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ASSESSING HYDROLOGICAL DROUGHT CHARACTERTICS: A CASE STUDY IN A SUB BASIN OF TAMIL NADU, INDIA

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Abstract: Assessment of hydrological drought and evaluation of drought characteristics provide useful information for sustainable water resources planning and management in a river basin. In the present study, streamflow drought index (*SDI*) was used to assess the hydrological drought characteristics in the Parambikulam-Aliyar basin of Tamil Nadu, India by considering streamflow volume as an indicator of drought severity. The temporal behavior of hydrological droughts were analyzed initially and then, frequency of annual drought severity and recurrence patterns of severe drought events was assessed. The temporal analysis of the *SDI* values indicated that moderate, severe and extreme droughts are common in the Aliyar sub basin and suggested that the basin suffered severe drought during the 1970s, 1980s and 2000s especially in 1972-74, 1982-85, 1987-88 and 2002-04. January followed by June are the months during which hydrological drought occurs most frequently. Frequency analysis of drought severity indicated that the drought that occurred in the 1970s, 1980s and 2000s has an associated return period of about 80 to 100 years. The results of this study can be used as guide to develop drought preparedness plans and formulate mitigation measures within the basin.

Key words: *streamflow, SDI, drought severity, return period*

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INTRODUCTION

Drought is a natural phenomenon that has significant damages both in human lives and economic losses. Drought is a normal, recurring feature of climate; it occurs in almost all climatic regimes. Drought is mostly related to scarcity of water for a period of time, such as a season or a year. Drought produces an impression of water scarcity resulted due to insufficient rainfall, high evapo-transpiration, and over-exploitation of water resources or combination of these parameters [1]. Drought adversely affects various sectors of human society, e.g. agriculture, hydropower generation, water supply, industry.

Droughts are defined based on the variables used for assessing different types of drought. The prime variable for the meteorological drought is precipitation/rainfall, whereas for the hydrological drought it is either river runoff/streamflow or reservoir levels and/or groundwater levels. For agricultural drought, the main variables are soil moisture and/or consumptive use. Historical data of these variables can be used to assess the respective types of drought. This study focuses on the hydrological drought which is defined as period during which streamflows are inadequate to supply established uses under a given water management system.

Droughts are usually assessed and monitored by drought indices. A drought index is typically a single value used for indicating the severity of a drought and is far more useful than raw data in understanding the drought conditions over an area. Numerous specialized indices have been proposed so far, to assess the various types of drought, some of them are region specific [2]. These indices can be used to assist water managers to assess droughts effectively and forecast future drought conditions, which will allow them to plan ahead the water management activities during droughts. This study uses Streamflow Drought Index (*SDI*) for assessing hydrological drought characteristics.

Drought is a frequent phenomenon in India. 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 [3]. 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 [4]. The western region of Tamil Nadu which lies in semi arid region have suffered with severe droughts at many times in the past. Due to the growth of population and expansion of agricultural and industrial sectors, the demand for water has increased manifold and even water scarcity has been occurring almost every year. Global climate change and increasing water demand have further intensified the droughts 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. The objectives of this study are to analyze the temporal variations of hydrological drought and assess the frequency of drought severity. Aliyar sub basin was selected as study area in the Parambikulam-Aliyar basin spread over drought prone districts of Coimbatore and Tiruppur, Tamil Nadu.

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). The basin is drained by eight west flowing rivers viz. Valaiyar, Koduvadiaru, Uppar, Aliyar and Palar (tributaries of Bharathapuzha river) and Parambikulam, Solaiyar and Nirar (tributaries of Chalakudi river). They are grouped into 4 sub basins such as Valaiyar, Aliyar, Palar, and Solaiyar 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. The water is diverted from west flowing rivers to east by constructing weirs, seven storage reservoirs, tunnels, open channels and contour canal etc. to irrigate the drought prone areas of Coimbatore, Tiruppur districts. 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. The *PAP* basin has a large geographic variation and it reflected in the rainfall over the basin. More rainfall can be observed in the southern parts of the basin (Solaiyar sub basin). When it comes to the middle (Aliyar and Palar sub basin) and northern parts of the basin (Valaiyar sub basin), the rainfall decreases. Mean annual areal rainfall over the whole *PAP* basin is about 1410 mm and it is distributed unevenly in space and time.

This study investigates the hydrological drought in the Aliyar sub basin. The Aliyar River has its source in the Anamalai Hills. It flows in a north-westerly direction for about 37 km in Tamil Nadu and enters into Kerala and finally confluence in Bharathapuzha. Aliyar reservoir is one among the main component in PAP with a surface area of 6.50 km^2 and formed in the plains across the river with a gross storage capacity of 109.42 *MCM*. The catchment area at the Aliyar Dam is 196.83 km^2. Apart from its own catchment, water can be diverted to this reservoir through the Aliyar Feeder canal and the Contour canal from the Parambikulam group of reservoirs. Total area of sub basin is 574.75 km^2 and command area of 20,536 ha that covers Pollachi (N), Pollachi (S) and Anamalai block of Coimbatore district. Crops grown in this sub basin area are Coconut, Sugarcane, Banana, Sapota, Mango, Fodder, besides annual crops, such as Paddy, Groundnut, Cotton, Vegetables, Pulses, Fodder, Tomato, Gaurds, Maize as I crop, and Paddy and Groundnut as II crop.

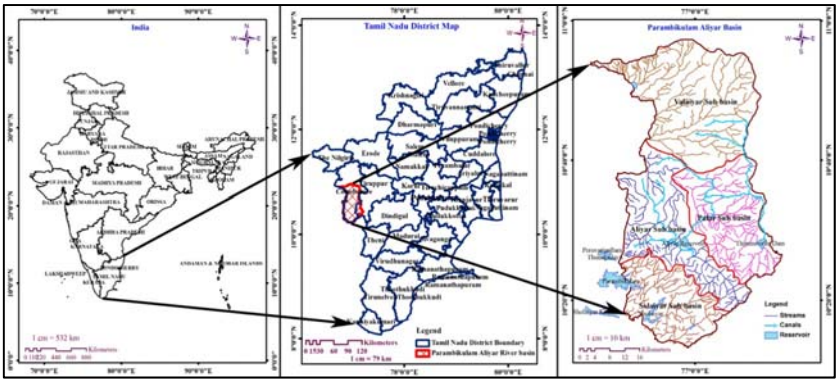

Figure 1. Location of Parambikulam-Aliyar of Tamil Nadu in India

Aliyar sub basin was considered as the study area in this research, since the management of water resources in this basin has great importance in terms of a wider

range of water uses as well as downstream user requirements and environmental flows. However, due to frequent droughts and increasing water demand in recent years, pressure on the water resources management activities have increased within the basin.

This study employs streamflow as hydrological drought indicator. Monthly streamflow data (inflows to the reservoir) at the Aliyar reservoir of Aliyar sub basin was obtained from the office of the Superintending Engineer, Parambikulam Aliyar Basin Circle, Water resource Organization, Public Works Department, Pollachi, Coimbatore. Data used to study hydrological drought cover the period from 1970-71 to 2010-11 for Aliyar sub basin. In this study July to June is considered as a hydrological year.

The methodology presented for analyzing the hydrological drought in this study and applied to Aliyar sub basin consisted of the calculation of the *SDI* values using the streamflow volume, analysis of the temporal characteristics of droughts (Occurrence of drought categories and assessment of drought parameters) and development of drought Severity-Frequency curves (*SF* curves) for annual droughts.

Use of SDI for drought analysis: The *SDI* used in this study is statistically similar to the most commonly used Standardized Precipitation Index (*SPI*) developed by McKee *et al.* [5] for meteorological drought analysis. Other hydrological drought indices such as Palmer Hydrological Drought Index (*PHDI*), or Surface Water Supply Index (*SWSI*) are, in general, data demanding and computationally intensive, where as *SDI* requires minimum input, easy to calculate and keeps the simplicity and effectiveness of *SPI*. The *SDI* for a given period is defined as the difference of streamflow from mean divided to standard deviation [6] as follows:

$$SDI_{i,j} = \frac{Q_{i,j} - \bar{Q}_j}{S_j} \tag{1}$$

Where:

$Q_{j,i}$ [mcf] - streamflow volume for a particular month *j* (Jan.- Dec.) of the ith hydrological year,

$\overline{Q_j}$ [mcf] - mean streamflow volumes for a particular month *j* (Jan.- Dec.),

S_j [mcf] - standard deviation of streamflow volumes for a particular month *j*.

The hydrological drought index of Eq. 1 is identical to the standardised streamflow volume. Generally, for small basins, streamflow may possess a skewed probability distribution which can well be approximated by the family of the Gamma distribution functions. The distribution is then transformed into normal [7]. In this study two parameter log normal distribution was used for which the normalisation is simple: it suffices taking natural logarithms of streamflow. The SDI index is defined as:

$$SDI_{i,j} = \frac{y_{i,j} - \bar{y}_j}{S_{y,j}} \tag{2}$$

Where $y_{i,k} = ln(Q_{i,k})$ *i=1,2,.. (year); j=1, 2, 3..12(month)* are the natural logarithms of cumulative streamflow volume with mean $\overline{y_j}$ and standard deviation $S_{y,j}$ as these statistics are estimated over a long period of time.

Based on *SDI* values computed for Aliyar sub basin, categories of hydrological drought are classified which are identical to those used in the meteorological drought

indices *SPI*. Four drought categories are considered which are denoted by *D1* (mild drought), *D2* (moderate drought), *D3* (Severe drought) and *D4* (extreme drought) and are defined through the criteria of Tab. 1.

Table 1. Drought classification by SDI value and corresponding probabilities

Sl.No.	*Drought Category*		*SDI*	*Probability (%)*
1	*D1*	*Mild drought*	*0 to -0.99*	*34.1*
2	*D2*	*Moderate drought*	*-1.00 to -1.49*	*9.2*
3	*D3*	*Severe drought*	*-1.50 to -1.99*	*4.4*
4	*D4*	*Extreme drought*	*≤ -2.00*	*2.3*

Analysis of occurrence of drought: The *SDI* values calculated from the time series of the monthly streamflow volume of the Aliyar sub basin help to assess the temporal variation of hydrological drought and estimate the drought parameters. The calculated monthly SDI values were classified based on drought categories as presented in Tab. 1. The occurrence of drought categories in percentage is computed by taking the ratio of number of drought occurrences under each drought category to the total occurrences of all drought categories in the sub basin [8][9]. Similarly monthly distribution of occurrence of drought categories was calculated.

Assessment of drought properties: The theory of runs as proposed by Yevjevich (1967) [10] is used to determine properties of hydrologic droughts. A run is defined as a part of time series of drought parameter X_t, in which all values are either below or above the selected truncation level of *Xo*; accordingly it is called either a negative run or a positive run (Fig. 2). The truncation level has been defined as the mean over a long period of time. Major components of a hydrologic drought event are [11][12]; Drought duration (D_d) is time period between the initiation (T_i) and termination (T_e) of a drought event expressed in years/months etc. during which a drought parameter is continuously below the truncation level. Drought severity (S_e) indicates a cumulative deficiency of a drought parameter below the truncation level. It is calculated as the sum of negative *SDI* values in dry spells (Between T_i and T_e). Drought intensity (I_e) is the average value of a drought parameter below truncation level. It is measured as the drought severity divided by the duration. Most intense drought is the extreme drought event during the period of water shortage (the highest departure of the *SPI* value from its normal value or peak negative *SDI* value). In this study, drought duration, severity and intensity of extreme drought and most intense drought experienced in Aliyar sub basin was derived from the monthly *SDI* values.

Development of drought Severity-Frequency (*SF*) curves: A method to assess the frequency of worst droughts experienced over the period of analysis with respect to drought severity of a basin is the drought severity-frequency (*SF*) curves. In this paper drought severity-frequency curves was developed similar to severity-areal extent-frequency (*SAF*) curves proposed by Henriques and Santos (1999) [13] and the same procedure adopted by Kim *et al.* (2002) [14]; Loukas and Vasiliasdes (2004) [15]; Mishra and Desai (2005) [3]; Zhang *et al.* (2012) [16]; Manikandan and Tamilmani, (2013) [17]. The areal extent of drought event which is very useful for meteorological drought was not considered for hydrological droughts analysis.

The *SF* curves were developed based on the weighted annual cumulative drought severity and average annual drought severity. The procedure employed in this study for deriving drought severity-frequency (*SF*) curves is: 1) The monthly *SDI* values for each year were calculated; 2) The annual weighted cumulative drought severity was estimated by multiplying the annual sum of negative SDI values in monthly dry spells by the probability of drought occurrence for each year; 3) The probability of annual drought occurrence for each year was estimated by dividing the number of months that have a negative *SDI* value by 12; 4) To find out the best distribution for the frequency analysis, drought severity was tested using different probability distributions; 5) Using the selected probability distribution drought severity was estimated at different return periods; 6) Severity of selected drought years was compared with estimated severity at different return periods. Severe drought years were selected based on least negative quantity of drought severity; 7) Weighted annual cumulative SF curves were developed and repeated the analysis for developing annual average drought severity-frequency curves. In this analysis duration of drought can be considered uniformly for a particular year, avoid intermittence, and the duration of monthly drought event within a particular year is implicitly taken into account [15].

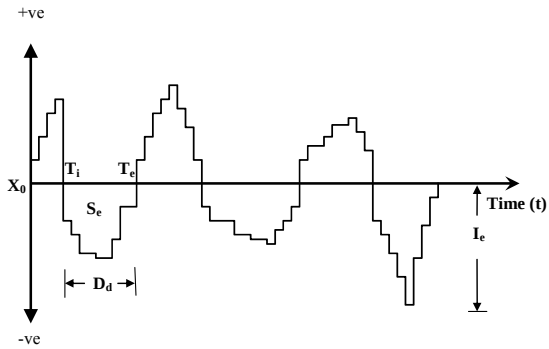

Figure 2. Drought characteristics using run theory for a given threshold level, X_0

The annual average drought severity was estimated by dividing the annual sum of negative SDI values in monthly dry spells for a particular time scale by 12. This analysis estimates the annual drought severity without giving any consideration on the duration of monthly drought event. This means that an extreme drought event that lasts few months may have the equal representation with a long lasting severe and moderate drought event. However, this analysis indicates, on average, how much intense a drought occur in a particular year.

The frequency analysis is the traditional and practical method used in hydrology and meteorology to assess the return period of particular events. Frequency analysis is performed using the selected probability distribution for annual weighted cumulative and annual average drought severity at different return periods. In this study, the annual drought severity has negative values. To be applied before fitting to an available distribution, the negative values of annual 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 annual weighted cumulative and annual average drought severity and tested by non parametric Kolgomorov–Smirnov (*K-S*) test and parametric Chi-Square tests at 5% and 1% significance levels. The annual drought severity X_T to be estimated for a given return period (T) may be represented as the mean μ plus the departure ΔX_T of the variate from mean. The departure may be taken as equal to the product of the standard deviation σ and a frequency factor K_T; that is, $\Delta X_T = K_T\sigma$. The departure ΔX_T and the frequency factor K_T are functions of the return period and type of probability distribution to be used in the analysis [18]. The expected annual drought severity at various return periods 2, 3, 5, 10, 20, 25, 50, 75 and 100 years were worked out by the best fit probability distribution.

RESULTS AND DISCUSSION

Temporal variation of hydrological drought: Time series of monthly streamflow volumes (mcf) of Aliyar sub basin is shown in Fig. 3. The average cumulative streamflow volume was compared to normal cumulative streamflow volume for Aliyar sub basin over the study period for identifying the worst streamflow deficit years. From this analysis, it was found that the Aliyar sub basin experienced streamflow deficits during the period 1970s, 1980s and 2000s. During these three periods the monthly and annual streamflow was considerably below normal. Fig. 4 illustrates the cumulative monthly streamflow volumes for selected deficit years and periods of Aliyar sub basin. The hydrological year of 1972-73, 1973-74, and 1982-83 are the first, second and third driest years in record, respectively for Aliyar sub basin (Fig. 4). The Aliyar sub basin experienced extreme dry periods during 1970s and 1980s. The prolonged and remarkable decrease of monthly and annual streamflow has a significant impact on water resources of the basin. Usually, the dry periods are associated with low rainfall, high temperatures, which lead to higher evapotranspiration rates and dry soils. These parameters inversely affect both the vegetation and the agriculture of the region as well as the available storage of the reservoirs. Severe and extremely dry conditions lead to irrigation cutbacks, overexploitation of groundwater and dramatic losses of crop yields.

The temporal variation of droughts in the Aliyar sub basin were analyzed by analyzing the time series of SDI values computed for the Aliyar sub basin (Fig. 5). The monthly SDI time series shows that the basin experienced frequent droughts for the period of drought analysis and detected several severe and extreme drought events.

Monthly distribution of occurrence of drought categories presented in the Table 2 showed that mild droughts occur most frequently and extreme droughts occur least frequently. The basin experienced frequent droughts for all months of the year. The Aliyar sub basin had experienced 44.51 per cent of occurrence of drought over the period of analysis. It is noted that the basin has experienced severe drought during 1970s, 1980s and 2000s in terms of annual drought severity. Annual drought severity was calculated by summing up the negatives SDI values in dry spells. The years which gives least quantity of drought severity was identified. 1972-74, 1982-85 and 2002-04 are the most severe drought years experienced over the period of analysis. Analysis of occurrence of drought shows that January, June and July are the months during which

the *SDI* values most frequently takes the negative *SDI* value and it is followed by February, March and May.

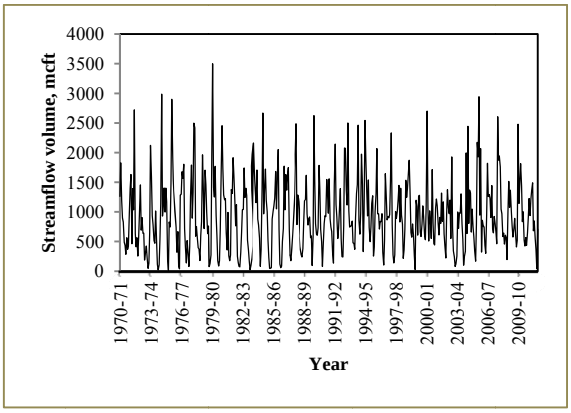

Figure 3. Time series of monthly streamflow volumes of Aliyar sub basin

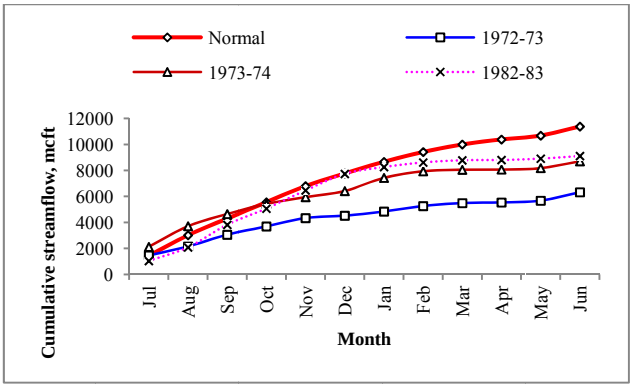

Figure 4. Cumulative monthly streamflow volumes for selected dry years of Aliyar sub basin

Tab. 3 presents the summary of hydrological drought properties derived from the Fig. 5 occurred in the Aliyar sub basin. The number of drought incidences is defined as the number of times drought occurs in the *PAP* basin over the period of analysis i.e number of times the negative *SDI* values continually follows. It is found that the total number of drought months and the number of drought incidences for Aliyar sub basin is 219 and 93 months respectively. Average duration of drought (number of drought months divided by number of drought incidences) calculated in the basin was 2.35 month. The period of longest duration of drought was experienced in 1972/08-1973/06 and its severity (sum of negative SDI values) was -14.47. Intensity (ration of severity and duration) of longest duration and highest severity drought was -1.16. The most intense quantity i.e. minimum negative of SDI values for Aliyar basin was observed in December 1972 ($SDI = -3.15$). It is referred as extreme drought month over the study period.

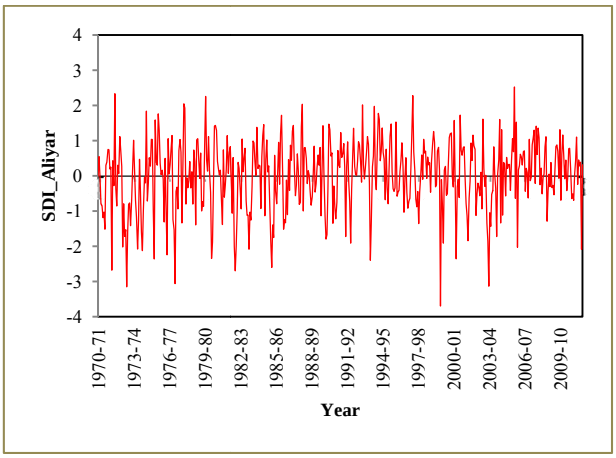

Figure 5. Temporal variation of SDI values in the Aliyar sub basin

Table 2. Monthly distribution of occurrence of drought categories in the Aliyar

Month	D1	D2	D3	D4	Total
January	3.46	0.41	0.00	0.41	4.27
February	2.64	1.22	0.00	0.20	4.07
March	2.64	0.81	0.20	0.20	3.86
April	2.24	0.41	0.61	0.20	3.46
May	2.64	0.41	0.61	0.20	3.86
June	3.25	0.41	0.20	0.41	4.27
July	3.25	0.41	0.20	0.41	4.27
August	2.24	0.41	0.41	0.41	3.46
September	1.83	0.20	1.02	0.20	3.25
October	1.63	0.81	0.00	0.61	3.05
November	1.22	1.22	0.20	0.41	3.05
December	2.44	0.61	0.41	0.20	3.66
Total	29.47	7.32	3.86	3.86	44.51

Table 3. Hydrological drought properties of SDI series for Aliyar sub basin

Sl.No.	Drought properties	Aliyar sub basin
1	No of drought months (<-0)	219
2	No of drought incidence	93
3	Average duration in months	2.35
4	Longest duration of drought (month)	10
5	Period of longest duration	1972/08-1973/06
6	Severity of longest duration	-14.47
7	Drought intensity	-1.45
8	Most intense drought	Dec 1972 (-3.15)

Analysis of frequency of drought severity: The results of Goodness fit test for candidate distributions for weighted and annual drought severity for Aliyar sub basin is presented in Tab. 4. The results as shown in Table 4 indicated that most of the

distributions passed the test. The Extreme Value Type I (*EV I*) distribution was selected in this study. This distribution is a special case of the Generalized Extreme Value (*GEV*) distribution with two parameters and its parameter values may be estimated with less uncertainty, as the small sample size is used here. It is also used for the numerous extreme drought studies [3] [14] [15]. For the Extreme Value Type I distribution frequency factor can be expressed as:

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + ln\left[ln\left(\frac{T}{T-1}\right)\right]\right\} \tag{3}$$

Frequency factor of Extreme Value Type I distribution was applied in the Eq. 3 and calculated annual drought severity for different return period (*T*).

Table 4. The results of Goodness fit test for candidate distributions for SDI values

Drought severity	*Weighted Severity*		*Average Severity*	
Goodness of fit Test Distributions	*K-S*	*Chi square*	*K-S*	*Chi square*
Gamma	*0.1232*	*1.528*	*0.0884*	*2.197*
Extreme Value Type I	*0.0811*	*1.517*	*0.0664*	*1.641*
Log-normal	*0.0929*	*2.632*	*0.0947*	*4.289*
Normal	*0.2176*	*13.2*	*0.1674*	*7.805*

Significant level of K-S Test at 1% = 0.26 and 5% = 0.21; Significant level of chi-square test for 4 degrees of freedom at 1% = 13.28 and 5% = 9.48.

Analysis of drought severity – frequency curves: The *SF* curves of annual weighted cumulative drought severity of Aliyar sub basin corresponds to different return periods constructed in this study are presented in Figs. 6a and 6b. The highest weighted annual cumulative drought severity was observed in the year 1972-73 has an associate return period of above 100 years. The drought that occurred in 1989-90 has an associate return period of 2 years (Fig. 6a). The highest annual average severity that observed in the year 1972-73 and the drought that occurred in 2003-04 has an associated return period of 100 years and 2 years respectively (Fig. 6b). The results of this study may provide a scientific basis for decision makers to formulate drought mitigation measures with respect to water resources planning and management.

CONCLUSIONS

This study was focused on analyzing hydrological drought characteristics in the Aliyar sub basin using the streamflow drought index (*SDI*) as an indicator of drought severity. The *SDI* was computed based on the monthly streamflow volume and drought severities were classified into four drought categories. Occurrence of drought categories was estimated and the results revealed that the basin experienced quite frequent moderate, severe and extreme droughts on monthly basis. The results indicated that the basin has experienced prolonged and severe droughts in terms of severity and durations in the 1970s, 1980s and 2000s. In particular, the persistent and prolonged drought of 1972-1974 and 1982-1985, 2002-2004 seriously affected drinking water supply, canal water supply for agricultural irrigation, ground water as well as reduction of inflows to

the reservoir. The drought severity - frequency curve constructed in this study are used to find out the return period of drought affected years in terms of their severity. Obtaining drought properties is important for planning and management of water resources system. Moreover, the estimation of return periods associated to severe droughts and probability of occurrence of drought severity can provide useful information in order to improve water systems management and to work out the best possible supply of canal water in the basin and planning drought mitigation measures under drought condition. These studies will be helpful once drought is identified and before it moves to next severity levels, information may be conveyed to other sectors to ensure that they will act timely and effectively to tackle with drought.

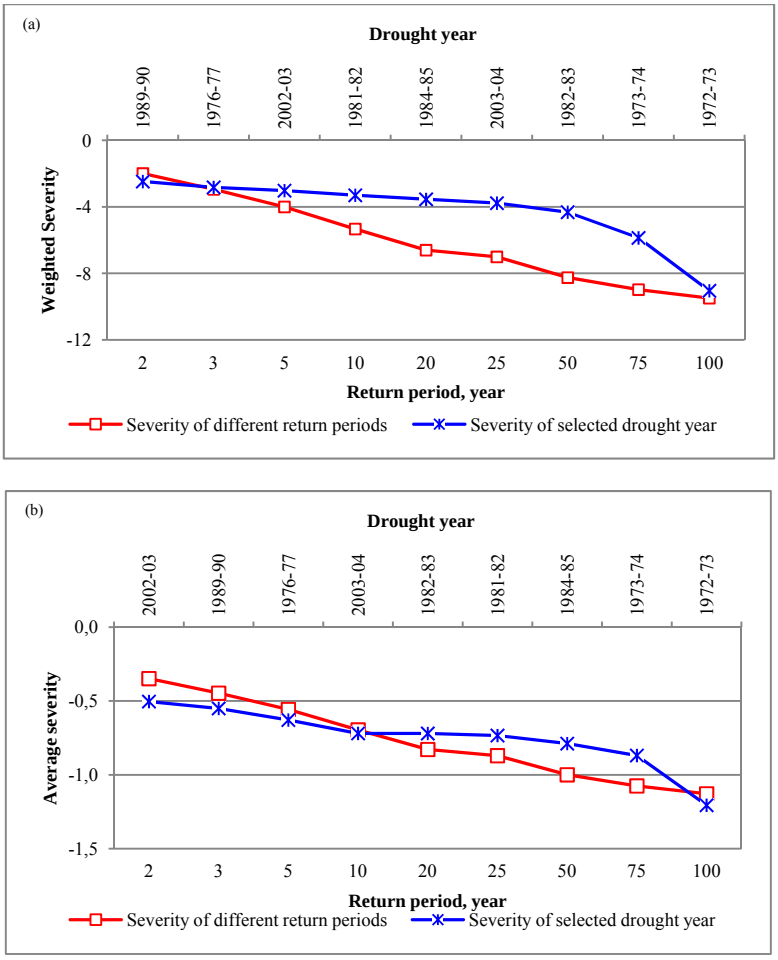

Figure 6. Drought severity-frequency curve for: (a) weighted severity, (b) average severity

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PROCENA HIDROLOŠKIH OSOBINA SUŠE: STUDIJA U OBLASTI BASENA TAMIL NADU U INDIJI

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Sažetak: Procenom hidroloških osobina suše dolazi se do korisnih informacija koje su od značaja prilikom upravljanja vodnim resursima u rečnom basenu. U ovoj studiji su karakteristike suše u basenu Parambikulam-Aliyar u oblasti Tamil Nadu u Indiji, opisane indeksom strujanja (*SDI* - streamflow index) kao indikatorom intenziteta sušnog perioda. Analizirane su pojedinačne promene hodroloških karakteristika, njihova učestanost ponavljanja i mogućnost za predviđanje njihovih budućih vrednosti. Na osnovu dobijenih *SDI* vrednosti, napravljena je klasifikacija intenziteta suše i to kao: umerena, ozbiljna i ekstremna suša. Utvrđeno je da je analizirani basen u oblasti Tamil Nadu bio izložen ozbiljnim sušnim periodima tokom 1970-ih, 1980-ih i 2000-ih naročito u periodu 1972-74, 1982-85, 1987-88 i 2002-04. Hidrološke karakteristike suše su najnepovoljnije u mesecu Januaru i mesecu Junu. Utvrđena je učestanost ponavljanja ozbiljnih sušnih perioda na svakih 80 do 100 godina. Rezultati uve studije se mogu iskoristiti prilikom planiranja mera zaštite od suša u basenu.

Ključne reči: *strujanje, SDI, intenzitet suše, učestanost*

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