

Development of Drought Indices for Semi-Arid Region Using Drought Indices Calculator (DrinC) – A Case Study from Madurai District, a Semi-Arid Region in India

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Abstract Drought is considered as a major natural hazard/ disaster, affecting several sectors of the economy and the environment worldwide. Drought, a complex phenomenon can be characterised by its severity, duration, and areal extent. Drought indices for the characterization and the monitoring of drought simplify the complex climatic functions and can quantify climatic anomalies for their severity, duration, and frequency. With this as background drought indices were worked out for Madurai district of Tamil Nadu using DrinC (Drought Indices Calculator) software. DrinC calculates the drought indices viz., deciles, Standard Precipitation Index (SPI), Reconnaissance Drought Index (RDI), Streamflow Drought Index (SDI) by providing a simple, though flexible interface by considering all the factors. The drought of 3, 6 and 9 months as time series can also be estimated. The results showed that drought index of Madurai region by decile method revealed that among the 100 years, 20 years were affected by drought and it is cyclic in nature and occurring almost every 3 to 7 years once repeatedly, except for some continuous period, i.e., 1923, 1924 and 1985, 1986, etc. During the last five decades, the incidence is higher with 13 events, whereas in the first five decades it was only 7. The SPI and RDI index also followed the similar trend of deciles. However, under SPI and RDI, the severely dry and extremely dry category was only seven years and all other drought years of deciles were moderately dry. Our study indicated that SPI is a better indicator than deciles since here severity can be understood. SDI did not follow the trend similar to SPI or RDI. Regression analysis showed that the SPI and RDI are significantly correlated and if 1st

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3 months rainfall data is available one can predict yearly RDI drought index. The results demonstrated that these approaches could be useful for developing preparedness plan to combat the consequences of drought. Findings from such studies are useful tools for devising strategic preparedness plans to combat droughts and mitigate their effects on the activities in the various sectors of the economy.

Keywords Drought · DrinC · Drought indices · Strategies

1 Introduction

Drought, an environmental catastrophe is common, and in recent days it has drawn increasing attention from scientists of several disciplines viz., agriculture, ecology, environmental science, meteorology, hydrology, as well as geology due to their enormous impacts on ecology, environment, hydrology and agriculture. It is defined as the deficiency of available water that severely affects the potential production of crops, causes scarcity of water for human/livestock consumption and influences the renewable economic resources. During the past century, a remarkable change in the global climate and environment have observed, resulting in intensified water cycle and frequent, with extreme open events such as droughts and floods at the global scale (Beniston and Stephenson 2004). The rate of recurrence of drought is anticipated to increase under the background of global warming (Dai 2011). Combined, water shortage resulting from the spatial-temporal inconsistency between water supply and demand is expected to become harsher under a warming climate.

Drought is strongly influencing the livelihoods of poor people in many ways by changing several sectors of the economy and the environment worldwide and happened to be a major natural hazard/disaster. Different specialist explains in a different way, for instance, agriculturists relate drought to moisture shortage in topsoil (the root zone) that influences the crops, for meteorologists it is mainly a prolonged scarcity of rainfall, and for hydrologists, it is related to low runoff; least stream flow, etc. These differences highlight the relative roles of precipitation, evapotranspiration (ET) and runoff in drought caused by climatic factors. Drought is a recurrent regional multi-dimensional phenomenon affecting vast areas and a significant number of people. In recent years, droughts have considerably increased in number and intensity over the last few decades, and more people are affected than any other natural hazard for extended periods of time. Drought, a complex phenomenon, can be characterised by its severity, duration, and areal extent. Among these three dimensions, for drought analysis, drought severity can be used. Therefore, it is essential to look into drought evolution characteristic, and especially the formation and propagation mechanism in a changing environment. In a significant way, drought indices measure the severity of the drought.

Drought indices will characterize and scrutinize the drought, by simplifying the complex climatic functions and can quantify climatic variance for their severity, duration, and frequency. Besides, these indices are also very useful, since they can communicate to all stakeholders' in an accessible and simpler format about the information regarding the severity of drought (Tsakiris et al. 2013). The output of these drought indices indicate and help several potential users ranging from students and researchers from academic, research field and by policy makers, bankers for planning purposes (decision making, proactive management, and drought mitigation, etc.) to plan their decisions. Of course, the review of drought studies showed that no universally suitable single index, it is necessary to consider more than one index. For

defining and monitoring meteorological droughts, the Standardized Precipitation Index (SPI) based on prolonged precipitation data, has been comprehensively used by researchers from America (Hayes et al. 1999; Anctil et al. 2002), Asia (Min et al. 2003), Africa (Ntale and Gan 2003; Mathieu and Richard 2003) and Europe (Tsakiris and Vangelis 2005; Nalbantis and Tsakiris 2009; Vasiliades et al. 2011).

There are equations and procedures for calculating the drought indices manually, or by using tools/ software/ models designed for this purpose. In this study, we have utilized a software named DrinC (Drought index calculator) for calculating the drought indices. Details about the structure and calculation steps can be referred from Tigkas et al. 2014. DrinC is a simple software which calculates the drought indices by taking into account all the factors through the flexible interface and providing a simple and understandable output. However, for better output, the meteorological data should be of long-term datasets (at least for 35 years periods). DrinC calculates the indices in the form of deciles, Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI) and Reconnaissance Drought Index (RDI), based on which the drought severity can be analysed, and predict the trend of drought occurrence.

The software is suitable for drought monitoring, drought spatial distribution assessment, investigation of climatic and drought scenarios and declaration of drought for subsidy related issues. Since it is a known fact that India is being affected by drought consecutively or once in 5 to 7 years, and the policy makers are finding it difficult to address the issues of the farmers, industrialists, and all stakeholders (Gupta et al. 2011). There are different methods followed by the governments to declare, and hence some uniform methods need to be developed in a country like India which covers diverse agro-ecological regions. In India, if the farmer needs to get the crop insurance money after the harvest failure due to drought/water scarcity, then entire district needs to be declared as drought affected. Hence for such purposes, these types of drought indices will help the administrators and policy makers to assess the drought impact. Therefore, drought indices using DrinC software are worked out for Madurai district, which is a semi-arid region of Tamil Nadu, India and could be used elsewhere with the similar climatic environment.

2 Materials and Methods

2.1 Details About the Study Area

Madurai District in Tamil Nadu, India is bounded on the North by the districts of Dindugal, Tiruchirappalli, on the East by Sivagangai, on the West by Theni and on the South by Virudhunagar (Fig.1). Analysis of (1901–2004) rainfall data shows that the district receives 47%, 32%, 17%, and 4% rain during NE monsoon, SW monsoon, summer, and winter respectively. The normal annual rainfall varies from 806 mm (Sholavandan rain gauge station) in the northern part to 964.1 mm (Melur rain gauge station) in the east of the district. The climate is subtropical, and the temperature varies from 15 to 41 °C in the region. The relative humidity ranges from 45 to 85% and is high during NE monsoon. Red soil, Black clayey soil, and Alluvial soil represent the study area. Red soil is found in most of the blocks of the district while black clayey soils are in Tirumangalam, Usilampatti and Peraiyur blocks of the district and alluvial soils are along the river courses.

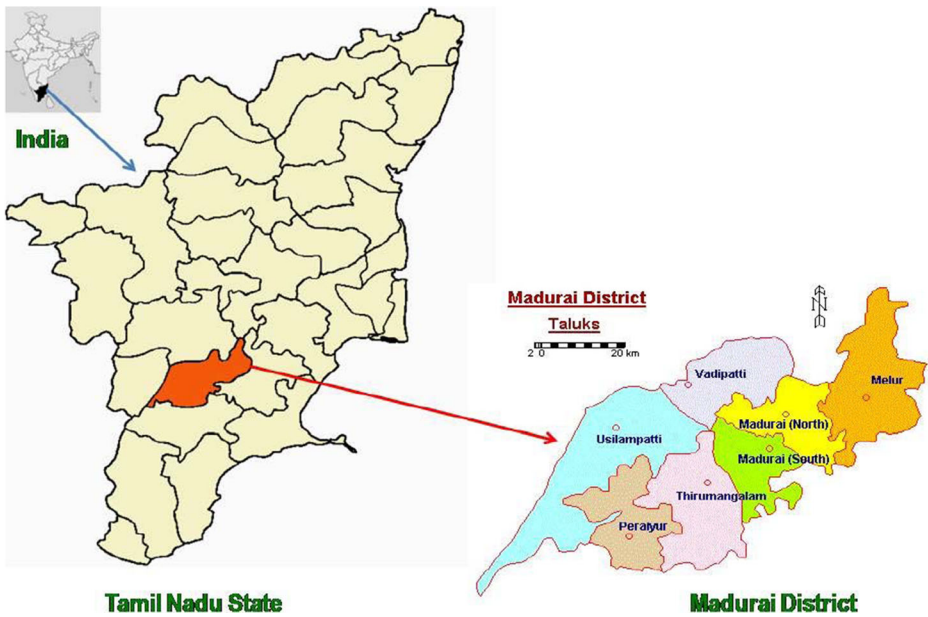


Fig. 1 Map of the study area

The inputs data used for the current study are maximum and minimum temperature, daily rainfall from Indian Meteorological Department (IMD) and stream flow data of CWC for Vaigai river basin. Calculation of drought indices such as deciles, Standard Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Streamflow Drought Index (SDI) worked out. DrinC facilitates the above indices calculation based on the log-normal method and gamma method both with a period of annual, six months and three months.

2.2 Drought Indices

A short description based on the severity of the drought, the drought indices is given below.

2.3 Deciles

The cumulative frequency of the distribution of ranked monthly and annual total precipitation determine the deciles and the value of deciles ranging 5 to 6 is considered to be normal. Classification of drought conditions according to deciles is presented in Table 1.

Table 1 Classification of drought conditions according to deciles

Decile class	Drought description
1–2	Lowest 20% much below normal
3–4	Next lowest 20% below normal
5–6	Middle 20% near normal
7–8	Next highest 20% above normal
9–10	Highest 20% much above normal

2.4 Standard Precipitation Index (SPI)

SPI is calculated based on the long-term rainfall/precipitation data, and these data will be fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (McKee et al. 1993; Edwards and McKee 1997). Transformation is performed on monthly rainfall which is not normally distributed such that the derived SPI values follow a normal distribution. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. Tigkas et al. 2014 describes the comprehensive stepwise approach. If the SPI values are greater than median precipitation, it is positive, and negative SPI values indicate less than median precipitation. The high negative value of SPI indicates the severely dry condition. The classification of drought conditions according to SPI is presented in Table 2.

2.5 Reconnaissance Drought Index (RDI)

To express the water deficit, in a more accurate way, Tsakiris and Vangelis 2005; Tsakiris et al. 2013 and Tigkas et al. 2014 developed the Reconnaissance Drought Index (RDI) and used it for drought monitoring and characterization. RDI is based on both on cumulative precipitation (P), and potential evapotranspiration (PET), in which P is measured and PET is calculated. The initial value (αk) of RDI is calculated for the i -th year on a time basis of k (months) as follows

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^k P_{ij}}{\sum_{j=1}^k PET_{ij}}, i = 1(1)N \text{ and } j = 1(1)k \tag{1}$$

in which P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the j -th month of the i -th year and N is the total number of years of the available data. The values of αk follow both the log normal and the gamma distributions in a wide range of locations and different time scales (Tsakiris et al. 2013) satisfactorily.

By assuming that the log-normal distribution is applied, RDI st calculated using the eq. (2).

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\hat{\sigma}_y} \tag{2}$$

in which $y^{(i)}$ is the $\ln(a_k^{(i)})$, y is its arithmetic mean, and $\hat{\sigma}_y$ is its standard deviation.

Table 2 Classification of drought conditions according to SPI

SPI value	Drought description
2.0 or more	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 or less	Extremely Dry

Positive values of RDI indicate wet periods, while negative values indicate dry periods compared with the average conditions of the area. Drought severity can be categorised as mild, moderate, severe and extreme classes, with corresponding boundary values of RDI (-0.5 to -1.0), (-1.0 to -1.5), (-1.5 to -2.0) and (< -2.0).

2.6 Streamflow Drought Index (SDI)

Streamflow Drought Index for CWC data of Vaigai river basin was worked out based on the method described by Nalbantis and Tsakiris (2009). Table 3 defines the criteria for the classification of hydrological drought index into five classes ranging from 0 (non-drought) to 4 (extreme drought). The input values of rainfall and temperature entered into the DrinC software, and the outputs were derived using the standard procedures adopted for the calculation of drought indices. Based on the calculated indices, an attempt was also made to forecast other indices based on the minimum meteorological data by adopting the uni-dimensional analysis of drought and the reconnaissance drought index (RDI) for assessing drought severity. The forecast method based on linear regression equations is linking the SPI, RDI and the SDI of various time series, viz., 3, 6, 9 months and annual.

3 Results and Discussion

The climate of the experimental site is semi-arid with hot, dry summers and cold winter season. The average annual rainfall observed during the period (1901 to 2002) is 884 mm, and nearly 80% of the rainfall is received during northeast monsoon season during October to December. The average maximum temperature observed during the study period was 33.8°C and minimum temperature observed was 23.9°C .

Drought index of Madurai region by decile method showed that among the 100 years, 20 years were affected by drought (lowest 20% below much normal) and the most affected years were 1904, 1907, 1911, 1913, 1923, 1924, 1934, 1935, 1952, 1958, 1959, 1961, 1965, 1968, 1969, 1974, 1980, 1982, 1985, 1986 (Fig.2). These data showed that the drought is cyclic in nature and occurring almost every 3 to 7 years once repeatedly, except for some period where it occurred consecutively, i.e., 1923, 1924; 1985, 1986, etc. However, for the 15 years period from 1986 to 2000 no occurrence of drought was observed, which indicate that there has been some shift in rainfall climatic parameters, particularly. The interesting observation is during the recent five decades, the incidence is higher with 13 events, whereas in the first five decades of our study it was only 7.

The SPI index also followed the similar trend (Fig.3). However, under SPI, the most affected year's, i.e., severely dry (1923, 1961, 1980 and 1982) and extremely dry category

Table 3 Definition of states of hydrological drought with the aid of SDI

Class	Description	Criteria
0	Non-Drought (Normal)	$\text{SDI} \geq 0.0$
1	Mild drought	$-1.0 \leq \text{SDI} < 0.0$
2	Moderate drought	$-1.5 \leq \text{SDI} < -1.0$
3	Severe drought	$-2.0 \leq \text{SDI} < -1.5$
4	Extreme drought	$\text{SDI} < -2.0$

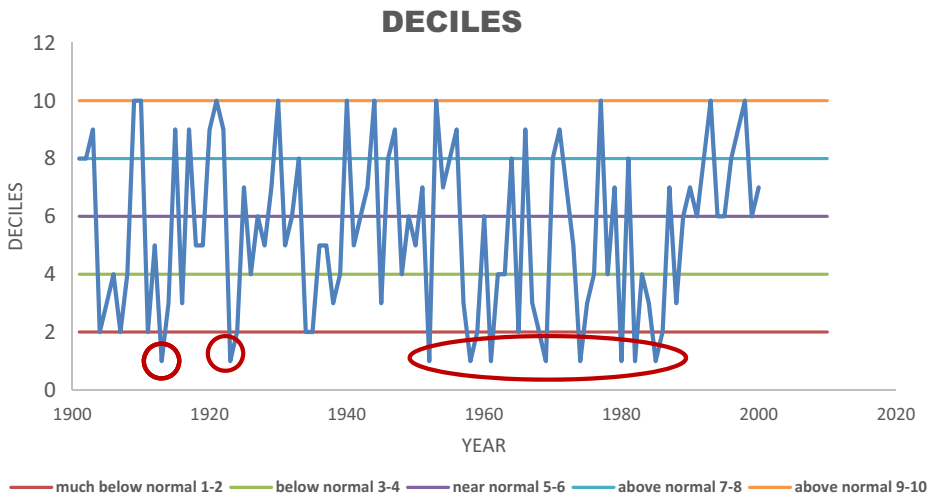


Fig. 2 Drought index by deciles for Madurai region

(1913, 1952, 1974) was only seven years and all other drought years of deciles were a moderately dry category. This SPI indicated the severity of dryness compared to the deciles, and it will help to assess the impact of drought, if we compare with the yield of crops, drinking water availability, etc., (Tigkas et al. 2014). Hence, SPI is a better indicator than deciles, as it helps us to understand severity better. Out of 100 years, only three years fall under extremely dry condition because of very low occurrence of rainfall during that period as compared to rest of the years.

The RDI index also followed the similar trend to that of SPI (Fig.4). However, under SPI, the year 1913, which falls under the extremely dry category, was under severe drought

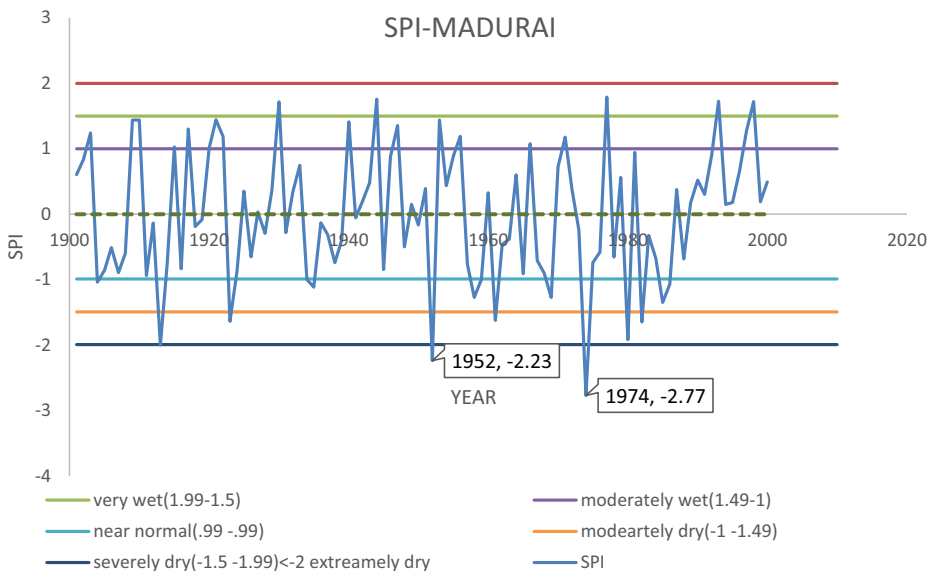


Fig. 3 Drought index by SPI for Madurai region

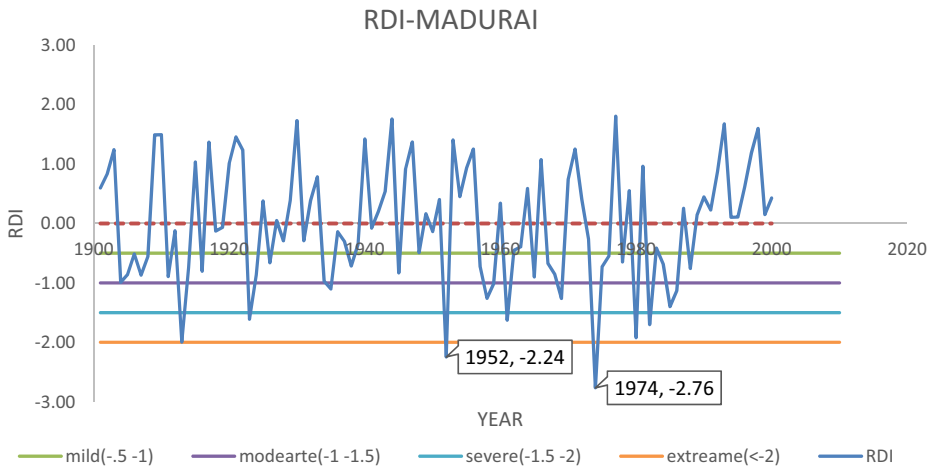


Fig. 4 Drought index by RDI for Madurai region

category in RDI and all other drought categories were similar to SPI. These RDI and SPI indicated the severity of dryness compared to the deciles. Hence, SPI is more robust in predicting the drought and drought impact by studying the yield of crops, irrigation and drinking water availability and crop failure, etc., (Tsakiris and Pangalou 2009; Tsakiris et al. 2013; Vangelis et al. 2013; Tigkas et al. 2014). In India, the farmers could get monetary benefits under crop insurance schemes of the government only when the government declare the entire district as drought affected. Hence such indices will help the policy makers and all stakeholders for effective agricultural land use planning to overcome the prolonged ill effects of drought.

The streamflow drought index (SDI) for 30 years period was worked out (1971 to 2000) and the SDI did not follow the trend similar to SPI or RDI. In SDI the years 1988 and 1991 come under the extreme drought category of class 4 in SDI (Fig.5). However the same is not reflected in Deciles, SPI, and RDI. For the year 1988, the decile showed it as below normal, SPI as near normal and RDI as mild drought, whereas SDI categorized as extreme drought. The possible reason for the difference in SDI with that of other indices is that it is being calculated based on the streamflow. The streamflow in a particular watershed will largely depend on the rainfall period, and its intensity, land use, topography, etc., and hence the hydrological drought sometimes will not be reflected in other indices. Out of 30 years data, SDI analysis showed that 16 years falls under drought category (either mild to extreme), and only 14 years falls under non-drought (average) years.

In a nutshell, all the four indices calculated by DrinC software never missed extremely dry/severely dry drought condition. Hence it may be concluded that this DrinC software based drought indices can be used as a tool in the semi-arid regions of India and elsewhere with a similar climate. Drought is one of the significant aspects which are responsible for the socio-economic imbalance in several parts of the India on a cyclic basis (every 3 to 7 years; Pandey and Ramasastri 2001). It has greater impacts on the Indian economy. For example, crop loss during 1987–1988 droughts (36 million tons of food production loss) had caused GNP decline by 7% (NIH 2002). Hence, such indices will help to develop integrated information for strategic planning and drought management control and also to make reactive to proactive strategies for coping with drought.

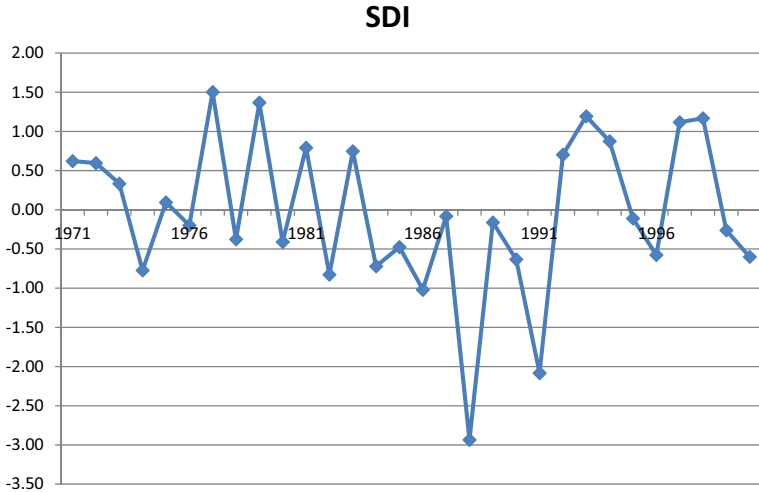


Fig. 5 Drought index by SDI for Madurai region

3.1 Regression Analysis

The meteorological drought of 3, 6, 9 and 12 months is also estimated using the reconnaissance drought index (RDI) and Standard Precipitation Index (SPI). These RDI values were correlated to the SPI values for Madurai region, and the linear regression line was produced between different categories and was presented in Fig. 6 a-d. The results showed that the RDI and SPI are significantly correlated. The drought years can be predicted with the equation shown in the graph by calculating the RDI even by having rainfall data alone. The R^2 value of 0.998 indicates that annual SPI and annual RDI was highly correlated and the linear regression is fitting well (Fig. 6a).

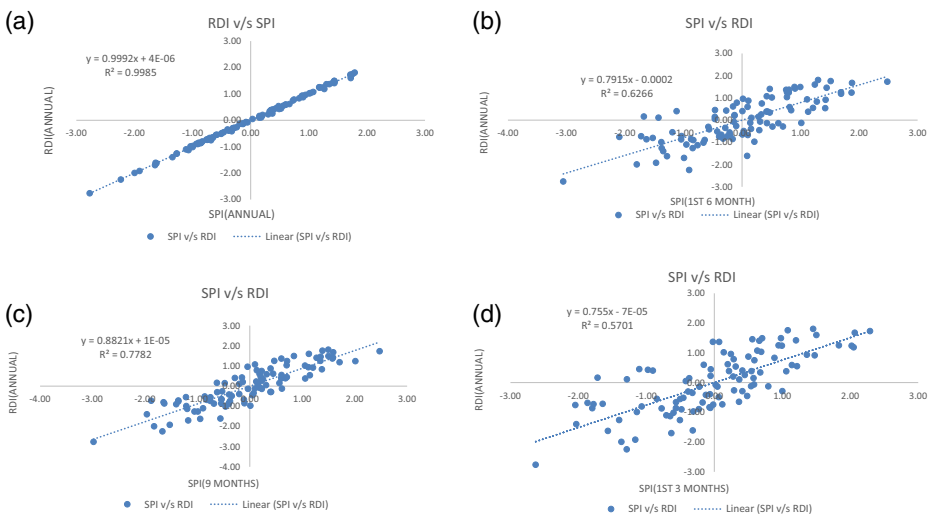


Fig. 6 **a** SPI Annual Vs RDI annual comparison. **b** SPI 9 months Vs RDI annual comparison. **c** SPI 6 months Vs RDI Annual comparison. **d** SPI 1st 3 months Vs RDI Annual comparison.

In the case of regression analysis, all different combinations, for instance, SPI 1st 3 months, 2nd 3 months, 3rd 3 months and 4th 3 months, 1st 6 months, 2nd 6 months and 1st 9 months data were compared with annual RDI values. Fig.6 b to d explains the best fit models. The results showed that SPI with 1st nine months, 1st half and 1st quarter data revealed that annual RDI period prediction was found to be safe with high R^2 value. The other combinations of SPI value are not fitting correctly. These results indicated that RDI drought index could be predicted even if 1st three months rainfall data is available and for the future years SPI are calculated.

Throughout the world in drought analysis, the Standardized Precipitation Index (SPI) is widely utilized. This study also confirmed that and SPI can monitor both short-term and long-term drought effects and is comparable among different locations due to its probabilistic nature. Importantly, the fundamental advantage of SPI is that for a variety of time scales one can compute SPI (Mishra and Singh 2010). Moreover, the right moment level of SPI can reflect the lag time of hydrological response to meteorological variations. Variations of SPI with different time scales can be linked with the water deficits in different hydrological cycle components (e.g., soil moisture and stream flow) (Van Lanen et al. 2012; Mohammad et al. 2014).

Similarly, the authors tried regression analysis of SPI, RDI versus SDI and the regression coefficient values are nonsignificant (Fig.7). This study is in contrast to the earlier findings of Tigkas et al. 2012, which showed the highest correlation between SPI and SDI and they had predicted the hydrological drought using SDI for different climate change scenarios. Our approach demonstrated that for this given location of Madurai district, prediction of SDI or hydrological drought is not possible if the stream flow data is missing and attempted mainly to predict the hydrological drought if in case an early assessment of meteorological drought is known using SPI or RDI. Our findings will give a chance to the authorities and stakeholders to predict the water availability of the entire year and to plan in advance measures for mitigating hydrological drought impacts. The possible reasons for nonsignificant trend may be due to other factors like change in land use, cropping pattern, topography and rainfall intensity (Surendran et al. 2014; 2017).

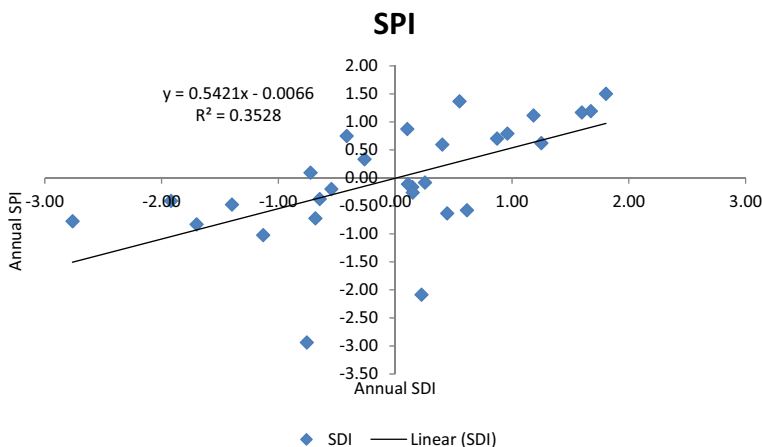


Fig. 7 Annual SPI Vs Annual SDI comparison

Further, using a broad range of scenarios representing possible climatic changes and drought events of varying severity, nomographs can be devised using these models and the regression equation which showed better fit, as indicated by higher R^2 value. Findings from such studies are useful tools for designing strategic preparedness plans to combat droughts and mitigate their effects on the activities in the various sectors of the economy. The RDI, apart from using as a drought index, can also be used as a climatic index, suitable to identify possible climatic trends in annual or seasonal basis. To detect the trend in the time series of annual RDI, one can use all appropriate methods for pattern detection (e.g. Spearman test, Mann-Kendall test, Runs test, Durbin-Watson test, etc.). If the trend is statistically significant, then it can be assumed that there are strong indications of climatic change on an annual basis (Tigkas et al. 2012; 2014). In this context, based on real or synthetic data, DrinC can evaluate the possible future climatic and drought conditions and for the assessment of the drought impacts on the economy, the society and the environment (e.g. crop production, drinking water availability, stream flow changes). To explain it further, normally in any country, drought preparedness will be by two kinds of processes, 1) by adopting preventive measures 2) by developing a preparedness plan. In India, the drought forecasting function is done by the Crop Weather Watch Group (CWWG) constituted by Inter Ministerial team, which keep an eye on the south west monsoon (June to September) and propose counteractive measures to minimize drought conditions on all sectors with proper contingency plan. This envisages an emergency action plan for drought management, with proper institutional set up and tries to implement the short, medium and long-term strategies to mitigate the adversity. In general, this involves ensuring availability of food grains for the people, fodder for livestock, cautious combined use of ground and surface water, adoption of suitable techniques in agriculture such as adjusting the planting period, selection of early / short maturing varieties, soil and water conservation agronomic practices, deterring the migration of humans and live stock, arranging the secondary income for the most affected people through rural employment guarantee schemes etc. (Surendran et al. 2016). Recently during the previous drought year, even these CWWG group suggested the researchers to develop suitable models for forecasting drought and anticipated environmental impact assessment of drought, since climate change and variability has become a reality, so that the mitigation plans may be developed well in advance (Gupta et al. 2011). Under such circumstances, our study confirmed that, based on the 3 month rainfall, the probability of drought occurrence may be predicted based on the DrinC and developed regression equation and the government can go ahead with the preparedness plan in all the sectors which have direct impact from drought.

4 Conclusions

DrinC calculates the drought indices by providing a simple, flexible interface by considering all the factors. DrinC calculates the drought indices viz., deciles, Standard Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Streamflow Drought Index (SDI). Following are the results obtained.

- Drought index of Madurai region by decile method showed that among the 100 years, 20 years were affected by drought and it is cyclic in nature and occurring almost every 3 to 7 years once repeatedly, except for some period where it occurred consecutively, i.e., 1923, 1924 and 1985, 1986, etc.

- The incidence is higher with 13 events in the recent five decades, whereas in the first five decades it was only seven events. The SPI and RDI index also followed the similar trend of deciles.
- However, under SPI and RDI, the severely dry and extremely dry category was only seven years and all other drought years of deciles were moderately dry. This study indicated that SPI is a better indicator than deciles since here severity can be understood.
- Stream flow index (SDI) did not follow the trend similar to SPI or RDI.
- Regression analysis showed that the SPI and RDI are significantly correlated and predict the yearly RDI drought index even if 1st 3 months rainfall data is available.

The results demonstrated that these approaches could be useful for developing preparedness plan to combat the consequences of drought. Findings from such studies are useful tools for devising strategic preparedness plans to combat droughts and mitigate their effects on the activities in the various sectors of the economy.

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