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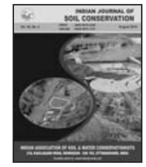

Assessing spatial characteristics of meteorological drought trends in the Parambikulam - Aliyar Basin, Tamil Nadu

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ABSTRACT

Evaluation of drought characteristics in a basin provides useful information for sustainable water resources planning and management. In the present study, the Standardized Precipitation Index (SPI) was employed to investigate the meteorological drought characteristics in the Parambikulam-Aliyar basin, Tamil Nadu. The basin was divided into 97 grid-cells of 5×5 km and monthly rainfall data for the period 1972-2011 from 28 rain gauge stations were used for spatial interpolation of rainfall using ArcGIS. Historical drought was analysed from the regional representative of SPI values calculated from mean areal rainfall over the basin and its spatial distribution was assessed. The analysis of the SPI suggested that the basin had suffered severe and extreme drought in the 1970s and 1980s. In particular, the year 1974, 1976 and 1982 experienced severe and extreme droughts and had a larger spatial coverage and longer duration. The linear trend of SPI values of each grid was calculated and spatially distributed. The results of linear trends showed that positive trends are seen over large parts of the basin. Critical rainfall values were derived for each grid to determine least amount of rainfall required to avoid drought initiation. The spatial map of critical rainfall exhibited that rainfall demand for non-drought conditions increases in north south direction toward the south eastern direction, and in general, the northern parts will be least affected from drought. The results of this study can be used for developing drought preparedness plans and mitigation strategies within the basin.

1. INTRODUCTION

Drought is a complex natural phenomenon that has significant economic, social, and environmental impacts. Drought is considered by many to be the most complex but least understood of all the natural hazards affecting more people than any other hazard (Wilhite, 2000). Drought occurs in virtually all climatic zones, such as high as well as low rainfall areas. Droughts are mostly related to the reduction in the amount of rainfall received over an extended period of time, such as a season or a year. Temperatures, high winds, low relative humidity, timing and characteristics of rains, including distribution of rainy days during crop growing seasons, intensity and duration of rain, and onset and termination, play a significant role in the occurrence of droughts (Mishra and Singh, 2010). Drought impacts both surface and groundwater resources and can lead to reduced water supply, deteriorate water quality, crop failure, reduced range productivity, diminished power generation, disturbed riparian habitats, and suspend recreation activities, as well as affect a host of economic and social activities.

Drought differs from other natural hazards in that its onset and end are difficult to determine. They are difficult to define, detect and monitor. It develops slowly and its impacts may remain for years after termination of the event. Timely determination of the level of drought will assist the decision making process to reduce the impacts of droughts. The definition of drought has been important for drought monitoring and analysis. Drought has been categorized into meteorological (lack of precipitation), hydrological (drying of surface water storage), agricultural (lack of root zone soil moisture) and socio-economic (lack of water supply for socio-economic purposes) ones. The first three categories are referred as environmental indicators and the last category is considered as a water resources indicator (Wilhite, 2000). This study focuses on the meteorological drought which is defined as deficit of rainfall over a region within a certain time interval.

There are several methods that have been used in the past as the drought assessment tools such as measurement of lack of rainfall, shortage of stream flow, reduced levels of water storage, and drought indices. Of these, drought indices are widely used for drought assessment (Heim Jr, 2002; Keyantash and Dracup, 2002; Smakhtin and Hughes, 2004; Morid *et al.,* 2006). Drought index is a function of a number of hydrometeorological variables (e.g., rainfall and stream flow), and expressed with a numeric number which is more functional than raw data during decision making. The most commonly used meteorological drought indices are: i) Rainfall deciles; ii) the Palmer Drought Severity Index (PDSI); iii) Percent of Normal; iv) Z-index; and v) the Standardized Precipitation Index (SPI). These rainfall based drought indices are widely used than other drought indices due to their less input data requirements, flexibility and simplicity of calculations (Smakhtin and Hughes, 2004). In this study, the drought was considered as a meteorological phenomenon characterized by prolonged periods of abnormal rainfall deficit. The SPI was used for identification and assessment of drought events. The SPI has been more widely used by decision makers for quantifying most types of drought events. In addition, it provides spatial and temporal representations of historical droughts.

Drought is a frequent phenomenon in India and drought areas are mainly confined to the Peninsular and Western parts of the country and there are only few pockets in the central, eastern, northern and southern parts. Out of 328 m ha of total geographical area in India, about 107 m ha of lands are subjected to different degrees of water stress and drought conditions (Mishra and Desai, 2005). More than 100 districts spread over 13 states of India have been identified as drought prone districts, and out of these, about 8 districts occur in Tamil Nadu (Gupta *et al.,* 2011). The western regions of Tamil Nadu (Coimbatore and Tiruppur districts) have suffered severe droughts many times in the past. Due to the growth of population and expansion of agricultural, energy and industrial sectors, the demand for water has increased manifold and even water scarcity has been occurring almost every year. Other factors, such as climate change and contamination of water supplies, have further contributed to the water scarcity. In recent years, droughts have been experienced with higher peaks and severity levels. Assessment of droughts is of primary importance for water resources planning and management. This requires understanding historical droughts in the region as well as different concepts of droughts that will be helpful to investigate different drought characteristics. The present study was carried out in the Parambikulam-Aliyar basin spread over drought prone districts of Coimbatore and Tiruppur in Tamil Nadu. The objective of this study is to analyze the meteorological drought characteristics using the SPI approach, to assess the drought trend and to estimate critical rainfall for non drought condition in the Parambikulam-Aliyar basin.

2. MATERIALS AND METHODS

Study Area and Data Used

Parambikulam-Aliyar basin (referred as PAP basin) is located in the south western part of the Peninsular India covering areas in Kerala and Tamil Nadu states (Fig.1). Parambikulam-Aliyar river basin is the only basin in Tamil Nadu which is drained by west flowing rivers *viz.,* Valayar, Koduvadiaru, Uppar, Aliyar and Palar (tributaries of Bharathapuzha river) and Parambikulam, Sholayar and Nirar (tributaries of Chalakudi river). They are grouped into 4 sub-basins (Valayar, Aliyar, Palar, and Sholayar) and spread over an area of 2388.72 km^2. One third of the basin area (822.73 km^2) is covered with hills and dense forest cover. The basin is bounded in the north and east by Cauvery basin and in the south and west by Kerala state. This basin area lies (except the ayacut area) within the coordinates of North latitude between 10°10'00” to 10°57'20” and East longitudes 76°43'00” to 77°12'30”. Parambikulam-Aliyar river basin has an undulating topography with maximum contour elevation in the plain (300 m) and the maximum spot height in the plain (385 m) above msl.

Mean monthly areal rainfall data in the PAP basin for the period of 1972-2011 is presented in Fig. 2. PAP basin experienced severe, extreme and persistent droughts during 1970s and 1980s. The average cumulative areal rainfall during these two periods is compared to normal cumulative areal rainfall in Fig. 3. During these two periods, the monthly and annual precipitation was significantly below normal. Especially, the year 1982 and 1976 were the first and second driest years in record, respectively. The average annual rainfall in the PAP basin has a large geographic variation. More rainfall can be observed in the southern parts of the basin. When it comes to the middle and northern parts of the basin, the rainfall decreases. Mean annual rainfall over the whole PAP basin is about 1410 mm and it is distributed unevenly in space and time. The mean annual precipitation varies from about 500 mm at the central and northern plain area to more than 4320 mm at the southern mountain areas. More than 70% of the PAP basin except the mountain areas received less than the normal rainfall. Generally, rainfall is rare from January to May (winter and summer season). The prolonged and significant decrease on monthly and annual rainfall resulted in irrigation cutbacks,

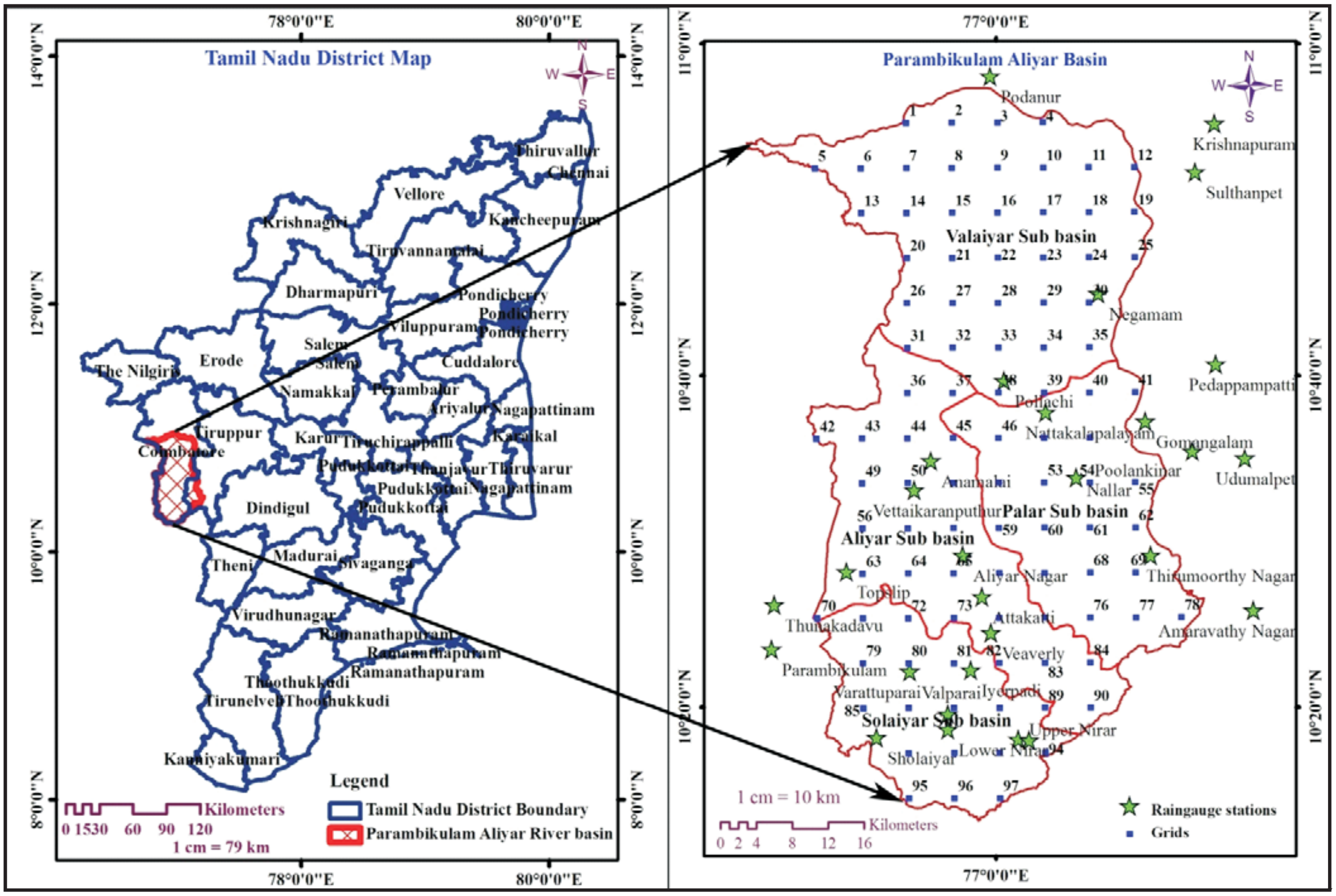

Fig. 1. Location of rain gauges in the PAP basin

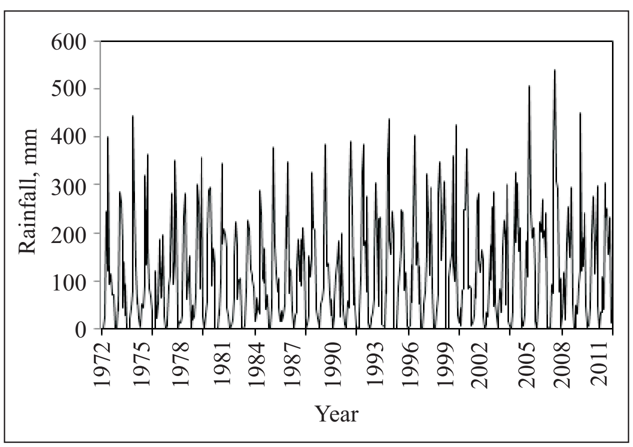

Fig. 2. Mean monthly areal rainfall data in the PAP basin for the period 1972-2011

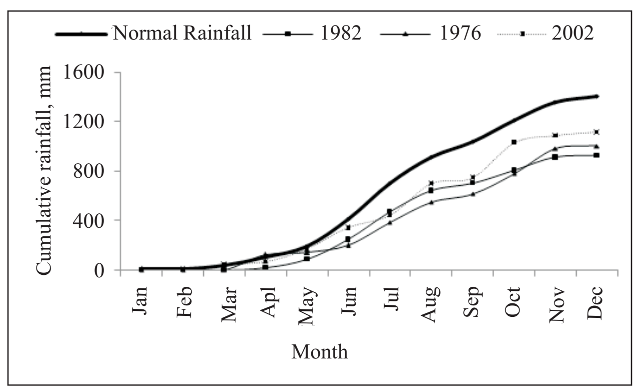

Fig. 3. The cumulative areal rainfall for selected drought years and periods in the PAP basin

over exploitation of groundwater and significant losses of crop yields.

The monthly rainfall data for the period of 40 years (1972-2011) of 28 rain gauge stations located in the PAP basin (Fig.1) was collected from the Office of Groundwater Division, Public Works Department, Coimbatore. The methodology comprised of the generation of gridded rainfall using spatial interpolation technique, development of mean monthly areal rainfall and gridded rainfall at 3- and 12-month time scale, calculation of SPI values using mean areal rainfall for temporal drought analysis, assess the drought trends and its spatial distribution, calculation of critical rainfall values for each grid and its spatial extent.

Gridded Rainfall

Total area of PAP basin was divided into 97 grids with each grid (5 × 5 km) approximately corresponding to 1.03% of total area (2425 km^2) (Fig. 1). Monthly rainfall recorded at 28 stations for 40 years (1972-2011) were interpolated by ArcGIS 9.3 using Inverse Distance Weighing (IDW) method and gridded monthly rainfall was created. Gridded rainfall at 3- and 12-month time scales in each grid was calculated. Mean monthly areal rainfall of PAP basin was estimated by averaging gridded rainfall for 3- and 12-month time scales.

Use of the Standardized Precipitation Index (SPI) for Drought Analysis

The SPI as a drought monitoring tool was proposed at Colorado State University, USA to quantify the rainfall deficit on multiple time scales, and has been used to monitor drought conditions (McKee *et al.,* 1993). A drought event occurs at the time when the value of SPI is continuously negative and the event ends when the SPI becomes positive. The main advantage of the SPI, in comparison with other indices, is that the SPI enables both determination of drought conditions at different time scales and monitoring of different drought types. Table 1 provides a drought classification based on SPI. Numerous studies have been conducted to analyse the meteorological droughts using SPI (Hughes and Saunders, 2002; Mishra and Desai, 2005; Patel *et al.,* 2007; Edossa *et al.,* 2010; Moradi *et al.,* 2011; Pradhan *et al.,* 2011).

Calculation of SPI

The SPI for any location is calculated, based on the long-term rainfall record for a desired period. This is performed separately for each month and for each grid in space. The long-term record is fitted to a probability distribution, which is then transformed to a normal distribution so that the mean SPI for the location is zero and standard deviation of unity (McKee *et al.,* 1993).

The gamma distribution defined by its probability density function is:

$$g(X) = \frac{1}{\beta^{\alpha}\,\Gamma\alpha}\, x^{\alpha-1} e^{-x/\beta} \quad \text{for } x>0 \qquad ...(1)$$

Where $\alpha>0$ = a shape factor, $\beta>0$ = a scale factor, and $x>0$ = the amount of rainfall. $\Gamma(\alpha)$ = the gamma function which is defined as:

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

Fitting the distribution to the data requires that α and β be estimated. Edwards and McKee (1997) suggested a method for estimating these parameters using the approximation of Thom (1958) for maximum likelihood as follows:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1+\frac{4A}{3}}\right) \qquad ...(3)$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \qquad ...(4)$$

Where, $A = \text{In}(\bar{x}) - \frac{\sum \text{In}(x)}{n}$ for n observations. ... (5)

The resulting parameters are then used to find the cumulative probability of an observed rainfall event for the given month or any other time scale.

$$G(X) = \int_0^x g(X)\, dx = \frac{1}{\hat{\beta}^{\hat{\alpha}} * \Gamma(\hat{\alpha})} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \qquad ...(6)$$

Substituting t for $x/\hat{\beta}$ reduces the above equation to incomplete gamma function:

$$G(X) = \frac{1}{\Gamma(\hat{\alpha})} \int_0^x t^{\alpha-1} e^{-1}\, dt \qquad ...(7)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(X) = q + (1-q)\, G(x) \qquad ...(8)$$

Where, q = the probability of zero precipitation. If m is the number of zeros in a rainfall time series, q can be estimated by m/n. In this analysis, a small amount of rainfall was substituted for zero rainfall for each grid. This substitution does not affect the distribution of precipitation.

The cumulative probability, $H(x)$ is then transformed to the standard normal random variable Z with a mean of zero and a variance of one, which is the value of SPI (Edwards and McKee, 1997; Hughes and Saunders, 2002).

$$Z = SPI = -\left(t - \frac{(C_o + C_1 t + C_2 t^2)}{(1 + d_1 t + d_2 t^2 + d_3 t^3)}\right) \text{ for } 0 < H(X) \leq 0.5 \qquad ...(9)$$

$$\text{Where, } t = \sqrt{\left(In \frac{1}{(H(X))^2}\right)} \qquad ...(10)$$

$$Z = SPI = +\left(t - \frac{(C_o + C_1 t + C_2 t^2)}{(1 + d_1 t + d_2 t^2 + d_3 t^3)}\right) \text{ for } 0.5 < H(X) \leq 1.0 \qquad ...(11)$$

$$\text{Where, } t = \sqrt{\left(In \frac{1}{(1 - H(X))^2}\right)} \qquad ...(12)$$

C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, d_3 = 0.001308.

In this study, gridded monthly rainfall data were used for the estimation of the SPI at each grid for each month of the period of analysis at multiple time scales (3 and 12 months). The procedure adopted in this study for the calculation of gridded SPI values, is called interpolate calculate, because first rainfall is spatially distributed and then the SPI time series are calculated in each grid (Loukas and Vasiliasdes, 2004).

Table: 1
Classification of droughts (McKee *et al.,* 1993)

SPI Values	Drought Category	
0 to -0.99	D1	Mild drought
-1.00 to -1.49	D2	Moderate drought
-1.50 to -1.99	D3	Severe drought
≤ 2.00	D4	Extreme drought

Monthly SPI values derived from gridded rainfall values for each grid were used to categorize the occurrence of droughts for each month of the year based on the classification of SPI values presented in the Table 1. In this study, severe and extreme drought was taken to estimate drought affected areas. In this respect, number of grids which expressed severe and extreme drought conditions over the given time scales (3- and 12-month) was determined for the corresponding SPI values for the period of analysis. In other words, number of grids that exhibited severe and extreme drought category for the pre-defined SPI values was identified and plotted for the 1972-2011 period to observe their areal extent.

Trends in Drought

One of the most useful parametric models used to develop functional relationships between variables is the "simple linear regression" model. A simple linear regression is calculated at each grid point in the PAP basin for each time scale of SPI to examine temporal changes over the period of study. The slopes of the linear trends are then mapped to see the spatial differences in temporal trends across the PAP basin. The sign of the slope defines the direction of the trend of the variable: increasing if the sign is positive and decreasing if the sign is negative. Spatial pattern of linear trends using regression models was analysed by Logan *et al.* (2010) in U.S. central plains and Pai *et al.* (2011) in India.

Critical Rainfall Analysis

Critical (Threshold) rainfall analysis provides information about the minimum amount of rainfall that is required to avoid a drought formation. Sonmez *et al.* (2005) studied the critical rainfall for non drought condition at different severity categories and varying time steps in Turkey for identifying drought vulnerability. They determined the critical rainfall from monthly SPI values for each station and analysed its spatial variation. In this respect, the critical rainfall values are defined as "0" (zero) SPI value *i.e.,* referred as threshold value, at which drought begins to form was calculated. At zero SPI value, the critical rainfall of each month will be equal to the mean monthly rainfall over the period of analysis. As stated previously, the SPI values below zero indicate a drought occurrence and as the values drop below zero the severity of drought increases. After computing the critical rainfall values for each grid, they are mapped to visualise their spatial distribution to identify areas where at least some amount of rainfall is needed for a drought event not to initiate.

3. RESULTS AND DISCUSSION

Historical Drought Analysis

In this study, the overall meteorological drought vulnerability in the PAP river basin was assessed by reconstructing historical occurrences of droughts at 3- and 12-month time scales and drought categories by employing the SPI approach. The basic idea is that this can be a guide to the decision makers in the PAP basin to develop strategies of water resources management in the context of drought. A 3 month SPI reflects short and medium-term moisture conditions and provides a seasonal estimation of rainfall. The SPI at 12-month time scale reflect long-term precipitation patterns.

The regional representative of SPI was calculated using the mean areal rainfall across the basin for 3- and 12-month time scale. Plots of time series of SPI values at the 3- and 12-month time scales are shown in Fig. 4 and it shows that, in the PAP basin, numerous droughts occurred since 1972 to 2011. Fig. 5 shows the percentage of occurrence of drought categories extracted from Fig. 4. The basin experienced droughts in terms of severity and duration in the 1970s and 1980s. During the period of 1972 to 2011, the basin had 158 months of mild, 45 months of moderate, 20 months of severe, and 9 months of extreme drought for 3-month time scale. For 12-month time scale, the basin experienced 185 months of mild, 45 months of moderate, 14 months of severe, and 11 months of extreme drought. The results show that mild droughts occur most frequently and extreme droughts occur less frequently. The number of drought incidences for SPI_3 is 65 with the maximum duration of 26 months. The number

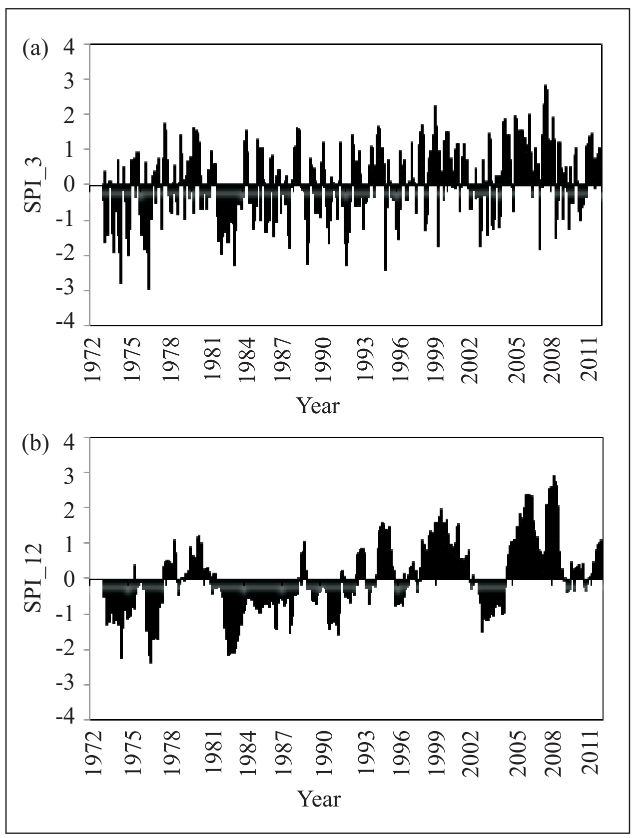

Fig. 4. SPI values in the PAP basin for the time scale of a) 3- month, b) 12-month

of drought incidences for SPI_12 is 22 with the maximum duration of 77 months. The average duration of drought was calculated by dividing total number of drought months with the total number of drought incidences for a particular time scale. The average duration of drought for SPI_3 and SPI_12 are 3.57 and 11.59 months, respectively. A notable point observed from the Fig. 5 is the change in drought frequency with the change in time scale. At the 3-month scale, drought frequency increases but its duration decreases. Drought becomes less frequent but lasts longer at 12-month time scale. In other words, SPI responds quickly to 3-month time scales, but it responds more slowly to 12-month time scale.

Areal extent of occurrence of severe and extreme drought categories is presented in Fig. 6. The year 1976 experienced extreme drought when more than 90% of the total area of the basin was under drought, followed by the years 1974, 1992 and 1983 with more than 65% of the total areas of the basin affected by drought at 3-month time scales. The year 1974 experienced severe drought when more than 80% of the total area of the basin was under drought, followed by the years 1991, 1982 and 1976 with 75% of the total areas of the basin affected by drought for SPI_3. At 12-month time scales, areal extent and frequency of severe and extreme drought was low when compared with 3-month time scales. The year 1976 is found to be the worst year, when about 85% of the total area of the basin was under severe drought, followed by the years 1982, 1974 and 1983 with 60% of the total areas of the basin suffered by drought for SPI_3. The extreme drought that occurred in 1976 at 12-month time scales covered about 60% area of the basin.

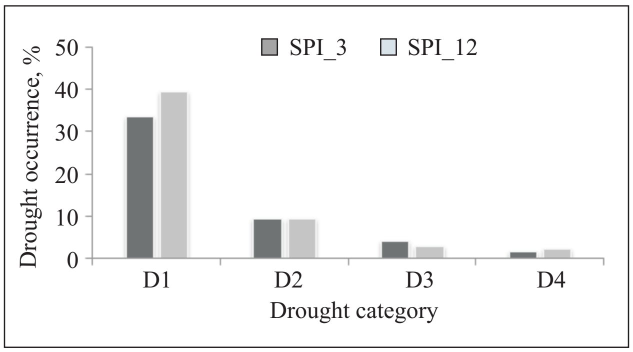

Fig. 5. Percentage of occurrence of drought categories for the time scale of a) 3- month, b) 12-month

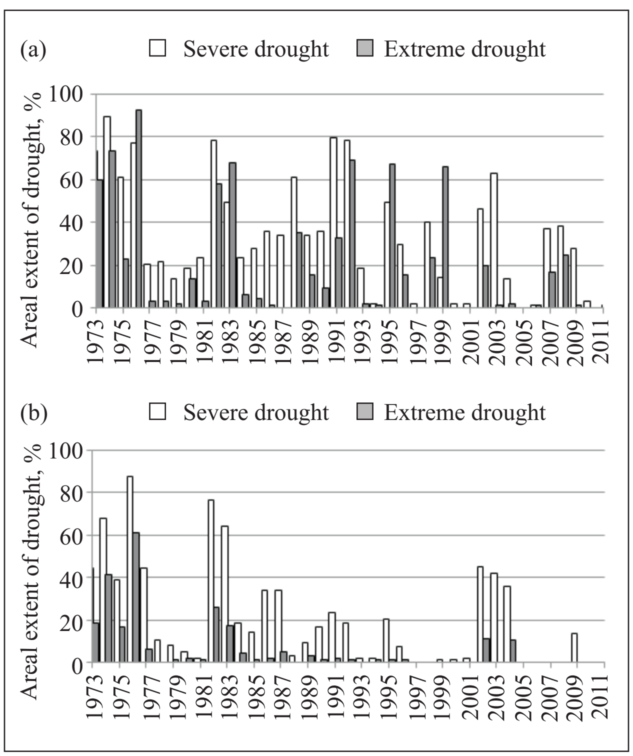

Fig. 6. Areal extent of severe and extreme drought in the PAP basin at the time scale of a) 3-month, b) 12-month

Spatial Distribution of Drought Trend

The linear trends in 3- and 12-month SPI exhibited a wide range of values across the basin (Fig. 7). A similar spatial variation was seen for these two SPI time scales. There was an increasing trend of SPI in most of the region, especially in the Southern and Northern areas. With the areas of increasing trend, however, it is not clear whether increased rainfall actually signifies any increase in water availability. Small negative trends were observed in both SPI time series. Particularly North Eastern areas have decreasing rates of SPI. Thus, the largest decrease in SPI was seen in areas that already have lower mean rainfall values and rely more heavily on irrigation.

Spatial Distribution of Critical Rainfall

The spatial variation of critical rainfall for non drought condition at 3- and 12-month time scale is presented in Fig. 8 and Fig. 9. It can be observed that the rainfall demand for no-drought occurrences increases from north to south in the PAP basin. At 3-month time step from June to August period covering south west monsoon season over the study area, critical rainfall values for non-drought conditions increases from the northern parts toward the southern parts and reach their maximums in the south-eastern parts of the basin (Fig. 8). The critical rainfall values at 12-month time scale exhibited a similar spatial pattern to those observed in the 3-month scale (Fig. 9). It was observed that the critical values exhibit sharp differences in their geographical distribution. For example, nearly 4328 mm of rainfall is needed to avoid a drought in the Solaiyar sub-basin, while the rainfall amount required for a non-drought condition decreases to as little as 511 mm in the Valaiyar sub-basin. A notable point is that the Solaiyar sub-basin located in the mountainous region of PAP basin usually receive higher rainfall than the other regions, it is likely that they will be more vulnerable to long-term droughts. The areas that have normally higher rainfalls are affected from a drought event more severely as compared to other parts, which receives

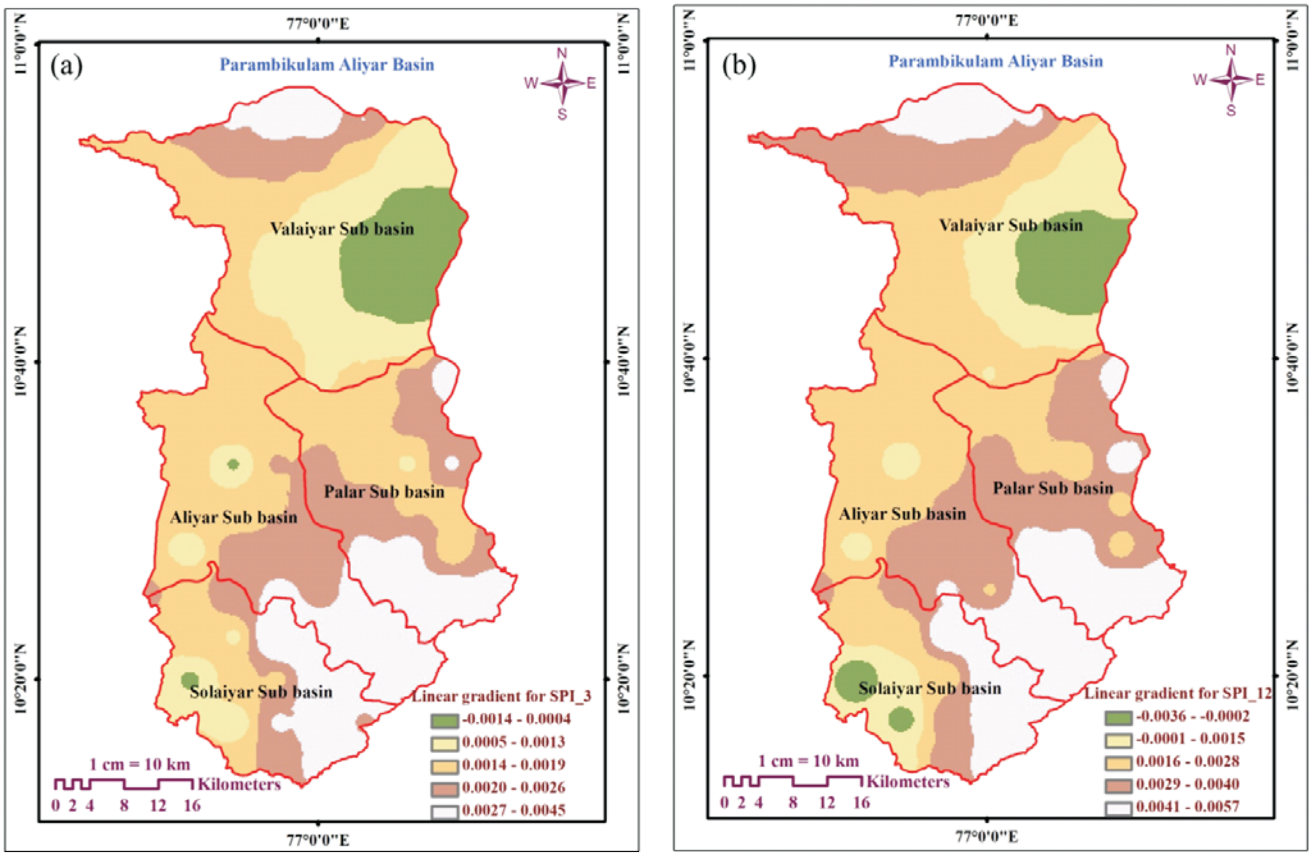

Fig. 7. Spatial variation of the line gradient of drought trends in the PAP basin for the time scales of a) 3-month, b) 12-month

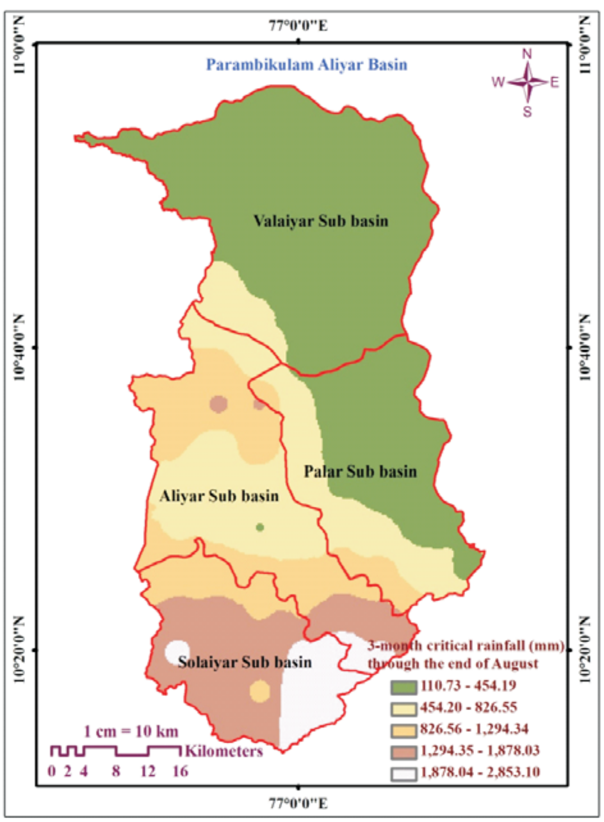

Fig. 8. Spatial variation of critical rainfall values for 3-months from June - August

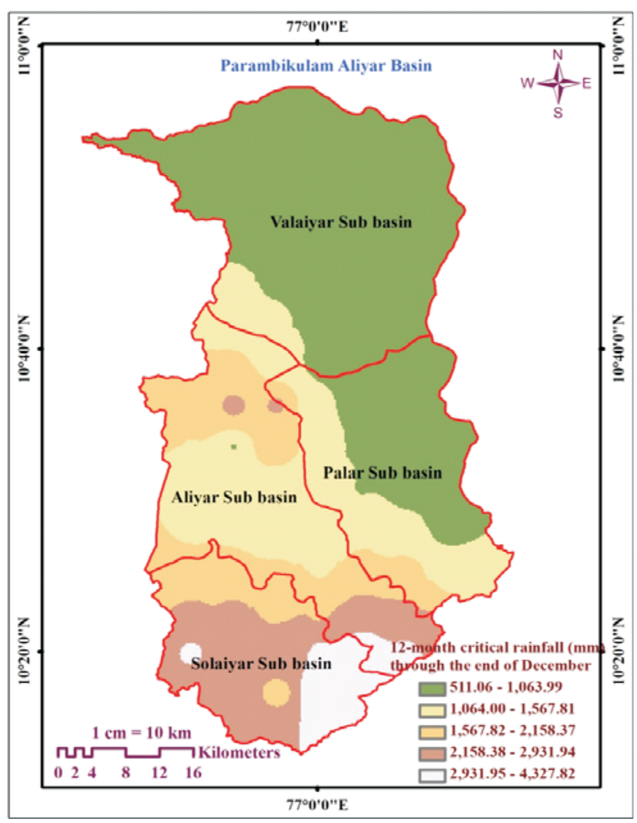

Fig. 9. Spatial variation of critical rainfall values for 12-months from January- December

lower rainfall. Presently, surplus water from Solaiyar sub-basin is diverted to Aliyar and Palar sub-basins through inter-connected contour canals and chain of reservoirs for irrigating dry areas of Coimbatore and Tiruppur districts. Increasing frequency of meteorological droughts associated with hydrological drought in the Solaiyar sub-basin will seriously impact the water supply to Aliyar and Palar sub-basins. Information on drought vulnerability with respect to the critical rainfall could aid decision makers in identifying appropriate mitigation actions for future drought events and minimize its impacts. With a map of drought vulnerability, decision makers can conceptually visualize the hazard risk and convey the vulnerability information to other sectors to ensure that they will act timely and effectively to tackle with drought related losses.

4. CONCLUSIONS

An improved understanding of drought characteristics in water scarce areas could help to identify risks associated with the drought, and in this regard this study was focused on analyzing historical and spatial extents of droughts in the PAP basin using the SPI as an indicator of drought severity. The regional representative of SPI values were computed using mean areal rainfall over the PAP basin. Drought characteristics such as frequency of occurrence of drought categories, average duration of drought, areal extent of annual drought event were analysed from regional representative of SPI values. Trend of SPI values and critical rainfall for non-drought conditions at each grid were determined for assessing spatial distribution under GIS environment. The results of analysis showed that the basin has experienced severe and extreme droughts in terms of severity in 1970's, 1980's and 2000's, particularly in the year 1974, 1976 and 1982 with larger spatial extent. The spatial pattern of drought trends showed decreasing trends in the north eastern parts and increasing trends in the SPI series were observed in the northern and south-eastern parts of the basin. The spatial extent of critical rainfall values for non-drought conditions showed that it increases from the northern parts to the southern parts and reaches their peaks in the south-eastern parts of the basin. The results arrived in this study can be an essential step toward addressing the issue to drought vulnerability in the basin and can guide for drought management strategies for mitigation purposes.

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