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Analysis of Meteorological Drought Characteristics in the Parambikulam-Aliyar Basin, Tamil Nadu

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The temporal and spatial characteristics of meteorological drought are investigated to provide a framework for sustainable water resources management in the Parambikulam-Aliyar river basin. Using the Standardized Precipitation Index (SPI) as an indicator of drought severity, the characteristics of droughts are examined. Parambikulam-Aliyar basin was divided into 97 grids of 5×5 km and monthly rainfall data for the period of 1972–2011 from 28 rain gauge stations were used for spatial interpolation of rainfall using inverse distance weighting approach. Temporal characteristics of drought were assessed using regional representative of SPI values calculated from spatially averaged gridded rainfall at 12-month time scales. Spatial characteristics of drought were analysed using gridded SPI values calculated from gridded rainfall. Temporal analysis of the SPI suggests that the basin suffered severe and extreme drought in the 1970s, 1980s and 2000s. Spatial variation of drought characteristics showed that the occurrence of drought was more in the southern parts; annual drought severity and most intense drought were high in the central and northern parts of the basin. The results of this study can be used for developing drought preparedness plan and formulating mitigation strategies within the basin.

Key words: Drought severity, GIS, rainfall, return period, SPI

Drought is a natural disaster which causes the greatest loss in the world and has the largest impacts among all the natural disasters. Drought has significant impact on socio-economic, agricultural, and environmental aspects (Bhuiyan, 2004). It is generally defined as a temporary meteorological event that stems from the lack of rainfall over an extended period of time compared with some long term average condition. A deficit of rainfall has different impacts on soil moisture, stream flow, reservoir storage, and groundwater levels. Droughts develop slowly but it is difficult to detect and monitor (Hayes *et al.,* 1999). The success of drought preparedness and mitigation depends, to a large extent, upon timely information on drought onset, progress and areal extent. These types of information may be obtained through drought monitoring. Monitoring is normally performed using drought indices. Drought indices provide decision makers with information on drought severity and can be used to trigger drought contingency plans, if they are available (Morid *et al.,* 2006). In general, drought indices is a function of several hydro-meteorological variables (e.g., rainfall, temperature, streamflow, soil moisture, etc.) and assess the different types of drought i.e. meteorological (precipitation), hydrological (streamflow), agricultural (soil moisture) drought. In this study, drought was considered as a meteorological phenomenon characterized by prolonged periods of abnormal rainfall deficit.

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 329 Million ha of total geographical area in India about 107 Million 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, out of these, about 8 districts falls in the Tamil Nadu (Gupta *et al.,* 2011). The western regions of Tamil Nadu (Coimbatore and Tiruppur districts) have suffered with severe droughts at 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 manyfold 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

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the region as well as different concepts of droughts that will be helpful to investigate different drought properties. The present study was carried out in the Parambikulam -Aliyar basin spread over drought prone districts of Coimbatore and Tiruppur, Tamil Nadu. The aims of this research are to investigate the temporal variation and spatial distribution of drought characteristics in the PAP basin.

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). PAP basin is the only basin in Tamil Nadu having west flowing rivers. PAP basin 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 such as Valayar, Aliyar, Palar, and Sholayar sub basin 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. This basin is bounded in north and east by Cauvery basin, 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". PAP basin has an undulating topography with maximum contour elevation in the plain is 300m and the maximum spot height in the plain is 385m above MSL. Northern parts of the basin include Thondamuthur, Madukkarai, Sultanpet and Kinathukadavu block; Central parts include Pollachi North, Pollachi South, Anamalai and Udumalaipet block; Southern parts include Valparai and some parts of Anamalai block.

PAP basin experienced severe, extreme and persistent droughts during the periods of 1970s, 1980s, 2000s. The average cumulative areal rainfall during these two periods is compared to normal cumulative areal rainfall in Fig. 2. During these two periods the monthly and annual precipitation was significantly below normal. Especially, the year 1982 and 1976 are the first and second driest years in record, respectively (Fig. 2). 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 central 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 per cent of the PAP basin except southern mountain areas recorded 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, over exploitation of groundwater and significant losses of crop yields.

The monthly rainfall data for the period of 40 years (1972- 2011) from 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 12-month time scale, calculation of regional representative of SPI values using mean areal rainfall for temporal drought analysis, calculation of gridded SPI values using gridded rainfall for analysing the spatial drought charactertics.

Spatial interpolation of rainfall

Spatial interpolation techniques estimate the value of the surface at locations where no observed data exists, based on the known data values (observations) . A number of spatial interpolation methods such as the inverse distance weighting (IDW), Splines and kriging are available for spatial analysis of any variables and some researchers have used these techniques for drought studies (Kim *et al.,* 2002; Edossa, *et al.,* 2010; Moradi *et al.,* 2011). In this study, IDW approach is used for spatial interpolation of rainfall and drought characteristics over the PAP basin. This interpolation technique weights the contribution of each input (control) points by a normalized inverse of the distance from the control point to the interpolated point. IDW assumes that each input point has a local influence that diminishes with distance. It weights the points closer to the processing points, greater than those farther away. A specified number of points or all points within a specified radius is used to determine the output value for each location. The power parameter in the IDW interpolator controls the significance of the surrounding points upon the interpolated value. A higher power results in less influence from distant points (Mishra and Desai, 2005). In the present study, the exponent of distance is taken as 2 to spatial interpolate the rainfall in the basin.

Total area of PAP basin was divided into 97 grids with each grid (5 × 5 km) approximately correspondence to 1.03% of total area (2425 km_2) (Fig. 1). Monthly rainfall data were spatially interpolated by ArcGIS 9.3 using IDW method and gridded monthly rainfall was created. Gridded monthly rainfall data for each grid at 12-month rainfall accumulations for each month of the period of analysis was estimated. Mean monthly areal rainfall of PAP basin was estimated by averaging gridded rainfall at 12-month time scales. Gridded monthly rainfall data were used for the estimation of the SPI at each grid for each month of the period of analysis. The procedure, applied 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).

Use of the Standardized Precipitation Index (SPI) for drought analysis

The Standardized Precipitation Index (SPI) as a drought monitoring tool was designed at Colorado State University, U.S. 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 (Patel *et al.,* 2007). This versatility allows the SPI to monitor short-term water supplies, such as soil moisture, important for agricultural production, and longer- term water resources such as groundwater supplies, streamflow, and lake and reservoir levels. Table 1 provides a drought classification based on SPI values. Numerous studies have been conducted to analysis the meteorological droughts using SPI (Hughes and Saunders, 2002; Mishra and Desai, 2005; 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 is defined by its probability density function is

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Where α>0 is a shape factor, β>0 is a scale factor, and x>0 is the amount of rainfall. ?(α) is the gamma function which is defined as

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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:

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Where

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for n observations.

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.

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Substituting t for λ reduces the above equation

to incomplete gamma function:

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

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where q is 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).

For 0<H(x)”0.5

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Where

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For 0.5<H(x)<1

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Where

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c0=2.515517	c1=0.802853	c3=0.010328
d1=1.432788	d2=0.189269	d3=0.001308

Regional drought analysis

Regional drought analysis provides useful information for sustainable water resources management. In this study, regional drought was analysed for determining the temporal variation and spatial distribution of drought characteristics. The temporal variation of SPI was assessed using the regional representative SPI values, calculated from mean monthly areal rainfall of the PAP basin at 12-month time scales. Spatial analysis of drought was performed using the gridded SPI values estimated for evaluating the most affected areas for a specific drought event. The spatial characteristics of droughts were analysed by analysing the drought parameters (severity, areal extent and frequency) of the PAP basin.

Analysis of drought occurrences

Drought occurrences in PAP basin have been investigated based on percentage of occurrence of drought events for each drought category at 12-month time scales. The aim here was to identify areas vulnerable to drought based on their occurrence frequencies. Percentage of drought occurrence was calculated by taking the ratio of number drought events in month to the number of total months for each grid over the study period (Edossa et al., 2010). Monthly distribution of percentage of occurrence of drought categories was determined from the regional representative of SPI series. 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. This study also analysed how severe drought-stricken areas evolved over time spatially. In this respect, number of grids which expressed mild, moderate, severe and extreme drought conditions over the given time scales was determined for the corresponding SPI values for the period of analysis (Sonamez et al., 2005).

Analysis of drought parameters

It is necessary, for the spatial analysis of droughts, to detect several drought features such as most intense drought, drought severity, and drought frequency (Loukas and Vasiliasdes, 2004). The most intense quantity is the highest departure of the SPI value from its normal value or peak SPI value or extreme drought month experienced at each grid. The most intense quantity observed in each grid during the study period was used to develop the spatial extent of most intense of droughts in the PAP basin.

Drought severity indicates a cumulative deficiency of a drought parameter below the critical level. In this study, annual weighted cumulative drought severity in each grid was estimated by multiplying the annual sum of SPI in monthly dry spells (negative SPI values) for 12-month time scale by the probability of drought occurrence for each year. The probability of annual drought occurrence for each year and in each grid was estimated by dividing the number of months that have a negative SPI value by 12. In this analysis each drought event can be allotted uniformly for a particular year, avoid intermittence, and the duration of dry spells within a particular year is implicitly taken into account. The worst drought year based on highest weighted annual cumulative drought severity over the study period in each grid was used to develop drought severity maps. Frequency analysis was performed using selected probability distribution to estimate the drought severity at 3 and 10 year return periods in each grid.

Frequency analysis

Frequency analysis is performed using the selected probability distribution for annual values of weighted cumulative drought severity at different return periods. To be applied before fitting to an available distribution, the negative values of cumulative drought severity were transformed to positive values in order to represent the extreme condition and to analyze the associated risk of droughts using the exceedance probability. The commonly used probability distributions viz. Normal, Lognormal, Gamma, and Extreme Value Type I were used to evaluate the best fit probability distribution for SPI_12 weighted annual cumulative drought severity and tested by Kolgomorov-Smirnov (K-S) test and Chi-Square tests at 5% and 1% significance levels.

The annual cumulative drought severity XT to be estimated for a given return period (T) may be represented as the mean μ plus the departure ΔXT of the variate from mean.

$$X_T = \mu + \Delta X_T \quad \text{---- (13)}$$

The departure may be taken as equal to the product of the standard deviation σ and a frequency factor KT; that is, ΔXT = KTσ. The departure ΔXT and the frequency factor KT are functions of the return period and type of probability distribution to be used in the analysis (Chow, 1951). The expected annual drought severity for each grid at 3 and 10 year return periods were worked out by the best fit probability distribution.

Results and Discussion

Temporal characteristics of droughts

The temporal variation of SPI was assessed by analysing the percentage of occurrence, monthly distribution, areal extent of drought categories and most intense drought using the regional representative of SPI. The time series of 12-month SPI values computed for the PAP basin (Fig. 3) showed that the region experienced frequent moderate, severe and extreme droughts. Visual inspection of 12-month SPI time series indicated that droughts were quite frequent during the 1970s, 1980s and 2000s.

Table 1. Drought classification by SPI value and corresponding probabilities

Drought Category	SPI	Probability (%)
D1 Mild drought	0 to -0.99	34.1
D2 Moderate drought	-1.00 to -1.49	9.2
D3 Severe drought	-1.50 to -1.99	4.4
D4 Extreme drought	d” -2.00	2.3

Table 2. Monthly distribution of occurrence of drought categories

Month	D1	D2	D3	D4	Total
January	3.42	0.85	0.21	0.21	4.70
February	3.42	0.85	0.21	0.21	4.70
March	3.63	0.64	0.21	0.21	4.70
April	3.42	0.43	0.21	0.21	4.27
May	3.63	0.85	0.43	0.00	4.91
June	2.99	0.85	0.21	0.21	4.27
July	2.78	1.28	0.43	0.00	4.49
August	3.63	0.43	0.43	0.21	4.70
September	2.99	0.85	0.21	0.21	4.27
October	3.42	0.64	0.00	0.43	4.49
November	2.78	1.07	0.21	0.21	4.27
December	3.42	0.85	0.21	0.21	4.70
Total	39.53	9.62	2.99	2.35	54.49

The results of monthly distribution of percentage of occurrence of drought at 12-month time scale in the PAP basin is presented in Table 2. From the table it can be observed that the basin experienced frequent droughts for all months of the year. The highest percentage of occurrence of drought was observed in the month of May followed by January, February, March, August and December. The percentage of occurrence of drought categories was computed as 39.53 per cent for mild drought, 9.62 per cent for moderate drought, 2.99 per cent for severe drought and 2.35 per cent for extreme drought (Table 2). The results show that mild droughts occur most frequently and extreme droughts occur least frequently. The analysis of the 12 -month SPI time series indicated that the minimum SPI (SPI_12 = -2.40) i.e. extreme drought month over the period of analysis was observed in September 1976.

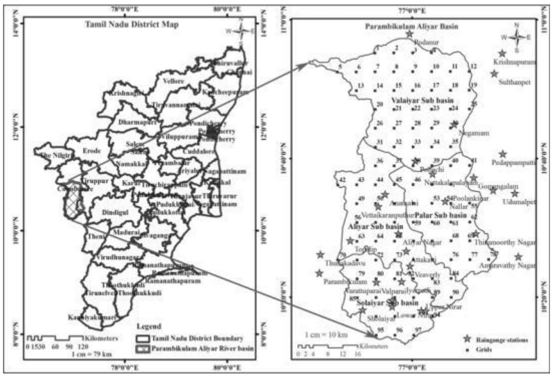

Fig. 1. Location of rain gauges in the PAP basin

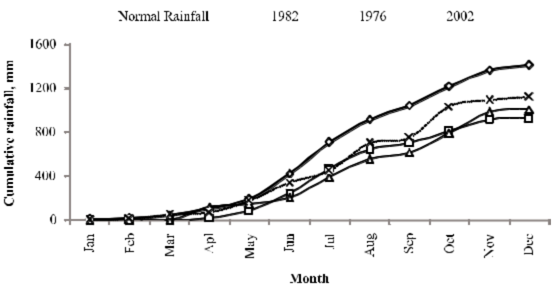

Fig. 2. The cumulative area rainfall for selected drought years and periods

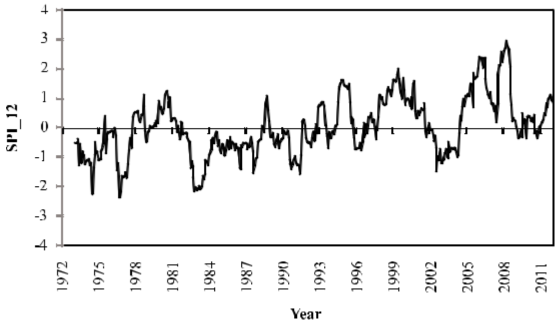

Fig. 3. Time series of 12-month SPI in the PAP basin

Areal extent (as percent of the total basin area) of the drought categories during 1973-2011 based on 12-months time scale is given in the Fig. 4.

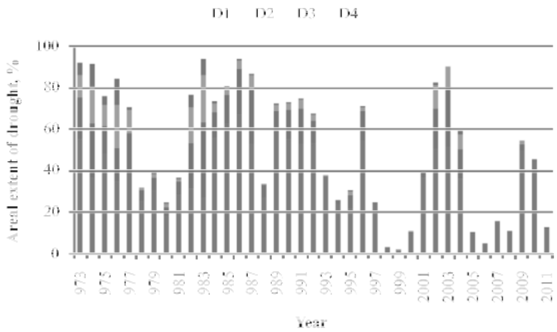

Fig. 4. Areal extent of drought categories based on SPI_12 series

Referring to the figure, the years when more than half of the total area of the basin is struck by drought (SPI < 0) are: 1973-1977, 1982-1987, 1989-1992, 1996, 2002-2004 and 2009. This means, more than 50 per cent of the total area of the basin is struck by drought events almost 50 per cent of the years (20 years) during the analysis period. The years 1973-76, 1982-83, 1985-87 and 2002-03 mark the most critical drought years in the basin with more than 75 per cent of the total basin area under drought. The year 1983 is found to be the worst year, when about 93 per cent of the total area of the basin was under drought, followed by the years 1986, 1973, 1974 and 2003 with 90 per cent of the total areas of the basin affected by drought.

Spatial characteristics of droughts

Although the estimation of drought severity at a point or as regional representative gives useful information for water management, it is interesting and important to assess the drought over a specified region or basin. The regional drought analysis is useful for determining the spatial distribution and characteristics of drought, and evaluating the most affected areas for a specific drought event. In the present study, spatial characteristics of droughts were assessed using gridded SPI_12 values by analysing the percentage of occurrence of drought, most intense drought, worst drought month, worst drought year based on annual weighted cumulative drought severity, expected severity at 3 and 10 year return period. Spatial variation of drought characteristics was developed using ArcGIS 9.3 with the help of IDW method and shown in Fig. 5-10.

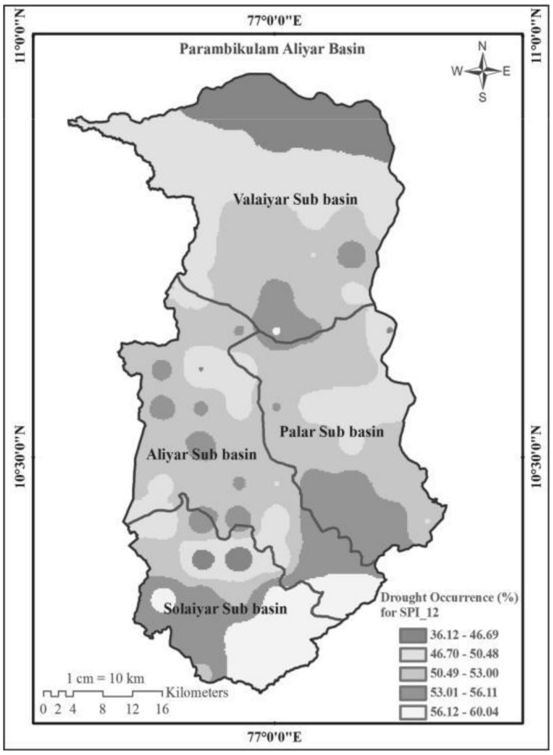

Fig. 5. Spatial variation of percentage of occurrence of droughts

Spatial variation of percentage of drought occurrences for SPI_12 time scales is presented in the Fig. 5. Percentage of occurrence of drought is

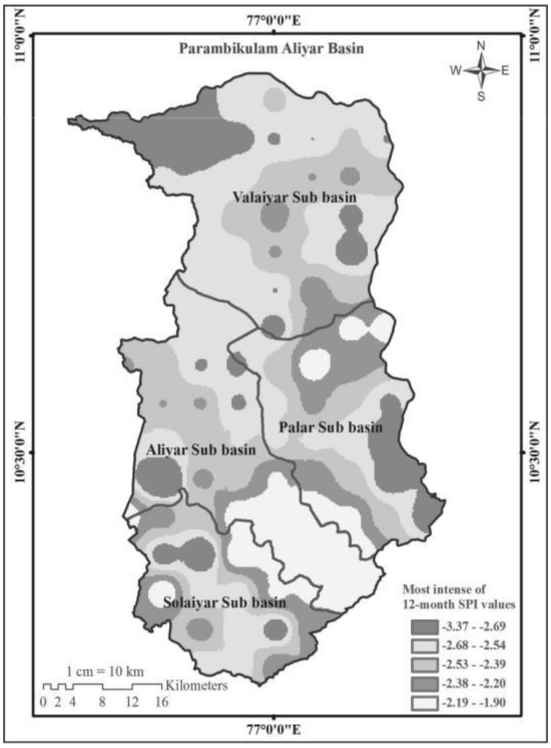

Fig. 6. Spatial variation of most intense droughts

more in the southern parts and it decreases towards northern direction. It is noted that occurrence of drought at mountainous region is much more than

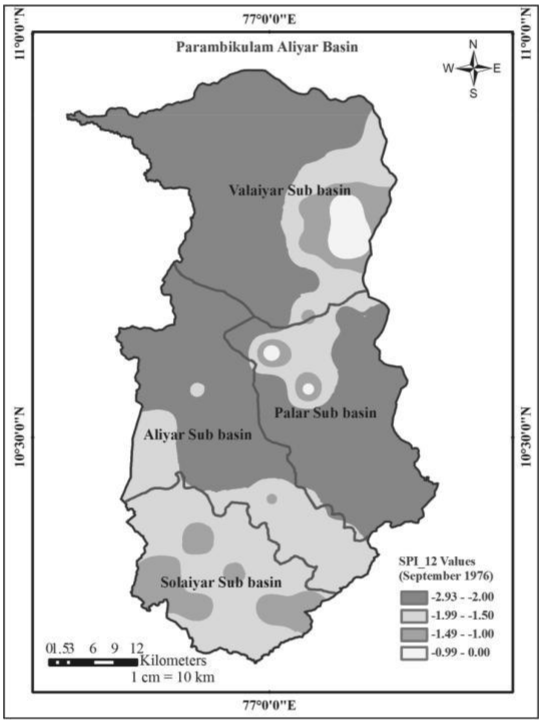

Fig. 7. Spatial variation of worst drought month occurred in September 1976

that at hillock areas and the plain. Due to undulation nature of the study area, uneven distribution of rainfall and increased evaporation has increased

Fig. 7 shows the spatial variation of worst drought month that occurred in September 1976. It should be noted that September 1976 is the first driest month for the period of analysis and it indicates that the most drought affected areas were central and northern areas of the basin. From the figure it can be observed that more than 80 per cent of the areas

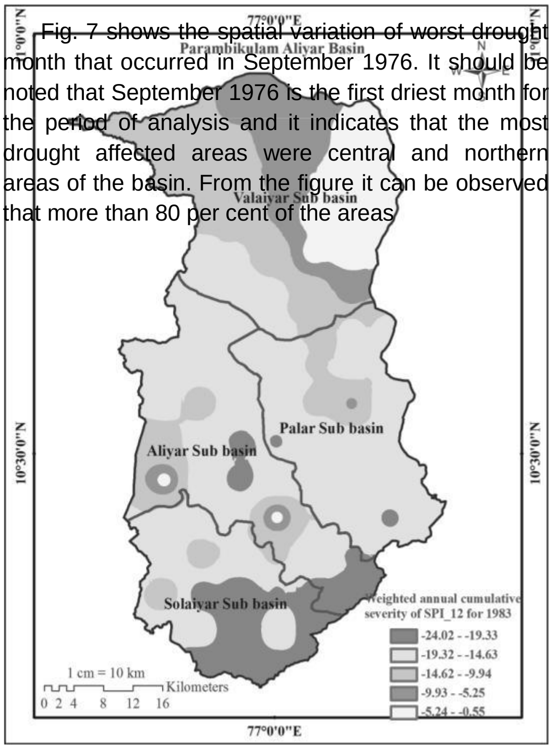

Fig. 8. Spatial variation of weighted annual cumulative drought severity for worst drought year of 1983

the percentage of occurrence of drought in the PAP basin. Spatial variation of most intense droughts in the PAP basin displayed in the Fig. 6 indicated that

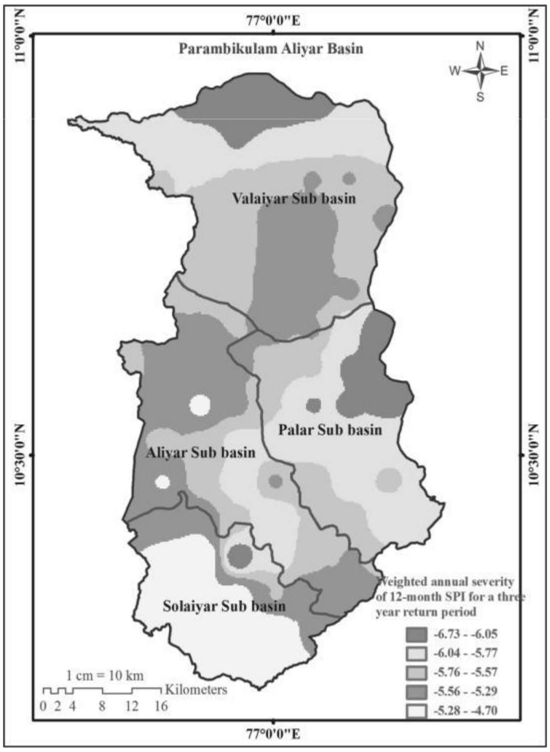

Fig. 9. Spatial variation of drought severity at 3 year return period

the most intense quantity was observed more in the lower and middle part of the basin than in the upper part basin. Some patches of most intensive extreme droughts were observed in the south-eastern parts.

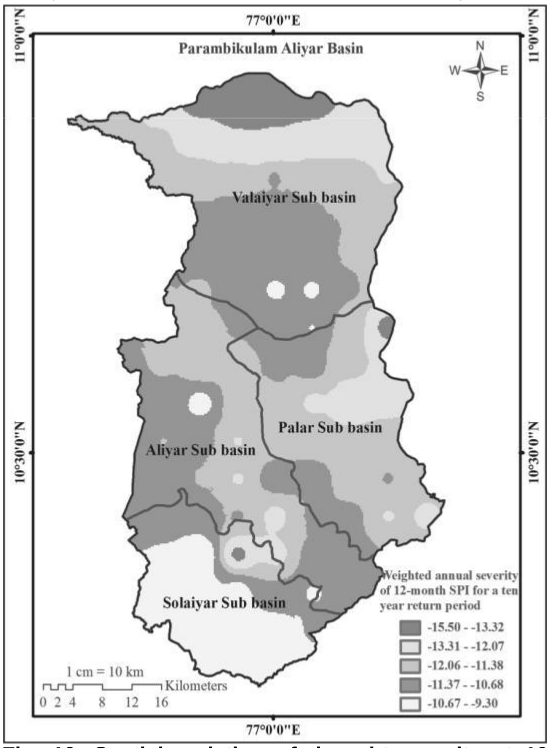

Fig. 10. Spatial variation of drought severity at 10 year return period

are affected by severe (-1.5>SPI>-1.99) and extreme droughts (SPI<-2.0).

Using the estimated weighted annual cumulative SPI drought severity, the spatial distribution of a particular annual drought episode could be assessed. Fig. 8 shows the spatial variation of weighted annual cumulative 12-month SPI for the first (1983) driest year and it indicates that during the year 1983, the weighted annual cumulative drought severity was larger for the southern areas of the basin.

In the present work Extreme Value Type I distribution is selected for the frequency analysis as it passed the two tests for SPI_12 time scale at all grids. For the Extreme Value Type I distribution frequency factor can be expressed as:

---- (14)

Frequency factor of Extreme Value Type I distribution was applied in the Equation 13 and calculated annual cumulative drought severity for 3 and 10 year return period (T). Spatial variation of weighted annual cumulative drought severity at 3 and 10 years return are given in Fig. 9 and Fig. 10. As a result, in the recurrence period of 3 and 10 years, the droughts will have greater severity in the northern parts in comparison to the other parts of the basin. Finally, the consequence of meteorological drought associated with hydrological drought has significant impacts on water resources of the basin. As the percentage of occurrence of drought in the southern mountainous region is high, it eventually affects the available water storage of the reservoirs of PAP basin. This leads to decrease the surface water supply to the Aliyar and Palar sub basin which have negative effect on agricultural activities.

Conclusion

This study was focused on analyzing temporal and spatial characteristics of droughts in the PAP basin using the SPI as an indicator of drought severity. The temporal drought analysis of the SPI indicates that mild, moderate, severe and extreme droughts are quite frequent and suggest that the basin suffered severe drought during 1983, 1976 and 2002. These prolonged and persistent droughts seriously affected domestic water supply and agricultural irrigation. The results of spatial characteristics of drought showed that the central and northern parts of the basin have more potential sensitivity to the droughts in comparison with the other areas of the basin based on drought severity. Droughts are more prevalent in southern areas of the basin in terms of percentage of occurrence of drought. The identification and characterization of droughts in the PAP basin will be useful for the development of a drought preparedness plan in the region so as to ensure sustainable water resource planning within the basin.

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