DROUGHT VULNERABILITY ASSESSMENT IN BUNDELKHAND REGION OF CENTRAL INDIA

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ABSTRACT

The complex process of climate change affects vulnerable populations and livelihoods in drought prone regions through a rise in frequency and severity of such events. Vulnerability assessment is a new paradigm in disaster management and is one of the main aspects of any drought mitigation strategy. The paper focuses on understanding and quantifying the drought vulnerability, which is one of the prominent climate extremes in Bearma basin located in the Bundelkhand region of Central India. Regular drought conditions have been prevailing in the region in the last decade with continuous drought from 2004-2007. Even though the mean annual rainfall in the basin is 1187 mm, but its high variability (28%) is one of the prominent reasons for the regular drought scenario. The maximum annual rainfall deficiency during drought years varied from -40.4% at Deori during 1992 to -62.8% at Damoh during 1979 with the drought frequency varying between once in 3 years and once in 4 years.

An integrated drought vulnerability assessment methodology has been developed to identify the drought vulnerable regions using a multiple indicator approach considering the spatially and temporally varying factors. The spatial indicators includes the water demands; topographical characteristics including the river basin reaches and basin slopes; land-use types; and soil type whereas the temporal indicators which vary during for every drought event includes the rainfall availability and soil moisture availability characterised by 3-m Standardised Precipitation Index (SPI), surface water availability represented by 6-m SPI and ground water availability identified by the Groundwater Drought Index (GDI). The spatial information of the indicators was categorised in layers prepared in the spatial domain on a 50 x 50 m grid scale using a geographic information system (GIS) and the integrated values of weights of various classes of the indicators computed to arrive at the integrated drought vulnerability. Results show that the proposed methodology was highly effective in assessments of drought vulnerability in the basin and the methodology can be replicated for drought vulnerability assessments in other basins.

INTRODUCTION

Drought is one of the significant aspects which are responsible for socio-economic imbalance in several parts of India on cyclic basis (every 3 to 7 years) and has pronounced impact on the Indian economy. In developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems and healthy economics, whereas in developed economies, drought poses significant economic risks and cost for individuals, public enterprises, commercial organizations and governments. 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.

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 growing body of literature on vulnerability and adaptation contains array of 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). 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). Naumann et al., (2013) conducted an indicator based analysis for exploring drought vulnerability in Africa for early warning systems and developed a drought vulnerability indicator (DVI). Hamid 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).

STUDY AREA

The River Bearma, an important tributary of the Ken river system is located between 23° 07′ and 24° 18′ N latitudes and 78° 54′ and 80° 00 E longitudes and lies in parts of Sagar, Damoh, and Panna districts in Madhya Pradesh (M.P.). It is an elongated leaf shaped basin with a catchment area of 5890 km^2 up to Gaisabad gauge-discharge site. The index map showing the Bearma river system up to Gaisabad is given in Fig. 1. The upper reaches of the basin comprise of undulating plateau (about 40%), with steep sloping hills at few places. The basin experiences dry sub-humid climate and the monsoon season spread over June to September with a mean annual rainfall of 1186.9 mm. The five rain gauge stations at Deori, Rehli, Damoh, Jabera and Hatta influence rainfall in the basin. About 36% of the geographical 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.

ANALYSIS & RESULTS

The annual rainfall of five influencing stations for the period from 1977-2010, have been analyzed. 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 to 30.7 % at Rehli with the average value of C_v for the basin being 28%.

Identification of Drought Years and Drought Frequency

The annual rainfall departure at a station has been computed as the deviation of the rainfall from its normal divided by the normal rainfall. The drought severity has been classified on the basis of percentage deviations from its normal values into three severity classes viz., mild drought for rainfall departures varying between -20% to -25%; moderate drought for rainfall departure varying between -25% to -50%, and departure greater than -50%, is considered to be severe drought. A summary of annual departure analysis is presented in Table 1. 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%. The analysis indicates that the average frequency of occurrence of drought in the basin is once in every 3 to 4 years. The rainfall departure map based on the rainfall departure at Rehli, Deori, Damoh, Hatta and Jabera for 2002-03 is given in Fig. 2.

Meteorological Drought Characteristics Using Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) developed by McKee et al. (1993) is a widely used index for assessing drought severity. The computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation for a given station. The SPI represents a statistical z-score or the number of standard deviation (following a gamma probability distribution transformation to a normal distribution) above or below that an event as demarcated with reference to means (Edward and McKee, 1997). The SPI allocates a single numeric

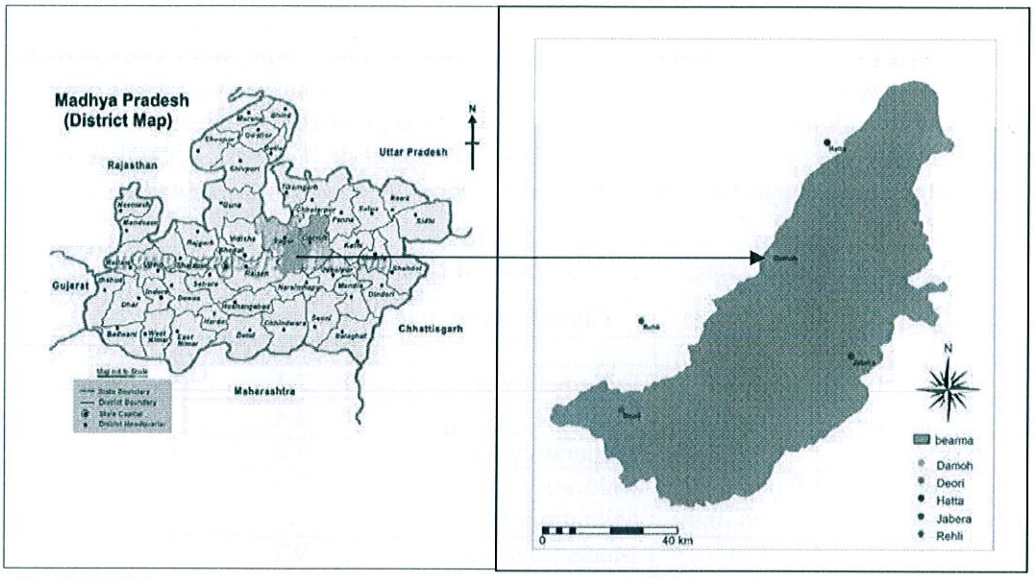

Fig.1: Location map of Bearma basin in Madhya Pradesh

Table 1: Summary of annual rainfall departure analysis

S. No.	Name of station	No. of years of data for analysis	No. of drought years	Av. drought return period (year)	Maximum recorded annual deficit (%)
1.	Damoh	53	12	4	-62 (1979)
2.	Hatta	47	14	3	-58 (1979)
3.	Jabera	43	11	4	-56 (1979)
4.	Rehli	33	11	3	-42 (2007)
5.	Deori	33	12	3	-40 (1992)

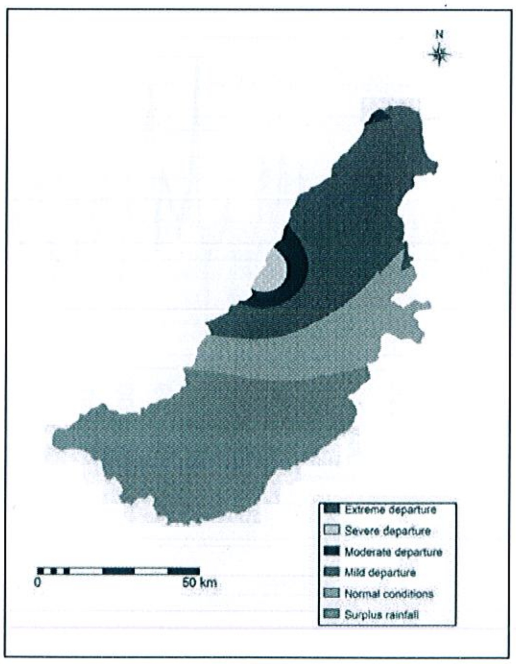

Fig. 2: Rainfall departure (2002-03)

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 is required for the analysis (Hayes et al. 1999). 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 2. The SPI has been applied to quantify monthly precipitation deficit anomalies on multiple time scales (1-, 3-, 6- and 12-month).

Table 2: Standard ranges of SPI values and their classification

S. No.	SPI range	Classification	Occurrence probability (%)
1.	2.0 ≥	Extremely wet	2.3
2.	1.5 to 1.99	Very wet	4.4
3.	1.0 to 1.49	Moderately wet	9.2
4.	0.0 to 0.99	Mild wet	34.1
5.	0.0 to -0.99	Mild drought	34.1
6.	-1.0 to -1.49	Moderate drought	9.2
7.	-1.5 to-1.99	Severe drought	4.4
8.	-2.0 ≤	Extreme drought	2.3

The drought characteristics including frequency, duration and intensity and magnitude have been calculated with the estimated SPI. The temporal variation of the 3-m SPI at Rehli is given in Fig. 3. Based on the 3-m SPI, five major drought events have been observed during 1984-85, 1991-92, 1996-97, 2000-03 and 2007-09. The distribution of the drought events at all the five rain gauge stations is given in Table 3. It has been 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.

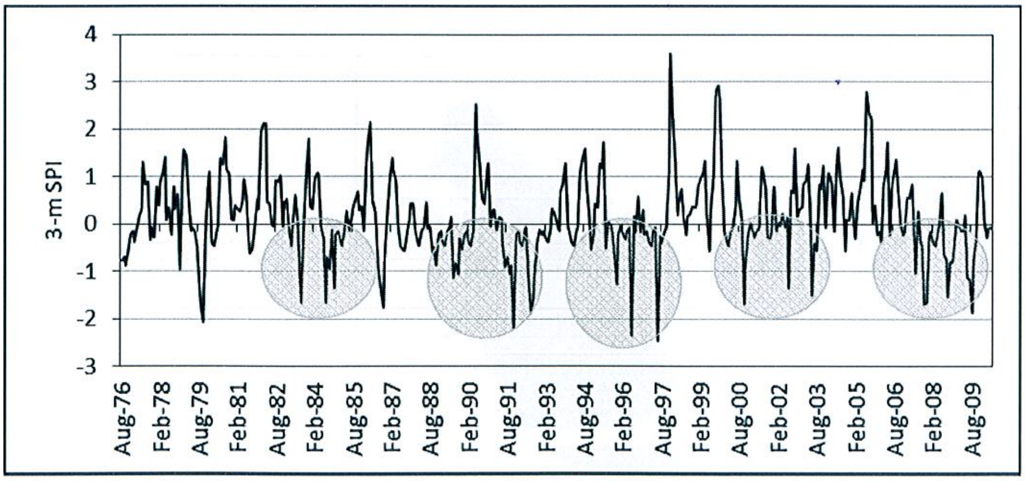

Fig. 3: Temporal variation of 3m-SPI at Rehli

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

Drought Vulnerability Assessment

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 software. The spatial indicators considered include user water demand, topographical characteristics including the river basin reaches, watershed slope, land-use, and soil type information. The temporal indicators, which vary for each drought event include rainfall departure, groundwater availability, soil moisture availability, and surface water availability. The spatial maps representing these indicators have been prepared on a grid system of 50 m x 50 m and 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.

Representation of Spatially Varying Physiographic Factors

The spatially varying factors considered in the vulnerability analysis include basin reach, land use pattern, soil type, water utilization and slope classes. The Bearma basin has been classified into three different elevation zones based on the Digital Elevation Model (DEM) viz., upper reach (elevation > 450 m), middle reach (elevation range of 350-450 m) and lower reach (elevation < 350 m) depending on flow characteristics in stream sections. The upper reaches of basin have been considered more vulnerable than the middle and lower reaches as more and more regions contribute towards the flow in the river from the middle and lower reaches. The map showing the various river basin reaches in the Bearma basin is given as Fig. 4. The land use is one of the important spatial factor for drought vulnerability assessment. The barren areas are considered to be least vulnerable as there are no habitation and vegetation whereas human settlements and cropped areas have highest vulnerability owing to higher water demands. Therefore vulnerability to drought has been considered to be minimum in barren areas and maximum in human settlements. The land use map of Bearma basin is given in Fig. 5.

Eight classes of soils are commonly found in the Bearma basin as per the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) classification. 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. The water utilization is critical for cities, towns and bigger villages and therefore these are considered to be critically vulnerable followed by agricultural areas which are highly vulnerable due to higher water demands and as it is linked to livelihood. The areas with least socio-economic 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. 7. 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 few livelihood activities on the extremely higher slopes these areas are considered to be least vulnerable as compared to plains and mildly sloping areas which are highly vulnerable.

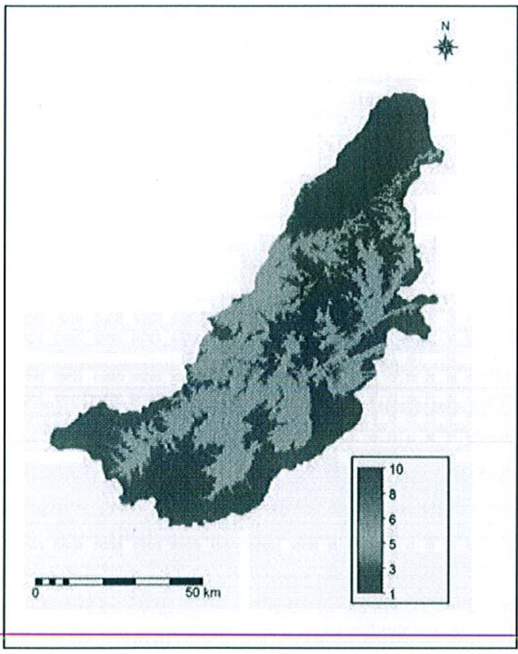

Fig. 4: Basin reaches map

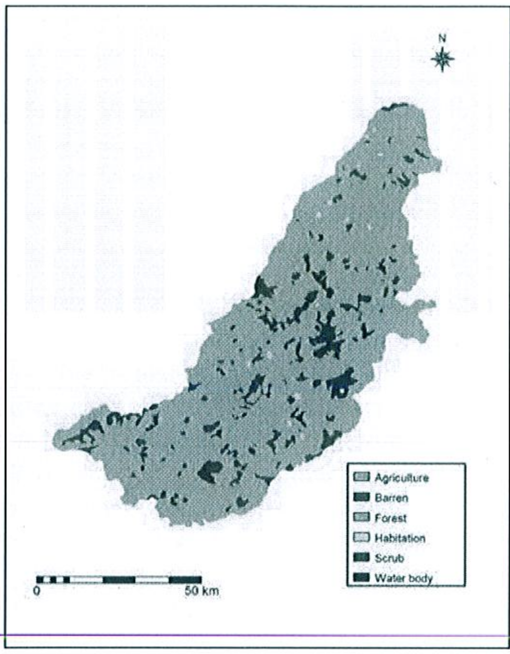

Fig. 5: Land use pattern

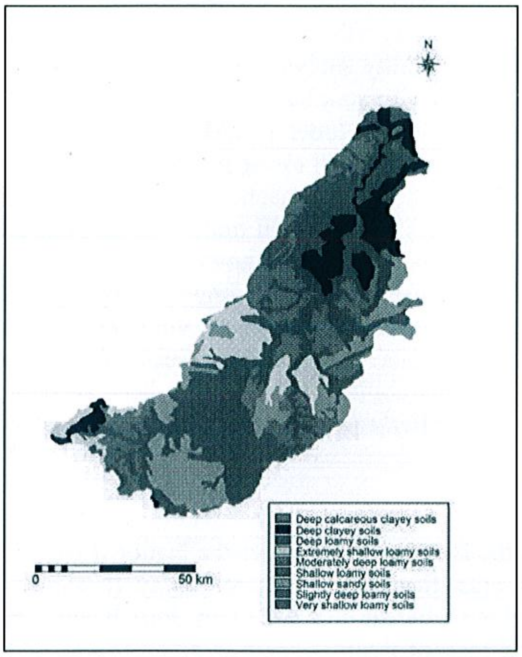

Fig 6: Soil map

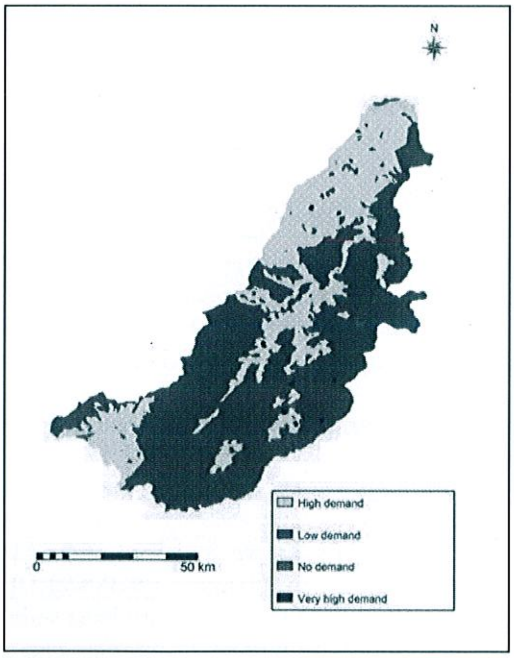

Fig. 7: Water utilization map

Spatial Representation of Temporally Varying Factors

The temporally varying factors considered in the vulnerability analysis include rainfall departure, soil moisture availability, surface water availability and ground water availability. The negative rainfall departure is more pronounced during drought years and varies for each drought year. The annual rainfall departure at the end of October has been considered to assess the vulnerability of drought as the monsoon withdraws completely by this time. The soil moisture which is directly linked to the rainfall, its intensity and duration, is another important factor responsible for drought vulnerability predominantly in agricultural areas. As there are no mechanisms available to measure the soil moisture which varies spatially and temporally in the basin, the 3-m SPI which is used widely as an indicator of soil moisture and has been considered to represent the soil moisture variation and is given in Fig. 8.

As the daily stream flow is available only at the outlet of the basin, the areal extent of a hydrological drought event cannot be exactly known. However the understanding of spatial variability of hydrological drought is equally important for the development of effective drought mitigation actions and plans. Based on recommendations of various researchers and subsequent analysis, the 6-m SPI has been considered to represent the hydrological drought variability in the basin and used in the

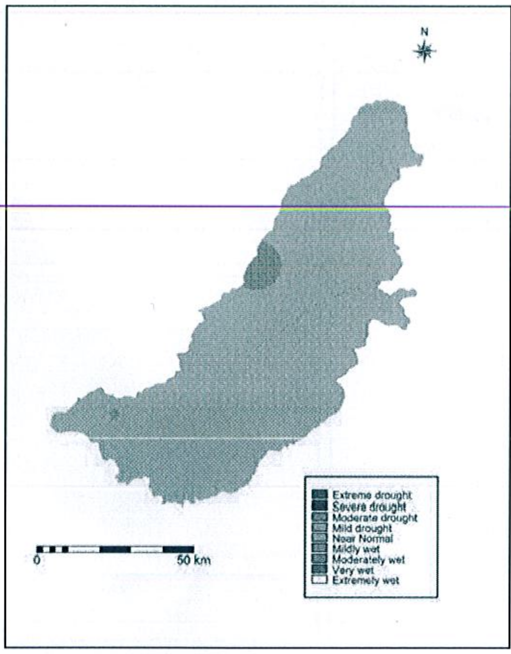

Fig. 8: Soil moisture availability

drought vulnerability assessment. The spatial distribution of surface water availability is given in Fig. 9. A ground water drought index (GDI) as given by Equation 1, 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.

$$GDI = \left\{\frac{GWL_{ij} - GWL_{im}}{\sigma}\right\} \quad \text{..............................} (1)$$

where, GWL_{ij} = seasonal water level for the ith well and jth observation; GWL_{im}= seasonal mean; σ = is the standard deviation.

INTEGRATED ASSESSMENT OF DROUGHT VULNERABILITY

A numerical weighting scheme has been proposed for assessment of integrated drought vulnerability. A high numeric value of weight within each sub-class 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 weight values as compared to heavy soils. The weights were assigned to different sub-classes 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 4. Each sub-class of vulnerability factors has been assigned a relative weight between 0 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 knowledge based relative contribution of each factor to overall drought vulnerability.

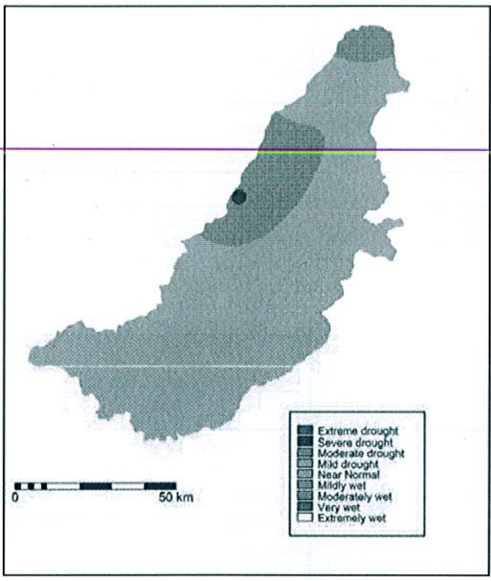

Fig. 9: Surface water availability

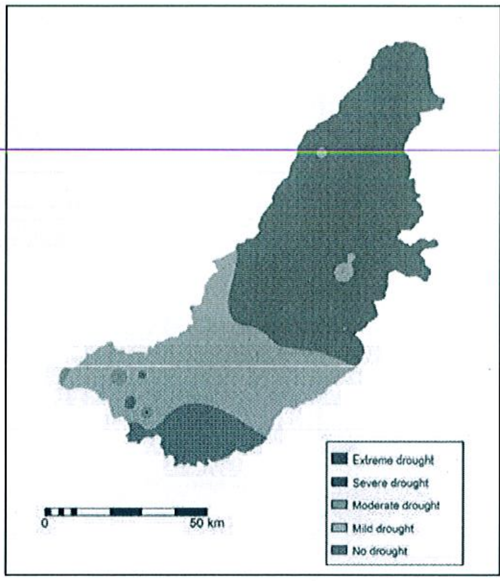

Fig. 10: Ground water availability

The five spatial physiographic the factors which spatially vary in the basin but do not have any temporal variation are namely, basin reach, land use, soils, water utilization and slope which have been evaluated and weights assigned to its sub-classes. 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 sub-classes. The weights assigned to various sub-classes of these factors have been integrated in a grid system of 50 x 50 m using a scheme of addition of weights 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 drought vulnerability map for the Bearma basin is given in Fig. 11. The area vulnerable to drought has been identified and the area falling under different vulnerability classes is given in Table 5. 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 have greater drought related negative impacts.

Table 4: Weighting scheme for drought vulnerability factors

S. No.	Classes	Sub-classes	Weight
1	Land use	Water body	0
		Barren/waste land	1
		Scrub	3
		Forest	4
		Agricultural	8
		Habitation	10
2.	Soil	Clay and deep clayey	1
		Deep calcareous clay	2
		Deep loamy	3
		Slightly deep loamy	4
		Moderately deep loamy	5
		Very shallow loamy	6
		Extremely shallow loamy	8
		Shallow sandy	10
3.	Slope	Extremely high slope (> 10%)	0
		Very high slope (6-10%)	1
		High slope (4-6%)	3
		Medium slope (1-4%)	6
		Mild slope (< 1%)	10
4.	Water utilization	None	0
		Low	1
		Medium	2
		High	5
		Very high	10
5.	River reach	Lower reach	1
		Middle reach	5
		Upper reach	10
6.	Rainfall departure	Normal and surplus (> -10%)	0
		Mild departure (-10 to -20%)	1
		Moderate departure (-20 to 25%)	5
		Severe departure (-25 to 50%)	8
		Extreme departure (> 50%)	10
7.	Groundwater availability (represented by GDI)	Normal conditions	0
		Mild groundwater drought	1
		Moderate groundwater drought	5
		Severe groundwater drought	10
8.	Soil moisture availability (represented by 3-m SPI)	Normal conditions	0
		Mild soil moisture deficit	1
		Moderate moisture deficit	5
		Severe moisture deficit	10
9.	Surface water availability (represented by 6-m SPI)	Surplus	0
		Moderated deficit	1
		Highly deficit	5
		Critically deficit	10

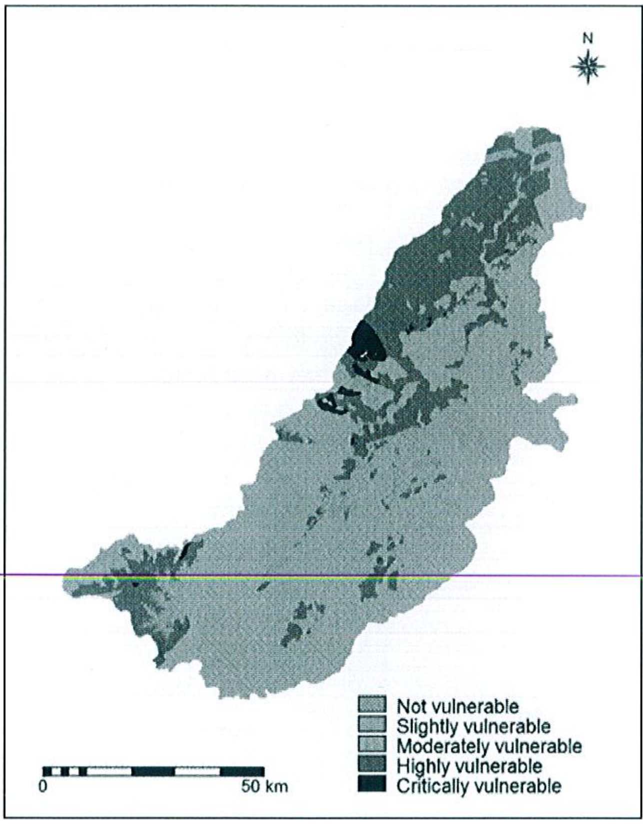

Fig. 11: Integrated drought vulnerability map

Table 5: 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

CONCLUSIONS

The assessment of drought vulnerability has been accomplished by an innovative 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% to -62% with the average drought frequency of once in every 3 to 4 years. The use of drought indicators viz., SPI 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 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 vulnerability assessment using GIS & 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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