



A detailed assessment of meteorological drought characteristics using simplified rainfall index over Narmada River Basin, India

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Abstract

Drought is amongst the most precarious phenomena that cause serious repercussions, especially over the agriculture-dominated regions. A detailed assessment of droughts is necessary to develop robust frameworks for combating its ill effects. This study presents an analysis of meteorological drought characteristics (frequency, severity and persistence) using precipitation data of twenty-four districts for 1954–2013 over the Narmada River Basin, which is located in the core of the Indian Monsoon region and has great agricultural importance. Further, the entire duration is divided into two epochs, i.e. 1954–83 and 1984–2013, for comparative analysis. A simplified rainfall index (RI_S) is proposed, which is based on the concept of percentage deviation from normal monsoon rainfall along with the uniform transition from moderate to severe and severe to extreme droughts. The basin is found to be prone to droughts and the drought frequency varied from once in three to 8 years over different districts. The droughts are more frequent and severe in the western portions of the basin as compared to the eastern portions. The majority of the districts have undergone droughts persisting for 3 years at least once. The epoch-wise analysis reveals a significantly higher frequency, severity and persistence of droughts in the recent epoch. The results of trend analysis using the Modified Mann–Kendall test indicate an increasing trend of droughts over twenty-one districts and significantly increasing over eleven districts. The information reported in this study will be helpful for proper planning and management of water resources over the basin and hence, reduce the pernicious effects of droughts.

Keywords Narmada Basin · Drought characteristics · Simplified rainfall index · Drought trend

Introduction

Drought is one of the most precarious natural phenomena striking mankind frequently and can be ascribed to precipitation aberrations, as evident from several prior studies (Dabanlı et al. 2017; Mishra et al. 2009; Rossi et al. 1992; Tigkas et al. 2012; Tsakiris and Vangelis 2004; Wilhite and Glantz 1985). This is a momentous issue for India due to its agro-based economy being excessively dependent on monsoon rainfall. Moreover, due to rapid urbanization, population explosion, and industrial growth, the problems of water

scarcity have increased manifold (Kundu et al. 2017). The anthropogenic activities have also deteriorated the water quality of existing resources (Adimalla et al. 2018a, b; Li and Wu 2019; Li et al. 2014). Agriculture and urbanization are the two major signatures of human activities. The responses of weather and climate extremes can be dangerous in terms of droughts to agriculture and intense storms to urban areas. It is also projected by several studies that climate change will intensify the global hydrological cycle, which may result in frequent hydrological extremes (Caloiero 2014; Gosain et al. 2006, 2011; Roxy et al. 2017; Singh et al. 2019; Wilhite et al. 2014). Further, the impacts of climate change are predicted to be more severe over South-Asian river basins (Lutz et al. 2019). The consequences will be more pronounced in arid and semiarid regions, possibly in terms of an increase in droughts (Mishra and Singh 2010). The changes in drought characteristics have significant impacts on crop productivity and management of water resources. Therefore, it is imperative to study the spatiotemporal patterns of droughts, which

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can help to manage scarce water resources and alleviate the alarming concerns of food security.

The droughts are commonly categorized into four types, i.e. meteorological, agricultural, hydrological and socio-economic (Dracup et al. 1980; Mishra and Singh 2010, 2011; Wilhite et al. 2007). Meteorological drought is defined as an abnormal rainfall deficit persisting for a long period, which propagates to other forms of drought. Therefore, meteorological droughts are characterized at long timescales, i.e. seasonal, annual or multi-monthly scales. The characterization of droughts is usually carried out using indices. Drought indices are crucial elements for the assessment and monitoring of droughts as they simplify the complicated inter-relationships between the climatic parameters, which helps researchers and professionals in evaluating the climatic anomalies in terms of their frequency, duration, intensity or spatial distribution (Mishra and Singh 2010; Montaseri and Amirataee 2017). Further, the quantitative assessment of onset, persistence and termination of droughts can be monitored effectively using these indices, which is a crucial issue for drought risk analysis. Some of the precipitation-based drought indices are: Standardized Precipitation Index (SPI) (McKee et al. 1993), Percent Normal Precipitation Index (PNPI) (Hayes 2006), Rainfall Anomaly Index (RAI) (van Rooy 1965), Decile Index (Gibbs and Maher 1967), Rainfall Departure (RD) (Amrit et al. 2018a, b), Percent Departure from Mean (PDM) (Swain et al. 2020), Bhalme and Mooly Drought Index (Bhalme and Mooly 1980), Drought Severity Index (Bryant et al. 1992), Z score (Kutiel et al. 1996), China Z Index (Ju et al. 1997), Effective Drought Index (Byun and Wilhite 1999), Topor Pluviometric Index (Sabău et al. 2015), Nitzche Index (Nitzche et al. 1985), Drought Frequency Index (González and Valdés 2006), maximum consecutive dry days (Yuan et al. 2015), etc. Among these indices, SPI is recognized to be the most widely used drought indicator (Montaseri and Amirataee 2017; Swain et al. 2017).

In the Indian context, as per the India Meteorological Department (IMD), when the rainfall over a particular region during a season/year is less than 75% of the corresponding expected value, i.e. long-term seasonal/annual mean of rainfall over that region, it is called a meteorological drought (Amrit et al. 2018a, b; Pandey et al. 2010; Udmale et al. 2014). In other words, a deficit of 25% or more with respect to the normal rainfall is regarded as a drought. There are several analogous indices based on percentage deviation from normal rainfall viz. PNPI, RAI, RD, PDM, etc. Among these, PNPI and RD have been extensively used for drought characterization. The advantages of using these indices are that these can be computed for different timescales, i.e. at monthly, seasonal or annual basis. They can be used effectively to analyze droughts over a single region or on a single season (Hayes 2006; Swain et al. 2017). Because of their

simplicity and transparency, these are advantageous for communicating drought levels to the public (Keyantash and Dracup 2002). However, the limitation of PNPI or RD is the assumption of normality in rainfall distribution. Therefore, they are applicable over the regions where there is no significant difference between the mean and the median of rainfall time series.

SPI has an inherent advantage of uniform characterization in terms of transitioning from one severity class to another, i.e. moderate to severe or severe to extreme droughts. SPI value less than or equal to -1 is regarded as drought, while the moderate, severe and extreme droughts are identified as $-1.5 < \text{SPI} \leq -1$, $-2 < \text{SPI} \leq -1.5$ and $\text{SPI} \leq -2$, respectively. However, this transition is not uniform in the case of PNPI or RD. Amirataee and Montaseri (2017) characterized severe and extreme droughts corresponding to below 55% and below 40% of normal precipitation, respectively. Similarly, Amrit et al. (2018a, b) defined severe and extreme droughts for respective deficits of 45% and 60% with respect to mean rainfall. Sayari et al. (2013) specified severe and extreme droughts at a deficit of 52% and 84% from normal rainfall, respectively. It is evident from these studies that the drought is defined at a 25% deficit from normal precipitation; however, their threshold for severe/extreme classes is very high (deficit) and with a non-uniform transition. As a result, although these indices perform well in recognizing the total number of drought events and achieve consistency with SPI, they tend to underestimate the severe or extreme droughts. Therefore, it is in order to develop a drought index based on the percent deficit approach with a uniform transition of moderate to severe and severe to extreme droughts. This will be a modified version of PNPI or RD, which will retain their advantages along with the ability to capture the severe/extreme droughts justifiably, particularly over the regions with near-normal precipitation distribution.

The application of statistical tools for trend detection of droughts has gained substantial contemporary attention. The historical trend and variability of meteorological droughts over Taiwan were investigated by Chen et al. (2009) using SPI at a trimonthly timescale, using long-term rainfall records from 22 weather stations and Mann–Kendall (MK) test. The results showed a significant increasing trend in the number of dry days and drought frequencies all over Taiwan. Using monthly rainfall data for 1951–2007, Kumar et al. (2012) carried out the spatiotemporal assessment of SPI-based drought occurrences using the MK test over parts of the Indian region during the southwest monsoon season. The moderate droughts were found to possess an increasing trend over most of the regions investigated. Thomas et al. (2015a, b) applied the nonparametric MK test for trend analysis of rainfall and drought events over the drought-prone Bundelkhand region. A decreasing trend was observed for seasonal rainfall and number of rainy days

over most of the stations. The 3-month SPI possessed statistically significant decreasing trends at a 95% confidence level, thereby indicating for an increasing trend of severe droughts during monsoon season. Mahajan and Dodamani (2015) carried out a trend analysis of droughts by nonparametric MK test using monthly rainfall data for 1960–2012 from 59 stations over the Upper Krishna river basin, which is frequently subjected to severe droughts. The droughts characterized by PNPI showed a significant increasing trend over only 5 stations at seasonal and annual scales. The trend analysis of SPI-based droughts over Kano, Nigeria, during 1911–2010 was performed by Achugbu and Anugwo (2016) using MK and Sen's slope estimator tests. The overall trend was found to be decreasing for some months; however, the trend of rainfall and SPI was increasing in the last three decades (1981–2010). Khadr (2016) evaluated the temporal and spatial characteristics of SPI-based meteorological droughts in the Upper Blue Nile basin using monthly rainfall data for 1960–2008 from 22 stations. The application of MK test inferred the trend of drought characteristics to be statistically insignificant over almost all the stations. Huang et al. (2014) investigated the trends in droughts over Wei River Basin, China from 1961 to 2005 using modified Mann–Kendall (MMK) test. The eastern portions of the basin had a significant drying trend, whereas the western portion had significant wet trend. Amirataee and Montaseri (2017) explored spatiotemporal drought trends over Iran during 1965–2014 using MMK test. The results revealed a significant (at 95% confidence level) increase in droughts over the country, especially in the northwestern portions. Ahmed et al. (2018) investigated meteorological drought trends over Pakistan during 1901–2010 using MMK test and found an increasing trend of drought frequency in both the seasons. Qutbudin et al. (2019) applied MMK test to assess the drought trends over Afghanistan from 1901 to 2010. The results indicated an increasing drought severity over the region. Apart from these studies, trend analysis of drought events has been performed using drought indices and MK or MMK tests over several parts of the globe, e.g., Kuwait (Almedej 2014), South Africa (Botai et al. 2016), Northern and East Asia (Sheffield and Wood 2008), Nebraska, USA (Wu et al. 2008), Coruh River Basin, Turkey (Tosunoglu and Kisi 2017) etc. Most of these studies revealed an increasing trend of drought events in the recent past. Recent studies (Ahmed et al. 2018; Amirataee and Montaseri 2017; Huang et al. 2014; Mehr and Vaheddoost 2020; Qutbudin et al. 2019; Vu et al. 2015) have suggested that the conventional MK test suffers from misleading trend results if the data points are autocorrelated and thus, the Modified MK test should be preferred for analyzing drought trends.

The Narmada River is the fourth-longest river in India and is also called “Life Line of Gujarat and Madhya Pradesh” for its huge contribution to these two large states of India.

Narmada River Basin, located in the core of Indian monsoon region, is known for exquisite crop productivity due to an ample amount of rainfall and improved irrigation system in certain parts (Gupta 2001; Pandey and Khare 2018). Nevertheless, in recent years, a downward trend of crop productivity has been observed, possibly as a consequence of prolonged severe droughts (Rickards et al. 2020; Thomas et al. 2015a, b). This is a major concern for India, due to its vast population and agro-based economy. Therefore, assessment of drought characteristics over the basin considering long-term precipitation data is of paramount concern; however, no study is found in the literature to have comprehensively addressed the same. Moreover, the assessment of regional variation in drought severities is mostly limited to the comparison of the most intense drought event, as evident from numerous prior studies (Amrit et al. 2018a, b; Bayissa et al. 2018; Ghosh 2018, 2019; Saravi et al. 2009; Toshunoglu and Kisi 2017). However, this may be misleading, especially for comparing drought severities among two or more districts. Therefore, accounting for the frequency of droughts in different severity classes (i.e. moderate, severe and extreme) can be useful.

Given all the above-mentioned research needs, this study aims to carry out a comprehensive characterization and assessment of droughts over the Narmada River Basin. The key objectives are to (a) assess the frequency of droughts over Narmada Basin using a suitable drought index, (b) quantify the drought frequency in moderate, severe and extreme classes for better analysis of the droughts severities, (c) divide the entire duration into two equal parts and carry out a comparative analysis of drought characteristics (frequency, severity and persistence) to understand the effects of climate change and (d) estimate the drought trends over the basin.

Description of study area and data used

Narmada River Basin is located at the core of Indian monsoon region. It spatially extends from 21.33° N to 23.75° N latitudes and 72.53° E to 81.75° E longitudes and covers an area of 99,000 km². The location of the Narmada basin and the enclosing districts (stations) are presented in Fig. 1. Narmada River is the major west-flowing river and one of the longest rivers of India. It traverses a total length of 1312 km through three states, i.e. Madhya Pradesh (~ 1100 km), Maharashtra (~ 40 km) and Gujarat (~ 165 km). The topographical features of the basin can be divided into two categories viz., hilly terrains in the upper eastern portions and fertile plains in the middle as well as lower regions of the basin. Narmada Basin has a sub-tropical climate (Mondal et al. 2015; Pandey and Khare 2017, 2018). Rainfall over the basin is monsoon-driven, i.e. a vast majority of annual rainfall over the basin is contributed by the southwest monsoon

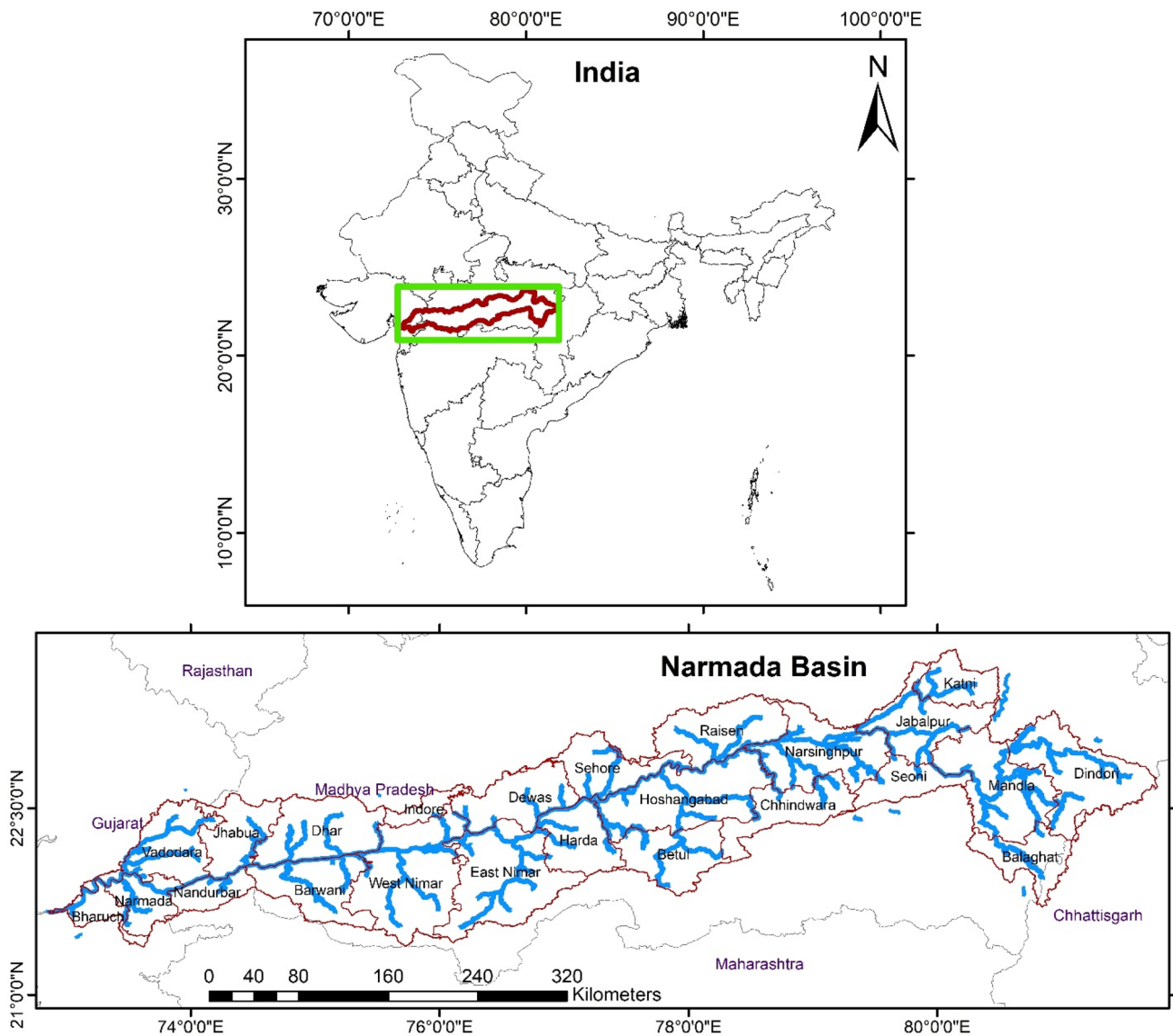


Fig. 1 Location of Narmada River Basin (India) with its constituent districts

season, prevailing from mid-June to mid-October. The population of the basin is mostly dependent on agriculture. Wheat, paddy, soybean, jowar, sugarcane, mung bean and gram are the major crops cultivated in the basin (Pandey et al. 2019).

There are 24 districts from three states (i.e. Madhya Pradesh, Gujarat and Maharashtra) enclosing the Narmada basin. However, a majority of the basin, i.e. 20 districts, lie within Madhya Pradesh. From the rest, three districts (Bharuch, Narmada and Vadodara) lie in Gujarat, whereas the Nandurbar district lies in Maharashtra. Monthly rainfall data for 60 years, i.e. 1654–2013, is collected for all 24 districts from India Meteorological Department (IMD), Pune. The mean annual rainfall and the mean monsoon season rainfall for all the districts over the Narmada basin are presented in

Table 1. It is noticeable that the percentage contribution of monsoon season to annual rainfall varies from 91.8 to 97.8. Considering the agricultural importance of the basin, a substantial rainfall deficit in monsoon season may result in severe repercussions. On the other hand, the rainfall in other seasons is scanty and thus, has little to negligible impacts on drought occurrences. Hence, in this study, only rainfall during the monsoon season, i.e. June–October, is taken for assessment of drought characteristics.

Table 1 Contribution of Monsoon season to the annual contribution over districts of Narmada basin

District	Mean annual rainfall (mm)	Mean monsoon rainfall (mm)	% contribution of monsoon season to annual rainfall
Balaghat	1375.6	1290.4	93.8
Barwani	701.0	675.3	96.3
Betul	1070.3	1002.7	93.7
Chhindwara	1108.5	1024.1	92.4
Dewas	978.7	942.0	96.2
Dhar	834.1	811.0	97.2
Dindori	1295.6	1205.5	93.0
East Nimar	866.5	825.6	95.3
Harda	1086.3	1038.7	95.6
Hoshangabad	1343.2	1278.8	95.2
Indore	925.7	887.6	95.9
Jabalpur	1224.2	1146.9	93.7
Jhabua	862.9	840.9	97.4
Katni	1131.2	1077.1	95.2
Mandla	1355.0	1257.7	92.8
Narsinghpur	1183.6	1121.2	94.7
Raisen	1183.8	1130.5	95.5
Sehore	1128.5	1079.0	95.6
Seoni	1192.7	1094.9	91.8
West Nimar	782.2	750.0	95.9
Bharuch	812.1	797.6	98.2
Narmada	1125.8	1110.8	98.7
Vadodara	964.9	945.3	98.0
Nandurbar	907.0	880.8	97.1

Methodology

Drought index

Among the drought indices, SPI (McKee et al. 1993) is used most widely. However, SPI follows a long and complex procedure of standardizing the rainfall amounts into a reduced variate. It is obtained by fitting the rainfall time series to a suitable probability distribution (preferably 2-parameter Gamma distribution) and inverse normalization of the cumulative distribution function (Blain and Meschiatti 2015; Guttman 1999). The computation procedure of SPI is described as follows. The probability distribution function (pdf) of 2-parameter Gamma distribution is given by,

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \text{ for } x > 0 \tag{1}$$

where, α and β are shape and scale parameters, respectively, and $\Gamma(\alpha)$ is the Gamma function.

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy \tag{2}$$

The cumulative distribution function (CDF) of Gamma distribution is given by,

$$G(x) = \int_0^x g(x) dx \tag{3}$$

The population mean (μ) and variance (σ^2) pertinent to Gamma distribution are related to α and β as,

$$\mu = \alpha\beta \tag{4}$$

$$\sigma^2 = \alpha\beta^2 \tag{5}$$

The integral expression of the probability function of μ and σ^2 are given by,

$$\mu = \int_0^\infty xg(x) dx \tag{6}$$

$$\sigma^2 = \int_0^\infty (x - \mu)^2 g(x) dx \tag{7}$$

The integrations in Eqs. (6) and (7) are challenging to perform. Thom (1958) developed an approach using maximum likelihood concepts to estimate α and β , as given in Eqs. (8), (9) and (10).

$$\alpha = \frac{1}{4A} \left[1 + \sqrt{1 + \frac{4A}{3}} \right] \tag{8}$$

$$\beta = \frac{\bar{x}}{\alpha} \tag{9}$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{10}$$

where, \bar{x} is the sample mean and is computed as,

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \tag{11}$$

\bar{x} is taken as the unbiased approximation of the population mean and thus, is utilized for estimating α and β parameters.

As Gamma distribution is not applicable to zero values, a mixed cumulative probability distribution is considered that accounts zeros and positive values (rainfall amounts).

$$H(x) = q + (1 - q)G(x) \tag{12}$$

where, q is the probability of zero values. If there is a data series of n data points and m records are zeros, then q can be estimated as m/n . $G(x)$ refers to the CDF of the Gamma distribution fitted to the positive rainfall values.

The cumulative probability $H(x)$ is transformed to a standard normal variable Z with a mean of zero and a standard deviation of one. Thus, SPI is the reduced variate of rainfall obtained by the inverse normalization of $H(x)$.

$$SPI = \psi^{-1}[H(x)] \tag{13}$$

Abramowitz and Stegun (1965) formulated a precise approximation of SPI as provided in Eq. (14) and (15). The cumulative probability $H(x)$ ranges from zero to unity. Owing to the equiprobability transformation, value of $H(x)$ below (above) 0.5 yields negative (positive) SPI value, thereby indicating dry (wet) conditions. Therefore, SPI is able to represent both dry and wet conditions effectively.

$$Z = SPI = -\left(t - \frac{c_0 + c_1t + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) \text{ for } 0 < H(x) \leq 0.5 \tag{14}$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1t + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) \text{ for } 0.5 < H(x) \leq 1.0 \tag{15}$$

$$t = \sqrt{\ln\left(\frac{1}{[H(x)]^2}\right)} \text{ for } 0 < H(x) \leq 0.5 \tag{16}$$

$$t = \sqrt{\ln\left(\frac{1}{1 - [H(x)]^2}\right)} \text{ for } 0.5 < H(x) \leq 1.0 \tag{17}$$

where, $c_0 = 2.515517$; $c_1 = 0.802853$; $c_2 = 0.010328$; $d_1 = 1.432788$; $d_2 = 0.189269$; and $d_3 = 0.001308$.

Although SPI theoretically ranges from $-\infty$ to $+\infty$, 99.8% of the values generally lie within $[-3, 3]$. A zero value of SPI indicates absolutely normal precipitation. Typically, SPI values ranging from -1 to 1 are considered near-normal conditions. A SPI value less than -1 is regarded as a drought condition and is further categorized into moderate ($-1.5 < SPI \leq -1$), severe ($-2 < SPI \leq -1.5$) and extreme ($SPI \leq -2$) droughts. For a normally distributed time series, a cumulative probability of less than 16% corresponds to SPI below -1.

The assumption of Gamma distribution to be the fitting distribution may be useful; however, it is impossible to determine the exact probability distribution for the rainfall data. For a higher length of data, the Gamma distribution converges towards the normal distribution, which is concordant to the central limit theorem. Therefore, several studies (Amrit et al. 2019; Angelidis et al. 2012; Mishra

et al. 2019) have advocated the use of normal distribution for computation of SPI for regions with long-term rainfall records. The normality of time series is also the inherent assumption for drought characterization using the percent-deficit-based indices. The percent departure of rainfall from normal (which is the basis of RD) is employed in several studies for the assessment of drought characteristics. RD is given by,

$$RD = \frac{P_i - P_m}{P_m} \times 100 \tag{18}$$

where P_i is the rainfall amount for the i th season/year, and P_m is the long-term mean value over that particular season/year. The long-term average or mean rainfall is regarded as the normal rainfall. In general, the long-term mean refers to the average value of the entire duration considered. In hydro-meteorological applications, the entire duration should be at least 30 years for their mean value to be regarded as long-term mean.

Considering the IMD criterion of 25% deficit from normal rainfall as drought, a Simplified Rainfall Index (RI_S) is proposed, which is given as,

$$RI_S = \frac{1}{25\%} \times \frac{P_i - P_m}{P_m} = \frac{P_i - P_m}{0.25 \times P_m} \tag{19}$$

Equation (19) may be rephrased as:

$$RI_S = \frac{4(P_i - P_m)}{P_m} \tag{20}$$

From the simple computation procedure of RI_S , it can be recognized that a deficit of 25% from the mean ($P_i = 0.75P_m$) results in a value of -1, which is the threshold of meteorological drought condition. Similarly, RI_S yields a value of 0 and -2 corresponding to absolutely normal ($P_i = P_m$) and extreme drought ($P_i = 0.5P_m$) conditions, respectively. The detailed classification of drought or wet conditions based on RI_S values is presented in Table 2.

Table 2 Classification of Simplified Rainfall Index into dry/wet categories

Condition	RI_S	Class
$P_i > 1.5P_m$	$RI_S > 2$	Extremely wet
$1.375P_m < P_i \leq 1.5P_m$	$1.5 < RI_S \leq 2$	Severely wet
$1.25P_m < P_i \leq 1.375P_m$	$1 < RI_S \leq 1.5$	Moderately wet
$0.75P_m < P_i \leq 1.25P_m$	$-1 < RI_S \leq 1$	Near normal
$0.625P_m < P_i \leq 0.75P_m$	$-1.5 < RI_S \leq -1$	Moderate drought
$0.5P_m < P_i \leq 0.625P_m$	$-2 < RI_S \leq -1.5$	Severe drought
$P_i \leq 0.5P_m$	$RI_S \leq -2$	Extreme drought

Both SPI and RI_S may not be able to identify droughts over the regions with a lot of zero rainfall values (Alsumaiei 2020; Wu et al. 2007). However, the advantage of the latter is its simplicity and exemption of complicated procedures to carry out the standardization of rainfall. RI_S also possess the uniformity in the transition of droughts from moderate to severe, and severe to extreme droughts, and thus, is capable of capturing the severe/extreme droughts. Further, RI_S is also equivalent to SPI in depicting both dry and wet conditions, as the classification system of RI_S presented in Table 2 is synonymous with that of SPI. It is pertinent to mention that only the monsoon season is considered in this study, which is practically impossible to yield any zero value of rainfall. The percent deficit-based indices are effective for modeling droughts over a single season (Hayes 2006). Moreover, almost all the districts over the Narmada basin possess near-normal distribution of rainfall as evident from the closeness of their mean and median values at annual as well as monsoon–seasonal bases (Table S1 of Supplementary Information). Hence, RI_S is applicable over the Narmada River Basin for characterizing droughts and their detailed assessments.

Procedure for drought assessment over Narmada Basin

The overall workflow of this study is presented in Fig. 2. The time series of RI_S is constructed for each district using monsoon season (June–October) rainfall data for 60 years. Based on the RI_S values, the drought years are identified. The number of droughts in total as well as in different severity classes (moderate, severe and extreme) during the entire period are analyzed. Further, the entire duration is divided into two

30-year periods/epochs viz., 1954–83 and 1984–2013. For each epoch, the number of droughts in aggregate as well as in different severity classes are determined. The maximum persistence of droughts over individual districts during both periods is also analyzed. On the other hand, the RI_S series of each district is evaluated for the presence of trends and their statistical significance using the Modified Mann–Kendall (MMK) test.

Regarding the MMK test, a positive (negative) value of the test statistic, Z_{MMK} , signifies an increasing (decreasing) trend. RI_S is the reduced variate of the monsoon rainfall; hence, a negative trend of RI_S implies a decreasing trend of rainfall, which exacerbates the drought condition. Therefore, when the MMK test is applied to the RI_S time series, if $Z_{MMK} < 0$, the trend of droughts is increasing and vice versa (Fig. 2). The detailed description of the MMK test is provided below.

Modified Mann–Kendall test

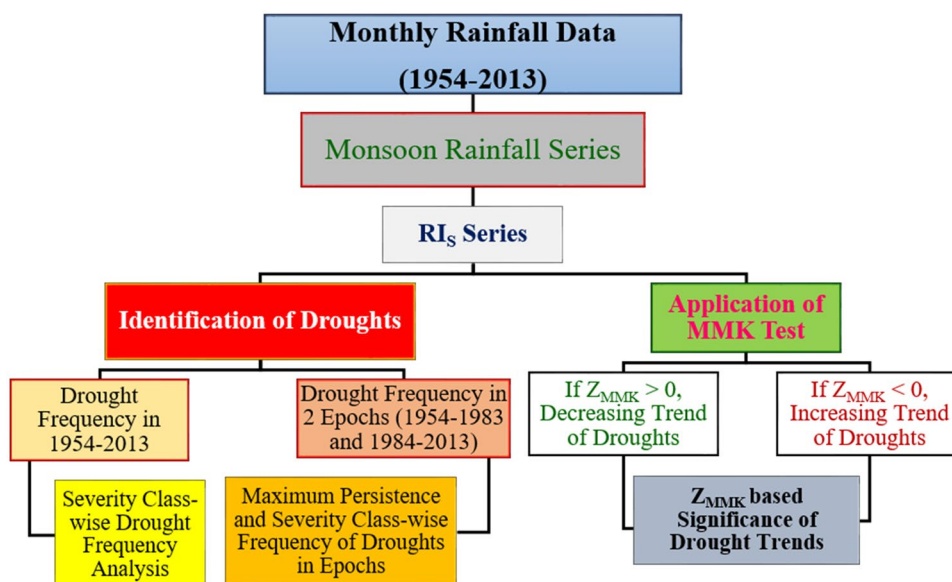
The MMK test statistic (Z_{MMK}) is computed as,

$$Z_{MMK} = \begin{cases} \frac{S-1}{\sqrt{V^*(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V^*(S)}} & \text{if } S < 0 \end{cases} \tag{21}$$

where S and $V^*(S)$ are computed as given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \tag{22}$$

Fig. 2 The methodology of drought assessment over Narmada Basin



$$\begin{aligned}
 V^*(S) &= \text{VAR}(S) \cdot C_f \\
 &= \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \cdot C_f
 \end{aligned}
 \tag{23}$$

Here, x_i and x_j refer to the data points in the time series with a condition of $i < j$, sgn refers to the signum function, n is the total number of data points, t_i refers to the tied groups, $V^*(S)$ and $\text{VAR}(S)$ is the variance of the MMK test and the original Mann–Kendall (MK) test respectively. The MK test suffers from misleading trend results if the data points are autocorrelated (Duhan and Pandey 2013; Hamed and Rao 1998; Kundu et al. 2015; Tiwari and Pandey 2019). The MMK test was proposed by Hamed and Rao (1998), where they introduced a correction factor (C_f) accounting for the autocorrelation of all lags $\rho_s(i)$ among the data points.

$$C_f = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i)
 \tag{24}$$

where,

$$\rho_s(i) = \frac{\frac{1}{n-i} \sum_{t=i+1}^n (x_t - \bar{x})(x_{t-i} - \bar{x})}{\sqrt{\frac{1}{n} \sum_{t=1}^n (x_t - \bar{x})^2} \sqrt{\frac{1}{n} \sum_{t=i+1}^n (x_{t-i} - \bar{x})^2}}
 \tag{25}$$

ρ_s is the serial autocorrelation of all lags in the series. The serial correlation occurs in a time series when a variable and a lagged version of itself (i.e. at time t and $t-i$) are correlated.

A positive (negative) value of Z_{MMK} indicates an increasing (decreasing) trend. A significance level (α) is also used to test the statistical confidence of the trend. Since Z_{MMK} is normally distributed, its magnitude above $Z_{\alpha/2}$ in a two-tailed test confirms the significance of the trend. The threshold of $Z_{\alpha/2}$ corresponding to 10%, 5% and 1% significance level are 1.645, 1.96 and 2.576, respectively (Suryavanshi et al. 2014).

Results and discussion

The number of droughts ($\text{RI}_S < -1$) over each district during 1954–2013 is identified, and is presented in Fig. 3 and Table 3. It can be seen from Fig. 3 that the number of

droughts varies from seven to seventeen over different districts in the considered 60 years duration. This implies the frequency of drought varies from once in 3–8 years over the basin. A majority (i.e., 15 districts) of districts experience a drought in every 5 years or less. It is also noticeable that the droughts are more frequent over the western portions of the basin compared to the eastern portions. Vadodara district has experienced a maximum of 17 droughts, followed by Jhabua and Narmada that have experienced 16 and 15 droughts, respectively. On the other hand, Balaghat, Raisen and Seoni districts have experienced the minimum number of droughts (i.e. seven) during 1954–2013 (Table 3).

The frequency of droughts alone may not be sufficient to understand the meteorological aberrations over a region. Two regions with the same frequency of droughts may undergo a remarkable difference in severities. Therefore, the frequency of droughts in different severity classes should be analyzed. The district-wise distribution of droughts in moderate ($-1.5 < \text{RI}_S < -1$), severe ($-2 < \text{RI}_S < -1.5$) and extreme ($\text{RI}_S < -2$) classes during 1954–2013 are presented in Fig. 4 and the detailed information can be referred from Table 3. The number of moderate droughts varies from three over Katni district to twelve over Barwani district. Three districts viz., Harda, Hoshangabad and Nandurbar, have undergone severe droughts six times. Raisen is the only district that has experienced no drought in severe class; however, it has experienced extreme drought once. Out of the twenty-four districts, fourteen districts have at least undergone an extreme drought during 1954–2013, with a maximum of four over the Vadodara district, followed by three over Jhabua, Katni and Bharuch districts. It is interesting to note that, although Katni district has been subjected to only three moderate droughts, it has experienced five severe and three extreme droughts. Regarding the severe or extreme droughts, Katni and Vadodara districts have experienced eight times, which is the highest among all the districts (Table 3).

Climate change leads to alterations in patterns of meteorological parameters. The adverse impacts of climate change includes intensification of hydrological cycle. This leads to frequent fluctuations of rainfall causing more intense rainfall and longer dry spells. Thus, climate change is regarded to be largely responsible for increasing the drought frequency, severity and area of exposure, as mentioned in recent studies (Aadhar and Mishra 2020; Mallya et al. 2016; Mukherjee

Fig. 3 Total number of droughts over districts of Narmada Basin during 1954–2013

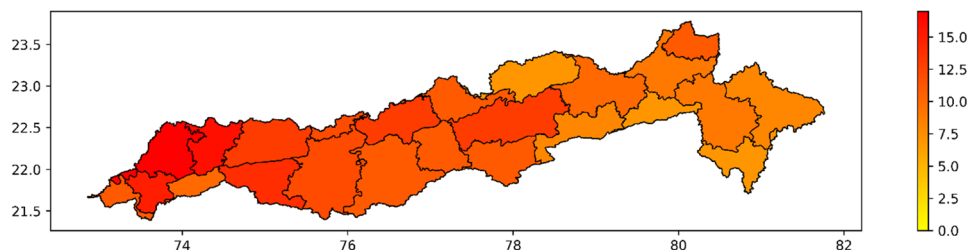


Table 3 Summary of RI_S-based drought frequencies over Narmada Basin

Phase District	1954–1983				1984–2013				1954–2013			
	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total
Balaghat	2	1	0	3	3	1	0	4	5	2	0	7
Barwani	4	1	0	5	8	1	0	9	12	2	0	14
Betul	2	3	0	5	3	2	1	6	5	5	1	11
Chhindwara	2	1	0	3	3	1	1	5	5	2	1	8
Dewas	1	1	0	2	9	1	1	11	10	2	1	13
Dhar	3	0	1	4	8	1	0	9	11	1	1	13
Dindori	1	2	0	3	4	0	1	5	5	2	1	8
East Nimar	1	1	0	2	5	3	1	9	6	4	1	11
Harda	1	3	0	4	4	3	0	7	5	6	0	11
Hoshangabad	1	1	0	2	6	5	0	11	7	6	0	13
Indore	2	1	1	4	4	4	0	8	6	5	1	12
Jabalpur	2	2	1	5	3	1	0	4	5	3	1	9
Jhabua	7	1	1	9	4	1	2	7	11	2	3	16
Katni	0	3	0	3	3	2	3	8	3	5	3	11
Mandla	4	1	0	5	4	0	0	4	8	1	0	9
Narsinghpur	2	1	0	3	6	1	0	7	8	2	0	10
Raisen	2	0	1	3	4	0	0	4	6	0	1	7
Sehore	3	0	0	3	5	3	0	8	8	3	0	11
Seoni	2	0	0	2	3	2	0	5	5	2	0	7
West Nimar	2	2	0	4	6	2	0	8	8	4	0	12
Bharuch	3	1	1	5	2	2	2	6	5	3	3	11
Narmada	4	1	1	6	6	3	0	9	10	4	1	15
Vadodara	4	1	1	6	5	3	3	11	9	4	4	17
Nandurbar	4	1	0	5	0	5	0	5	4	6	0	10

et al. 2018; Tabari and Willems 2018). To investigate this, the entire duration was divided into two epochs, i.e. 1954–83 and 1984–2013, for comparative analysis. The number of droughts over the districts of the Narmada Basin during these two periods is presented in Fig. 5 and Table 3. The frequency of droughts is higher during the recent epoch over twenty out of twenty-four districts. The frequency of droughts has been lower in recent epoch over only three districts, viz., Jabalpur, Jhabua and Mandla, whereas Nandurbar is the only district to have experienced the same number of droughts during both the periods. It can be observed from Table 3 that the number of drought ranges from two to nine during 1954–83 and from four to eleven during 1984–2013. In the first epoch, only Jhabua district has undergone nine droughts, followed by six droughts over Narmada and Vadodara districts. However, in the recent epoch, the districts Dewas, Hoshangabad and Vadodara experienced eleven droughts, followed by nine over Barwani, Dhar, East Nimar and Narmada. Further, sixteen districts have at least experienced six droughts in the second epoch. Tacitly, it also indicates an increase in the area exposed to drought events over the basin.

The frequency of droughts in different severity classes during 1954–83 and 1984–2013 are presented in Fig. 6 and Table 3. It can be seen that the frequency of droughts has increased in all the severity classes over most of the districts. The number of droughts over different districts during 1954–83 ranged from 0 to 7, 0 to 3 and 0 to 1 for moderate, severe and extremes classes, respectively. However, the corresponding range during 1984–2013 is 0 to 9, 0 to 5 and 0 to 3. It is interesting to note from Table 3 that Nandurbar experienced four moderate droughts and one severe drought during 1954–83 whereas, all the five droughts it experienced during 1984–2013 were in severe category. Therefore, although the total number of droughts is equal in both the periods, the severity is significantly higher in the latter one.

The maximum persistence (in years) of droughts over individual districts of Narmada River Basin during 1954–83 and 1984–2013 is presented in Fig. 7. It is evident that the highest persistence of droughts has remarkably increased over the basin. During 1954–83, it varied between one to 3 years. Only three districts, i.e. Betul, Harda and Jhabua had experienced droughts for three consecutive years at least once. There are twelve districts where the maximum persistence of droughts was 2 years and nine districts where

Fig. 4 Total number of droughts in moderate, severe and extreme classes over districts of Narmada Basin during 1954–2013

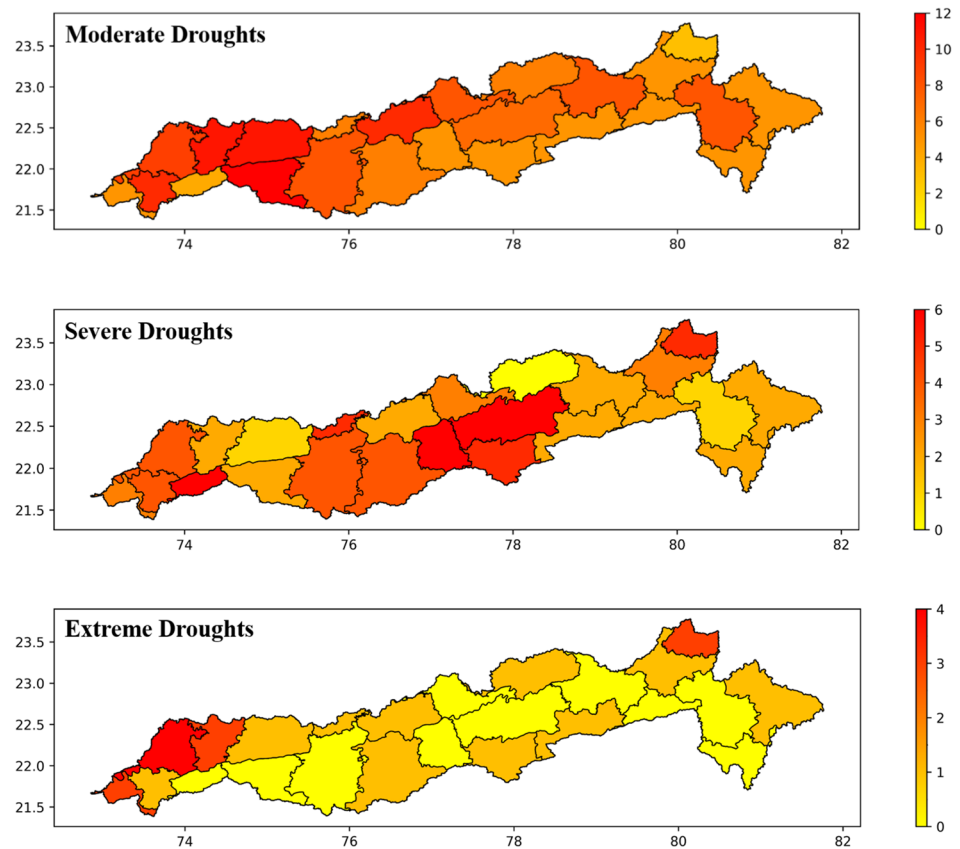
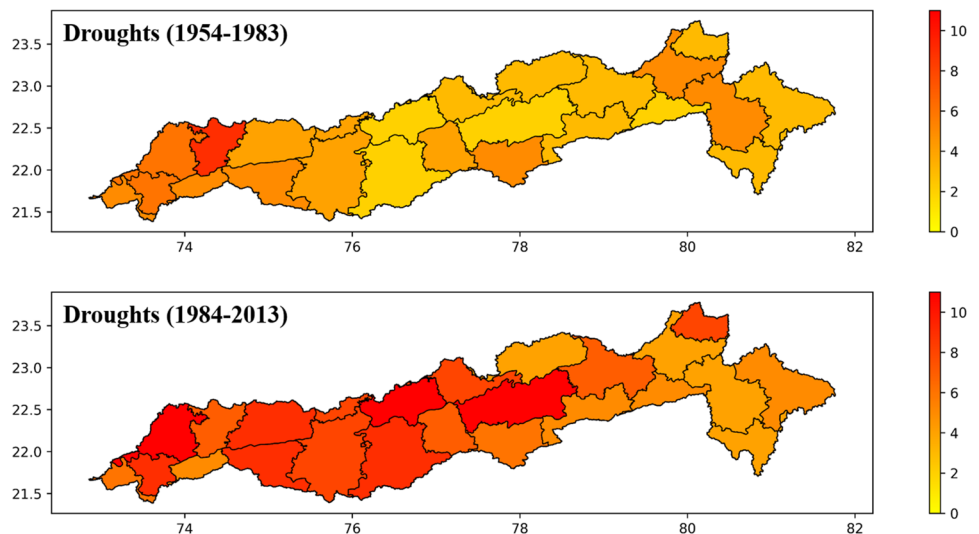


Fig. 5 Total number of droughts over districts of Narmada Basin during 1954–1983 and 1984–2013



droughts never occurred for two consecutive years during 1954–83. On the other hand, during 1984–2013, the persistence or continuity of droughts varied between one to 4 years. There are only five districts that have not witnessed droughts for two consecutive years. Similarly, there are five districts with the maximum drought persistence of 2 years, while a majority (13 out of 24 districts) has experienced

droughts for three consecutive years at least once in 30 years. Further, one district (i.e. Narmada district) has experienced a drought continuing for four consecutive monsoons. Therefore, the continuity of drought years has been longer in the recent epoch. Further, a comparison between the two epochs also reveals that the maximum persistence in 1984–2013 is higher than that of 1954–83 over twelve districts whereas,

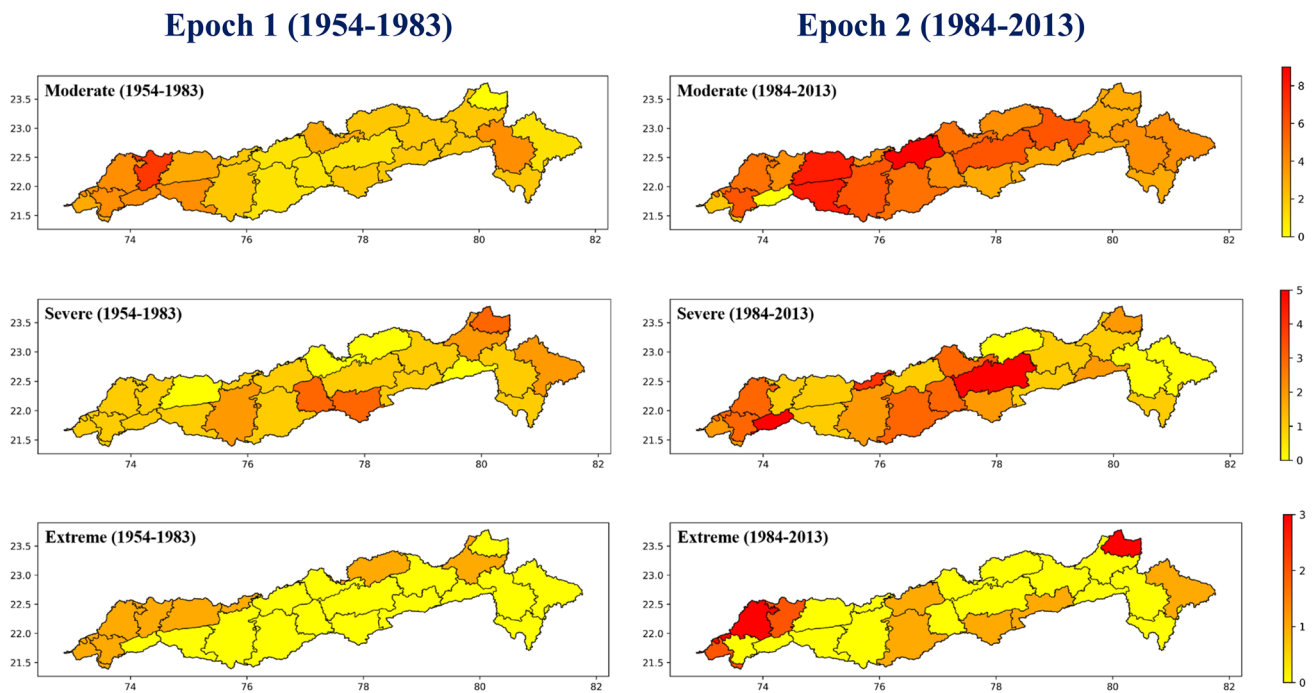
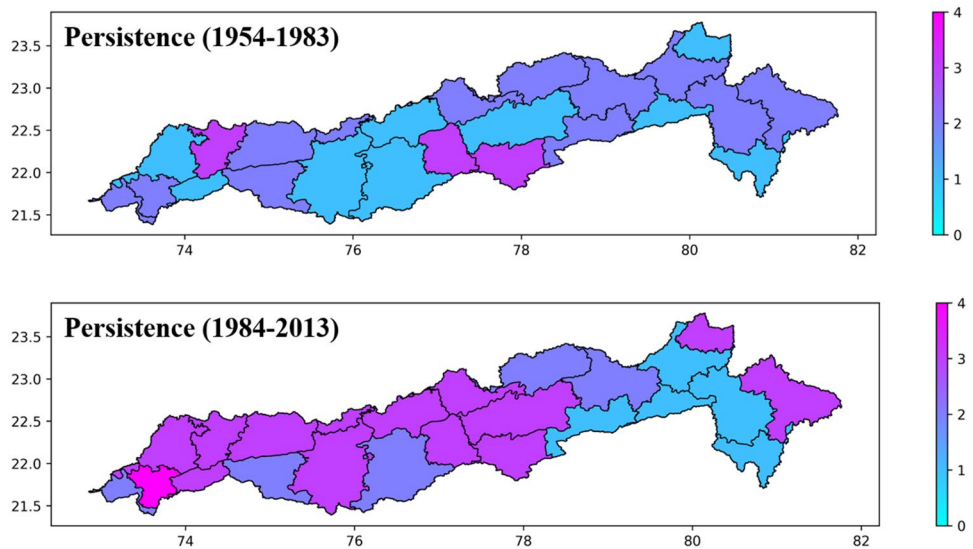


Fig. 6 Total number of droughts in moderate, severe and extreme classes over districts of Narmada Basin during 1954–1983 and 1984–2013

Fig. 7 Maximum persistence of droughts (in years) over the districts of Narmada Basin during 1954–1983 and 1984–2013

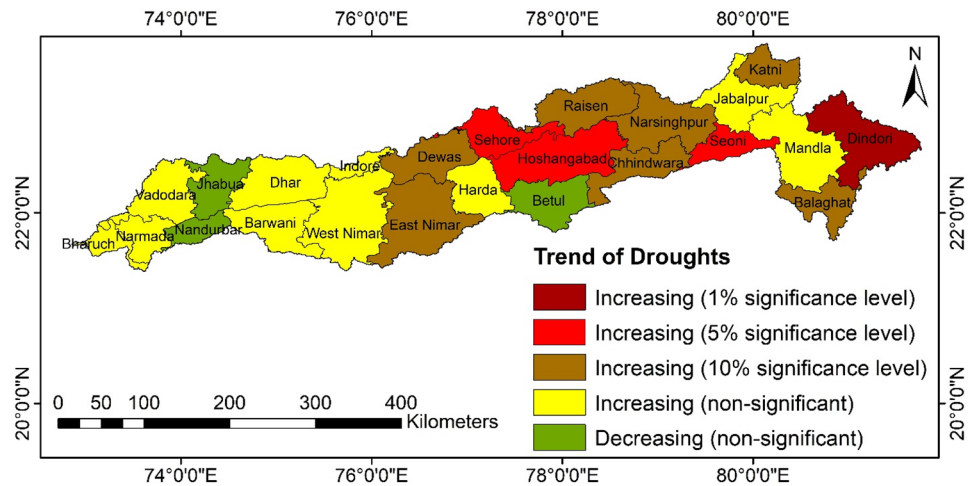


it has been the same for both the periods over nine districts. For the remaining three districts only, the maximum persistence is relatively lower in the recent epoch. This increasing persistence of droughts in the recent periods may be critical, especially for an agriculture-dominated region.

The results of the trend analysis of droughts using the MMK test are presented in Fig. 8. It is evident that almost all the districts over the Narmada basin show an increasing trend of droughts. The Dindori district exhibits the highest increasing trend and the only district with 1% significance

level. Three districts viz, Hoshangabad, Sehore and Seoni, show an increasing trend at 5% significance level. Similarly, the droughts are increasing at a 10% significance level over seven districts viz., Balaghat, Chhindwara, Dewas, East Nimar, Katni, Narsinghpur and Raisen; whereas, ten districts exhibit non-significant increasing trends. The droughts have a decreasing trend over only three districts (Betul, Jhabua and Nandurbar); however, none of them is statistically significant. Therefore, the Narmada Basin has possessed an increase in the trend of droughts during 1954–2013, which

Fig. 8 The trend of droughts (in years) over the districts of Narmada Basin using MMK test



implies the exacerbating severities of droughts with time. The results reconcile with the increased frequency of severe and extreme droughts in the recent epoch.

Overall, the study reports a significant increase in frequency, severity and persistence of droughts in recent times over the Narmada basin. This may be attributed to the influence of climate change in terms of frequent rainfall aberrations. The erratic rainfall patterns are more likely to aggravate due to anthropogenic activities (Emiru et al. 2018; Singh et al. 2019; Wu et al. 2014). Further, the increasing industries and rampant exploitation of natural resources may also hamper the surface as well as groundwater quality (Adimalla et al. 2018a, b; Li et al. 2017). Under these circumstances, sustainable management of water resources becomes crucial, both in terms of quantity and quality (Li and Qian 2018a, b; Li and Wu 2019; Li et al. 2016; Mishra et al. 2015; Tsakiris et al. 2013). As the Narmada basin has significant agricultural importance and over 80% of water usage is allocated for irrigation, the results of this study will be useful in proactive planning for drought mitigation. This study will not only benefit the area in question, but it will also encourage carrying out similar studies over different regions of the world that have been affected by climate change and its repercussions, mostly in the form of lower crop yield, especially in developing and under-developed countries.

Conclusions

A detailed assessment of droughts is carried out over the twenty-four districts in Narmada River Basin, India using the monsoon rainfall data for 60 years, i.e. 1954–2013. A simplified rainfall index, RI_S is utilized to characterize the frequency, severity and persistence of droughts. A comparative analysis of drought characteristics is carried out

between two equal epochs viz., 1954–83 and 1984–2013 for understanding the effects of climate change. Further, the drought trends are estimated through the non-parametric MMK test. The specific conclusions drawn from the study are as follows:

1. RI_S is based on the concept of percentage deviation from normal rainfall and is rescaled to have consistency with the widely used SPI; however, RI_S does not require the complicated and lengthy computation procedures of standardization used for SPI. Hence, RI_S can be preferred for characterizing droughts over the regions, where rainfall follows a near-normal distribution.
2. The Narmada Basin is found to be prone to droughts with frequency varying between once in three to 8 years over different districts. The droughts are more frequent and severe in the western portions of the basin compared to the eastern portions.
3. The epoch-wise analysis revealed that the droughts have become more frequent, severe and persistent during 1984–2013 compared to 1954–83. The frequency of droughts is higher during the recent epoch over twenty out of twenty-four districts, mostly with increasing severity. The maximum persistence in 1984–2013 is higher than that of 1954–83 over twelve districts whereas, it has been the same for both the periods over nine districts.
4. The trend of droughts is increasing over twenty-one out of twenty-four districts. Out of these, the statistically significant increasing trends are found over one, three and seven districts at 1%, 5% and 10% significance levels, respectively. The alarming results urge for proper water management over the basin to combat the harmful impacts of deficient rainfall.

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Data availability The district-wise rainfall data are procured from India Meteorological Department (IMD), Pune, India. The data used in this study is not openly available. However, it can be purchased from IMD at a nominal cost.

Declarations

Conflict of interest The authors declare no competing interest.

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