

# Reliability–Resilience–Vulnerability Analysis of Droughts Over Maharashtra



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**Abstract** Extreme events are one of the serious challenges society is facing with the changing climate; extreme events like droughts have a significant impact on both human and animal livelihood. In India, one of the most frequent natural calamities is drought, and its assessment is required in order to support policy makers and water managers in the region. This study presented reliability–resilience–vulnerability (R–R–V) analysis of droughts, which uses the duration and severity of drought properties, estimated using the Standardized Precipitation Index (SPI). The study is carried out over Maharashtra (grid-wise) at 0.25° resolution using the precipitation data collected from India Meteorological Department (IMD) for a period of 41 years (1980–2020). The spatial variation of drought parameters, duration and severity at 50, 70, and 90 percentile levels are plotted and analysed to elucidate the regions that have higher drought risks. The most resilient areas are Amaravati, part of the Nashik, and Konkan division. Nagpur and Aurangabad divisions require utmost attention as they have the least reliability. The R-R-V maps of Maharashtra strongly show that the Aurangabad division has the highest drought risk among the other divisions. The results clearly show that Vidarbha and Marathwada are more prone to droughts. The RRV index map showed Latur, Beed, Parbhani, Chandrapur, and Nagpur fall under high to very high category of drought risk. The spatial plots give a clear picture of the areas that require immediate action and thus can be helpful for decision-makers and government bodies.

**Keywords** Reliability · Resilience · Vulnerability · Severity

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## 1 Introduction

In the natural climate cycle, drought is a prolonged dry period that can happen anywhere in the world. It is a calamity that develops slowly and is defined by a lack of precipitation that causes a water scarcity. In India, one of the most frequent natural calamities is drought. One third of the country is either prone to drought or covered by desert due to its increased frequency and wider distribution in recent years. Both in terms of agriculture and overall economic growth, these regions fall behind. Drought can have a terrible consequence on agriculture, health, energy, economies, and the environment. Drought is one of the extreme events which not only causes in a short-term impact, but it may also have a severe long-term impact, and it increases with its frequency and duration over the same region. The consequences lead to the migration of people and animals and leave behind barren land; hence it is very important to have a drought assessment for every region. Several studies over the globe and in India have shown an increasing trend of drought with climate change and global warming.

Extreme events are one of the serious challenges society is facing with the changing climate (Ganjir et al. 2022). The underlying processes causing the drought are reduction in precipitation or altered precipitation patterns, as well as increased evaporative demands brought on by higher temperatures. Around 30% of the emerging areas will experience current 100-year droughts (severe droughts that currently only happen once per 100 years) with a 3°C increase in temperature (Naumann et al. 2018). These scenarios show that if appropriate steps are not made to mitigate and adapt to climate change, the risk of drought will increase for many economic sectors and vulnerable areas. Droughts could cause major losses in many areas of the world with large population concentrations and susceptible communities that rely on local agricultural production. Drought management and adaptation will continue to be based on better-targeted impact monitoring and quantification in these areas. One consequence of recent climate change, characterized in particular by rising global temperatures, is a rise in the frequency of weather-related extreme events (IPCC 2014). Drought is not an exception, and in recent years, scientific literature has noted a general trend towards increasingly frequent and severe droughts (Dai 2013).

India is agriculture-based country, and a huge ratio of population is completely dependent on it. The below normal precipitation is great trouble for the farmers as they mostly rely on the monsoon. The drought is like curse for farmers. Mahmoudi et al. (2021) studied the change in spectral patterns of droughts in Iran based on the concepts of reliability, resilience, and vulnerability (RRV). Integration of climatic variables with R-R-V indicators is helpful for generating drought information (Hazbavi and Sadeghi 2017). The Drought Management Index (DMI) was calculated as a five-year time series at each grid point using joint cumulative distribution functions (CDF) of resilience and vulnerability by Chanda et al. (2014).

The reliability–resiliency–vulnerability (R-R-V) framework is used in this study to analyse drought. To evaluate potential changes in the drought features of Maharashtra, an aggregate index of RRV was applied. The region’s drought characteristics can be analysed using this method, and long-term drought planning strategies can be developed for the region. In the following, Sect. 2 contains study area and data details, Sect. 3 gives details of methodology, Sect. 4 discusses the application and results, and finally, the conclusions of the study are given in Sect. 5.

## 2 Study Area

The study area considered for drought analysis is Maharashtra state, in India. Maharashtra occupies 307,713 km<sup>2</sup>, or 9.36% of the nation’s total land area, and is situated in the western peninsular part of the country. The state is bounded on the north by Gujarat and Madhya Pradesh, on the east by Chhattisgarh, on the south by Telangana, Karnataka, and Goa, and on the west by the Arabian Sea. It is situated between 15° 35′ N and 22° 02′ N latitude and 72° 36′ E and 80° 54′ E longitude. Deccan Plateau, Western Ghats, and West Coast are the three physiographic zones of the state. It has a tropical monsoon climate, which includes hot, rainy, and cold seasons as well as dry summers. The yearly temperature varies from 25 to 27 °C, while the annual rainfall ranges from 400 to 6000 mm. Several rivers, including the Bhima, Godavari, Koyna, Krishna, Tapti, and Narmada, drain the state. Thirty-five districts, including 12 tribal and 7 hill districts, make up the state. According to the 2011 census, Maharashtra has a population of 112.37 million, or 9.28% of all the residents in India. While 45.22% of people reside in cities, 54.78% live in rural areas. 9.35% of the state’s population is tribal. The state has a 365 person per square kilometre population density, which is similar to the national average. Semiarid climatic conditions represent about 83% of Maharashtra’s land area. The study area map is shown in Fig. 1.

The rainfall data is taken from IMD daily data at 0.25° × 0.25° resolution for the period of 1980–2020. The daily data is converted into monthly data using the climate data operator (CDO) command.

## 3 Methodology

The meteorological drought is identified by using Standardized Precipitation Index (SPI). For the computation of SPI index, the frequency distribution of precipitation is modelled by a two- parameter gamma probability density function in the original SPI (McKee et al. 1993; Ganguli and Reddy 2012):

$$g(x) = \frac{1}{\beta\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (1)$$



The drought parameters, namely duration and severity, are defined as follows. The number of continuous periods (months) during which the SPI remains below the designated threshold value ( $SPI < 0.8$ ) is considered the length or duration of the drought ( $D$ ). The cumulative SPI readings over the course of the drought duration are drought severity ( $S$ ).

$$S_i = \sum_{t=1}^D SPI_{i,t} \quad (4)$$

The reliability, resilience, and vulnerability are calculated using the following definitions.

### 3.1 Reliability

The probability that a system is in a satisfactory state defines reliability (Hashimoto et al. 1982). Reliability in the context of SPI can be described as the probability that the SPI is higher than a specific threshold. Hence, the reliability is given as (Sung et al. 2018).

$$\text{Reliability} = 1 - \frac{\sum_{j=1}^M d(j)}{T} \quad (5)$$

where  $d(j)$  is the duration of  $j$ th drought event,  $T$  is the total number of time intervals, and  $M$  is the total number of the drought events.

### 3.2 Resilience

Resilience measures how quickly a system can improve once it has dropped below the threshold for satisfactory performance (Sung et al. 2018).

$$\text{Resilience} = \left\{ \frac{1}{M} \sum_{j=1}^M d(j) \right\}^{-1} \quad (6)$$

### 3.3 Vulnerability

Vulnerability is the likely value of deficits  $v(i)$ , if they occur. Vulnerability can be thought of as the average failure because it essentially indicates the intensity of failures. The vulnerability is calculated as the average of the overall deficit, which is calculated by dividing the total number of deficit events by the sum of all the deficits (Sung et al. 2018; Veetil et al. 2018).

$$\text{Vulnerability} = \frac{1}{M} \sum_{j=1}^M v(j) \quad (7)$$

where  $v(j)$  is the value of deficits of  $j$ th drought event. After calculating the reliability, resilience, and vulnerability, using the extreme standardization procedure, they were standardized to range from zero to one (Loucks 1997; Hazbavi and Sadeghi 2017).

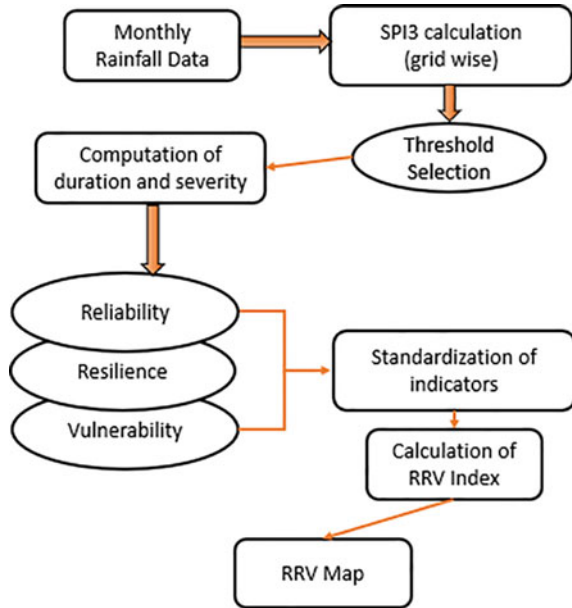
$$N = \frac{(X_i - X_{min})}{(X_{max} - X_{min})} \quad (8)$$

where  $X_i$  is the value being considered,  $X_{min}$  and  $X_{max}$  are the minimum and maximum observed values, respectively, and  $N$  is the standardized value of each individual indicator. Since reliability and resilience fall in cost criteria, standardized value is given by  $(1 - N)$  and for vulnerability given by  $N$ . Finally, after standardization of R-R-V indicators, the geometric mean, as indicated in Eq. (9), was used to express the aggregated RRV index. Because it is more sensitive to changes in individual variables than other averages, the geometric mean was chosen for the study (Loucks 1997; Yu et al. 2013).

$$G_{RRV} = [\text{Rel.Rev.Vul}]^{1/3} \quad (9)$$

Where, Rel, Rev and Vul stands for standardized reliability, resilience, and vulnerability respectively. Based on the RRV index, a five-category classification scheme was devised to rate the drought-prone areas from high to low. This was suggested by Ding et al. (2008) and Yu et al. (2013) “Very high (0.81–1.00)”, “high (0.61–0.80)”, “moderate (0.41–0.60)”, “low (0.21–0.40)”, and “very low (0.00–0.20)” are the names of the five classes (I–V). The greater the value, the more susceptible the area is to drought. The flow chart of research methodology is shown in Fig. 2.

**Fig. 2** Flow chart of RRV framework to analyse droughts



## 4 Results and Discussion

### 4.1 Total Number of Drought Events

The spatial variation plot of total number of drought events occurred in the Maharashtra region (grid wise) is shown in Fig. 3. The figures clearly show that the Nagpur division and Aurangabad division and Solapur, Aloka, and Yavatmal districts have the highest number of drought events in years between 1980 and 2020 they have 40–45 drought events and other districts have drought events between 20 and 38. The least number of drought events is seen in the part of Nashik, Buldhana, Thane, and Pune districts.

### 4.2 Spatial Variation of Drought Parameters: Duration and Severity

The duration and severity grid-wise plot is shown in Fig. 4 with quantiles at 50, 70, and 90 percentile levels. The figure depicts duration (in months) and severity values corresponding to the percentile level. It can be clearly seen from the 50-percentile duration and severity plots 4(a) and 4(d) that the Marathwada region has high values of 2–2.5 (both duration and severity), suggesting that the 50% of the value at Marathwada region are high compared to the rest of Maharashtra, except

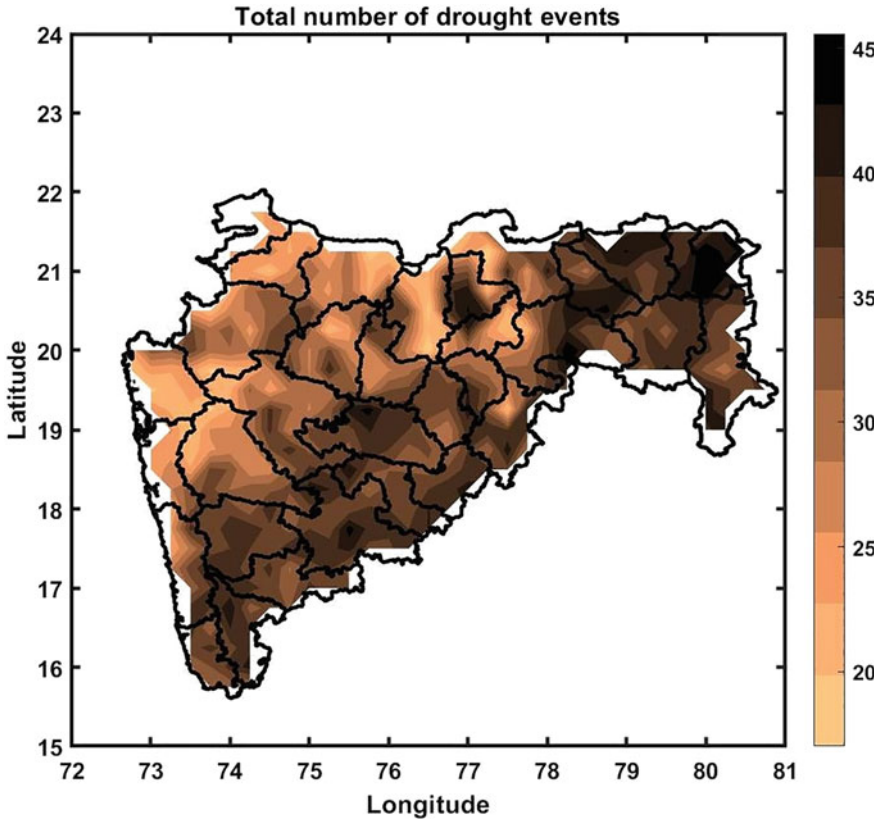
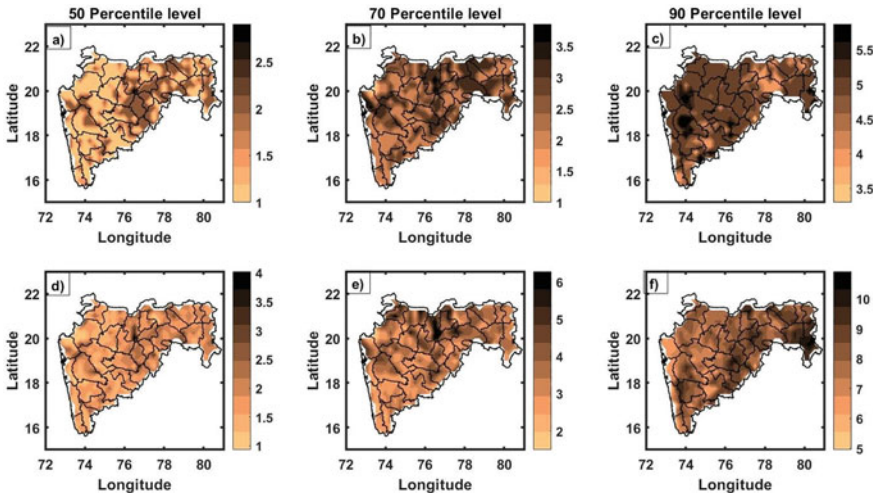


Fig. 3 Spatial variation of total number of drought events over period of 1980–2020

the Marathwada region the rest shows the value of 1–1.5 months of drought duration which means that short duration drought events were more in that region. Buldhana District shows highest value at 50-percentile level with duration of 3 months. The 70- percentile duration and severity plots 4(b) and 4(e) shows that the duration lies between 1 and 4 months and the severity lies between 2 and 6. The spatial variation shows the part of Nagpur, Aurangabad and Amaravati regions have drought duration of 3.5–4 months for 70-percentile values, and the part of Nashik district has shown the highest values corresponding to 70-percentile level. The 70-percentile severity is highest in Buldhana and Washim districts.

The 90-percentile level plot of duration and severity shows that the Pune division (namely Sangli and Pune) and Nashik and Gadchiroli have the highest duration of 5–6 months. The 90-percentile severity plot also shows Pune division and Nagpur division have high severity values of 8–9. From the percentile plot, it can be clearly stated that the Pune division has a contrasting high and low duration and severity variation as 50% of the event have a duration between 1 and 1.5 months, whereas the





**Fig. 4** Spatial variation of drought parameters: Duration (row 1) (a, b, c) and severity (row 2) (d, e, f) at 50, 70, and 90 percentile level, respectively

Marathwada region has high values for all the percentile plots except the 90-percentile plot. That is also reflected in the reliability map.

### 4.3 Spatial Variability of Reliability, Resilience, and Vulnerability

The spatial variability of R-R-V is shown in Fig. 5. The Nagpur and Aurangabad division shows the least reliability compared to Nashik, Amravati, and Konkan division as shown in Fig. 5a. The reliability ranges from 0.8 to 0.9 (80–90%). As the probability that a system is in a satisfactory state defines reliability, i.e. the system having the least drought events will have high reliability. Hence, we can compare the total number of drought events in Fig. 3 and see that the area having high drought events have the least reliability. From reliability map (Fig. 5a), we can say that Nagpur and Aurangabad division requires utmost attention.

The spatial plot of drought resilience over Maharashtra at 0.25° grid level is shown in Fig. 5b. How soon a system can achieve a satisfactory condition again is measured by its resilience, and here, higher value of resilience is desirable. From Fig. 5b, we can see that the resilience varies from 0.35–0.55. The most resilient areas are Amravati, part of the Nashik, and Konkan division. The least resilient part is some parts of Chandrapur and the lower part of Nashik. It can be noticed that those having the high mean severity and mean duration have the least resilience.

The spatial variation of vulnerability over Maharashtra is shown in Fig. 5c. The vulnerability ranges from 2.2 to 4.5. The higher vulnerability is the least desirable.

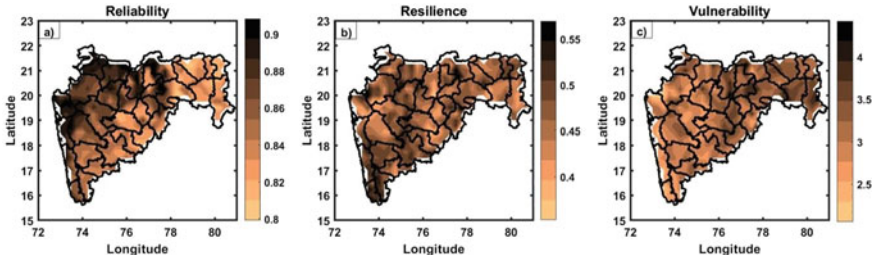


Fig. 5 Spatial variation of a Reliability, b Resilience, and c Vulnerability

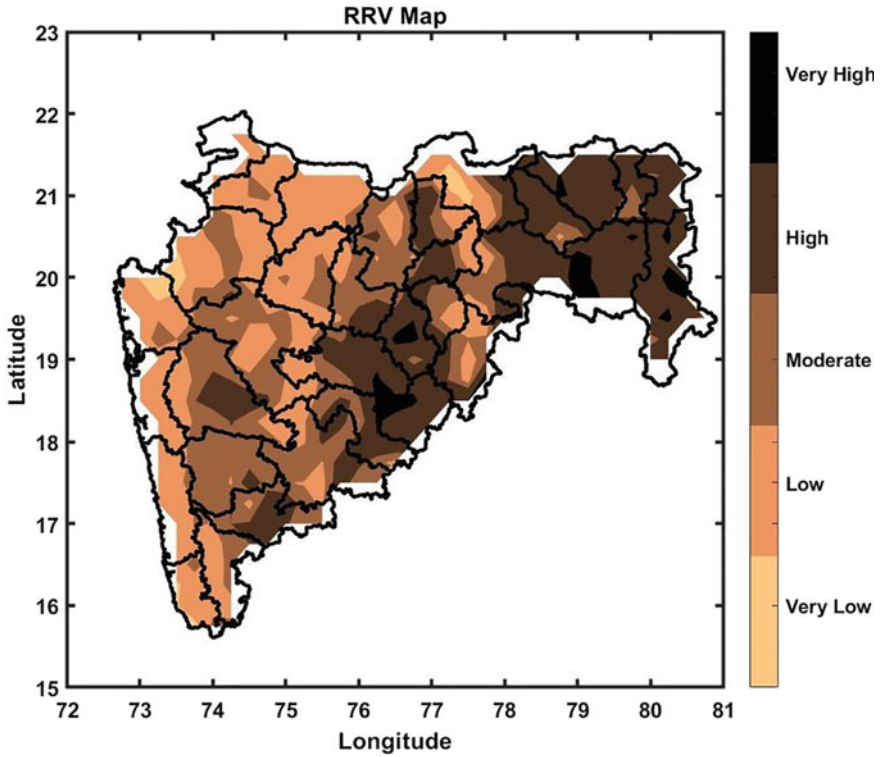
Overall, the vulnerability mostly lies between 2.8 and 3 over most of the grids, but the high vulnerability can be seen at exact same grids, which have high severity as the severity is directly proportional to vulnerability.

#### 4.4 RRV Index Map of Maharashtra

The RRV index map is shown in Fig. 6. The dark colour shows the region which is more prone to drought, and light colour shows region that is comparatively less drought-prone. The regions with very high drought are part of Chandrapur, Gagchiroli, Parbhani, Beed, and Latur. These districts also fall under high drought; other than that districts including Sangli, Satara, and eastern part of Maharashtra come under high drought region. The North-western Maharashtra falls under the low and very low drought scale. Most of the lower part of Maharashtra falls in moderate drought zone. Overall, we can precisely find from Fig. 6, which part of the district falls under which category of drought and accordingly, the action plans can be suggested to bring that region from high to moderate/low drought category.

### 5 Conclusions

This study presented a reliability–resilience–vulnerability (R–R–V) framework for analysing the droughts. The meteorological droughts are characterized using the Standardized Precipitation Index (SPI). The study area of Maharashtra state in India is considered for drought analysis at spatial resolution of  $0.25^\circ \times 0.25^\circ$  utilizing IMD monthly precipitation data over a 41-year period (1980–2020). To understand the spatial variation of drought parameters, duration and severity at 50, 70, and 90 percentile levels are computed and plotted, which clearly show that the Marathwada region has high duration and severity; the 90-percentile plot shows Pune division has high duration and severity, but it has low severity and duration at 50-percentile level. The presented plots depict which areas are more (or less) vulnerable to droughts.



**Fig. 6** RRV combined index map for the periods 1980–2020

Amaravati, part of Nashik, and the Konkan division are the most resilient locations, and they require the least attention. The divisions of Nagpur and Aurangabad deserve special care because they are the least reliable. The R-R-V maps of Maharashtra firmly demonstrate that the Aurangabad and Nagpur division has the highest drought risk among the other divisions. The spatial plots provide a clear picture of locations that demand immediate action, which will be useful to decision-makers and government entities.

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