A Comparative Study on Regional Drought Characterization Using Estimated Drought Indices in Conjunction with Trend Analysis in Peninsular India

M. P. Akhtar, L. B. Roy, and Abhishek Sinha

Abstract

The objective of the present study is the characterization of drought conditions in two important peninsular states of India namely Tamil Nadu and Karnataka through assessment of meteorological drought indices namely drought index (DI), Palmer index (PI), and standardized precipitation index (SPI). For this, monthly and yearly data of precipitation and temperature have been considered for 110 years (1901–2010). Precipitation deficit conditions have been estimated and compared for both regions using annual rainfall classification thresholds. The annual variability of rainfall and associated trend were estimated using Mann-Kendall test and comparative analysis was done to assess the regional variation during the last 110 years. Comparative study on results implied that drought characterization using SPI may amply facilitate the standardization of threshold classification for severity and frequency that was good agreement with observed events. The application of trend detection framework resulted in the identification of significant trends in those districts which were reported to be drought prone regions. Study amply suggested that drought vulnerability in Tamil Nadu was relatively more than that of Karnataka region depending upon the number of dry and wet years in terms of SPI threshold values and areal extend within 110 years of study period however in terms of severity and number of occurrence, Karnataka was more vulnerable. Analysis based on droughts indices suggests that SPI is simple to evaluate and may relatively more meaningful and conclusive in terms of decision making for the study region if compared with other indices.

1 Introduction

Drought may be defined as deficient precipitation for long period inducing negative or adverse impact on socioeconomic activities in a region (Warrick, 1975). Drought in different regions may have classifications according to their precipitation pattern. As per Indian Meteorological Department (IMD), drought in region may be defined as the rainfall shortfall greater than 26% of its long term normal in that region. Furthermore, it can be classified as moderate drought if the rainfall deficiency varies between 26 and 50% of long term normal in that area. Similarly, 50% or less than long term normal is considered as *severe* drought condition. Drought may be considered one of the major reasons for desertification. Rainfall is one of the most important climatic indicators that primarily determines different drought condition depending upon its long-term intensities, distribution, and frequency. Any shortage of rainfall directly influences the agriculture and running economy (Mooley & Parthasarathy, 1984).

Numerous studies have been carried out and reported for analysis of rainfall trend and drought indices using different methodologies for regions with distinct climatic variability. De et al. (2005) presented a factual and a brief review of the extreme weather events that occurred in India during the 100 years (1991–2004). Severe drought conditions were also included under extreme condition for analyzing socioeconomic impact on human society. Pai et al. (2011) compiled

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districtwide drought climatology of the southwest monsoon season over India based on drought indicator estimation namely standardized precipitation index (SPI). Yosuf et al. (2013) attempted characterization of drought properties with bivariate copula analysis. Shah et al. (2015) have reported drought index computation using standard precipitation index method for Surat District in Gujrat (India). Pathak and Dodamani (2016) reported study on comparison of two chosen hydrological drought indices namely stream flow drought index (SDI) and standardized runoff index (SRI). To obtain these indices, 36 years (1972–2007) of daily discharge data measured in Ghataprabha river basin (a sub-basin of Krishna river) were considered. Huang et al. (2016) worked out on drought forecasting using SPI and effective drought index (EDI) under Representative Concentration Pathway (RCP) −8.5 Climate Change Scenarios for Langat River Basin, Malaysia. Langat et al. (2017) investigated temporal variabilities and rainfall trend and discharges of Tana River Basin in Kenya using Mann-Kandell nonparametric tests. Numerous analytical works related to trend analysis for climatic parameters of regional hydrological time series were presented in past such as Hirsch et al. (1982), Coles (2001), Yue et al. (2002), Yue and Hashino (2003), Modarres and Da Silva (2007), Longobardi and Villani (2010), Ghanem (2011), Jain and Kumar (2012), Duhan and Pandey (2013) Da Silva et al. (2015), and Mohorji et al. (2017).

Similarly, drought assessment for arid and semi-arid regions across the Globe has been carried out continuously to develop efficient decision support systems for regional ground and surface water management and planning. Palmer (1965) evolved index to identify drought condition with a statistical correlation with mean and standard deviation of mean. Gibbs and Mehar (1967) worked out on rainfall decile as drought indicator. Subsequently McKee et al. (1993) devised more meaningful indicator namely standard precipitation indicator to analyze and prediction regional drought conditions derived from meteorological data. Hammori and El Naqa (2007) deployed remote sensing data and GIS tools to assess drought condition in Amman-Zarqa Basin of Jordan. Kumar et al. (2018) analyzed regional drought characteristics namely frequency, severity, and occurrence of meteorological droughts in arid and semi-arid regions of northwestern India and identified region-specific event years with extreme drought severity. Mallya et al. (2016) findings amply facilitated insight, looking into detailed investigation on drought severity and recurrence with estimated drought indices with apparent drought vulnerability in peninsular India. Such studies need to be considered to get more meaningful results for planning regional drought mitigation measures. Many works have been reported on drought analysis for regions with distinct climatic variability. More recently, numerous related works have been reported. Some

of them are Oguntunde et al. (2017a), (2017b), Musafa and Rehaman (2018), Quenum et al. (2019), Al Bakri et al. (2019), and Al adaileh et al. (2019). Al adaileh et al. (2019) attempted evolvement of a drought adaption management system for ground water resources based on combined drought index and vulnerability analysis. Furhermore, several studies have also been reported on comparative analysis of drought indices with an objective to get better insight into their suitability and accuracy of assessment for chosen study areas, such as Gutmann (1998), Sims et al. (2002), Dubrovsky et al. (2006), Bonsal and Regier (2007), Krysanova et al. (2008), Paulo and Pereira (2006), Zhai et al. (2009), Paulo et al. (2012), Hughes and Saunders (2002), Liu et al. (2013), Jacobi et al. (2013), and Al adaileh et al. (2019). These reported works were carried out exclusively for chosen study areas. It can be inferred that performance and efficiency of drought indicators depend on many factors such as climatic variability, geography and initial soil moisture conditions. It can further be inferred that a drought assessment or quantification should not rely on a single drought indicator rather it should preferably be done with multiple indicators to get better insight and realistic drought assessment and suitability. Bonsal and Regier (2009) and many others pointed out that no universally accepted definition for drought exists. Numerous indices have been deployed to quantify its severity. Meteorological approaches range from indices that only consider precipitation e.g., SPI, (Mackee, 1993, World Meteorological Organization, 2012) to more complex methods that incorporate a water balance approach using precipitation and potential evapotranspiration such as PDI (Palmer, 1965).

Two most water stressed states of southern India are Tamil Nadu and Karnataka. Tamil Nadu is the eleventh largest state of India whereas Karnataka has the second largest rain-fed area in India after state of Rajasthan. Only 35–45% of rainwater is presently used to grow dryland crops in the Karnataka. Hence, there is huge scope for improving rainwater harvesting and efficient use of it for rain-fed crops to tackle drought condition in such arid regions, provided an adequate assessing severity and recurrence of drought condition with spatial distribution is done through estimating and analyzing appropriate metrological drought indicators in conjunction with trend analysis of historical precipitation data.

Furthermore, both regions of Indian peninsula were chosen for comparative analysis of drought situations keeping in view of the prevailing water crisis between them. Tamil Nadu is facing acute water shortage due to erratic rainfall and depleting reservoir levels. The main source of water is Cauvery River Basin which lies mostly in Karnataka region. Both states have been locked—long dispute over sharing of Cauvery Water. The conflict has continued since long and impasse is persisted (Anand, 2007, Gebert, 1983; Pani, 2009). A lack of multilevel, intersectoral, and

participative approaches, on the one hand, has led to inadequate conditions in water management and water use in both states (Ferdin et al., 2010). This study will facilitate a better scientific insight into prevailing issue with respect to meteorological drought situation and relative regional water scarcity for comparison and help decisionmakers to arrive at consensus solution that may lead to equitable share of Kaveri Water among both states.

In view of the above, the objectives of the present work are set as follows.

1. To investigate the monotonic trend of rainfall and comparison thereof for Tamil Nadu and Karnataka regions with a period of 110 years using nonparametric methods such as Mann-Kendall and Sen's Slope tests.
2. To analyze the annual series of the available historical climatic data and assessment of severity distribution with comparison in both states using estimated drought indices namely drought index (DI), Palmer drought index (PDI) and standard precipitation index (SPI) and development of vulnerability map-based chosen drought indicator.

To begin with, this paper first discusses indicators and methodology those used and adopted for assessing severity and trend analysis of climate parameters.

2 Material and Methodology

2.1 Trend Analysis of Annual Rainfall by Using Mann-Kendall's Test (Mann, 1945; Kendell, 1975)

The Mann-Kendall test is applied where the data values x_i of a time series can be assumed to obey the model as enumerated below (Eq. 1) (Alexander et al., 2006; Mann, 1945; Kendell, 1975)

$$x = f(t) + \varepsilon_i \qquad (1)$$

where $f(t)$ is a continuous monotonic increasing or decreasing function of time and the residuals ε_i is assumed to be from the identical distribution with zero mean. Hence, it is assumed that the variance of the distribution is temporally constant. The Mann-Kendall test statistic S is computed using the following formula (Eq. 2)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_i - x_k) \qquad (2)$$

where x_j and x_k are the annual values in years j and k, $j > k$, respectively, $\mathrm{sgn}(x_i - x_k)$ can be given as shown in Eq. (3),

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if} \quad x_j - x_k > 0 \\ 0 & \text{if} \quad x_j - x_k = 0 \\ -1 & \text{if} \quad x_j - x_k < 0 \end{cases} \qquad (3)$$

If $n \leq 9$, the absolute value of S is compared directly to the theoretical distribution of S derived by Mann and Kendall (Gilbert 1987). A positive and negative value of S suggests an upward and downward trend, respectively. The minimum values of n with which these four significance levels may be arrived at are obtained from the probability Table 1 for S.

If $n \geq 10$, the normal approximation test is used. However, if there are several equal values in the time series, it may reduce the validity of the normal approximation when the number of data values is close to 10. At first, the variance of S is computed using Eq. (4) presented below, which takes into consideration of equals,

$$\mathrm{VAR}(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right] \qquad (4)$$

Here, q is the number of groups with equal values and t_p is the number of data values in the pth group. The values of S and VAR(S) are used to compute the test statistic Z as shown in Eq. (5)

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR}}} & \text{if} \quad S > 1 \\ 0 & \text{if} \quad S = 1 \\ \frac{S+1}{\sqrt{\mathrm{VAR}}} & \text{if} \quad S < 1 \end{cases} \qquad (5)$$

The presence of statistically significant trend is evaluated using the Z value. A positive or negative value of Z indicates an upward or downward trend, respectively. The statistic Z has a normal distribution. To test for an upward or downward monotone trend (a two-tailed test) at α level of significance, $H0$ is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. Here, the tested significance levels α are 0.001, 0.01, 0.05, and 0.1.

To estimate the true slope of an existing trend (as a change per year), the Sen's nonparametric method (Sen, 1968) is used. The Sen's method can be used in cases where the trend can be assumed to be linear.

Table 1 Significance level verses required n

Significance level α	Required n
0.1	≥ 4
0.05	≥ 5
0.01	≥ 6
0.001	≥ 7

2.2 Drought Index

Numerous methods are applied to compute the drought events in terms of severity and occurrence drought. Drought index can be defined as shown in the following equation (IMD 1971 and NCA 1976)

$$\text{DI} = \frac{P - X}{\text{SD}} \times 100 \qquad (6)$$

where P is annual precipitation, X is long-term mean and SD is standard deviation. The DI values may be categorized into four conditions namely *no drought*, *mild drought*, *moderate drought*, and *severe drought* conditions as shown in Table 2.

2.3 Palmer Drought Index (Palmer, 1965)

One of the most common indicators to assess drought is Palmer drought index (PDI) introduced by Palmer (1965) to simulate moisture content month by month and to compare its monthly anomalies at regions with different climatic conditions and seasons. PDI indicates the severity of wet or dry spell, the greater the absolute value more severe the dry or wet period. In this paper, the methodology adopted is based on Guttman (1998).

The PDI was designed to quantify metrological drought. It is a prolonged and abnormal moisture deficiency rather than an indicator of the affect of a prolonged weather anomaly.

The index is computed by carrying out monthly hydrological accounting for prolong time series. Then the coefficients depending upon the climatic condition of the study area were obtained. The monthly departures from normal conditions are converted to determine the amount of moisture required for normal weather during each month.

Climatically appropriate precipitation P_c for individual time scale (month) is,

$$P_c = \alpha P_{et} + \beta P_r + \gamma P_{ro} - \delta P_l \qquad (7)$$

where
P_{et} = Potential evapotranspiration
P_r = Potential recharge
P_{ro} = Potential runoff
P_l = Potential loss.

And coefficients $\alpha, \beta, \gamma, \delta$ are ratios of long-term mean quantities for evapotranspiration, recharge to potential recharge, runoff to potential runoff, and loss to potential loss, respectively.

The difference between the observed precipitation and P_c is monthly moisture anomaly. It is then multiplied by standardizing factor at different size (can be designed to account the variations in climate (using climatic parameters such as long-term mean precipitation and temperature in this case) and the product is called the moisture anomaly index Z.

Thus, Palmer drought index (PDI) for month t is then computed by,

$$\text{PDI} = 0.897\text{PDI}_{t-1} + 0.333Z_t \qquad (8)$$

The values of the coefficients show that a current month's PDI is comprised of only one-third of the current month's precipitation deficit and almost nine-tenth of the previous month's PDI. In other words, the PDI for a given month contains a long-term memory of previous moisture content. The PDI calculation requires both precipitation and temperatures data as evapotranspiration estimation is also involved. Separate indices are calculated for wet and dry spells. The final PDI is either the wet or dry index.

The PDI has several advantages when compared with other drought indices. It considers soil moisture content at a monthly time interval along with meteorological data. It allows also spatial and temporal representation of historical

Table 2 *IMD* classification of drought

Intensity of meteorological drought	% of departure from normal rainfall	Code
No drought	0.0 or above	M0
Mild drought	0.0 to −25.0	M1
Moderate drought	−25.0 to −50.0	M2
Severe drought	−50.0 or above	M3

Source (IMD, 1971 and NCA 1976)

droughts. There are some limitation also such that it: (a) simplifies soil representation (b) uses the simplified Thornthwaite method (Thornthwaite, 1978) for estimating potential evapotranspiration, and (c) does not take into account precipitation that falls as snow and snow cover (Krysanova et al., 2008) (Table 3).

The SPI values may be classified into seven categories namely extremely wet, very wet, moderately wet, near normal, moderately dry, severely dry, and extremely dry as shown in Table 4

2.4 Standardized Precipitation Index (SPI)

Standardized precipitation index (SPI), a tool derived by McKee et al. (1993), is a measure of meteorological drought. It is computed from the available rainfall data for a given duration. For transforming precipitation values to SPI values, following steps have been adopted (Guttman, 1999).

1. Transforming the mean of the precipitation values adjusted to 0.
2. Standard deviation of the precipitation is adjusted to 1.0.
3. Skewness of the existing data readjusted to zero.
4. SPI values now may be interpreted with mean as 0 with standard deviation 1.0.
5. Mean of precipitations can be computed as follows

$$\text{Mean}(\overline{X_{\text{im}}}) = \frac{\sum (X_{ij})}{N} \tag{9a}$$

where N = Number of precipitation observations, where X_{ij} is seasonal precipitation at the ith rain gauge station and the jth observation, $\overline{X}_{\text{im}}$ is long-term seasonal mean and s is the standard deviation for precipitation dataset is computed as,

$$s = \sqrt{\frac{(X_{ij} - \overline{X}_{\text{im}})}{N}} \tag{9b}$$

6. The skewness of the given dataset is computed as

$$\text{Skew} = \frac{1}{(N-1)(N-2)} \sum \frac{(X_{ij} - \overline{X}_{\text{im}})^3}{s} \tag{9c}$$

7. The precipitation values are converted to lognormal values in terms of statistical value U as

$$\text{Long term mean} = \ln(\overline{X}_{\text{im}}) \tag{9d}$$

$$U = \overline{X}_{\text{im}} - \frac{\sum \ln(\overline{X}_{\text{im}})}{N}$$

$$\text{Shape parameter} = \beta = \frac{1 + \sqrt{1 + \frac{4U}{3}}}{4U} \tag{9e}$$

$$\text{Scale parameter} = \alpha = \frac{\overline{X}_{\text{im}}}{\beta} \tag{9f}$$

10. Equations (9a)–(9f) are computed using built-in functions in Excel software. The resulting parameters are then used to find the cumulative probability of observed precipitation events. The cumulative probability is given by

$$G(x) = \frac{\int_0^x x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^\alpha \Gamma(\alpha)} \tag{10}$$

Table 3 Drought classification based on SPI values

Classification	Extremely wet (EW)	Very wet (VW)	Moderately wet (MW)	Near normal (NN)	Moderately dry (MD)	Severely dry (SD)	Extremely dry (ED)
SPI value	≥ 2	1.5–1.99	1–1.49	−0.99 to 0.99	−1.0 to −1.49	−1.5 to −1.99	≤ -2

Source (Shah et al., 2015; Zhai et al., 2009; Paulo Ana & Pereira, 2006)

Table 4 Drought classification based on PDI values

Classification	Extremely wet (EW)	Very wet (VW)	Moderately wet (MW)	Slightly wet (SW)	Incipient wet spell (IWS)	Near normal (NN)	Incipient dry spell (IDS)	Mild drought (MiD)	Moderate drought (MoD)	Severe drought (SD)	Extreme drought (ED)
PDI value	4.0 or more	3.0–3.99	2.0–2.99	1.0–1.99	0.5–0.99	0.49 to −0.49	−0.5 to −0.99	−1.0 to −1.99	−2.0 to −2.99	−3.0 to −3.99	−4.0 or less

Source (Paulo and Pereira, 2006; Zhai et al., 2009)

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeroes, the cumulative probability may be considered as

$$H(x) = q + (1 - q)G(x) \qquad (11)$$

The cumulative probability $H(x)$ is then transformed to standard normal random variable Z (mean = 0, standard deviation: 1) values and considered the SPI values as suggested by Edward and McKee (1997).

10. The approximate conversion as per Abromowitz and Stegun (1965) is adopted as

$$Z = \text{SPI} = -\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right] \qquad (12a)$$

for $0 < H(x) \le 0.50$ and

$$Z = \text{SPI} = +\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right] \qquad (12b)$$

for *$0.5 < H(x) \le 1.00$ and* where,

$$t = \sqrt{\ln\left(\frac{1}{H(x)^2}\right)} \text{ for } 0 < H(x) \qquad (13a)$$

$$t = \sqrt{\ln\left(\frac{1}{H(x)^2}\right)} \text{ for } 0 < H(x) \le 1 \qquad (13b)$$

where $C_0 = 2.515517$, $C_1 = 0.802583$, $C_2 = 0.010328$, $D_1 = 1.432788$, $D_2 = 0.189269$, $D_3 = 0.001308$.

The SPI values may be classified into eleven categories namely *extremely wet (EW)*, *very wet (VW)*, *moderately wet*, *slightly wet (SW)*, *incipient wet spell (IWS)*, *near normal (NN)*, *incipient dry spell (IDS)*, *mild drought (MiD)*, *moderate dry (MoD)*, *severely dr (SD)y*, and *extremely dry (ED)* as shown in Table 3.

3 Study Area and Data Used

Tamil Nadu in southeastern region of India and is the eleventh largest state of India with having geographical area of 130,058 km^2 (https://www.walkthroughindia.com/offbeat/top-15-largest-states-india-geographical-area/) extending its length and breadth approximately between 8° N-14° N, 76° E-81°E. Tamil Nadu is having the third largest costal line of 940 km after Gujarat and Andhra Pradesh (https://en.wikipedia.org/wiki/Coastline_of_Tamil_Nadu). It is located

on the inward side of the Western Ghats resulting in relatively low rainfall compared to outward coastline of Western Ghats of Kerala state. Hence, drought-like situation is prevalent on the part of Western Ghats which lies in western Tamil Nadu, whereas Karnataka is a landlocked state situated in southern India. It is having longitudinal extent of 74˚E to 78°30′E and latitudinal extent of 11°30′N to 18°30′ N. It is the seventh largest state of India approximately 191,791 km^2 (https://www.walkthroughindia.com/offbeat/top-15-largest-states-india-geographical-area/).

The southernmost point of India (Indira Point) in Kanyakumari is also located in Tamil Nadu. Figure 2 representing mean annual rainfall and temperature suggests that Karnataka has relative higher annual rainfall in comparison of Tamil Nadu with respect to districtwide distribution (Fig. 2) but temperature pattern for those districts is distinct. The location map of study region that contains both states is represented as Fig. 1.

Monthly precipitation and temperature data of all districts covering a period of 110 years (1901–2010) for Tamil Nadu and Karnataka were obtained from India Water Portal (https://www.indiawaterportal.org/metdata/). A prewhitening procedure is done before applying these data for further statistical analysis namely Mann-Kendall's test.

4 Results and Discussion

4.1 Rainfall Trend Analysis

4.1.1 Annual Rainfall Classification

Data analysis was worked out in steps to get better insight into drought conditions considering rainfall data for 110 year for both regions. Monthly rainfall gauge data for each district or climatic division of both regions were acquired and annual rainfall were computed for 110 years. Rainfall dataset for 110 years for Tamil Nadu and Karnataka was segregated according to regional rainfall classification suggested by Subramanya (2013) and presented in Table 5 in order to understand the relative wetness status of two study regions. A number of years within study time of 110 years for annual rainfall under low, medium, high, and very high ranges for both states were counted, statistically analyzed and presented in graphical form in Fig. 3a and corresponding distribution shown in map represented in Fig. 3b.

It is readily inferred from Fig. 3a, b that relative wetness in Karnataka region was higher if compared with Tamil Nadu. In Karnataka region, three district stations were exhibiting high annual rainfall status whereas Tamil Nadu had majority of district having medium annual rainfall for the last 110 years of time span. This is due to the fact that Tamil Nadu lies in eastern zone of Western Ghats. The Eastern Ghats lying in Tamil Nadu, is irregular, broken, and
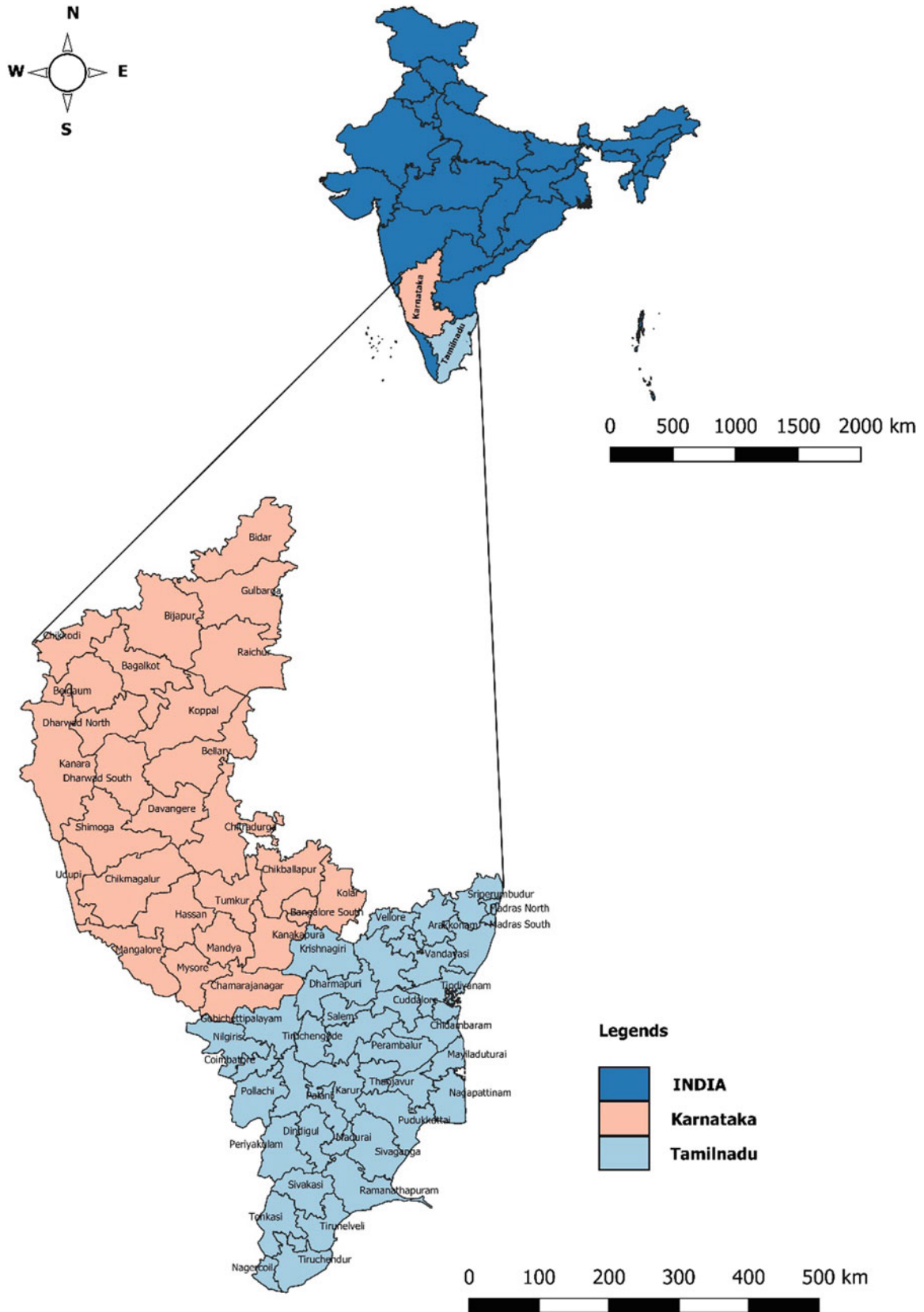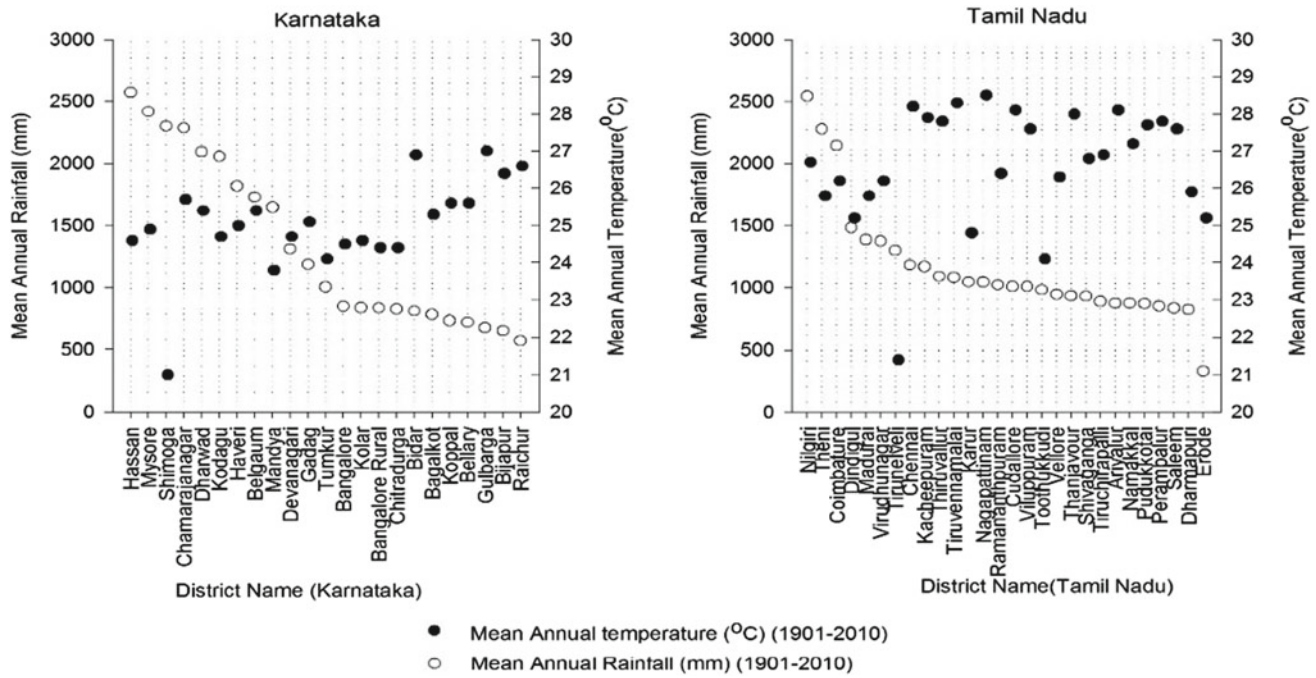
Fig. 1 Location map representing Karnataka and Tamil Nadu states of India

Fig. 2 Districtwide mean annual rainfall and mean annual temperature for two states

Table 5 Ranges of rainfall distribution

Classification	Range (in mm)
Low rainfall	<750
Medium rainfall	750–1125
High rainfall	1125–2000
Very high rainfall	>2000

Source (Subramanya, 2013)

smaller in heights compare to Western Ghats. However, moisture laden winds reach on the eastern part leading to moderately good rainfall condition in this region. Hence, one can even find large variation in rainfall intensities between eastern and western Tamil Nadu.

4.1.2 Rainfall Trend Analysis Using Mann-Kendall's Test

Rainfall data all district gauge stations for two states were further analyzed using Mann-Kendall's test and trend of rainfall variation using linear regression techniques had been worked out. All the district stations those registered decreasing trends were identified and corresponding trends with data points were graphically represented in Fig. 4a, b for Karnataka and Tamil Nadu, respectively. The district gauge stations with decreasing trends were segregated after performing Mann-Kendall's test and represented in tabular form in Table 6 with all its indicators and parameters. Further districts with decreasing trends are vividly depicted in

map showing two states in Fig. 5. From all the results shown, it can be inferred that number of districts with decreasing rainfall trend was 14 whereas in Tamil Nadu districts with rainfall decrease is 8. In Karnataka, the trend lines of districts with rainfall decrease were considerably higher with respect to that of Tamil Nadu. This behavior is natural as the average annual rainfall in Karnataka was relatively higher side with respect to Tamil Nadu and may not necessarily indicate meteorological drought condition in Karnataka. However, insignificant or slight rainfall decrease in regions with low annual rainfall may come under meteorological drought condition as region is already water scarce in character.

From the obtained result, it may be inferred that Karnataka as being rain-fed region may have decreased rainfall trends in many districts, however, with respect to drought conditions, Tamil Nadu has more vulnerability with areal extends. It can be easily inferred from Fig. 4a, b that Tirunelveli, Dindigul, Madurai, Vidyut Nagar are reported to
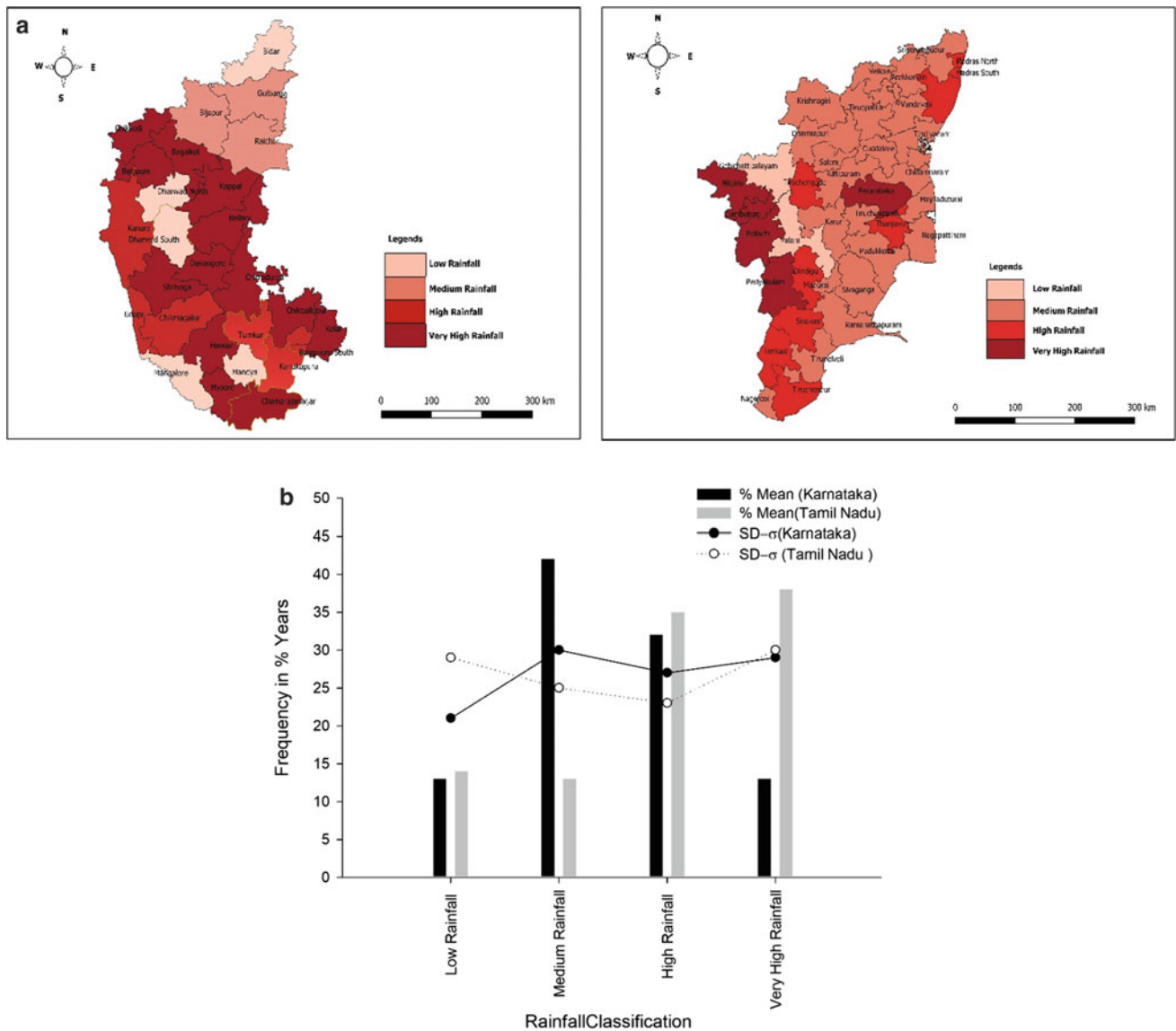
Fig. 3 Rainfall distribution of study area based on annual rainfall classification. **b** Number of year verses rainfall classification for all districts

exhibit more water scarce situation than any of the districts of Karnataka with decreasing rainfall trends. Situation could be further analyzed in the subsequent section where decadal percentage departures from the normal have been analyzed for both states to get more vivid findings.

The nonparametric trend of annual rainfall of districts of Karnataka with decreasing trends is also presented in Table 6. Only Karur district in Tamil Nadu state lies under the lowest decrease rainfall interval of less than 1.0 mm. None of the districts are having decreasing rainfall less than 0.5 mm. Study also suggests that Ariyalur, Namakkal, Ramanathapuram, Thoothukudi, Vellore are the districts which lies under the lowest increase rainfall interval of less than 0.5 mm while Cuddalore and Nagapattinam districts lie under the highest rainfall increase interval between 2 and

3 mm. None of the districts are having rainfall increasing value more than 3 mm. Similarly, Bellary and Koppal are the districts in Karnataka which lie under the lowest decrease rainfall interval of less than 0.5 mm while Dharwad, Mysore, Hassan, and Chamarajanagar districts lie under the highest rainfall decrease interval of above 5 mm. Trend analysis also suggests that Bagalkot and Kolar are the districts which lie under the lowest increase rainfall interval of less than 0.5 mm while Bangalore, Bijapur, Gulbarga, and Kodagu districts lie under the highest rainfall increase interval between 1 and 2 mm. None of the districts were having rainfall increase value more than 2 mm

Figure 5 shows a map of Karnataka and Tamil Nadu, where all the districts are with decreasing rainfall trend and increasing rainfall trend for the study period (1901–2010). It
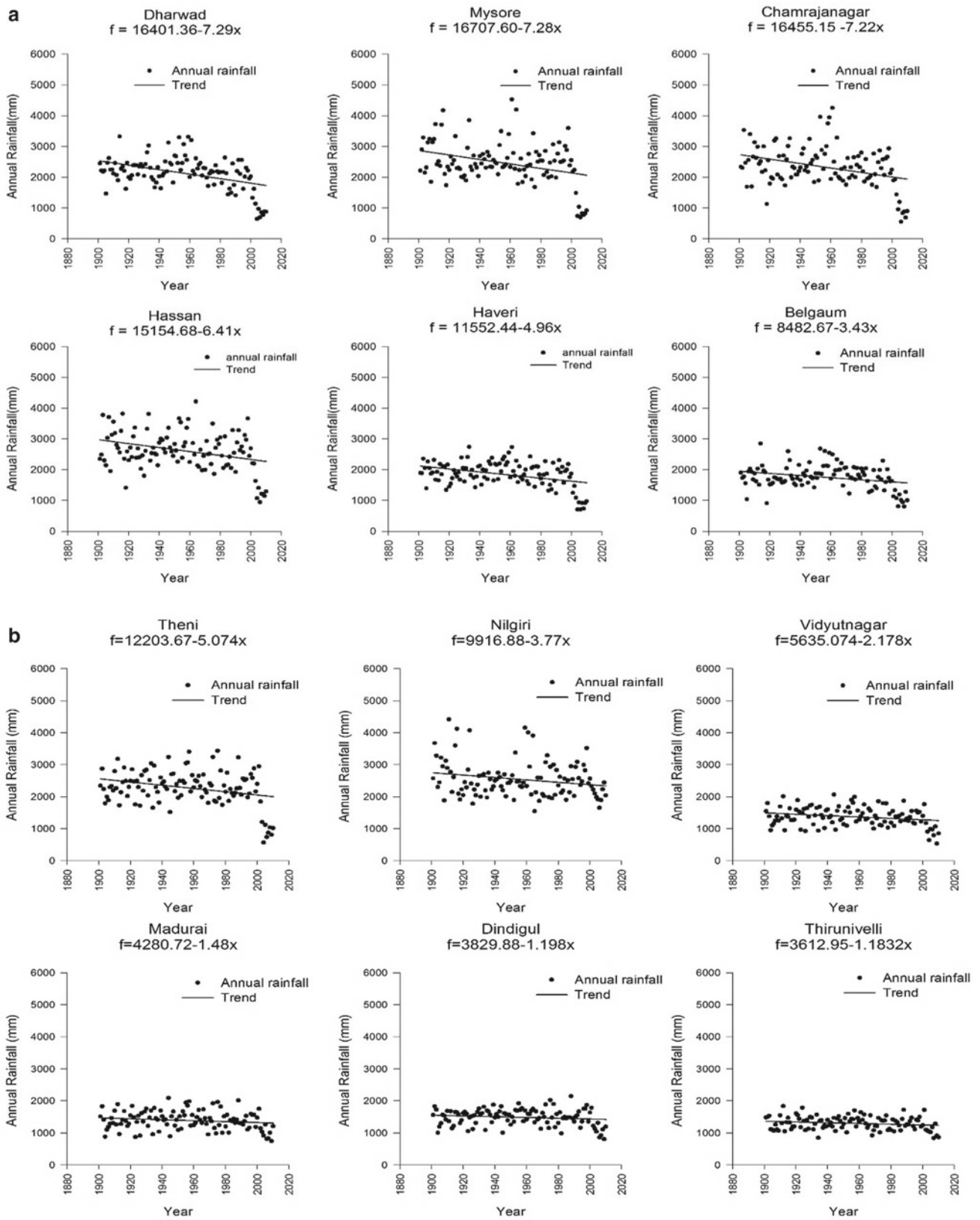
Fig. 4 District with higher decreasing rainfall trends in Karnataka. **b** Districts with higher decreasing rainfall trends in Tamil Nadu

Table 6 Consolidated Mann-Kendall test results (of decreasing rainfall trends) for study regions for 110 years

District	Kendall's Tau	Mann-Kendall statistics (S)	P-district two value (two-tailed)	Alpha	Trend
Karnataka					
Bangalore Rural	0.09	531	0.17	0.05	Decreasing
Belgaum	−0.15	−911	0.02	0.05	Decreasing
Bellary	−0.03	−191	0.62	0.05	Decreasing
Chamarajanagar	−0.20	−1219	0.00	0.05	Decreasing
Chitradurga	−0.08	−493	0.20	0.05	Decreasing
Devanagari	−0.19	−1147	0.00	0.05	Decreasing
Dharwad	−0.26	−1543	0.00	0.05	Decreasing
Gadag	−0.21	−1231	0.00	0.05	Decreasing
Hassan	−0.17	−1025	0.01	0.05	Decreasing
Haveri	−0.20	−1181	0.00	0.05	Decreasing
Koppal	0.01	83	0.83	0.05	Decreasing
Mandya	−0.10	−601	0.12	0.05	Decreasing
Mysore	−0.14	−839	0.03	0.05	Decreasing
Shimoga	−0.12	−725	0.06	0.05	Decreasing
Tumkur	−0.05	−325	0.40	0.05	Decreasing
Tamil Nadu					
Coimbatore	−0.138	−825	0.033	0.05	Decreasing
Dindigul	−0.090	−539	0.165	0.05	Decreasing
Karur	−0.057	−339	0.383	0.05	Decreasing
Madurai	−0.104	−621	0.109	0.05	Decreasing
Nilgiri	−0.127	−761	0.050	0.05	Decreasing
Tirunelveli	−0.118	−707	0.068	0.05	Decreasing
Virudhunagar	−0.141	−847	0.029	0.05	Decreasing
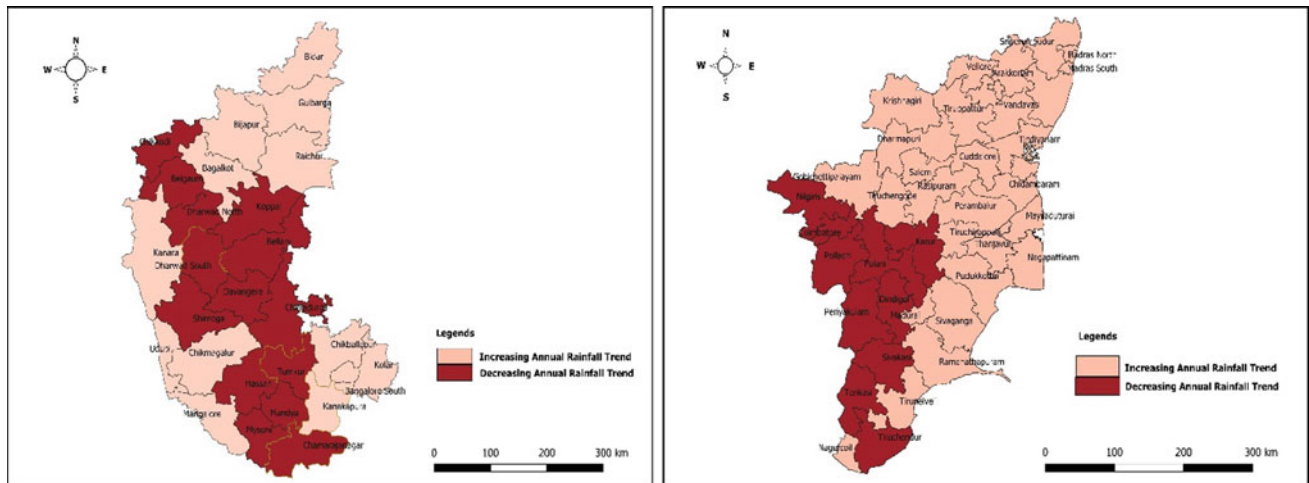
Fig. 5 Districtwise annual rainfall trend for both states

is noticeable that slight decrease or insignificant increase in rainfall in most districts of Tamil Nadu would have larger impact on drought vulnerability with respect to that of Karnataka and the mean annual rainfall in Tamil Nadu region comparatively lower than that of Karnataka region. It is pertinent to mention that, for the period of study (1901–2010) based on annual rainfall classification, there were either high rainfalls in 38 years or medium rainfalls in

15 years. However, there were low rainfalls only for 15 years in some of the districts of Karnataka. Very high rainfalls were recorded in 42 years for some districts of Karnataka.

On the basis of annual rainfall classification, it was found that four districts were having low rainfall (high risk of drought), seven districts were having medium rainfall (high risk of drought), five districts were having high rainfall (low risk of drought), and six districts were having very high rainfall (very low risk of drought), whereas in Tamil Nadu region, for the period of study (1901–2010) in general, there were either high rainfalls in 35 years or medium rainfalls in 45 years. However, in 16 years, there were low rainfalls in some of the districts of Tamil Nadu. Very high rainfalls were recorded in 14 years for the districts of Tamil Nadu. On the basis of annual rainfall classification, it was found that one district was having low rainfall (very high risk of drought), 18 districts were having medium rainfall (high risk of drought), six districts were having high rainfall (low risk of drought), and only three districts were having very high rainfall (very low risk of drought). Precipitation data analysis using annual rainfall classification in conjunction with trend analysis can depict a qualitative indication of meteorological processes however adequate metrological drought characterization requires further in-depth analysis.

4.2 Drought Analysis

4.2.1 Drought Index (DI) Analysis

It can be readily inferred from the previous section, that based on annual rainfall classification (Fig. 3a), there were 11–12 districts with high/very rainfall (low risk of drought) for many of the years in Karnataka whereas almost 19 districts of Tamil Nadu had medium or low rainfall in most of the years (high risk of drought) of the study period of 110 years (1901–2010).

However, one can observe that a relatively qualitative idea can possibly be established from this analysis. Districts namely Dharwad, Mysore, Begaum, Devnagri, and Bagalkot were representing considerable numbers of years under high rainfall if one considers only the classification. Similarly, Nilgiri and Vidyut Nagar in Tamil Nadu came under high rainfall category. However, looking at the statistical trend analysis as described in last section, rainfall was on decreasing trend in these districts leading to meteorological drought condition which supported realistic scenario of those districts. Hence, it is apparent that annual rainfall classification has limitation and cease to suggest concrete drought situation in the study region. To get a deeper insight into drought situation, one can appropriately choose a drought indicator that possibly incorporate the cumulative impact of

rainfall decrease or increase for a longer span of time with possible data analysis for further in-depth study.

Keeping in view of the fact, drought index (IMD, 1971) was computed using Eq. (6) considering 110 years of monthly rainfall data. It was found that out of 110 years and out of 23 districts of Karnataka, 14 districts were found with average 44 event years of mild drought, 10 event years of moderate drought and 2 event years of severe drought condition during the year 1901 to 2010 as per the threshold values presented in Table 2. Similarly, in Tamil Nadu too, average 46 times mild drought, 6 times moderate drought, and 1 times severe drought in 28 districts were found during the study period (1901 to 2010). The only difference that can be readily inferred is that % areal extend of drought condition was more in Tamil Nadu than that of Karnataka due to low-to-medium annual rainfall recorded in Tamil Nadu. The areal extend of drought affected of Karnataka and Tamil Nadu as per DI values is shown in Fig. 6.

The graphical comparison based on no drought, mild drought, moderate drought, and severe drought based on DI values for both states are vividly depicted in Fig. 7 for illustration. It can be found that so far drought recurrence is concerned (mostly mild drought cases), Tamil Nadu is predominating however in terms of severity (Moderate or severe drought situation) Karnataka is ahead of Tamil Nadu. However, to get better insight another drought index namely Palmer drought index as described in previous Sect. 2.3 was evaluated for all meteorological district stations for both study regions in subsequent section.

4.2.2 Palmer Drought Index (PDI) Analysis

Palmer index values were computed using climatic data, i.e., precipitation and temperature (Palmer, 1965) using the relation presented in Eqs. (7) and (8) and methodology presented in Sect. 2.3. The practical calculation illustrates the complexity of the PDI (Gutmann, 1998). To reduce the complexity, Eq. (7) was simplified with considering the evapotranspiration term only. The simplified Thornthwaite method (Thornthwaite, 1978) was used for estimating potential evapotranspiration. Thus, PDI is calculated from precipitation deficits for monitoring long-term drought conditions with 12-month intervals to compare it with twelve-month SPI values. Event years including different intensities of meteorological drought, wet and near normal (NN) condition (based on threshold values presented in Table 3) based on computed PI values for precipitation for both study regions are presented in graphical form in Fig. 8, respectively.

It was found that incipient dry spell (IDS) condition was predominant in all most all district gauge stations of Karnataka for considerable number of years during the study period. However, moderate-to-severe drought was observed
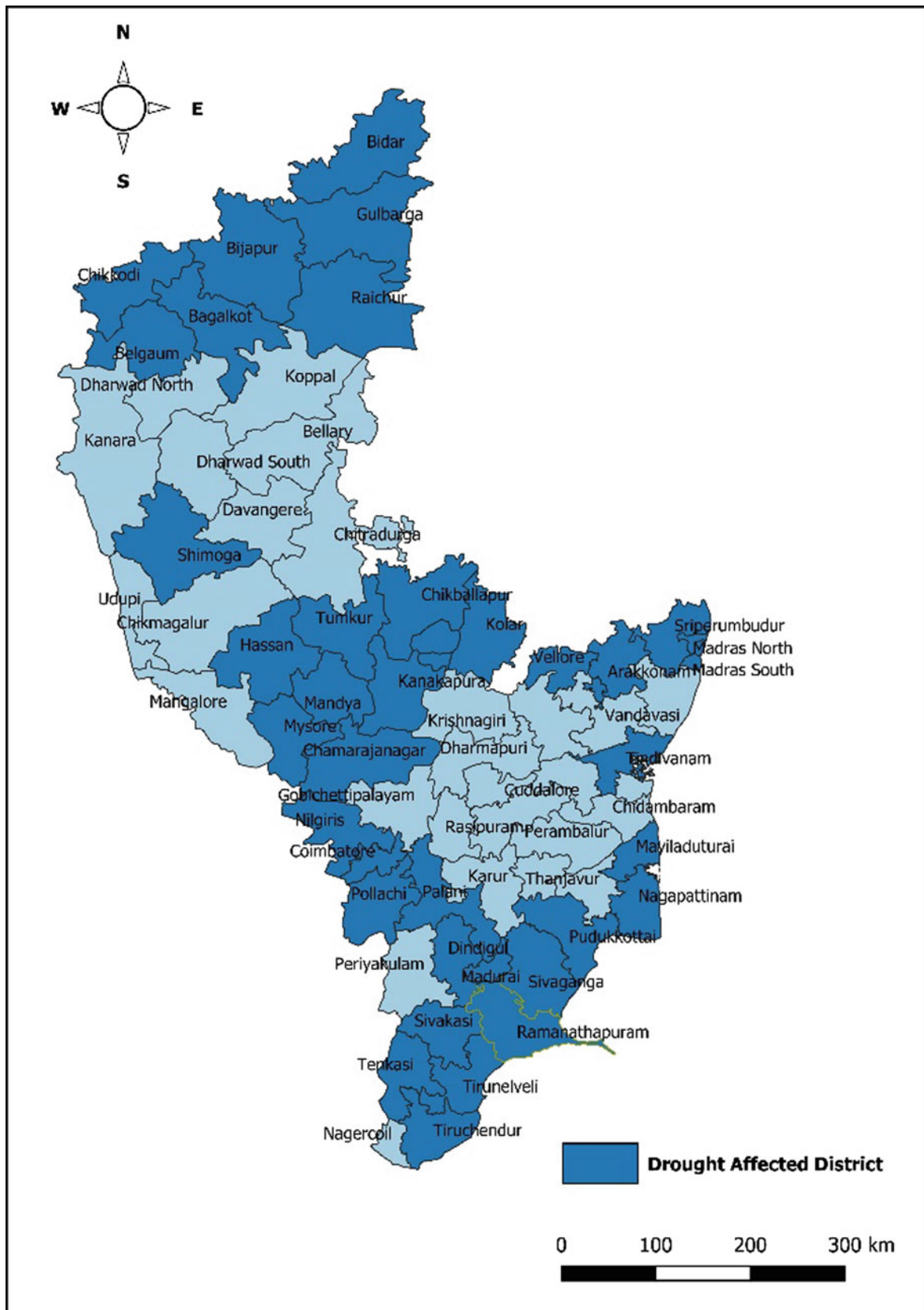
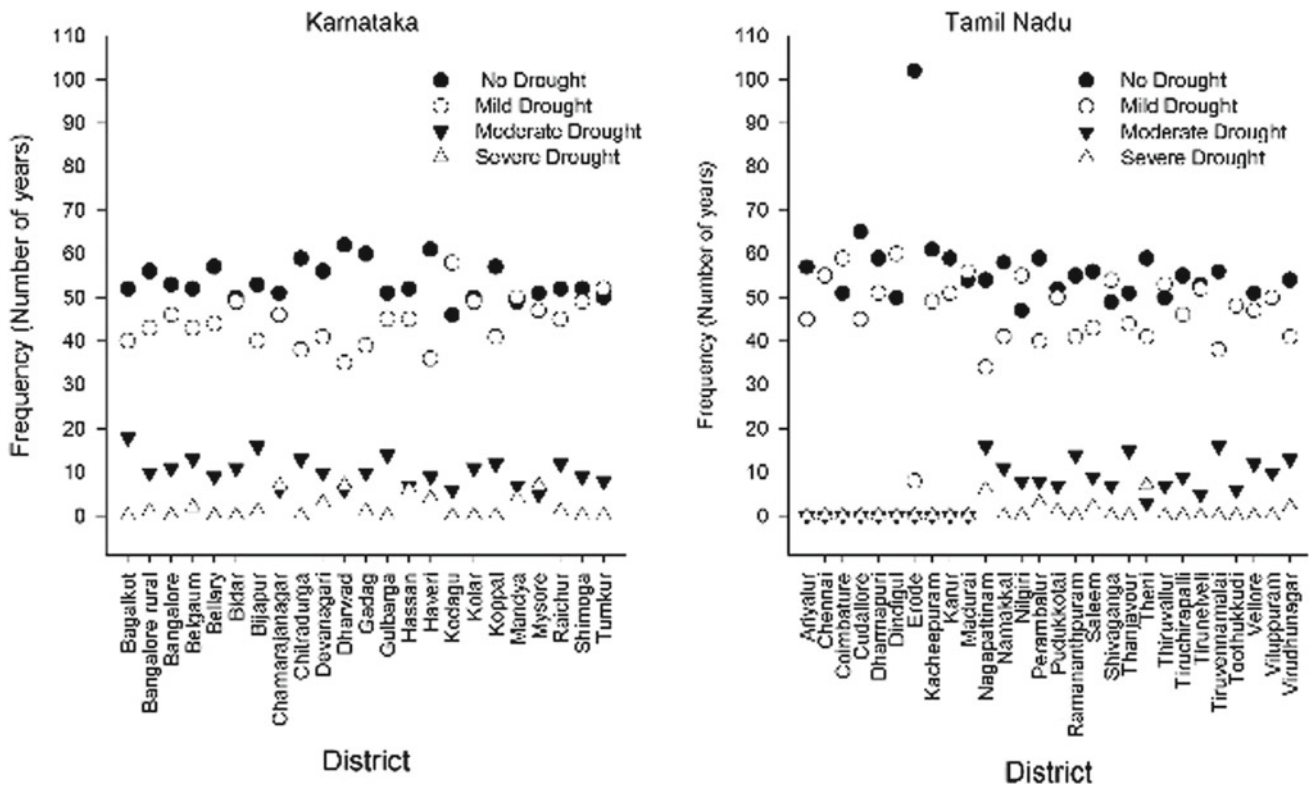**Fig. 6** Drought-affected districts of study region as per DI values

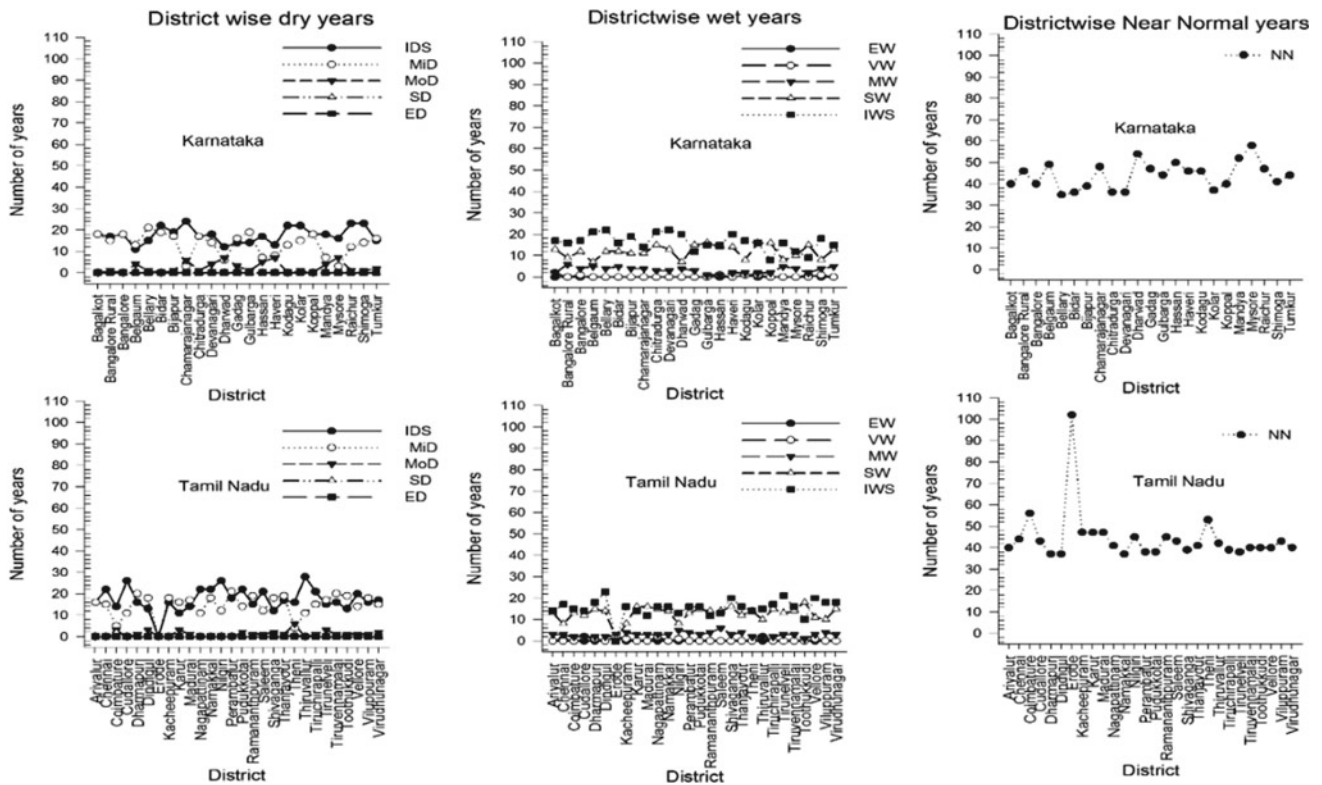**Fig. 7** Drought intensity based on DI values

Fig. 8 Drought intensity based on PDI values

Table 7 Number of drought event years with respect to SPI values for districts of Tamil Nadu and Karnataka region

Sl. no.	Tamil Nadu				Karnataka			
	District	MD (event years)	SD (event years)	ED (event years)	District	MD (event years)	SD (event years)	ED (event years)
1	Ariyalur	12	5	0	Bagalkot	14	4	0
2	Chennai	11	5	0	Bangalore rural	8	7	1
3	Coimbatore	2	3	5	Bangalore	9	9	0
4	Cuddalore	8	4	0	Belgaum	8	5	4
5	Dharmapuri	17	3	1	Bellary	18	4	1
6	Dindigul	12	6	3	Bidar	16	4	0
7	Erode	0	0	0	Bijapur	14	4	1
8	Kanchipuram	12	6	0	Chamarajanagar	1	2	6
9	Karur	11	5	3	Chitradurga	11	7	1
10	Madurai	10	7	1	Devanagari	12	3	4
11	Nagapattinam	16	2	0	Dharwad	4	2	7
12	Namakkal	13	5	0	Gadag	11	5	3
13	Nilgiri	10	2	0	Gulbarga	14	5	2
14	Perambalur	16	5	0	Hassan	4	3	5
15	Pudukkottai	9	5	2	Haveri	7	1	7
16	Ramanathapuram	11	8	1	Kodagu	12	2	0
17	Salem	16	3	1	Kolar	9	6	1
18	Sivaganga	11	7	2	Koppal	14	4	2
19	Thanjavur	16	3	1	Mandya	5	2	4
20	Theni	3	1	7	Mysore	0	0	0
21	Thiruvallur	5	6	0	Raichur	10	3	1
22	Tiruchirappalli	9	5	1	Shimoga	12	3	1
23	Tirunelveli	15	2	3	Tumkur	11	5	2
24	Tiruvannamalai	15	5	1				
25	Thoothukudi	14	6	1				
26	Vellore	9	5	1				
27	Viluppuram	13	5	1				
28	Virudhunagar	12	3	2				
Mean		11	4.36	1.32		9.74	3.91	2.30
Standard deviation		4.28	1.87	1.63		4.54	2.04	2.21

in at least 5–10-year counts in several districts namely Chamarajanagar, Dharwad, Belgaum, Haveri, and Mysore. Similarly, Palmer index values were also computed for temperature parameter. It was found that there was no cases of extreme drought (ED) nor severe drought (SD) events in any of 23 districts of study region. Apart from drought event years, in an average 3 event years of moderately wet (MW), 31 events of near normal (NN), 14 events of slightly wet (SW) and 12 events of incipient wet spell (IWS) climatic situations could be identified in different districts. In three districts, one event year with very wet climate was found along with two event year of very wet condition (in Shimoga district). None of the districts have indicative of extremely

wet (EW) climate condition as in case of Palmer drought index values.

Similarly, in case of Tamil Nadu, incipient dry spell (IDS) was prevalent in all most all districts of Tamil Nadu. At least 15–17 event years of mild drought-to-moderate droughts, 18 event years of incipient dry spell were inferred in Tamil Nadu, mostly in districts of Nilgiri, Vidyut Nagar, Dindigul, and Theni in past 110 years. It is pertinent to mention that for both states almost identical event years (44 times) were under near normal (NN) condition with 12–13 event years as slightly wet and 3 event years as moderately wet conditions. Furthermore, no extremely wet or very wet conditions were observed during the period of study for all district of both

states. The finding suggests that mild-to-moderate drought was predominating (with higher event years) in Tamil Nadu whereas moderate-to-severe drought were existed but for lesser number of years (10–11 years) in Karnataka.

4.2.3 Standardized Precipitation Index (SPI) Analysis

Standardized precipitation index (SPI) as suggested by McKee et al. (1993, 1995) incorporates the seasonal variation of rainfall and may be analyzed statistically through fitting to gamma distribution function (Rahmat et al., 2015), computed using methodology presented in Sect. 2.4 for available precipitation data. Twelve-month *SPI* values were chosen considering the suitability for water resources studies (Bonaccorso et al., 2003; Raziei et al., 2009). A number of event years were found to be under drought situation in categories such as moderately dry, severely dry, and extremely dry for all meteorological district stations of both states. It is presented in Table 7 with statistical mean and standard deviations and is graphically represented in Fig. 9.

One can observe that mean event years for moderately dry and severely dry were considerably higher in case of Tamil Nadu whereas for extremely dry condition, Karnataka was registering higher value. Similarly, for statistical spread of the distribution, Tamil Nadu landed up with lower values than that of Karnataka. It means that higher numbers of event years were nearer to peak events values. That is also suggestive of relatively higher vulnerability of drought situations in Tamil Nadu. In conclusion, Tamil Nadu had more vulnerability of moderate-to-severe drought situation with larger areal extend whereas Karnataka had more localized drought vulnerability with severity on higher side.

4.2.4 Comparison of Three Drought Indices for Two Study Regions.

Districtwide computed drought indicators namely DI, PI (precipitation), PI (temperature), and SPI for both states for the study period were compared with percentage mean frequency of occurrence with their indicatorwise threshold values and presented in Fig. 10. Near normal (NN) condition was prevailing more than 50 percent of the study period for all considered indices. However, there were visible difference of estimated frequencies of occurrence for mild-to-severe drought conditions for each index analysis of two study regions. Noticeably, pattern is coherent in case of DI, PDI, and SPI for the with small variations. Furthermore, it is interesting to note that for extreme drought condition all indicators are registering more vulnerability for Karnataka if compared with that of Tamil Nadu. Corresponding standard deviation (SD—σ) values are also plotted in order to have insight into the spread of the variation of severity for all districts of each state (Fig. 10).

From the above analysis, it can be concluded that drought characterization using three drought indicators namely DI, PDI, and the SPI produced somehow coherent information, but the use of PDI is limited and complex to assess with respect to DI and SPI, as it requires huge additional data and computations to perform an adequate and accurate soil water balance while the DI and SPI need only precipitation data, which are more easily available in numerous location of the study areas. It is also concluded that using SPI is more meaningful relative to DI as it incorporates seasonal variation also and better statistical information can be obtained for further in-depth analysis.

4.2.5 Identification of Drought Events Using Log Pearson Type—III Distribution Technique for Karnataka

As the meteorological drought indicator values involves precipitation and computed indicators were based on rainfall data in this study, Log Pearson type III distribution presumed (Rahmat et al., 2015) to be fit nicely to get more meaningful analysis. The statistical parameters for implementing Pearson III are the obvious way using the mean, standard deviation, and skewness of the sample. A popular approach is to sort the sample and assign rough probability estimates to each point according to its rank (Hovey and DeFiore, 2003). The computed SPI data for Karnataka were further analyzed to compute the probability of exceedance for threshold values of SPI with respect to severity.

The Log Pearson Type III distribution on the modified nonzero drought deficit in terms of *SPI* (namely 'Scaled SPI' using a nonzero drought deficit parameter = SPI threshold value plus five as presented in Table 8) for 110 years (1901–2010) were computed. Further, percentage exceedance of drought deficit hence return period of all 23 districts of Karnataka was computed using analytical method with probability estimates using skewness functions as per equations presented in Eqs. (14a)–(14c). The Microsoft Excel spreadsheet has skewness functions (Hovey and DeFiore, 2003) that return estimates of γ_1 as follows.

$$PIII(x) = \Gamma D(x - \Upsilon, \alpha, \beta); \gamma_1 > 0 \qquad (14a)$$

$$PIII(x) = \Gamma D(\Upsilon - x, \alpha, \beta); \gamma_1 < 0$$

One can write combining the above two expression as,

$$PIII(x) = \Gamma D\left((x - \Upsilon) \cdot \frac{\gamma_1}{|\gamma_1|}, \alpha, \beta\right) \qquad (14b)$$

where ΓD is the standard gamma distribution function and 'shape' $\alpha = 4/\gamma_1^2$; 'scale' $\beta = |\sigma\gamma_1/2|$ ($\beta = \sigma/\sqrt{\alpha}$); 'shift' $\gamma = \mu - 2\sigma/\gamma_1$ ($\gamma = \mu \pm \alpha\beta$, depending upon the sign of γ_1.
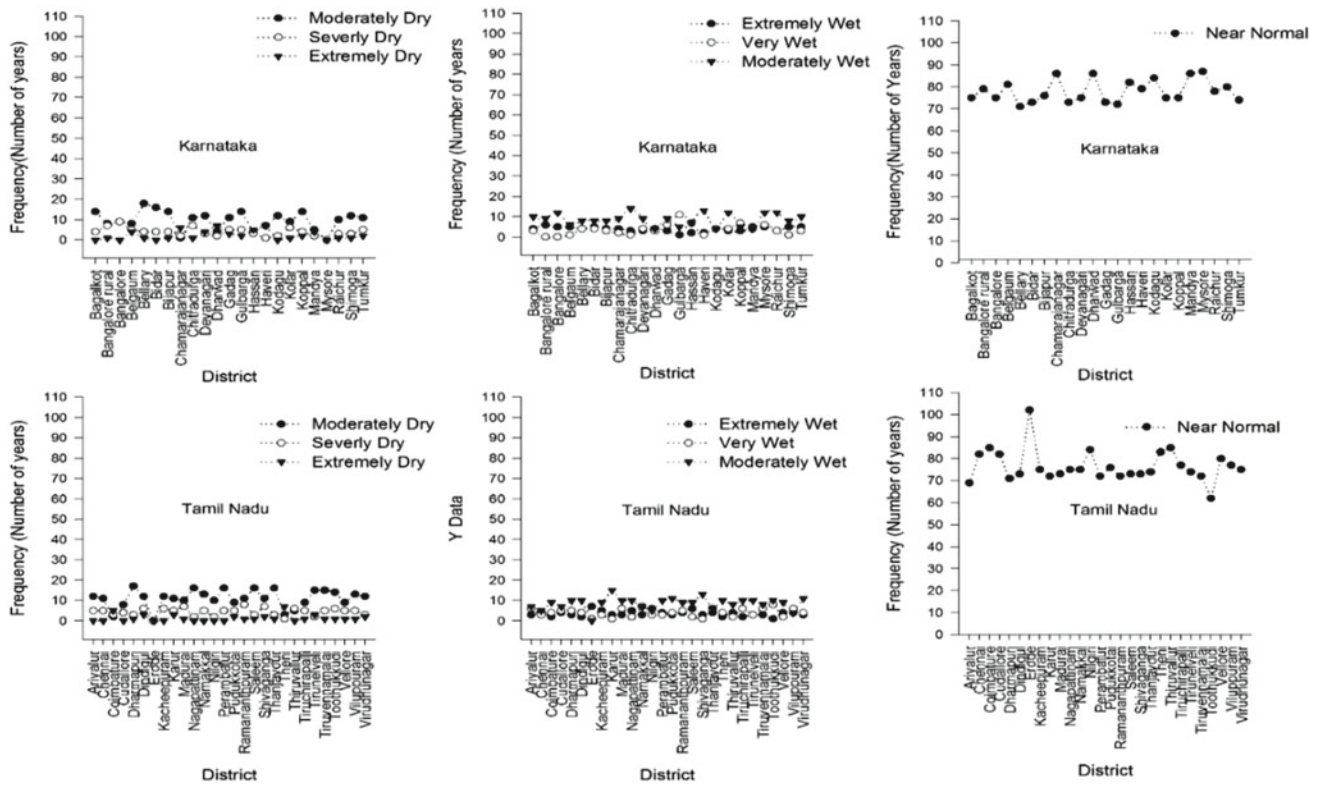
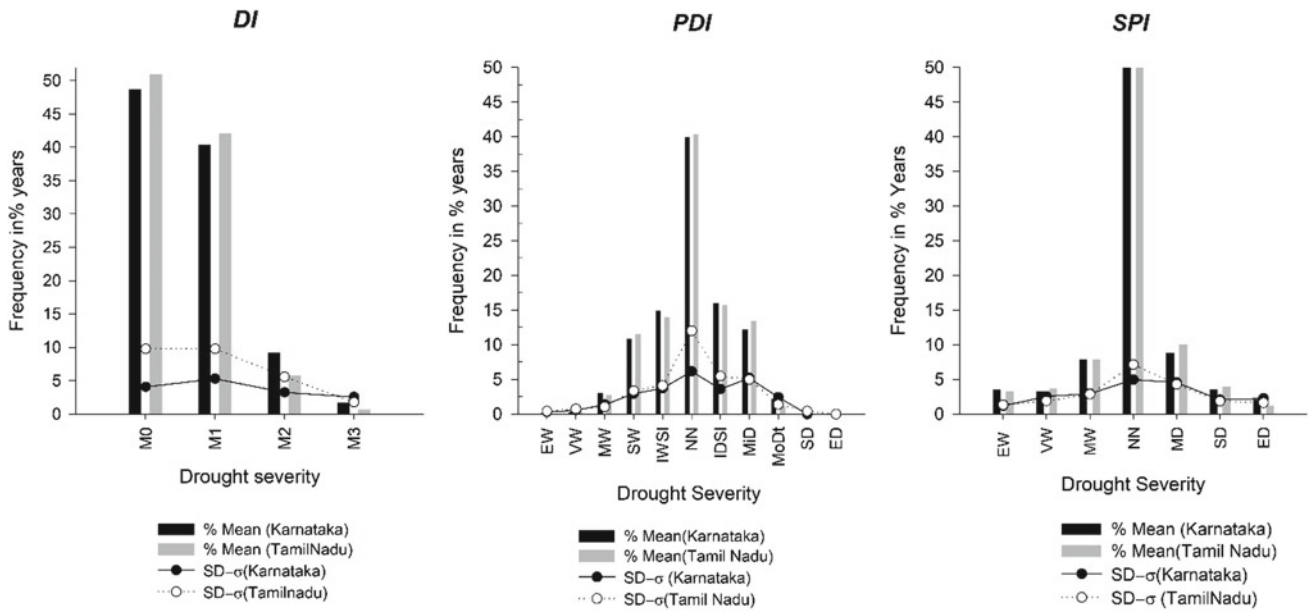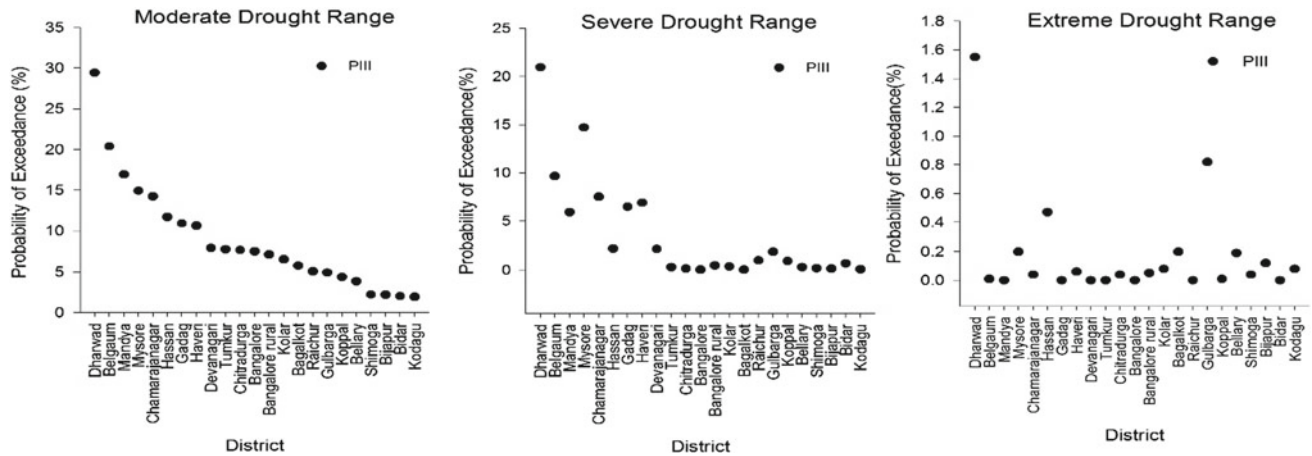Fig. 9 Drought intensity based on SPI values

Fig. 10 Yearly drought intensity for 110 years based on PI with respect to precipitation values

Table 8 Threshold values of *Scaled SPI* (drought deficit)

Classification	EW	VW	MW	NN	MD	SD	ED
Scaled SPI value	≥ 7	6.5–6.99	6–6.49	4.01–5.99	4.0–3.51	3.5 to −3.01	≤ 3

Fig. 11 Percentage exceedance probabilities for drought events using analytical LPIII technique for 110 years on with scaled *SPI* values for Karnataka

where $\mu, \sigma,$ and γ_1 are mean, standard deviation, and skewness of the distribution.

The logarithmic transformation will be written as follows,

$$PIII(x) = \Gamma D\left(\log(x - \Upsilon) \cdot \frac{\gamma_1}{|\gamma_1|}, \alpha, \beta\right) \qquad (14c)$$

where α, β, Υ and μ, σ, γ_1 are defined in terms of log (x) instead of x (base is 10). The distribution is not defined for x beyond the shift, which is the lower bound for the positive skew case and the upper bound for the negative, if γ_1 is exactly zero. The in-built functions are available in Excel software. Accordingly, the Log Pearson Type III distribution on the modified nonzero drought deficit in terms of SPI (namely 'Scaled SPI' using a nonzero drought deficit parameter = SPI threshold value plus five as presented in Table 8) for 110 years (1901–2010) has been computed.

The derived dataset for all 23 districts of Karnataka region in Indian Peninsula is graphically represented in Fig. 11 for moderate, severe, and extreme drought events based on the threshold values (presented in Table 8).

Analyzing Fig. 11, it is found that under moderate drought condition, Dharwad district is having maximum percentage probability of exceedance of drought, followed by Belgaum district. On the other hand, Kodagu district is having minimum percentage of probability of exceedance, i.e., 2.3%. Similarly, for severe drought condition, again Dharwad district is having maximum exceedance probability followed by Mysore, while Bangalore and Bagalkot are having least exceedance probabilities. In case of extreme drought condition, again Dharwad district is found to be having largest exceedance probability followed by Gulbarga district. However, Mandya, Gadag, Devnagri, Tumkur, Bangalore, Raichur, and Bider are found to be having least exceedance probabilities.

5 Conclusion

1. The present study to predict meteorological drought condition of classified thresholds namely moderate, severe, and extreme drought conditions using standard precipitation index with assessment of twelve-month SPI along with other two indices namely Palmer index and drought index for two southern Indian states and compared.

2. Results from climatic divisions of two states under study show that drought characterization using three drought indicators namely DI, PDI, and the SPI produce somehow coherent information, but the use of PDI is limited and complex to assess with respect to DI and SPI, as it requires huge additional data and computations to perform an adequate and accurate soil water balance while the DI and SPI need only precipitation data, which are more easily available in numerous location of the study areas. It is also concluded that using SPI is more meaningful relative to DI as it incorporates seasonal variation also and better statistical information can be obtained for further in-depth analysis.

3. Tamil Nadu was found to be more vulnerable to moderate-to-severe drought situation with larger areal extend whereas Karnataka had more localized drought vulnerability with severity on higher side.

4. The monotonic trend of rainfall of the districts of Karnataka and Tamil Nadu in the past 110 years using nonparametric methods namely Mann-Kendall and Sen's Slope tests were investigated and six districts of each state with decreasing rainfall trends have been critically analyzed. It was found that decreasing trend in Karnataka is more significant as compared to that of Tamil Nadu.

5. Log Pearson probability distribution technique using SPI is attempted to assess exceedance probabilities of meteorological drought condition of classified thresholds for Karnataka region. It was found that Dharwad district in Karnataka is the most vulnerable among 23 districts, with respect to severity and recurrence of drought conditions.

6 Conflict of Interest/Competing Interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

7 Availability of Data and Materials

The online version of this article contains supplementary material, which is available to authorized users.
Code availability: custom code part is absent.

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