drought indices, and their relationships are developed. The details of methodology adopted for different analysis are discussed in the next section.

4 Analysis, results and discussion

4.1 Statistical analysis of rainfall data

The annual and seasonal rainfall records of five influencing stations in and around the basin, viz., Damoh, Hatta, Jabera, Rehli and Deori, have been analyzed. The data have been checked for inconsistencies. The mean annual rainfall varies between 1034.4 mm at Hatta to 1260.1 mm at Damoh with the coefficient of variation (C_v) ranging between 24.6 % at Deori and 30.7 % at Rehli with the average value of C_v for the basin being 28 %. The high variability of the annual rainfall is also one of the primary causes of the drought prevailing in the basin on a regular basis.

The average rainfall for the basin has been computed using the Thiessen Polygon method in ILWIS 3.6, a geographic information system (GIS) software. In order to derive the basin average rainfall, initially a base map showing the basin boundary as well as a map showing the location of the rain gauge stations has been prepared. Subsequently, the nearest point algorithm has been used for interpolation and the requisite polygons obtained, after which the resultant map has been crossed with the base map to obtain the Thiessen

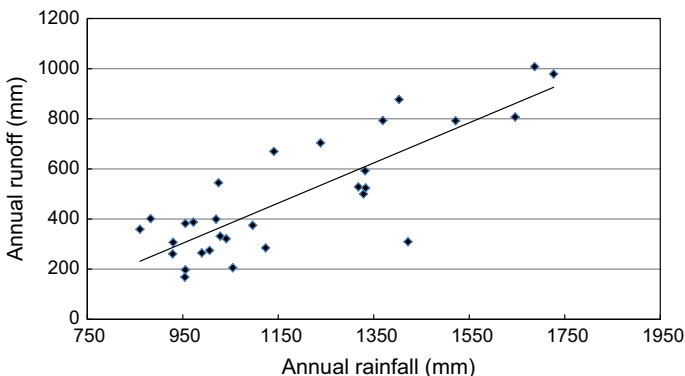


Fig. 2 Rainfall–runoff relationship in Bearma basin

Polygon map of Bearma basin. The corresponding histogram depicting the area under influence of the influencing rain gauge stations has been used to compute the Thiessen weights. The average basin rainfall has been computed using these Thiessen weights. The Thiessen weights for the Bearma basin are Damoh (0.17), Hatta (0.20), Jabera (0.33), Deori (0.26) and Rehli (0.04).

4.2 Analysis of discharge data

The discharge data at the Gaisabad gauging site from 1976–1977 to 2008–2009 were processed to check for errors and inconsistencies. A rainfall–runoff relation was developed between the annual rainfall and annual runoff. The annual runoff coefficient for the basin varied from 0.28 to 0.50. The scatter plot depicting the rainfall–runoff relationship in the basin is given in Fig. 2.

4.3 Departure analysis-based drought characteristics

The departure analysis of the annual rainfall indicated that the maximum annual rainfall deficiency during drought years varied from −40.4 % at Deori during 1992–1993 to −62.8 % at Damoh during 1979–1980. An area/region is considered to be drought affected if it receives seasonal rainfall less than 75 % of its normal value as per the classification of India Meteorological Department (Appa Rao 1986). The annual rainfall departure was computed as the deviation of the rainfall from the mean divided by the mean rainfall for the station. The year having annual/seasonal rainfall deficiency more than or equal to 25 % is considered as a drought year/season. In this study, the drought severity has been classified on the basis of percentage deviations from the normal rainfall into three severity classes viz., mild drought for annual rainfall departures between −20 and −25 %; moderate drought for annual rainfall departure between −25 and −50 %; and departure greater than −50 % that is considered as a severe drought. The departure analysis of annual rainfall has been performed for all the five influencing rain gauges falling in Sagar and Damoh districts, and subsequently the drought years have been identified. A summary of annual departure analysis is presented in Table 1.

Based on the departure analysis, the average drought frequency is once in every 3–4 years in Bearma basin. The highest annual rainfall deviation of −62 % was recorded in Damoh district in 1979 with the other blocks of the district also facing annual rainfall deficits of more than 55 % which is indicative of the severe drought conditions. However, Rehli and Deori blocks in Sagar district faced comparatively lesser annual rainfall departures of −42 and −40 %, respectively. The plots of annual rainfall departure for

Table 1 Summary of annual rainfall departure analysis

S. no.	Name of station	No. of years of data for analysis	No. of drought years	Avg. drought return period (year)	Maximum recorded annual deficit (%)
1.	Damoh	53 (1956–1957 to 2008–2009)	12	4	−62 (1979)
2.	Hatta	47 (1962–1963 to 2008–2009)	14	3	−58 (1979)
3.	Jabera	43 (1966–1967 to 2008–2009)	11	4	−56 (1979)
4.	Rehli	33 (1976–1977 to 2008–2009)	11	3	−42 (2007)
5.	Deori	33 (1976–1977 to 2008–2009)	12	3	−40 (1992)

Deori rain gauge station are shown in Fig. 3. The deficit southwest monsoon is primarily responsible for the regular occurrence of drought and subsequent water stress in the study area, thereby adversely affecting the major agricultural operations.

4.4 Probability distribution of annual rainfall

The probability analysis of annual rainfall is important to predict the relative frequency of occurrence of annual rainfall. The probability distribution of annual rainfall has been calculated using Weibull's plotting position formula, and plots between the probability of exceedance and the corresponding annual rainfall were prepared as given in Fig. 4. From this plot, the probability corresponding to various rainfall amounts can be estimated. The 75 % dependable annual rainfall and the probability of occurrence for annual rainfall equivalent to 75 % of normal rainfall have been estimated and are given in Table 2. The overall variation of annual rainfall at 75 % dependability level ranges between from 797.1 mm to 1026.3 mm. The probability of occurrence of 75 % of normal rainfall varies between 75 % at Rehli to 86 % at Damoh. This is indicative of the fact that areas of the basin influenced by Hatta, Rehli and Deori are drought prone (Probability <80 %) and facing regular water scarcity and droughts as compared to Damoh and Jibera which are not prone to droughts.

4.5 Standardized precipitation index (SPI)-based assessment of drought severity

The standardized precipitation index (SPI) developed by McKee et al. (1993, 1995) is a widely used index for assessing drought severity, and it has the advantages of statistical consistency. Keyantash and Dracup (2002) established the strength of SPI in drought analysis based on six weighted evaluation performance criteria viz., robustness, tractability, transparency, sophistication, extendibility and dimensionality. SPI can be computed for different time scales at which the drought occurs and can therefore be used to compare drought conditions among different time periods and regions with different climatic conditions (Thomas et al. 2015a). Basically, SPI represents the number of standard deviations that the observed value deviates from the long-term mean for a normally distributed random variable, but as precipitation is not normally distributed, a transformation is first applied to the precipitation time series, so that the transformed precipitation values follow a normal distribution.

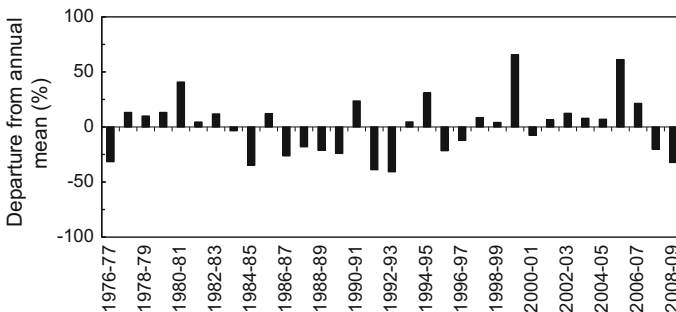


Fig. 3 Plot of annual rainfall departure at Deori

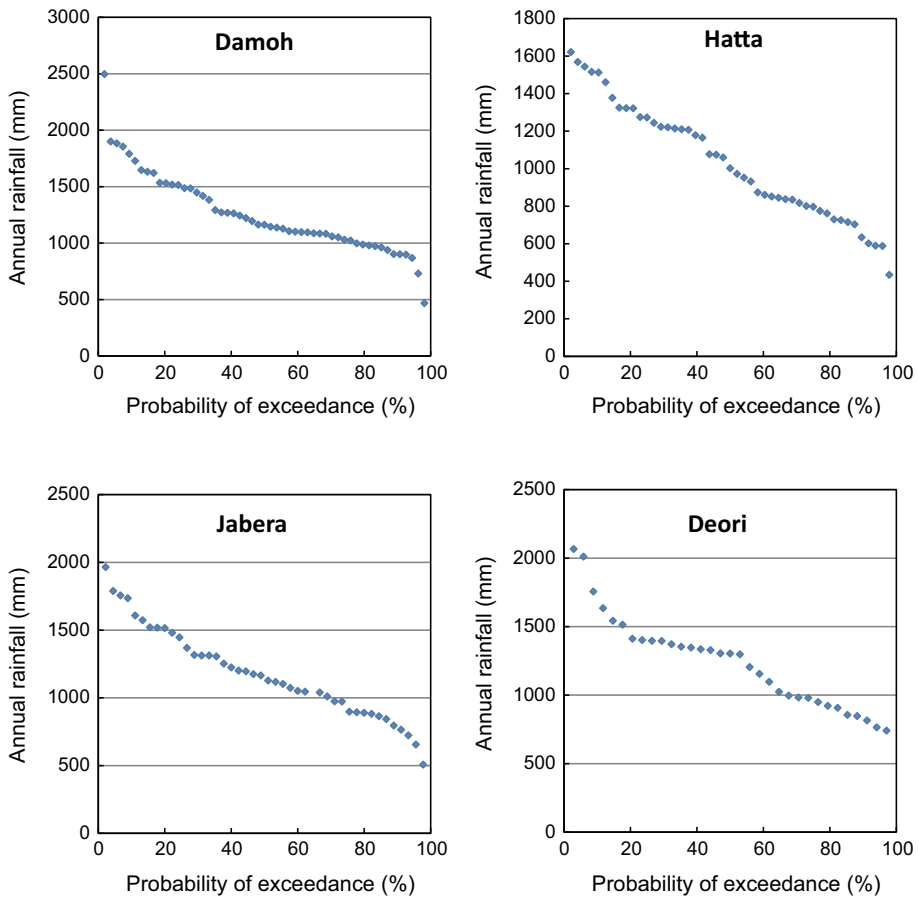


Fig. 4 Probability distribution plots of annual rainfall at few rain gauge stations in Bearma basin

Table 2 Probability distribution of annual rainfall

S. no.	Station name	Mean rainfall (mm)	75 % dependable annual rainfall (mm)	Probability of occurrence of rainfall equivalent to 75 % of mean rainfall
1.	Damoh	1260.1	1026.3	86 % (945)
2.	Hatta	1034.4	797.1	79 % (776)
3.	Jabera	1184.9	916.0	84 % (889)
4.	Rehli	1179.8	884.2	75 % (885)
5.	Deori	1242.6	964.2	78 % (932)

The SPI is computed by fitting a gamma probability density function to the frequency distribution of precipitation and is a statistical z-score or the number of standard deviation above or below that an event as demarcated with reference to means (Edward and McKee, 1997). The SPI allocates a single numeric value varying between -3 and $+3$ to the

precipitation, which can be compared across different climatic regions. The SPI allows determining the occurrence probability of dry or wet events at different time scales varying from 3 to 24 months, and monthly rainfall data for a minimum of 30 years are required for the analysis (Hayes et al. 2010). A drought event occurs during the period when the SPI is continuously negative with an intensity of -1.0 or less. The severity classes of the drought have been analyzed based on the values of SPI as given in Table 3 (Hayes et al. 2010).

The SPI has been applied to quantify monthly precipitation deficit anomalies on multiple time scales (1, 3, 6 and 12 months). The drought characteristics including frequency, duration and intensity and magnitude have been calculated with the estimated SPI for the various time scales which are considered to represent the various types of droughts viz., meteorological, agricultural and hydrological droughts (Thomas et al. 2015b). The temporal variation of the 3-m SPI and 6-m SPI at Rehli is depicted in Fig. 5. It can be observed that the drought characteristics including the onset of drought, its duration as well as its severity can be easily identified from these graphs. Based on the 3-m SPI (Fig. 5), five major drought events have been observed during 1984–1985, 1991–1992, 1996–1997, 2000–2003 and 2007–2009. The influence of the time scales on the drought characteristics is also clearly visible on comparison of Fig. 5. The drought duration as well as the drought severity increases, whereas the drought frequency decreases with the increase in time scale.

A number of drought events faced at all the five rain gauge stations have been analyzed; it is observed that four extreme drought events occurred at Rehli, Deori and Damoh, whereas five extreme drought events occurred at Hatta and Jabera during the period of 1979–2010. The maximum 11 severe drought events occurred at Deori, whereas the maximum number of moderate events occurred at Rehli, both in Sagar district. However, the total number of drought events has been fairly uniformly distributed in the basin varying between 23 events at Damoh to 29 events at Rehli.

4.6 Drought vulnerability assessment

Drought has considerable impacts on water availability, agriculture, social as well as economic activities depending on the various physiographic, environmental and social factors, and therefore the vulnerability depends on water demands for domestic, industrial and agriculture activities, topographic features, soil type, land use/land cover, availability and utilization of ground water and the extent of water resources development in the region (Pandey et al. 2010). A suitable method for assessment of vulnerability to drought has been devised for the spatial depiction of vulnerability to drought in Bearma basin. The multiple indicator approach has been used for arriving at the drought vulnerable zones. The integrated drought vulnerability assessment is based on various spatial and temporal factors using ILWIS.

Table 3 3-m SPI-based drought events in Bearma basin

S. no.	Drought class	Rehli	Deori	Damoh	Hatta	Jabera
1.	Extreme	4	4	4	5	5
2.	Severe	3	11	6	4	3
3.	Moderate	22	13	13	18	15
4.	Total	29	28	23	27	23

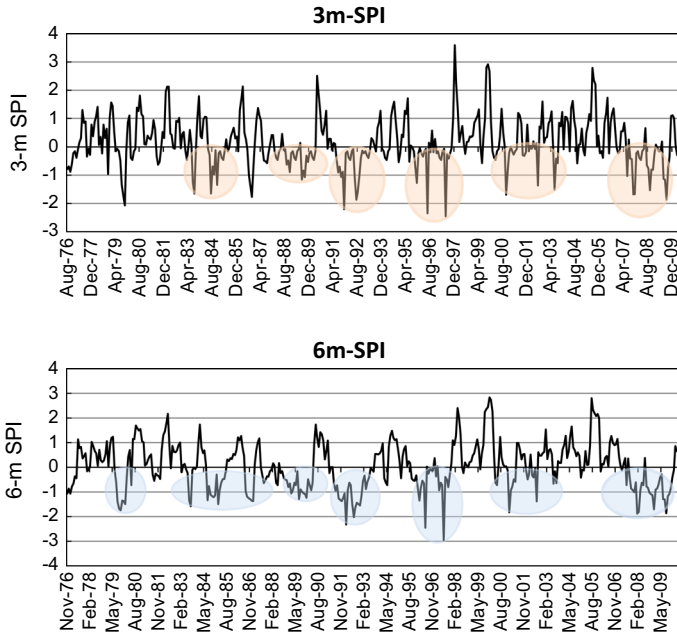


Fig. 5 Temporal variation of 3-m SPI and 6-m SPI at Rehli

The spatial indicators which do not vary with each drought event include water demands, topographic characteristics (river basin reaches and basin slope), land use, and soil-type information. The temporal indicators, which vary during every drought event, include rainfall departures, groundwater availability represented by groundwater drought index (GDI), soil moisture availability represented by 3-m SPI, and surface water availability represented by 6-m SPI (based on developed relationships). The spatial maps representing these indicators have been prepared on a grid system of 50 m × 50 m. Spatial information of the above maps has been categorized into different classes with respect to their degree of significance to drought vulnerability. The temporal indicators were also categorized into different classes in the spatial and temporal domain on a similar grid system.

4.7 Spatially varying indicators of drought vulnerability

4.7.1 Basin reach

The basin has been demarcated into three topographic elevation zones based on the digital elevation model (DEM) viz., upper reach, middle reach and lower reach depending on flow characteristics in stream sections. Even though the flow originates in the upper region, more and more regions contribute toward the flow in the river from the middle and lower reaches. Therefore upper reaches of basin have been considered more vulnerable than the middle and lower reaches. Moreover the lower reaches of stream often get more base flow as compared to the upper reaches. The areas with elevations less than 350 m have been considered to fall in the lower reach; 350–450 m in the middle reach; and >450 m in the

upper reach. The map showing the various river basin reaches in the Bearma basin is given as Fig. 6.

4.8 Land use pattern

Since the water demand varies considerably based on the predominant land use in a region, the land use is one of the important spatially varying indicators for assessment of drought

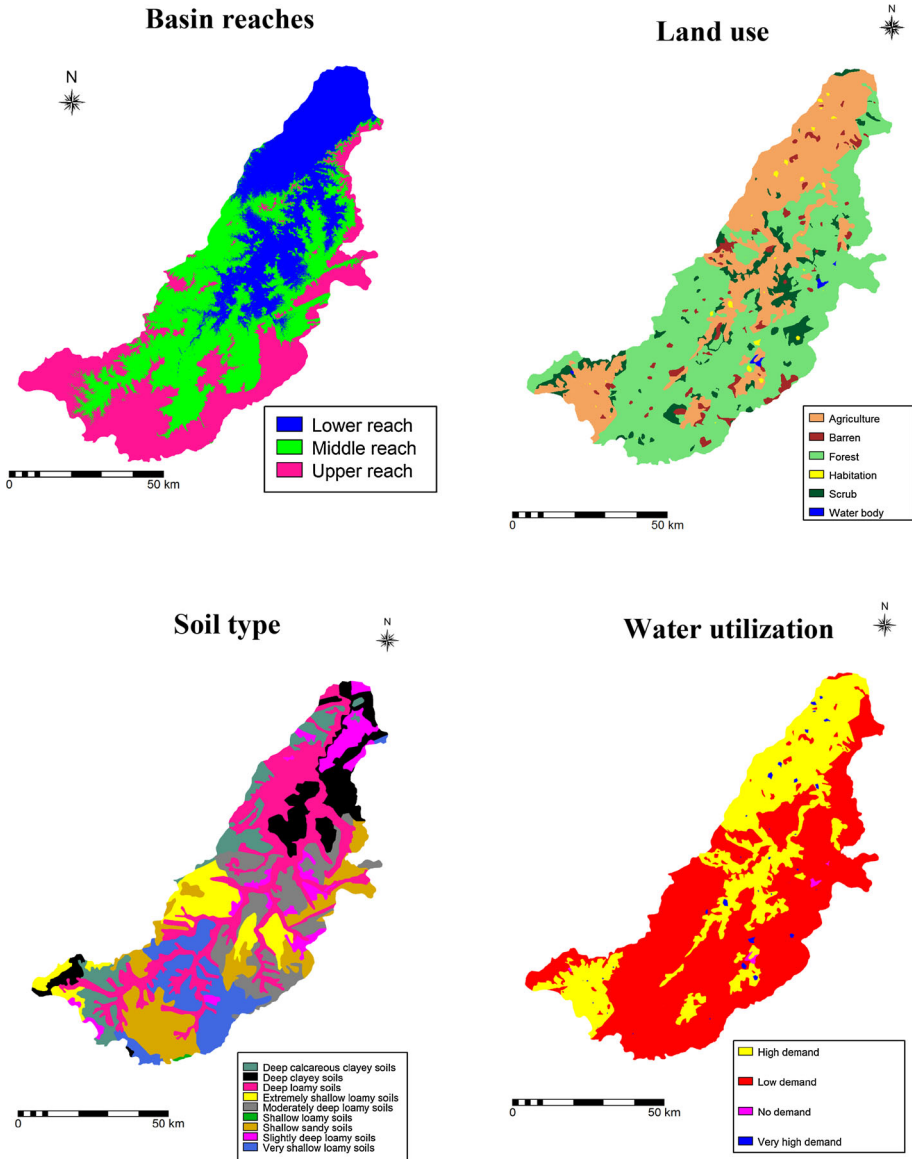


Fig. 6 Classification of spatially varying indicators in Bearma basin

vulnerability. The barren areas are considered to be least vulnerable as there is no habitation as well as vegetation. However, human habitations and cropped areas have highest vulnerability due to higher water demands and any water deficit here would lead to loss of crops and cause suffering to population including migration and livestock abandonment. Therefore vulnerability to drought has been considered to be minimum in barren areas and maximum in human-inhabited areas. The land use map of Bearma basin is given in Fig. 6.

4.9 Soil type

The soils in the Bearma basin have been divided into eight classes as per the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) classification. The soils with greater water-holding capacity are considered less vulnerable, whereas lighter soils with lower water-holding capacity are highly vulnerable. Therefore clayey (heavy) soils having greater water-holding capacity are least vulnerable, whereas shallow sandy soils having lower water-holding capacity are highly vulnerable. The soil map of Bearma basin is given in Fig. 6.

4.10 Water utilization

During periods of droughts, water demands are more in densely populated regions and irrigated agriculture zones. As such, these areas comprising of cities, towns and bigger villages are considered to be critically vulnerable. The agricultural areas have been considered highly vulnerable as the seasonal water utilization by agriculture is considerable, whereas areas with least socioeconomic activities and low water utilization have been considered to be least vulnerable. The spatial distribution of water utilization in the Bearma basin is given in Fig. 6.

4.11 Slope classes

The slope map of the Bearma basin has been created from the DEM. The slopes have been classified into five slope classes as mild, medium, high, very high and extremely high slope with the upper bounds at 1, 4, 6, 8 and 10 %, respectively. As there are very little habitation and livelihood activities on the extremely higher slopes, the water demands are negligible and these areas are considered to be least vulnerable as compared to plains and mildly sloping areas which are highly vulnerable, owing to both human settlements and agricultural activities.

4.12 Temporally varying indicators of drought vulnerability

4.12.1 Rainfall departure

There are five influencing rain gauge stations located in and around the basin, and the precipitation varies spatially as well as temporally over the basin. The annual rainfall departure from its normal has been computed for all the years of record. The negative rainfall departure is more pronounced during drought years and varies for each drought year. The percentage rainfall departure has been considered to assess the vulnerability of drought at the end of October by which time, the monsoon withdraws completely. The

rainfall departure map based on the rainfall departure at Rehli, Deori, Damoh, Hatta and Jabera is given in Fig. 7.

4.12.2 Soil moisture availability

The soil moisture is another important factor responsible for drought vulnerability in agricultural areas. The soil moisture availability is directly linked to the rainfall, its intensity and duration as well as the total seasonal rainfall. If there has been a sufficient

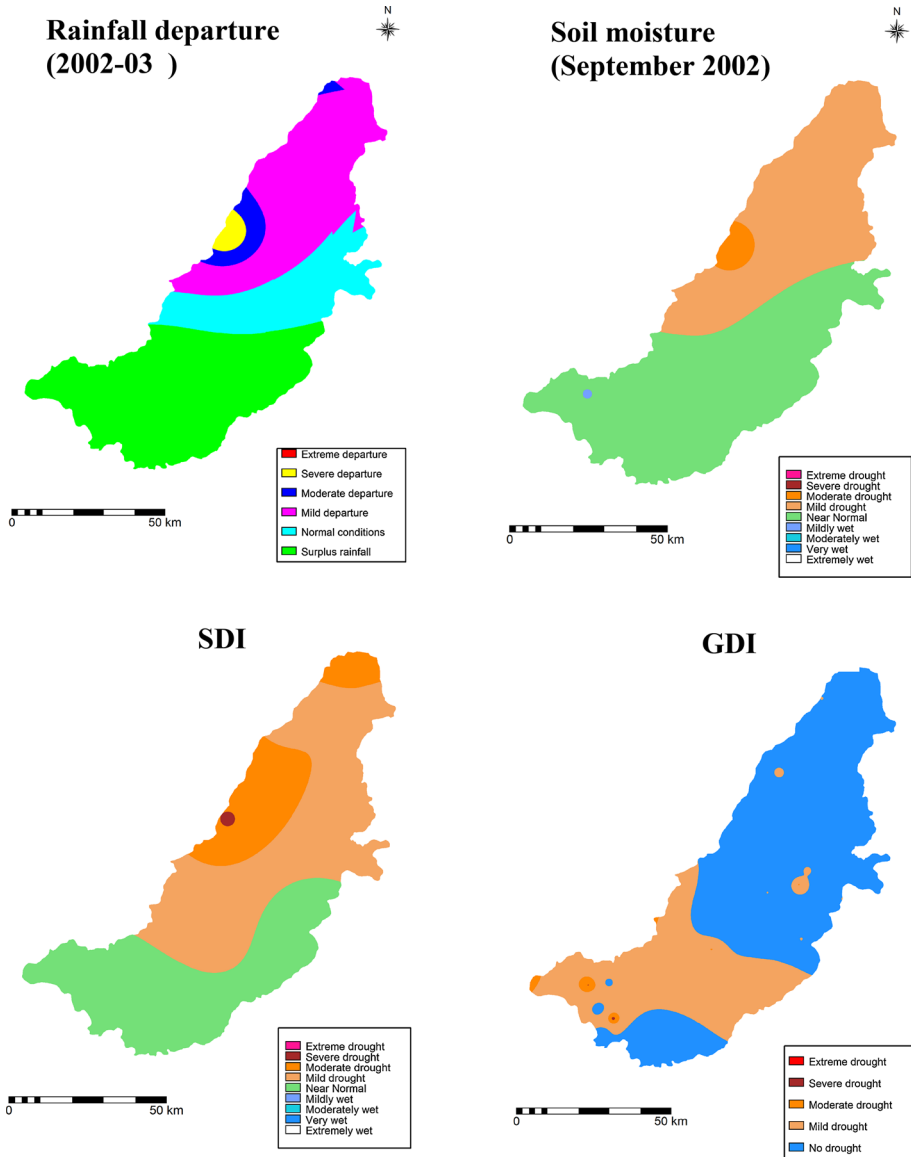


Fig. 7 Classification of temporally varying indicators in Bearma basin

build-up of soil moisture owing to the favorable rainfall conditions, then the demand on the available water resources will be reduced to a great extent. However, in Bearma basin, there are no mechanisms to measure the soil moisture which varies both spatially and temporally. Therefore 3-m SPI, which is considered as an indicator of soil moisture (Sims et al. 2002), has been considered to represent the soil moisture variation in the basin. The variation of the soil moisture availability has been depicted in Fig. 7 based on the 3-m SPI at various rain gauge stations in and around the basin by the end of October during the drought years.

4.12.3 Surface water availability

The surface water availability is another important indicator of the drought vulnerability which may comprise of stream flow in rivers and water stored in tanks and reservoirs. There are no watershed interventions presently in the form of reservoirs and tanks in the Bearma basin. However, the stream flow, which is again dependent on the rainfall, occurs in the main river but ceases soon after the monsoon season is over. Moreover the daily stream flow is only available at the outlet of the basin at Gaisabad G/D site. Therefore, the areal extent of a hydrological drought event cannot be exactly known as the stream flow is monitored only at the outlet of the basin. However, the understanding of spatial variability of hydrological drought is equally important for the development of effective drought mitigation actions and plans.

4.13 Development of surface water drought index (SDI) and development of SPI–SDI relationships

A relationship thus needs to be developed between the low flow characteristics and time scale-based SPI to spatially represent the stream flow variability in the basin. The development of a hydrological drought index with multiple objectives of evaluating the hydrological drought characteristics as well as development of a suitable relationship with ‘n-month SPI’ is essential. Once a suitable relation has been developed between ‘n-month SPI’ and the ‘hydrological drought index,’ the ‘n-month SPI’ at the five rain gauge stations can then be directly used to spatially represent the hydrological drought variation in the basin for drought vulnerability assessment. Therefore to assess the variability of hydrological drought in the basin at different locations, a relationship has been developed between ‘n-month SPI’ and ‘stream flow drought index (SDI).’

The SDI developed by Nalbantis and Tsakiris (2009) is an index analogous to SPI and is used for characterizing the severity of hydrological droughts and is helpful in obtaining a meaningful relationship between SPI and SDI. Time is treated in an overlapping zone with June 1, being considered as the beginning of the hydrological year and after every three months (i.e., 31 August, 30 November, 28 February, 31 May) a drought assessment is made for the period from the start of the hydrological year up to that time. The cumulative stream flow is used for overlapping periods of 3, 6, 9 and 12 months within each hydrological year. The SDI calculation is based on monthly observed stream flow volumes for a chosen reference period k of the i th year as given below:

$$SDI_{i,k} = \frac{y_{i,k} - \bar{y}_k}{\sigma_{y,k}}, \quad i = 1, 2, \dots, k = 1, 2, 3, 4 \tag{1}$$

$$y_{i,k} = \ln(V_{i,k}), \quad i = 1, 2, \dots, k = 1, 2, 3, 4 \tag{2}$$

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1, 2, \dots, j = 1, 2, \dots, k = 1, 2, 3, 4 \tag{3}$$

where \bar{y}_k is the average of all $y_{i,k}$ values; $\sigma_{y,k}$ is the standard deviation of all $y_{i,k}$ values; $V_{i,k}$ is the cumulative stream flow volume for the i th hydrological year and k th reference period.

In the analysis, $k = 1$ for June to August, $k = 2$ for June to November, $k = 3$ for June to February, and $k = 4$ for June to May. While McKee, 1993 suggested that Gamma distribution could be applied to stream flow (Nalbantis 2008; Shukla and Wood 2008; Tabari et al. 2013; Zamani et al. 2015) suggested log-normal distribution as a better choice for stream flow-based indices. The classification of the drought categories is based on the values of SDI namely, non-drought ($SDI \geq 0.0$); mild drought ($-1.0 \leq SDI \leq 0.00$); moderate drought ($-1.5 \leq SDI \leq -1.0$); severe drought ($-2.0 \leq SDI \leq -1.5$); and extreme drought ($SDI < -2.0$).

To develop a relationship between SPI and SDI, the monthly mean areal rainfall computed by the Thiessen Polygon method in Bearma basin has been used for the computation of the SPI which is analogous to the SDI, for the four overlapping time periods of June–August, June–November, June–February and June–May. The SPI has then been computed for this reference time periods. Similarly, for the computation of the SDI, the daily stream flow at Gaisabad is initially converted into volume terms in MCM. Subsequently, the SDI has also been computed for the same four overlapping time periods after conversion of daily stream flow to volume terms.

The development of a relationship between SPI and SDI which have both been computed in an analogous manner is very important in understanding the relation between meteorological and hydrological droughts in Bearma basin. The development of a precise relationships between ‘n-month SPI’ and SDI for the four different overlapping periods of June–August, June–November, June–February, and June–May will help to identify whether the meteorological drought will develop into a hydrological drought and use of ‘n-month SPI’ for defining hydrological drought characteristics in the basin. This information is vital as the short supply of surface water and ground water is of prime concern to the

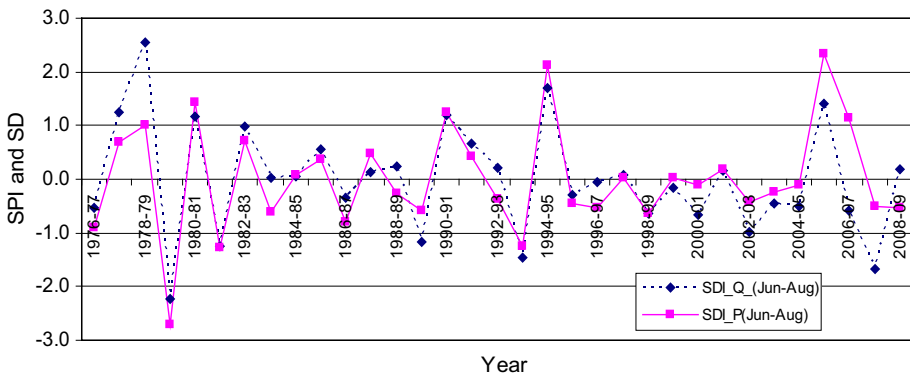


Fig. 8 Comparison of 3-m SPI and 3-m SDI for June–August reference period

local population as all activities including domestic, agricultural and industrial are directly dependent on the quantum of available water resources at the user end.

Various linear and nonlinear relationships were explored between (a) 3-m SPI and 3-m SDI; (b) 6-m SPI and 6-m SDI; and (c) 12-m SPI and 12-m SDI for all the four reference periods of June–August, June–November, June–February, and June–May. The variation of the 3-m SPI and 3-m SDI (June–August) for Bearma basin up to Gaisabad is illustrated in Fig. 8. It can be observed that the variation of both the indices is depicting a similar pattern and hence there is sufficient scope for development of further relationships between these indices for all the four reference periods. The relationships were developed and their suitability explored for each reference time period as given in Table 4. The linear relationships developed between SPI and SDI have a statistically significant correlation coefficient (more than 0.80) for all the reference time periods. This implies that a meteorological drought of certain severity produces a hydrological drought of definite severity, which can be estimated through the developed relationships even in the absence of stream flow data in future. This relationship can be used to estimate the SDI directly from the SPI to assess the hydrological drought conditions in Bearma basin. The analysis suggests that the 6-m SPI (highest correlation coefficient of 0.83) represents the hydrological drought variability in the basin and can be used directly in the drought vulnerability assessment. The 6-m SPI at the five influencing rain gauge stations for October has been interpolated for understanding the spatial distribution of surface water availability and is given in Fig. 8.

4.14 Ground water availability

The monitoring of ground water levels is carried out on a quarterly basis in the basin during August, November, January and May. Quarterly ground water levels during August, November, January and May from 1976–1977 to 2008–2009 have been used in the evaluation of groundwater drought index (GDI) to classify ground water drought characteristics. A map showing location of groundwater observation network in Bearma basin is depicted in Fig. 9. The GDI is computed by normalizing seasonal groundwater levels by dividing the seasonal ground water departures by its long-term standard deviation. For normalization, an incomplete gamma function has been used to calculate GDI. The GDI is an indicator of water-table decline and an indirect measure of recharge and thereby an indirect reference to drought. The GDI is computed as per the following equation given below.

$$GDI = \left\{ \frac{GWL_{ij} - GWL_{im}}{\sigma} \right\} \lim_{x \rightarrow \infty} \tag{4}$$

where GWL_{ij} is seasonal water level for the i th well and j th observation; GWL_{im} is seasonal mean; σ is the standard deviation.

Table 4 Relationships between SPI and SDI in Bearma basin

S. no.	SPI-time scale	Relationship	Corr. coefficient
1.	3 m: (Jun–Aug)	SDI = 0.8370SPI–0.0129	0.816
2.	6 m: (Jun–Nov)	SDI = 0.8683SPI–0.7044	0.827
3.	9 m: (Jun–Feb)	SDI = 0.8775SPI–0.8368	0.819
4.	12 m: (Jun–May)	SDI = 0.8657SPI–0.8758	0.814

The negative anomalies correspond to ‘water stress,’ while positive anomalies represent ‘no drought’ conditions. The cumulative deficit of the summation of negative anomalies of groundwater level below a threshold level over a time period indicates the severity of the ground water drought in that region which can be visualized through spatial interpolation. The ground water drought index (GDI) has been developed for the observation wells falling in and around the basin, and the GDI values have been spatially interpolated to arrive at the map showing the groundwater availability scenario during droughts. The study area has been categorized into critically deficit (extreme drought), high deficit (severe drought), moderate deficit (moderate drought), mild deficit (mild drought) and surplus (normal conditions) groundwater zones. The map showing the spatial groundwater availability based on the GDI for October is given in Fig. 10.

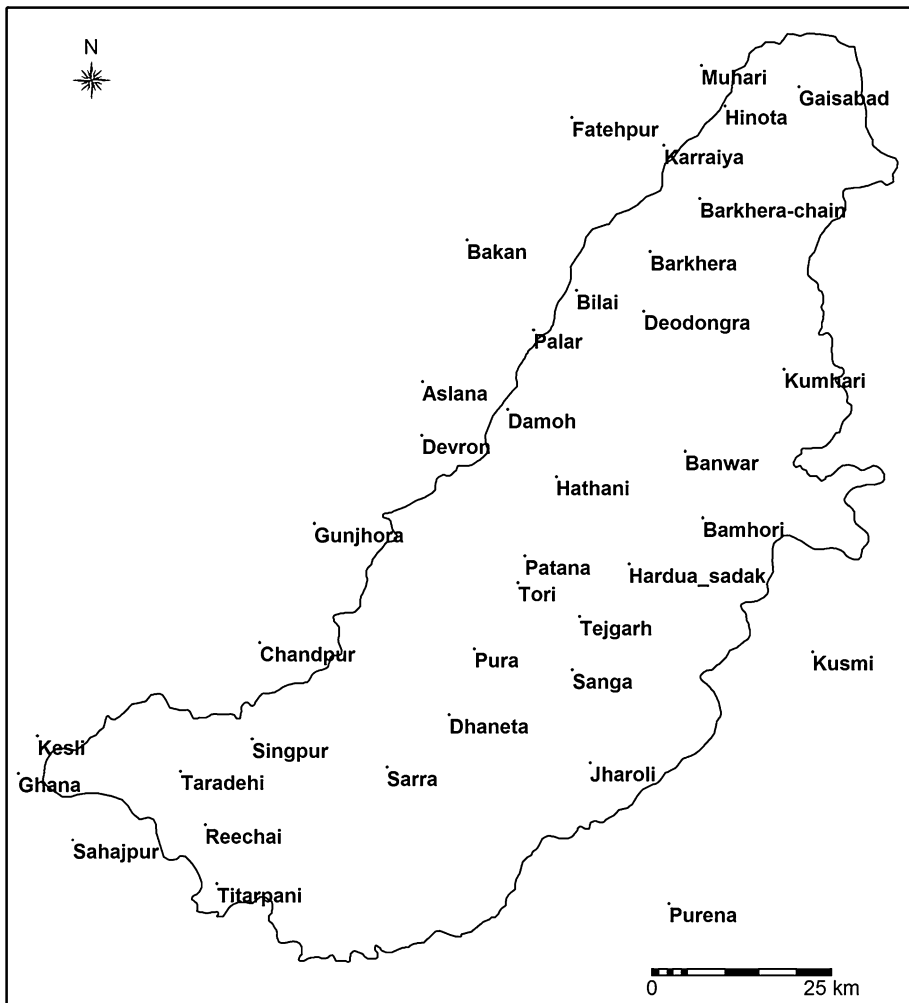


Fig. 9 Location of groundwater observation network in Bearma basin

Fig. 10 Integration of spatially

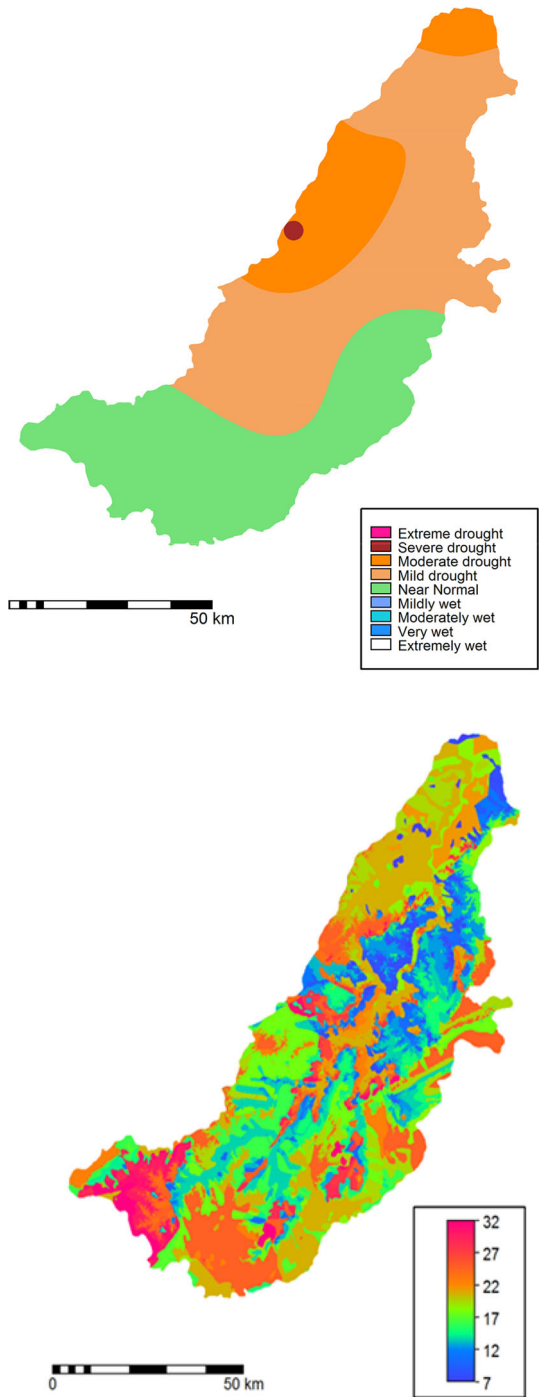


Table 5 Weighting scheme for drought vulnerability factors

S. no.	Factors	Classification	Weight	Normalized weight
1	Land use	Water body	0	0.00
		Barren/waste land	1	0.04
		Scrub	3	0.12
		Forest	4	0.15
		Agricultural	8	0.31
		Habitation	10	0.38
2.	Soil	Clay and deep clayey	1	0.03
		Deep calcareous clay	2	0.05
		Deep loamy	3	0.08
		Slightly deep loamy	4	0.10
		Moderately deep loamy	5	0.13
		Very shallow loamy	6	0.15
		Extremely shallow loamy	8	0.21
		Shallow sandy	10	0.26
3.	Slope	Extremely high slope (>10 %)	0	0.00
		Very high slope (6–10 %)	1	0.05
		High slope (4–6 %)	3	0.15
		Medium slope (1–4 %)	6	0.30
		Mild slope (<1 %)	10	0.50
4.	Water utilization	None	0	0.00
		Low	1	0.06
		Medium	2	0.11
		High	5	0.28
		Very high	10	0.56
5.	River reach	Lower reach	1	0.06
		Middle reach	5	0.31
		Upper reach	10	0.63
6.	Rainfall departure	Normal and surplus (>–10 %)	0	0.00
		Mild departure (–10 to –20 %)	1	0.04
		Moderate departure (–20 to 25 %)	5	0.21
		Severe departure (–25 to 50 %)	8	0.33
		Extreme departure (>50 %)	10	0.42
7.	Groundwater availability (represented by GDI)	Normal conditions	0	0.00
		Mild groundwater drought	1	0.04
		Moderate groundwater drought	5	0.21
		Severe groundwater drought	8	0.33
		Extreme groundwater drought	10	0.42

Table 5 continued

S. no.	Factors	Classification	Weight	Normalized weight
8.	Soil moisture availability (represented by 3-m SPI)	Normal conditions	0	0.00
		Mild soil moisture deficit	1	0.04
		Moderate moisture deficit	5	0.21
		Severe moisture deficit	8	0.33
		Extreme moisture deficit	10	0.42
9.	Surface water availability (represented by 6-m SPI)	Surplus	0	0.00
		Mild deficit	1	0.04
		Moderated deficit	5	0.21
		Highly deficit	8	0.33
		Critically deficit	10	0.42

4.15 Devised weighing scheme

A numerical weighing scheme has been designed for assessment of integrated drought vulnerability in Bearma basin. A high numeric value of weight within each subclass is indicative of higher vulnerability to drought. This can be understood clearly viz., heavy soils have greater water-holding capacity than sandy soils and therefore sandy soils are more vulnerable than heavy soils. Therefore sandy soils have been assigned higher weights as compared to heavy soils. The weights were also assigned to different subclasses of other indicators in a similar manner. The numerical weighting scheme used to distinguish the contribution of the various factors for vulnerability to drought is given in Table 5. Each subclass of vulnerability factors has been assigned a relative weight between 1 and 10, 1 being considered least significant in regard to drought vulnerability and 10 the most significant. The choice of weights is based on the assumption of relative contribution of each factor to overall drought vulnerability. Since area under water bodies does not have any significance in the drought vulnerability assessment, therefore, '0' weights have been assigned to water bodies.

4.16 Integration of spatially varying and temporally varying indicators

The physiographic features which spatially vary in the basin but do not have any temporal variation are the five spatial factors, namely basin reach, land use, soils, water utilization and slope which have been evaluated, and weights were assigned to its subclasses. The weights assigned to various subclasses of these spatial factors and integrated in a grid system of 50×50 m using a simple scheme of addition of weights to arrive at the composite spatial map given in Fig. 10. Similarly all the temporally varying factors, namely rainfall departure, soil moisture availability, surface water availability and ground water availability which vary considerably during each drought event, have been evaluated and weights assigned to its subclasses. The weights were assigned to various subclasses of these four temporal factors and integrated in a grid system of 50×50 m using a simple scheme of addition of weights to arrive at the composite spatially varying temporal map as given in Fig. 11.

Fig. 11 Integration of temporally varying vulnerability factors

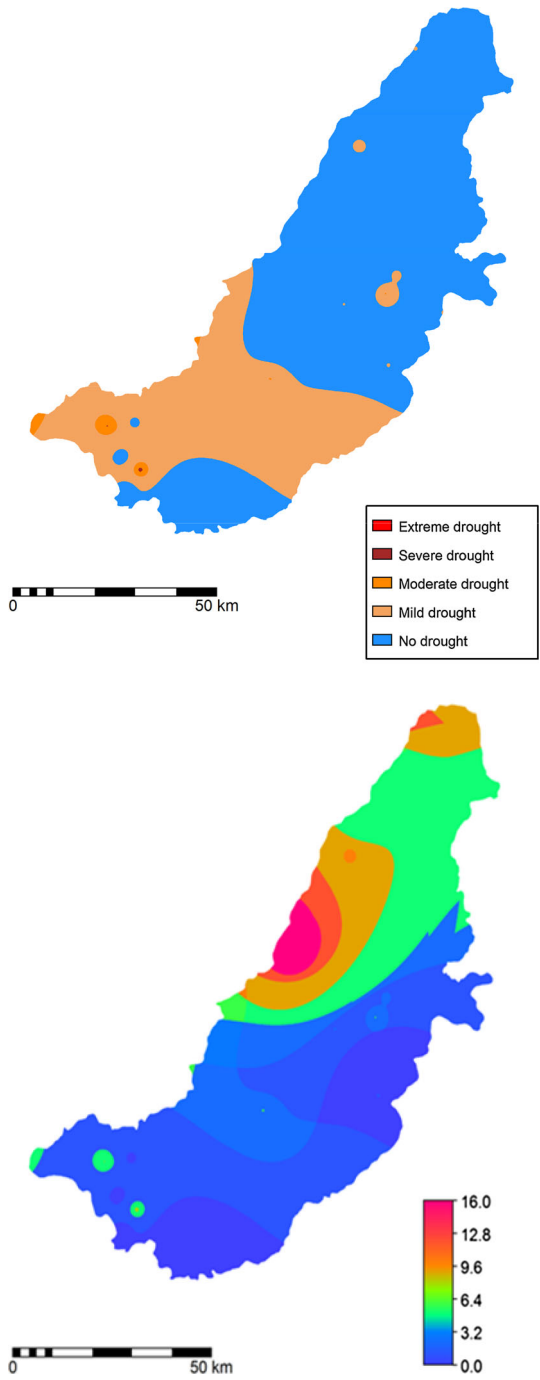
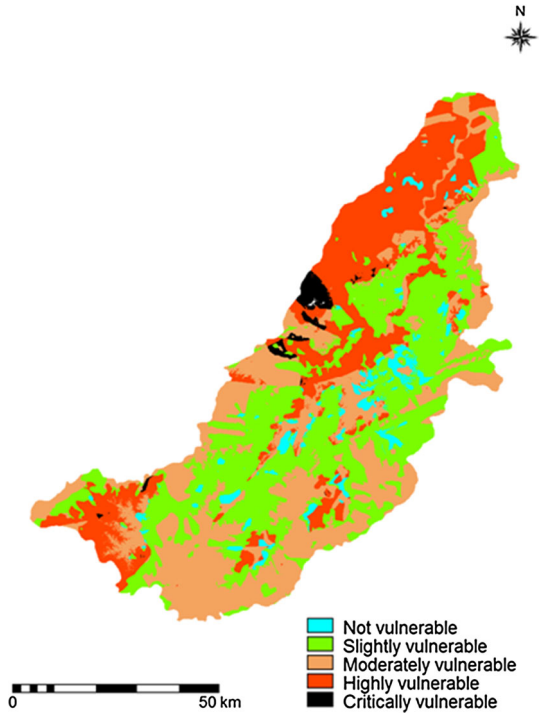


Fig. 12 Integrated drought vulnerability map (September 2007)



4.17 Integrated assessment of drought vulnerability

For integration of various factors in spatial domain, the combined numeric values of weights for each grid (50 m × 50 m) for the composite spatial map and composite temporal map were calculated by simple addition to arrive at the integrated drought vulnerability map of the basin. A geographic area with greater numeric value of total weights is relatively more vulnerable to drought. Thereafter, the basin has been classified into five vulnerability classes, namely critically vulnerable, highly vulnerable, moderately vulnerable, slightly vulnerable and not vulnerable. The integrated drought vulnerability map for the Bearma basin is given in Fig. 12. The area vulnerable to drought has been identified, and the area falling under different vulnerability classes is given in Table 6. The highly vulnerable areas are located in the southern and northern regions of the Bearma basin. It has been observed that more than 26 % of the basin lies in the highly and critically vulnerable classes and consequently has greater drought-related negative impacts. The unique methodology developed considering the spatially and temporally varying factors with the use of drought indicators and their

Table 6 Area falling under various vulnerability classes

S. no.	Vulnerability classes	Area (sq. km)	Area (%)
1.	Not vulnerable	224.56	3.87
2.	Slightly vulnerable	2082.12	35.84
3.	Moderately vulnerable	1986.26	34.19
4.	Highly vulnerable	1429.59	24.61
5.	Critically vulnerable	86.46	1.49

interrelationships helps to provide identify drought vulnerable zones in a basin which will be greatly helpful in better decision making for drought mitigation and management.

5 Conclusions

The assessment of drought vulnerability has been accomplished by a new methodology incorporating the various spatially and temporally varying factors which have been integrated to arrive at the drought vulnerability map. The annual rainfall departure in the basin varied between -40 and -62% with the average drought frequency of once in every 3–4 years. The use of drought indicators viz., SPI, SDI and GDI and their application in spatially representing the soil moisture, surface water and ground water availability during droughts is as state-of-the-art approach and takes into account all the components of the water cycle responsible for water stress during drought periods. This technique yielded reliable estimates of drought vulnerable zones for identifying the basin scale vulnerabilities and can therefore be effectively used in demarcating vulnerable zones in drought prone basins for prioritized planning and development of effective response mechanisms. This methodology can serve as a guideline for computing the integrated influence of all vital factors responsible for drought vulnerability in the spatial and temporal domain. The drought mitigation measures can be made more effective, provided the activities are more focused toward the identified critically and highly vulnerable areas. The drought vulnerability assessment using GIS and remote sensing techniques can help decision makers in visualizing the hazard and help to disseminate the concept of vulnerability to stakeholders, natural resource managers, agricultural producers and others.

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