



# Inclusion of groundwater and socio-economic factors for assessing comprehensive drought vulnerability over Narmada River Basin, India: A geospatial approach

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## Abstract

Drought is amongst the most precarious natural hazards associated with severe repercussions. The characterization of droughts is usually carried out by the sector-specific (meteorological/agricultural/hydrological) indices that are mostly based on hydroclimatic variables. Groundwater is the major source of water supply during drought periods, and the socio-economic factors control the aftermaths of droughts; however, they are often ignored by the sector-specific indices, thereby failing to capture the overall impacts of droughts. This study aims to circumvent this issue by incorporating hydroclimatic, socio-economic and physiographic information to assess the overall drought vulnerability over Narmada River Basin, India, which is an agriculture-dominated basin highly dependent on groundwater resources. A Comprehensive Drought Vulnerability Indicator (CDVI) is proposed that assimilates the information on meteorological fluctuations, depth to groundwater level, slope, distance from river reach, population density, land use/land cover, soil type, and elevation through a geospatial approach. The CDVI showed a remarkable geospatial variation over the basin, with a majority (66.4%) of the area under highly to extremely vulnerable conditions. Out of 35 constituent districts of the basin, 9, 22, and 4 districts exhibited moderate, high, and extreme vulnerability to droughts, respectively. These results urge an immediate attention towards reducing drought vulnerability and enhancing resilience towards drought occurrences. The proposed multi-dimensional approach for drought vulnerability mapping would certainly help policy-makers to proactively plan and manage water resources over the basin, especially to ameliorate the pernicious impacts of droughts.

**Keywords** Drought · Vulnerability · Groundwater · CDVI · Narmada River Basin

## Introduction

Drought is a precarious natural hazard, which mankind has been scrambling since ages. It could reverberate in catastrophic effects to socio-ecological systems (Byun and Wilhite 1999; Tsakiris and Vangelis 2004; Wilhite et al. 2007, 2014). The remarkable fact about droughts is that they have maximum frequency, prevail for longer duration and affect large regions as well as population, amongst all the natural disasters (Mirabbasi et al. 2013; Mishra and Singh, 2010, 2011; Swain et al. 2021). The global yield loss due to

droughts over the last two decades is reported to be 166 billion USD from approximately 75% of the global harvested areas (Kim et al. 2019). But droughts are complicated events and very toilsome to understand (Hisdal and Tallaksen 2003). It is a natural menace resulting from very low precipitation leading to shortages in water for a prolonged period. Consequently, it affects people from all fields, i.e. hydrologists, meteorologists, environmentalists, geologists, ecologists and agricultural scientists (Dabanli et al. 2017; Dracup et al. 1980; Mishra and Singh 2010). With rapidly increasing population and industrialization, the water demand has risen up significantly, resulting in scarcity of water worldwide (Swain et al. 2020). The deterioration in the water quality of surface and groundwater resources has further aggravated the problems (Adimalla and Taloor 2020; Adimalla et al. 2018a, 2018b, 2019, 2020; Li and Qian 2018a, 2018b). According to the reports of the United Nations Framework Convention on Climate Change (UNFCCC), based on per

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capita Annual Water Resources (AWR), over 20 nations have been in water-stressed conditions by 1996, and the number is expected to increase further, leading to two-third of the global population face water paucities by 2050 (Gosain et al. 2006, 2011). Moreover, according to the Intergovernmental Panel on Climate Change (IPCC) reports, the global freshwater availability will be reduced by 10–30%, and about 5–10% fall in global runoff will occur by the middle of the twenty-first century (Suryavanshi et al. 2014; Swain et al. 2021). All these concerns encourage a detailed analysis and management of droughts; however, an explicit physical quantification of drought and its attributes is a perplexing geophysical endeavour.

The problems of drought quantification initiate from the first step, i.e. in recognizing the drought phenomenon. It is challenging to provide an accurate definition of drought (Mishra et al. 2015; Rossi et al. 1992; Tsakiris et al. 2013). Because of its influence over different sectors, the definition given based on impacts on one field may not beseech to other fields. Spatiotemporal variations in water demands, diversified socio-economic impacts, and association of numerous variables have made it extremely difficult for researchers around the globe to compile an unobjectionable definition for drought. Conceptually, droughts are commonly categorized into four types based on the sector of influence and the relevant hydro-meteorological variables. These are meteorological, hydrological, agricultural, and socio-economic droughts (Amirataee and Montaseri 2017; Amrit et al. 2018a, 2018b; Mishra and Singh 2010; Swain et al. 2017; Wilhite and Glantz 1985). While precipitation is mostly considered the key variable for meteorological droughts, soil moisture and streamflow are mostly associated with agricultural and hydrological droughts, respectively. In general, these three types of droughts are primarily of interest to scientists. A socio-economic drought arises whenever the demand for an economic good exceeds supply significantly as a consequence of meteorological/agricultural/hydrological droughts (Dumitraşcu et al. 2018; Kalura et al. 2021). All four types of droughts are interlinked; however, from the operational point of view, the droughts are commonly defined by the indices that are mostly specific to the drought type. A drought index is a single numerical value obtained by assimilating the relevant hydro-meteorological variables (Keyantash and Dracup 2002; Khadr 2016; Sayari et al. 2013; Swain et al. 2020, 2021). Though such indices are certainly popular, they fail to capture the overall impacts of droughts. For example, the indices based on only precipitation may be useful in quantifying the meteorological perspectives of historical drought events, which is obviously the most important factor for instigating drought events. However, two distinct regions with similar meteorological drought characteristics may experience diverse consequences. This poses a major challenge to the water resources

managers. Further, the commonly used indices generally do not consider groundwater into account, mainly due to the constraints of data availability. It is well known that groundwater is a major source of water supply for fulfilling agricultural, industrial and municipal demands, especially over the arid or semi-arid regions. Particularly during the drought periods, the dependence of the populace is maximum on groundwater due to unavailability or acute deficit of water from other sources. Mishra and Singh (2010) emphasized on understanding the role of groundwater in relation to droughts and the importance of its inclusion in drought characterization, though it is highly challenging. Given the fact that India is the largest user of groundwater amongst all the countries with a withdrawal of 251 km<sup>3</sup>/yr (Sahoo et al. 2021), the inclusion of groundwater in drought assessment becomes even more important for the Indian region. Therefore, it is in order to develop an approach to ameliorate these issues, thereby helping in robust management of droughts.

The concept of ‘vulnerability’ has been in wide use in water resources or environmental sectors in last few years (Azam et al. 2021; Formetta and Feyen 2019; Fuchs and Thaler 2018; Hajra et al. 2017; Kalura et al. 2021; Sam et al. 2017). It basically refers to the inability of a system to withstand a hazardous condition. In other words, it is the degree of susceptibility to a disaster. Vulnerability is a function of two broad factors: (a) exposure to the disaster and (b) inability to cope with the impacts (Pandey et al. 2010). A region with both the factors on the higher side is highly vulnerable to droughts. To understand the actual vulnerability to droughts, it is imperative to include meteorological, hydrological, agricultural, and socio-economic aspects. The physiographic factors, viz. soil, elevation, slope, etc., play a vital role in the impact analysis and prioritization of droughts. A few prior studies (Azam et al. 2021; Dumitraşcu et al. 2018; Hajra et al. 2017; Noy and Yonson 2018; Sam et al. 2017) have advocated assessing the socio-economic vulnerability of disasters, which includes human behaviour with respect to surrounding conditions. More importantly, the occurrence and repercussions of hydrologic extremes (e.g. droughts) are largely influenced by anthropogenic activities, as evident from several recent studies (Aadhar and Mishra 2020; Lutz et al. 2019; Mishra et al. 2019; Mukherjee et al. 2018; Roxy et al. 2017; Singh et al. 2019). For example, the extraction of groundwater is relatively high over the drought-stricken regions, thereby aggravating the water availability concerns. Similarly, land use/land cover (LULC) is another vital component. Typically, a region with an agricultural LULC is more susceptible to the harmful impacts of droughts. The population is obviously a pivotal factor governing the decisions of water distribution. However, the commonly used drought indices often ignore the non-climatic factors, particularly the anthropogenic ones. For proper planning and management of droughts, proactive coping strategies must

be developed, which requires information integrated from several dimensions. Certainly, there is a need for comprehensive drought vulnerability assessment.

The vulnerability may remarkably vary with space depending on different factors. For example, drought leads to serious economic risk for individuals, as well as government and private organizations, in developed economies. On the other hand, apart from hampering the economy, drought poses risks to the maintenance of the productive system and a threat to livelihood in developing nations (Azam et al. 2021; Formetta and Feyen 2019; Fuchs and Thaler 2018; Pandey et al. 2010). A spatially varying vulnerability map considering a multi-dimensional approach would be helpful to water managers in drought risk assessments and developing adaptive plans. Therefore, this study aims to develop an approach to evaluate the geospatial drought vulnerability by integrating hydroclimatic, social and physiographic factors. In this regard, the availability of relevant data for multiple facets of drought characterization may be a hindrance; however, the application of remote sensing can be useful in obtaining some of the essential input data, which may not be available in field at desirable resolutions. With the advancements in technology, remotely sensed datasets are providing high-resolution information, particularly on physiographic factors (Guptha et al. 2021; Jasrotia et al. 2013, 2016, 2019; Khan et al. 2020; Sarkar et al. 2020; Taloor et al. 2020, 2021). Further, GIS can conveniently overlay various information into a single platform to quantify the geospatial drought vulnerability.

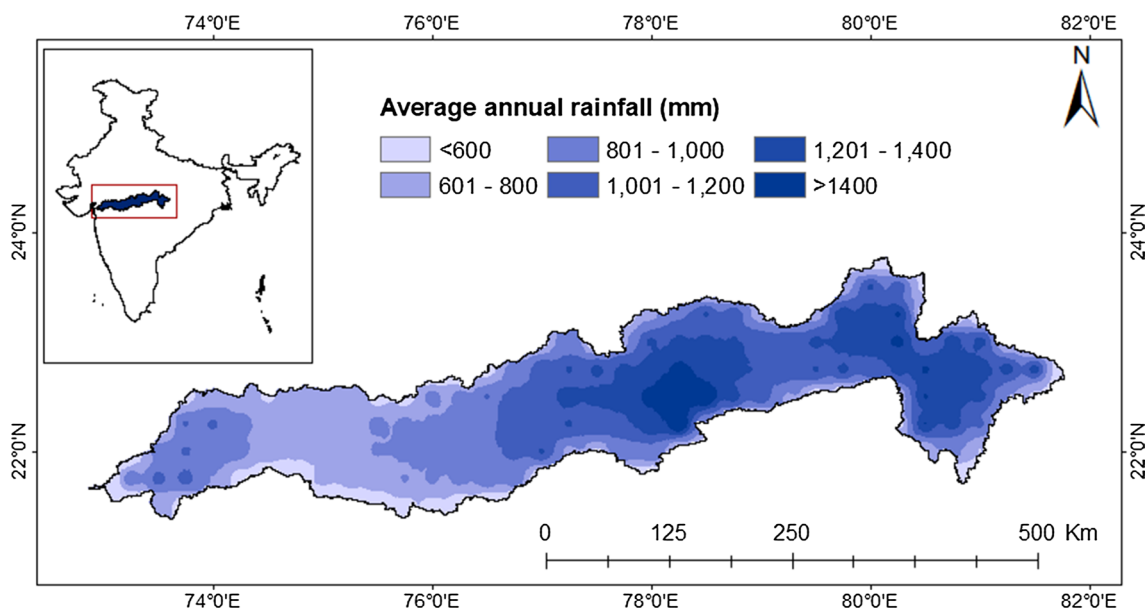
In the context of the large river basins in India, sub-basin-wise assessments are generally carried out. However, the

geospatial drought vulnerability accounts for multi-faceted characterization, which would be helpful to the administrators in better decision-making. As districts are crucial administrative units in India, a district-wise vulnerability mapping would be instrumental in drought prioritization, which would help to mitigate the pernicious impacts of droughts. The specific objectives of this study are as follows: (a) to evaluate the characteristics of the historical droughts using precipitation records, (b) to quantify the different (i.e. hydroclimatic, socio-economic and physiographic) factors over the concerned region, and (c) to integrate all the factors in a GIS framework to accomplish a comprehensive drought vulnerability assessment.

## Materials and methods

### Study area

The Narmada River Basin is selected as the study area. The areal extent of the basin is nearly 100,000 km<sup>2</sup>. It is located in Central India and extends from 21.33°N to 23.75°N latitudes and 72.53°E to 81.75°E longitudes (Fig. 1). The basin area encompasses regions from four states of India, i.e. Chhattisgarh, Gujarat, Madhya Pradesh and Maharashtra, with a majority lying in Madhya Pradesh. The length of the river is 1312 km, making it one of the longest rivers of the Indian sub-continent (Gupta 2001; Pandey et al. 2019, 2021a, 2021b; Swain et al. 2019; Thomas et al. 2015). It is the major west-flowing river of India. The climatic condition of the basin is normally wet and tropical, though extreme hot



**Fig. 1** Location of the study area (Narmada River Basin, India)

and cold conditions are also experienced in some parts. The annual rainfall over the basin varies from 700 to 1400 mm across different parts (Fig. 1), with above 90% of the rainfall received during June to October. The magnitude of annual rainfall is relatively higher over the eastern portions, which decreases towards the western portions of the basin. The temperature varies from 8 to 20 °C across the parts during the winter and above 40 °C during summer. The Narmada Basin mainly consists of black soils. The plains are very fertile and, therefore, the majority of the land use is dedicated to agriculture (Dayal et al. 2021; Pandey and Khare 2017, 2018; Rai et al. 2017; Swain et al. 2021). The basin is enclosed by 35 administrative districts in four states of India. The location details of the districts are provided in Table S1 of the Supplementary Information.

## Data used

As the study aims to assess the vulnerability to droughts in a comprehensive manner, the datasets pertaining to hydro-climatic, physiographic and socio-economic factors are the requisites. The details of the data types used in this study and their sources are provided in Table 1. The long-term (1901–2019) rainfall records are obtained from the India Meteorological Department (IMD). The digital elevation model (DEM) at 90 m resolution is downloaded. The purpose of selecting 90 m resolution in place of 30 m is to reduce the processing time as Narmada Basin covers a very large area (nearly 100,000 km<sup>2</sup>). The elevation and slope maps of the entire basin are obtained from the DEM. Further, DEM is used for watershed delineation, stream order generation and creation of river shapefile. The buffer distance from the river for any point is obtained through this separate river shapefile. For hydrological and agricultural aspects, depth to groundwater level for the recent period, soil types, distance from river reach and LULC are considered. The distance from the river and LULC, along with the population density, also account for the socio-economic factors.

**Table 1** Details of the data types used in this study and their sources

| Data type                  | Details of source  |
|----------------------------|--|
| Rainfall (1901–2019)       | India Meteorological Department (IMD) gridded (0.25° × 0.25°, daily) product. <a href="https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html">https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html</a>  |
| Groundwater data (2019)    | Depth to groundwater level data all over India is available at Water Resources Information System (India-WRIS) Portal, Central Water Commission. <a href="https://indiawris.gov.in/">https://indiawris.gov.in/</a>   |
| Population density (2020)  | Population predicted for 2020 all over the world in gridded form is available from <a href="https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/data-download">https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/data-download</a> |
| Soil                       | National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). <a href="https://www.nbsslup.in">https://www.nbsslup.in</a>   |
| Elevation                  | Digital Elevation Model at 90 m resolution is available from Shuttle Radar Topography Mission (SRTM). <a href="https://srtm.csi.cgiar.org/">https://srtm.csi.cgiar.org/</a>  |
| Land use/land cover (2019) | Copernicus Global Land Service provides classified LULC maps at 100 m resolution all over the world since 2015–2019 (updated annually). <a href="https://land.copernicus.eu/global/products/lc">https://land.copernicus.eu/global/products/lc</a>                                  |

## Methodology

### Standardized precipitation index (SPI)

SPI (McKee et al. 1993) is the most commonly used drought index owing to its uniformity in representing dry/wet conditions, simplicity in computation, and applicability in different timescales. World Meteorological Organization has recommended using SPI to monitor meteorological droughts (Mehr et al. 2020). The calculation of SPI involves fitting the rainfall time series to a probability distribution (preferably Gamma), and then inverse normalization of the cumulative distribution function. SPI can be used to carry out comparative analysis over different climates (Amrit et al. 2019; Swain et al. 2021). Typically, SPI less than zero indicates dry conditions, whereas its value greater than or equal to zero represents a non-drought condition. The classification of SPI into different drought categories is provided in Table 2. The detailed procedure to calculate SPI can be referred from the literature (McKee et al. 1993; Guttman 1999; Swain et al. 2021; Wu et al. 2007).

### Comprehensive drought vulnerability indicator (CDVI)

This study proposes a novel metric, i.e. Comprehensive Drought Vulnerability Indicator (CDVI) to incorporate multiple factors viz. dry year frequency, depth to groundwater

**Table 2** Classification of SPI into different drought categories (McKee et al. 1993)

| Class             | Criteria             |
|-------------------|----------------------|
| Non-drought (Wet) | $SPI \geq 0$         |
| Mild drought      | $0 < SPI < -1$       |
| Moderate drought  | $-1 \leq SPI < -1.5$ |
| Severe drought    | $-1.5 \leq SPI < -2$ |
| Extreme drought   | $SPI \leq -2$        |

level, slope, distance from river reach, population density, LULC, soil type, and elevation. The methodology of CDVI-based vulnerability assessment is presented in Fig. 2. The spatial maps of all these factors are prepared individually. Each factor is then categorized into sub-classes that are assigned weights according to their contribution to drought vulnerability. The weight-assigned spatial layers for all the individual factors are overlaid. Then, CDVI is computed as the weighted sum of all the factors. A higher value of CDVI indicates higher vulnerability to droughts and vice versa. Based on CDVI, the entire basin may be re-classified into different drought vulnerability categories. The CDVI is given by

$$CDVI = \frac{\sum_{i=1}^n W_i}{\sum_{i=1}^n W_{i(max)}} \quad (1)$$

where  $W_i$  and  $W_{i(max)}$  refer to the weight of a sub-class and maximum weight amongst all sub-classes for  $i$ th factor,

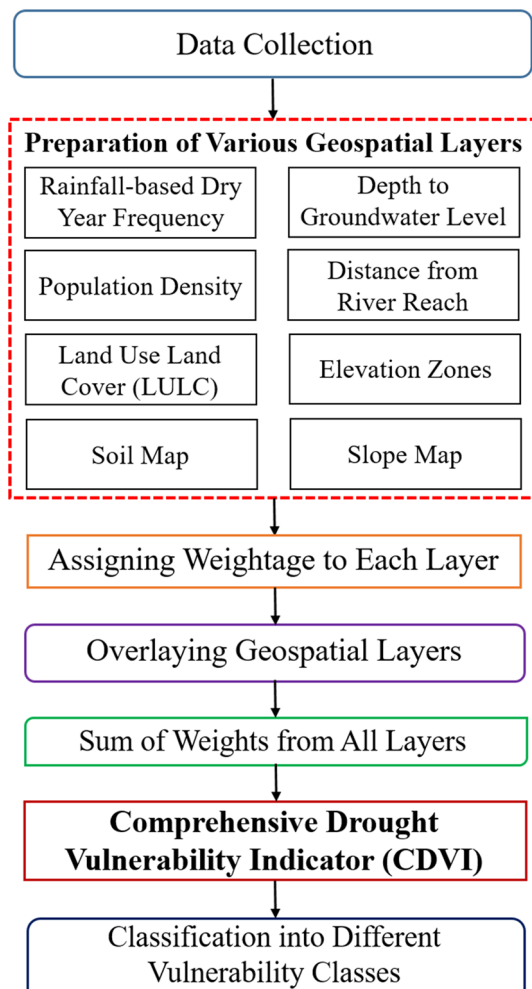


Fig. 2 The methodology adopted for comprehensive drought vulnerability classification

respectively. The values of  $W_i$  along with the percentage area of the Narmada Basin under each sub-class of each factor can be referred from Table 3.

### Results and discussion

It is well known that rainfall plays a significant role in aggravating or ameliorating the drought conditions. Therefore, the analysis of rainfall variation is imperative for drought assessments. The annual rainfall over the Narmada River Basin from 1901 to 2019 is presented in Fig. 3. It is to be noted that the rainfall over the basin is computed by area-weighted rainfall from all the grids, which is a commonly adopted method in hydrology to estimate average rainfall depth over a large area. From Fig. 3a, it is clear that the rainfall over the entire basin ranged from 681 to 1687 mm, with a remarkable inter-annual variation. The low-rainfall years are more frequent in the second half of the time series. Moreover, the trend line of the time series shows a declining pattern, which is also evident from the slope value of  $-0.683$ . A negative trend of annual rainfall can be interpreted as a higher probability of dry years, or more chances of drought occurrences. Hence, there might be more frequent droughts or dry years in recent periods.

The frequency distribution of annual rainfall over the Narmada River Basin in different class intervals of size 100 mm is presented in Fig. 3b. It can be observed that though the annual rainfall may be near-normally distributed, there is skewness in the frequency distribution. Hence, the use of SPI may be preferred over the per cent-departure based indices that typically suffer from the assumption of normal distribution of the data. The mean annual rainfall over the basin is 1127 mm, which falls in the fifth class interval, i.e. 1050–1150 mm (Fig. 3b). Therefore, the first four class intervals and a major portion of the fifth class interval represent the dry conditions.

Considering the high variabilities in the area-averaged annual rainfall over the large Narmada River Basin, it is obvious that the inter-annual rainfall variation over the constituent grids must be significantly higher. Therefore, it is necessary to assess the frequency of rainfall-deficit years at finer scales too. As the normal rainfall (calculated as the mean annual rainfall of above 30 years) varies from region to region, the frequency of dry years is taken as the representative meteorological factor for drought vulnerability. As mentioned previously, the drought years are characterized by negative SPI values. The spatial distribution of the number of dry years ( $SPI < 0$ ) is presented in Fig. 4. In general, SPI represents the equiprobability transformation of dry/wet conditions. Therefore, the regions with 59–60 dry years in a duration of 119 years were given medium weightage for drought vulnerability, whereas the



**Table 3** Weightage of various factors contributing to drought vulnerability

| S. No. | Factors                                       | Categories        | Weights | % Area |
|--------|---|-------------------|---------|--------|
| 1      | Frequency of dry years                        | < 57              | 1       | 12.3   |
|        |   | 57–58             | 2       | 18.1   |
|        |   | 59–60             | 3       | 34.4   |
|        |   | 61–62             | 4       | 29.2   |
|        |   | > 62              | 5       | 6.0    |
| 2      | Depth to groundwater levels (mbgl)            | < 2               | 1       | 4.3    |
|        |   | 2–4               | 2       | 43.2   |
|        |   | 4–6               | 3       | 35.6   |
|        |   | 6–8               | 4       | 12.1   |
|        |   | > 8               | 5       | 4.8    |
| 3      | Population density (persons/km <sup>2</sup> ) | < 100             | 1       | 10.6   |
|        |   | 100–200           | 2       | 35.8   |
|        |   | 200–300           | 3       | 31.1   |
|        |   | 300–400           | 4       | 12.7   |
|        |   | > 400             | 5       | 9.8    |
| 4      | Distance from river reach (km)                | < 1               | 1       | 3.7    |
|        |   | 1–3               | 2       | 6.3    |
|        |   | 3–5               | 3       | 6.1    |
|        |   | 5–7               | 4       | 5.5    |
|        |   | > 7               | 5       | 78.4   |
| 5      | Slope (%)                                     | < 5               | 1       | 69.4   |
|        |   | 5–10              | 2       | 14.1   |
|        |   | 10–15             | 3       | 6.6    |
|        |   | 15–20             | 4       | 3.9    |
|        |   | > 20              | 5       | 6.0    |
| 6      | Soil  | Clayey            | 1       | 60.7   |
|        |   | Clay Skeletal     | 2       | 31.2   |
|        |   | Loam              | 3       | 3.3    |
|        |   | Loamy Skeletal    | 4       | 4.1    |
|        |   | Rock outcrop      | 5       | 0.7    |
| 7      | LULC  | Water bodies      | 1       | 1.6    |
|        |   | Barren land       | 2       | 0.2    |
|        |   | Shrubland         | 3       | 8.2    |
|        |   | Open forest       | 4       | 9.6    |
|        |   | Dense forest      | 5       | 15.2   |
|        |   | Settlements       | 6       | 1.1    |
|        |   | Agricultural land | 7       | 64.1   |
| 8      | Elevation (m)                                 | < 100             | 1       | 3.2    |
|        |   | 101–150           | 2       | 6.4    |
|        |   | 151–200           | 3       | 17.1   |
|        |   | 201–250           | 4       | 28.2   |
|        |   | 251–300           | 5       | 16.0   |
|        |   | 301–350           | 6       | 12.4   |
|        |   | 351–400           | 7       | 8.3    |
|        |   | 401–450           | 8       | 4.8    |
|        |   | 451–500           | 9       | 2.3    |

**Table 3** (continued)

| S. No. | Factors | Categories | Weights | % Area |
|--------|---------|------------|---------|--------|
|        |         | > 500      | 10      | 1.3    |

regions with a higher (lower) frequency of dry years were given more (less) weightage. It is noticeable in Fig. 4 that the meteorological drought frequency is relatively lower in some parts of the eastern half of the basin. The northernmost regions of the basin exhibited the lowest frequency of dry years.

Groundwater is a major source of water supply for fulfilling agricultural, industrial and municipal demands, especially over the arid or semi-arid regions. Particularly during the drought periods, groundwater may act as the primary source due to unavailability or acute deficit of water from other sources. Particularly over agriculture-dominated regions, the coordinated use of surface water and groundwater (i.e. conjunctive use of water) is highly encouraged. Therefore, the availability of groundwater is a crucial factor for drought vulnerability. Generally, depth to groundwater level, which is measured in metres below ground level (mbgl), is considered as the proxy for groundwater availability. An increase in depth to the groundwater table is unfavourable to drought-prone regions. Moreover, these data for all over India are easily available through India-WRIS portal, which makes it possible to monitor the groundwater availability at regular intervals. In this study, the Narmada River Basin is categorized into five classes with increasing order of vulnerability based on groundwater depth of < 2, 2–4, 4–6, 6–8, and > 8 mbgl. The spatial distribution of depth to groundwater level over the basin is presented in Fig. 5, while the percentage of basin area under each category can be referred from Table 3.

The population is a crucial socio-economic factor affecting drought vulnerability. Higher is the population, lesser is the per capita water availability and vice versa. Given the direct linkage of population and water demand, several studies have considered population density as an indicator for computing water stress (Gao et al. 2018; Jaafar et al. 2020; Munia et al. 2018; Gosain et al. 2006). Therefore, the water demand or usage is considerably higher over the urban areas due to a high population density. In this study, the population density over the entire basin is classified in five different categories, i.e. > 400, 300–400, 200–300, 100–200 and < 100 persons/km<sup>2</sup>, where the population density of above 400 and below 100 persons/km<sup>2</sup> is considered to possess, respectively, the highest and the least vulnerability towards droughts. The spatial distribution of population density over the basin is presented in Fig. 6, while the percentage of basin area under each category can be referred from Table 3. It is evident that nearly 10% of the basin area

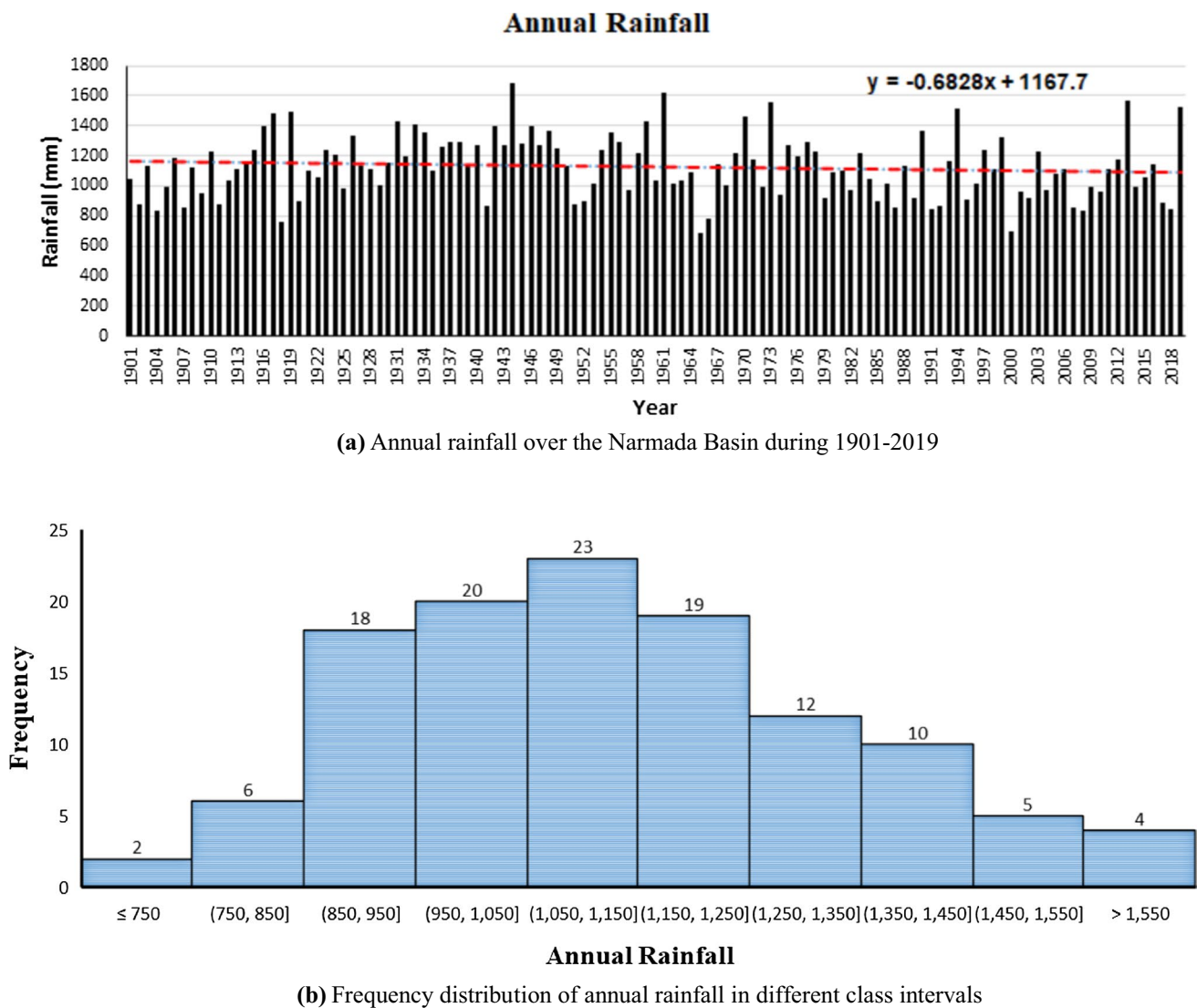


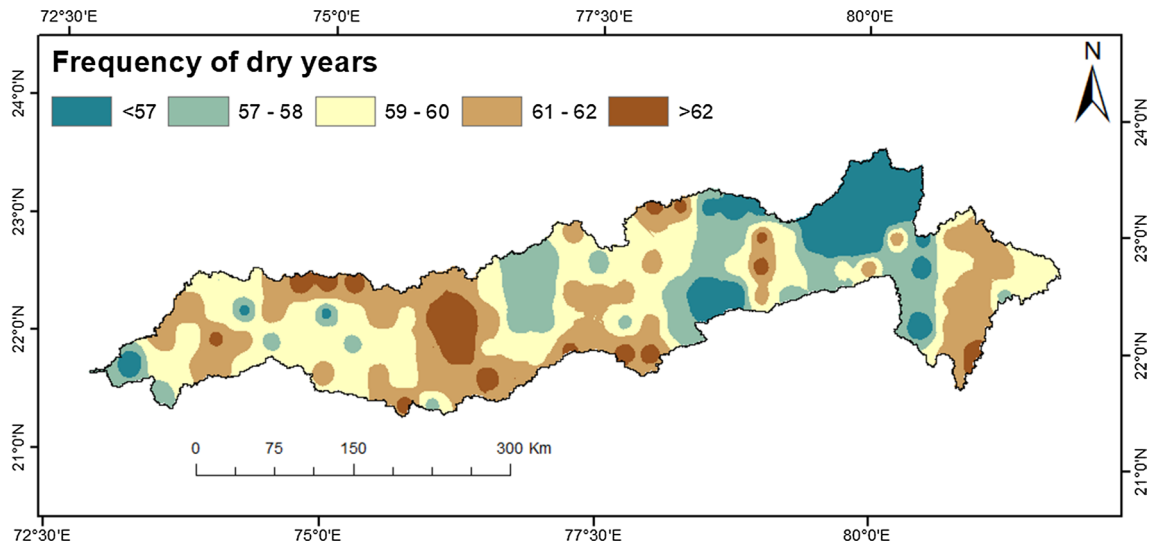
Fig. 3 Time series and frequency distribution of annual rainfall over Narmada Basin during 1901–2019

has a population density of above 400 persons/km<sup>2</sup> and, thus, is most vulnerable to drought or water scarcities.

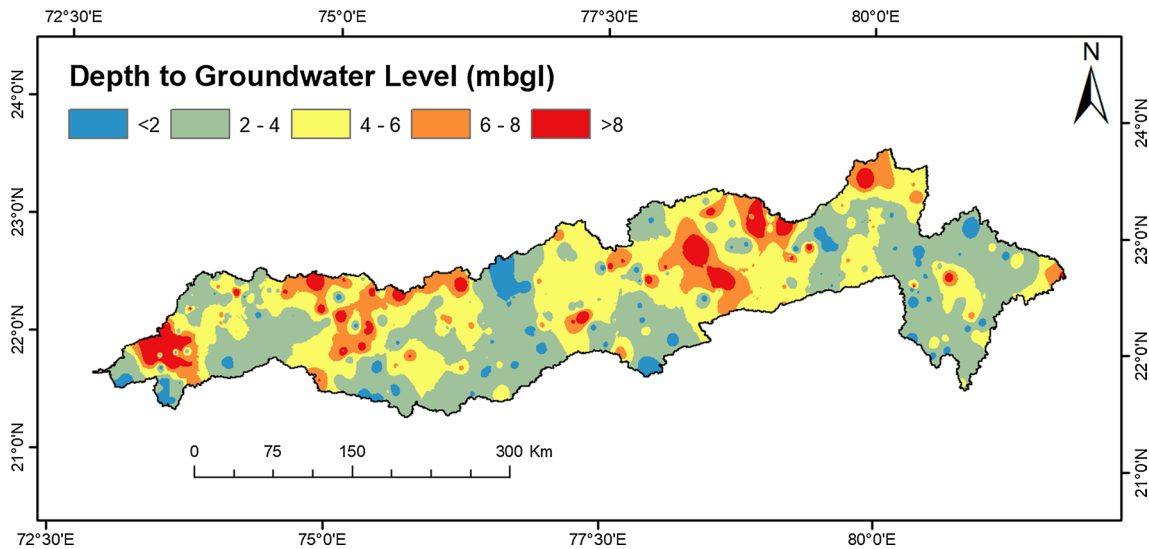
The distance from river reach can be regarded as a proxy for access to the available water. In general, the water availability is better in the nearby regions of the river’s main-stream. These regions are expected to be benefited from relatively higher baseflow compared to the regions distant from river reach. This may be attributed to higher groundwater availability, as well as moisture retention. Access to water decreases with increasing distance from the river reach, thereby increasing the vulnerability towards drought occurrences. In the present study, the basin area is divided into five categories of distance from the river reach, i.e. less than 1 km, 1–3 km, 3–5 km, 5–7 km, and above 7 km, as presented in Fig. 7. It is evident from Table 3 that the percentage area of the basin under these categories are 3.7, 6.3,

6.1, 5.5 and 78.4%, respectively. Therefore, the majority of the basin is under the most vulnerable category in terms of length from river reach.

LULC is amongst the vital components for assessing the impacts of drought occurrences. It is also considered as a signature of the anthropogenic activities of a region. LULC is an important factor to understand the response of the basin to different hydroclimatic factors. It is also directly linked with the spatial variation in water demands. Regarding land use, the impacts of droughts are expected to be maximum over agriculture-dominated regions, followed by the residential areas. Similarly, from the point of view of land cover, the areas with higher vegetation cover are more affected by droughts than the areas with less vegetation cover. Given the fact that a majority of the population in India is directly dependent on agriculture for their livelihoods (Mallya et al.



**Fig. 4** Spatial distribution of frequency of dry years (SPI < 0) over Narmada River Basin



**Fig. 5** Spatial distribution of depth to groundwater level over Narmada River Basin

2016; Udmale et al. 2014), LULC is a crucial socio-economic indicator for drought assessments. The LULC classification of the Narmada River Basin is presented in Fig. 8. There are seven LULC classes over the basin, viz. agricultural land, settlement, dense forest, open forest, shrubland, barren land and water bodies, with decreasing weightage towards drought vulnerability. The weights and percentage of basin area under each class can be referred from Table 3. It is evident that a majority (64.1%) of the basin area is covered by agricultural lands and, therefore, is most vulnerable to droughts.

Soil type is considered as a contributing factor to the drought vulnerability assessments due to the property of

water retention abilities. The water retention capacity varies with the soil type, specifically with respect to the texture or grain structure of the constituent particles. Soils with finer particles (e.g. clay) can hold more water than soils with coarser particles. The classified soil map of the Narmada River Basin is presented in Fig. 9. There are five soil types over the basin, viz. clayey, clayey skeletal, loamy, loamy skeletal, and rock outcrops, with increasing weightage towards drought vulnerability. The ability of clayey soil to hold more moisture for a longer period is helpful for supplying water to crops/plants during water-scarce conditions and, therefore, is most effective in dealing with droughts. The basin is majorly dominated by clayey (60.7%) and clayey



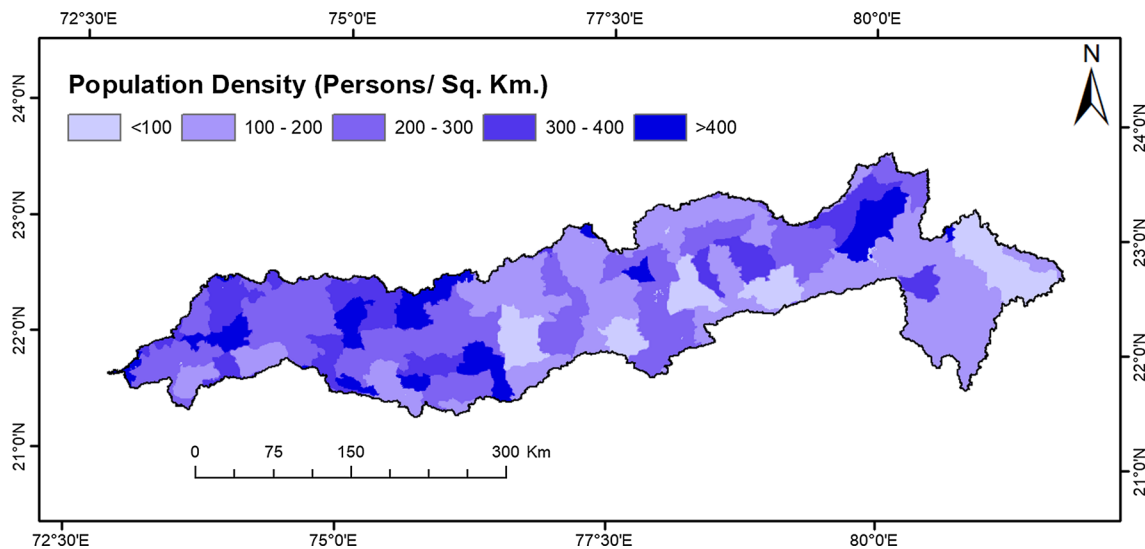


Fig. 6 Spatial distribution of population density over Narmada River Basin

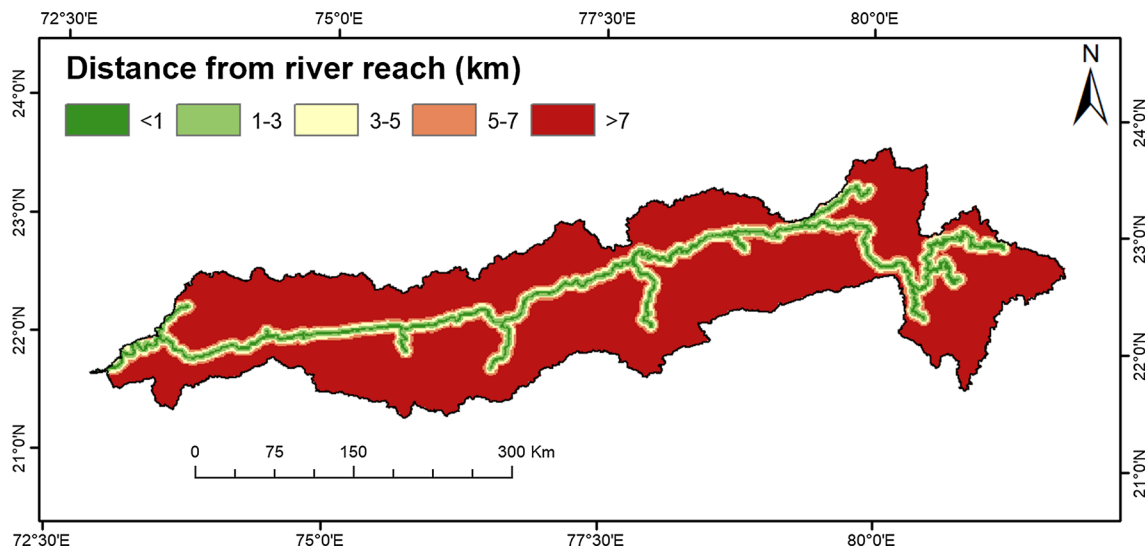


Fig. 7 Spatial distribution of distance from river reach over Narmada River Basin

skeletal (31.2%) soil types (Table 3). Hence, from the point of view of soil types, Narmada Basin is in desirable condition as most parts of the basin possess the least vulnerability to droughts.

The elevation zones and slopes can also be adjudged as crucial factors from the point of view of drought consequences. In general, water availability is negatively correlated with elevation and slope, i.e. higher is the elevation, lower is the water availability. This is due to the fact that higher elevation zones are associated with undulating terrain with generally high slopes. Consequently, their soil moisture retention is lower, and thus, the streams are ephemeral (fail to sustain flow all around the year). Moreover, these

regions consist mostly of first- or second-order streams. On the other hand, the lower elevation zones have higher soil moisture retention due to their flat topography. These areas are also mostly associated with streams of higher orders, and thus, high flow sustains throughout the year. Even if the streams originate from high elevation zones, they receive contributions from more regions towards the lower elevations, thereby enhancing their flow. Further, the high elevation zones often get less baseflow compared to the lower reaches. Therefore, the lower elevation zones and low slopes can be assumed to be less vulnerable to droughts. In the present study, the elevation of the Narmada Basin is divided into 10 classes with a class interval size of 50 m (Table 3).

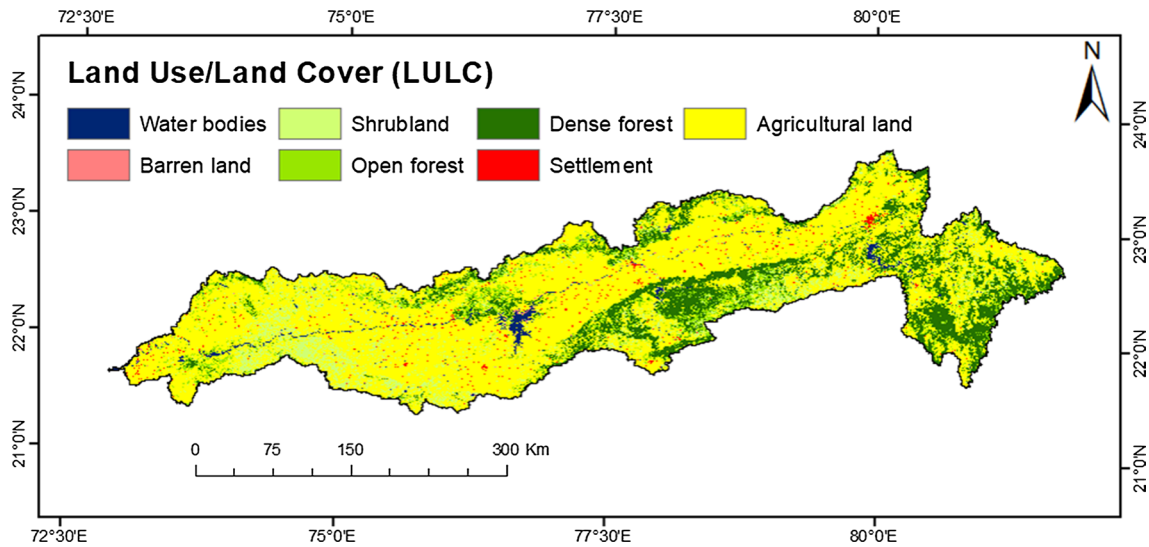


Fig. 8 Classified LULC map of Narmada River Basin

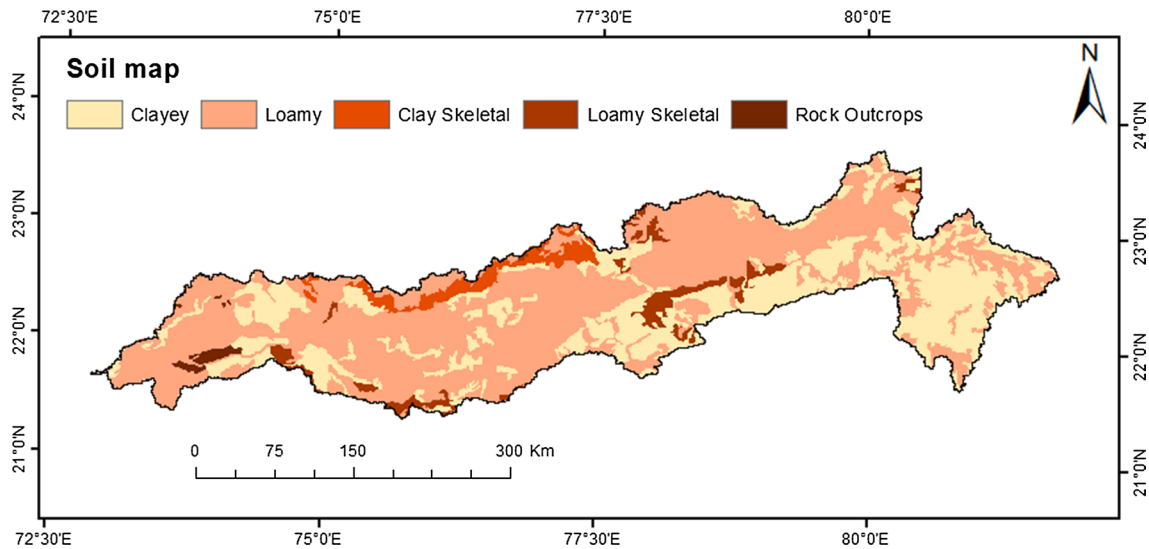
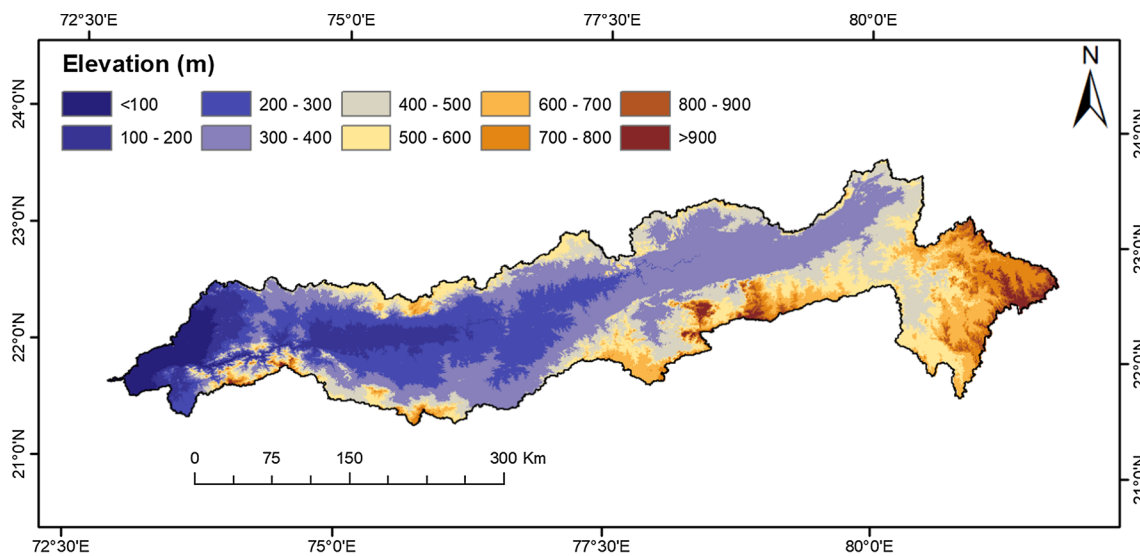


Fig. 9 Classified soil map of Narmada River Basin

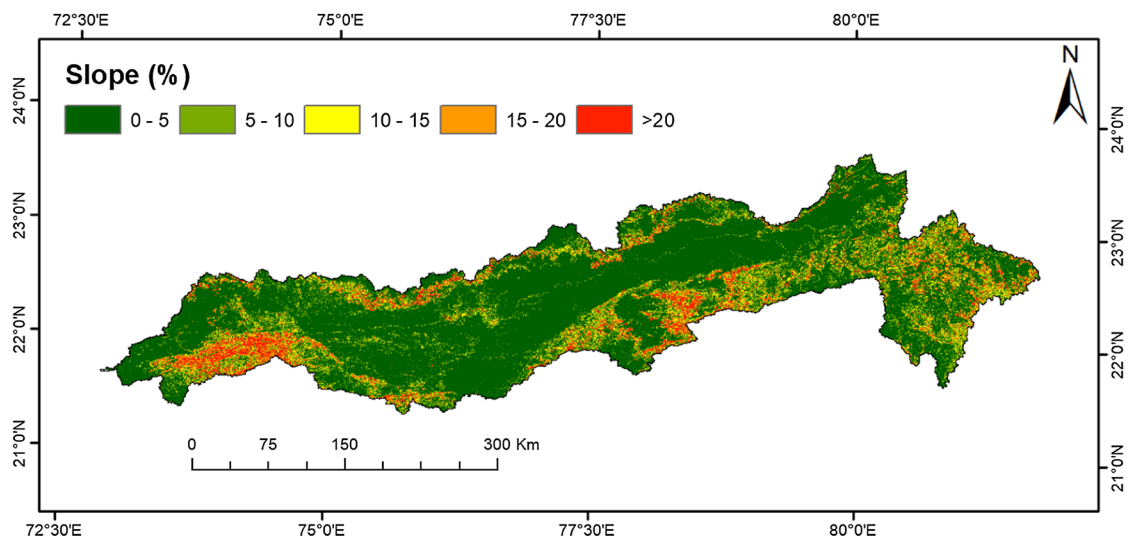
The regions with elevations above 500 m and below 100 m are considered most vulnerable and least vulnerable, respectively. Similarly, the slope over the basin is classified in five different categories, i.e. <5, 5–10, 10–15, 15–20 and >20%, with increasing order of vulnerability towards droughts. The spatial variation in elevation and slope over the Narmada Basin is presented in Fig. 10a, b, respectively. From Table 3 and Fig. 10, it is evident that the basin is mostly associated with flat slopes, although some portions have steep slopes due to hilly terrains. Similarly, the majority of the catchment lies under low to middle elevation zones.

The geospatial layers of different variables are overlaid in GIS, and the comprehensive drought vulnerability

indicator (CDVI) is derived using the weighted-sum approach. The CDVI map of the Narmada River Basin is presented in Fig. 11. It is evident that the CDVI possesses a significant geospatial variation over the basin. It is to mention that CDVI is the direct representation of the region’s vulnerability to droughts. Therefore, a region with a high CDVI indicates its diminished capacity to resist or recover from drought’s impacts, which implies that particular region to be highly vulnerable to drought conditions. From Fig. 11, it can be observed that some regions in the western part of the basin showed a very high CDVI, while high CDVI values are also exhibited by some regions in the upper eastern portions. The consequences of droughts would be relatively



(a) Elevation map of Narmada River Basin



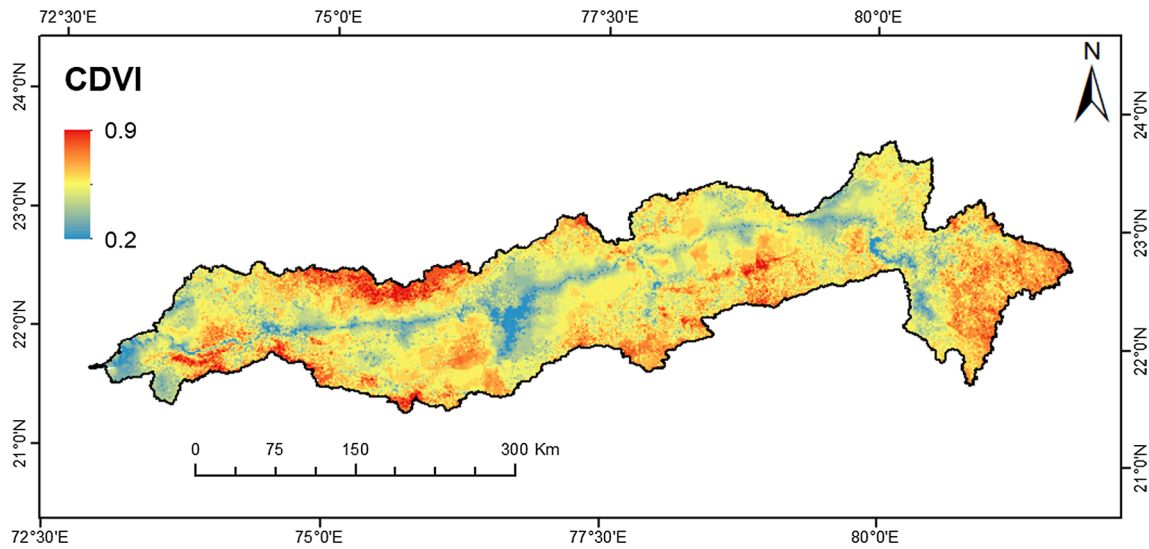
(b) Slope (%) map of Narmada River Basin

**Fig. 10** Spatial variation of **a** elevation, **b** slope over Narmada River Basin

more severe over these regions. Interestingly, some regions in the central and westernmost portions of the basin exhibited lower CDVI, even though the mean annual rainfall over these regions is relatively lower. This can be attributed to their location in the vicinity of the river, groundwater availability at lower depth, low elevation and flat slopes. Similarly, the northernmost regions of the basin, which showed the lowest frequency of meteorological droughts in the basin (refer Fig. 4), also exhibited high CDVI. This is due to high population density, longer distance from the river reach, higher depth to the groundwater table, and urban settlements within these regions. It is well known that the water demand is very high over the urban settlements, as well as

the areas in their vicinity. These results substantiate that the information on only meteorological fluctuations or SPI time series may be misleading in determining drought vulnerability over a region, which the multi-dimensional CDVI can circumvent.

The CDVI is categorized into five drought vulnerability classes, viz. non-vulnerable, less vulnerable, moderately vulnerable, highly vulnerable and extremely vulnerable. This re-classification aims to make it convenient for communicating the drought vulnerability information to the general audience. The CDVI range for these classes and the percentage area of the basin under each vulnerability class is presented in Table 4. Further, Fig. 12 depicts the re-classified



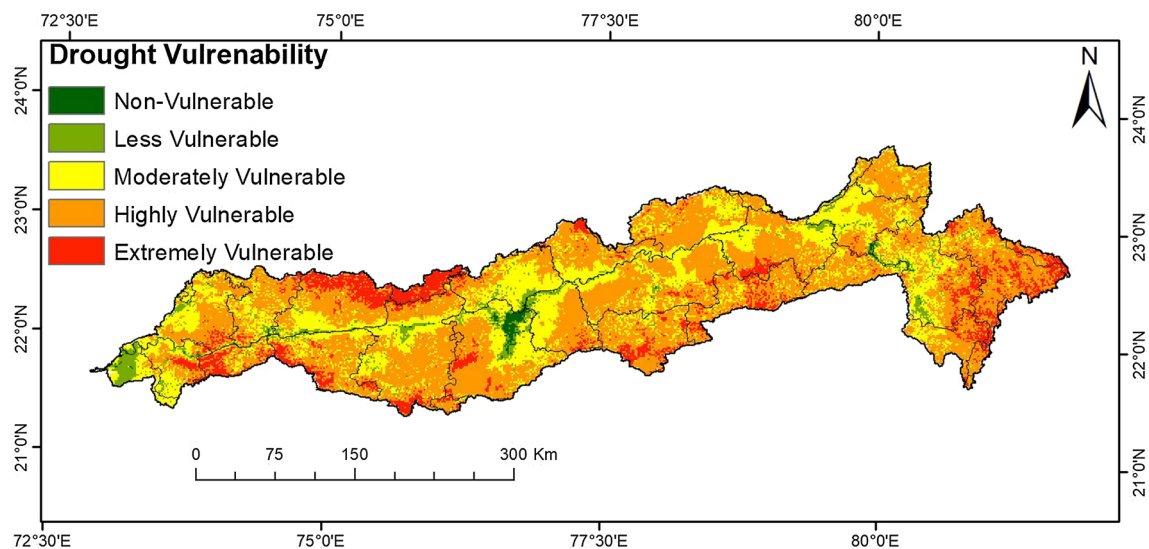
**Fig. 11** Spatial distribution of CDVI over Narmada River Basin

**Table 4** Classification of CDVI into different drought vulnerability categories

| S. No. | CDVI Range | Drought vulnerability class | Area (%) |
|--------|------------|-----------------------------|----------|
| 1      | <0.35      | Non-vulnerable              | 0.77     |
| 2      | 0.35–0.45  | Less vulnerable             | 4.57     |
| 3      | 0.45–0.55  | Moderately vulnerable       | 28.30    |
| 4      | 0.55–0.65  | Highly vulnerable           | 55.48    |
| 5      | >0.65      | Extremely vulnerable        | 10.88    |

drought vulnerability map of the Narmada River Basin. As evident from Fig. 12 and Table 4, the majority of the basin falls under the highly vulnerable class (55.48%), followed by moderately vulnerable (28.3%), extremely vulnerable (10.88%), less vulnerable (4.57%) and non-vulnerable (0.77%) classes. Hence, almost two-thirds of the basin falls under highly to extremely vulnerable categories.

The primary purpose of this multi-dimensional drought vulnerability approach is to help policy-makers or administrators for effective planning and management of water resources over the basin. As districts are crucial administrative units in India, a district-wise quantification of drought vulnerability would be highly useful in drought



**Fig. 12** Classification of Narmada Basin into different vulnerability categories based on CDVI

prioritization, which would help to mitigate the pernicious impacts of droughts. To this end, the mean CDVI of individual districts is determined by area-averaging of the CDVI values in the constituent grids. The district-wise CDVI and the corresponding drought vulnerability class over the Narmada River Basin are presented in Table 5. It can be observed that none of the 35 constituent districts of Narmada Basin is under non-vulnerable or less vulnerable conditions, whereas 9, 22 and 4 districts exhibited

moderate, high and extreme vulnerability to droughts, respectively. The Bharuch district exhibited the lowest vulnerability (Mean CDVI = 0.464), followed by Surat (Mean CDVI = 0.491). On the other hand, Indore, Dhule, Bhopal, and Anuppur are found to be the most vulnerable districts with Mean CDVI of 0.704, 0.702, 0.681, and 0.651, respectively. The results emphasize immediate attention towards developing adaptation and mitigation strategies over the basin, taking the district-wise prioritization into

**Table 5** District-wise CDVI-based drought vulnerability classification over Narmada River Basin

| S. No. | District Name | Latitude | Longitude | Mean CDVI | Drought Vulnerability Class |
|--------|---------------|----------|-----------|-----------|-----------------------------|
| 1      | Anuppur       | 23.06    | 81.68     | 0.651     | Extremely Vulnerable        |
| 2      | Balaghat      | 21.88    | 80.36     | 0.593     | Highly Vulnerable           |
| 3      | Barwani       | 21.79    | 75.02     | 0.578     | Highly Vulnerable           |
| 4      | Betul         | 21.88    | 77.87     | 0.595     | Highly Vulnerable           |
| 5      | Bharuch       | 21.79    | 72.93     | 0.464     | Moderately Vulnerable       |
| 6      | Bhopal        | 23.47    | 77.39     | 0.681     | Extremely Vulnerable        |
| 7      | Burhanpur     | 21.37    | 76.37     | 0.606     | Highly Vulnerable           |
| 8      | Chhindwara    | 22.12    | 78.85     | 0.605     | Highly Vulnerable           |
| 9      | Dahod         | 22.86    | 74.11     | 0.573     | Highly Vulnerable           |
| 10     | Damoh         | 23.81    | 79.53     | 0.528     | Moderately Vulnerable       |
| 11     | Dewas         | 22.74    | 76.46     | 0.532     | Moderately Vulnerable       |
| 12     | Dhar          | 22.50    | 75.10     | 0.598     | Highly Vulnerable           |
| 13     | Dhule         | 21.11    | 74.60     | 0.702     | Extremely Vulnerable        |
| 14     | Dindori       | 22.89    | 81.05     | 0.613     | Highly Vulnerable           |
| 15     | East Nimar    | 21.93    | 76.57     | 0.533     | Moderately Vulnerable       |
| 16     | Harda         | 22.23    | 77.12     | 0.547     | Moderately Vulnerable       |
| 17     | Hoshangabad   | 22.59    | 77.99     | 0.556     | Highly Vulnerable           |
| 18     | Indore        | 22.71    | 75.78     | 0.704     | Extremely Vulnerable        |
| 19     | Jabalpur      | 23.23    | 79.98     | 0.533     | Moderately Vulnerable       |
| 20     | Jhabua        | 22.89    | 74.67     | 0.563     | Highly Vulnerable           |
| 21     | Kabirdham     | 22.09    | 81.22     | 0.634     | Highly Vulnerable           |
| 22     | Katni         | 23.75    | 80.40     | 0.564     | Highly Vulnerable           |
| 23     | Mandla        | 22.64    | 80.51     | 0.553     | Highly Vulnerable           |
| 24     | Nandurbar     | 21.55    | 74.22     | 0.607     | Highly Vulnerable           |
| 25     | Narmada       | 21.74    | 73.64     | 0.549     | Moderately Vulnerable       |
| 26     | Narsinghpur   | 22.94    | 79.09     | 0.561     | Highly Vulnerable           |
| 27     | Panch Mahals  | 22.72    | 73.63     | 0.508     | Moderately Vulnerable       |
| 28     | Raisen        | 23.22    | 78.12     | 0.560     | Highly Vulnerable           |
| 29     | Raj Nandgaon  | 21.04    | 80.82     | 0.614     | Highly Vulnerable           |
| 30     | Sagar         | 23.85    | 78.76     | 0.568     | Highly Vulnerable           |
| 31     | Sehore        | 22.99    | 77.13     | 0.569     | Highly Vulnerable           |
| 32     | Seoni         | 22.32    | 79.69     | 0.564     | Highly Vulnerable           |
| 33     | Surat         | 21.27    | 73.07     | 0.491     | Moderately Vulnerable       |
| 34     | Vadodara      | 22.25    | 73.24     | 0.552     | Highly Vulnerable           |
| 35     | West Nimar    | 21.92    | 75.77     | 0.566     | Highly Vulnerable           |



account, thereby reducing the vulnerability and enhancing the resilience towards droughts.

Given the fact that many of the contributing factors of drought vulnerability are dynamic, the concept of comprehensive drought vulnerability may be used to monitor the effects of proactive management strategies in regular time intervals. The simple geospatial approach to compute CDVI enables visualizing the increase or decrease in the drought vulnerability in a dynamic manner. The water management in transboundary river basins is a major challenge; however, the proposed approach of district-level drought vulnerability prioritization can certainly help to move forward. Further, this study substantiates the advantage of the all-inclusive approach over the ones based on only historical rainfall records, especially in the era of Anthropocene. Such studies should also be extended to other basins or regions of the world suffering from the adverse impacts of droughts and water scarcity, thereby being instrumental in fulfilling the sustainable development goals.

## Conclusions

This study presented a detailed analysis of drought vulnerability over the Narmada River Basin, India, considering the hydroclimatic, socio-economic and physiographic factors. A novel drought vulnerability metric, i.e. CDVI is proposed that assimilates the information on meteorological fluctuations, depth to groundwater level, slope, distance from river reach, population density, land use/land cover, soil type and elevation through a weighted-sum geospatial approach. The key conclusions drawn from the study are as follows:

1. Regarding individual factors, LULC and distance from river reach over major portions of the basin are in highly vulnerable conditions. On the other hand, soil and slope are less vulnerable to drought over most of the basin area. The basin possesses diversity in vulnerability weights for the remaining factors (groundwater availability, rainfall fluctuations, elevation zones, and population density).
2. The CDVI map revealed a remarkable geospatial variation in overall drought vulnerability, with a majority (66.4%) of the basin under highly to extremely vulnerable conditions.
3. The district-wise assessment revealed that no constituent district of Narmada Basin is under non-vulnerable or less vulnerable conditions, whereas 9, 22 and 4 districts exhibit moderate, high and extreme vulnerability to droughts, respectively.

4. The results emphasize an immediate attention towards developing adaptation and mitigation strategies over the basin, taking the district-wise prioritization into account, thereby reducing the vulnerability and enhancing the resilience towards droughts. The all-inclusive approach proposed in this study for drought vulnerability mapping would certainly help the administrators or policy-makers to effectively plan and manage water resources over the basin, especially to ameliorate the pernicious impacts of droughts.

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**Availability of data and material** The sources of all the datasets used are provided in the manuscript. The finally prepared geospatial layers can be available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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