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Spatiotemporal Analysis of Historical Droughts in the Central Anatolia, Turkey

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ABSTRACT

The spatiotemporal characteristics of meteorological droughts in the Central Anatolia, a semiarid region in Turkey, are determined utilizing the Standardized Precipitation Index (SPI) as a measure for drought severity. Using the temporal and spatial characteristics of monthly SPI, drought intensity-areal extent-frequency curves for various return periods are constructed for the region, and then the spatiotemporal characteristics of selected historical droughts are evaluated. The results indicate that the region is usually under the influence of droughts with low return periods, in other words, high frequency droughts during the study period (from 1953 to 2004). However, the areal extent of drought may be significant because of its negative impact on the water resources in the region. The overall evaluation of study results reveal that this method can provide useful information for spatial and temporal variations of droughts and can be utilized for water resources management in this region.

Keywords: Drought, frequency curve, semi-arid region, SPI, the Central Anatolian Region, Turkey.

1. INTRODUCTION

Droughts are generally perceived to be a prolonged period with significantly lower precipitations relative to normal levels. The meteorologic drought is related to precipitation deficits which cause decreases in water supplies for domestic and other purposes affecting the flora and fauna of a region [1-3].

The effects of a drought are generally characterized by severity, frequency, area, and duration which are necessary factors for regional drought analysis or spatiotemporal analysis [4]. Information on regional drought characteristics is critical and should be incorporated in strategic short as well as long term water resource management [5]. Several studies on regional drought analysis are available in the literature. Clausen and Pearson [6] developed a method to investigate the spatial and temporal variability of droughts by a regional frequency analysis of annual maximum streamflow deficits. Shin and Salas [7] proposed a method for analyzing and quantifying the spatial and temporal patterns of meteorological droughts based on annual precipitation data by using neural networks. Kim et al. [8] investigated the temporal and spatial characteristics of droughts in the Conchos River basin, Mexico, with the drought intensity-areal extent-frequency curve obtained from the Palmer Drought Severity Index (PDSI). Sırdaş and Şen [9] presented a spatial and temporal drought analysis in the Trakya region of Turkey with the SPI method and the run analysis. Hisdal and Tallaksen [10] introduced a method to calculate the probability of a specific area to be affected by a drought of a given severity and demonstrated its potential for calculating both meteorological and hydrological drought characteristics in Denmark. Vicente-Serrano and López-Moreno [11] used the SPI at different time scales to compare with surface hydrological variables in a big closed basin located in the central Spanish Pyrenees. Mishra and Desai [12] developed quantitative relationships between drought severity, area and frequency using SPI values for different time scales in Kansabati catchment, India. Andreadis et al. [13] constructed drought history from 1920 to 2003 by deriving severity–area–duration (SAD) curves to relate the area of each drought to its severity over the continental United States. Vicente-Serrano [14] analyzed the evolution of droughts in the Iberian

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Peninsula employing the SPI method at 12-month temporal scale. Yıldız [15, 16] applied SPI method to investigate frequency, intensity and areal extent of selected historical droughts in the central Anatolia and the Hirfanli Dam Basin, Turkey. Burke and Brown [17] developed tools to assess regional drought events based on limited periods of record and applied them to regional climate model output to examine potential future changes in drought due to increased greenhouse gases over United Kingdom. Núñez et al. [18] presented a regional frequency analysis method based on L-moments for estimating and mapping return periods of severe droughts in the arid and semiarid region of Chile.

Located in a semiarid region, Turkey experiences frequent drought events. The climate of Turkey is mainly characterized by the Mediterranean macroclimate. Continental tropical airstreams from the northern African and Arabian deserts particularly dominate throughout the summer causing generally long-lasting warm (hot) and dry conditions over the country, except the Black Sea and the northeastern regions. The country is generally characterized by high topography with increasing elevations from the coasts to inner regions and from west to east. With a mean altitude of 1100 m more than 55% of the country is located above 1000 m, while only 17.5% of it varies between sea level and 500 m. Annual average rainfall in the country is about 630 mm ranging from about 300 mm over the continental central Anatolia to more than 1000 mm along the Eastern and Western Black Sea, and Western Mediterranean coasts. Sudden decreases in precipitations in the African Sahel and the subtropics during the 1960s affected the Eastern Mediterranean Basin and Turkey as well in the 1970s, especially, during winter months. Severe and widespread droughts occurred over the country during 1932, 1955-1956, 1973, 1977, 1984, 1989-1991, 1999-2001 periods [19, 20].

This study presents an analysis of spatiotemporal characteristics of meteorological droughts in the Central Anatolian region, a semi-arid region in Turkey. For this purpose, the methodology proposed by Kim et al. [8] is employed to develop drought intensity-areal extent-frequency curves using the monthly SPI time series obtained from the precipitation data between 1953 and 2004. The characteristics of selected historical droughts are determined by this method which enables to obtain useful regional drought information for water resource management purposes.

2. THE STUDY REGION

The region is geographically located at 30-39^{o}E longitudes and 37-40.5^{o}N latitudes with a land surface area of 151,000 km^2 which corresponds to 20% surface area of Turkey (Fig. 1). Approximately with a 17 million population the region has 13 cities including the capital city of Ankara. The region is generally characterized by highlands and wide ranging plateaus with an average altitude of 1150 m. The northern Anatolian mountain ranges in the north and the Taurus mountain ranges in the south have a significant influence on the climate of the region acting as a barrier against humid air masses from coastal regions. The region has a typical dry climate with a mean temperature of about 10^{o}C and a mean annual precipitation of about 400 mm. It receives the lowest amount of rainfall as compared with other regions in the country. Convective and frontal rainfall systems are dominant over the region.

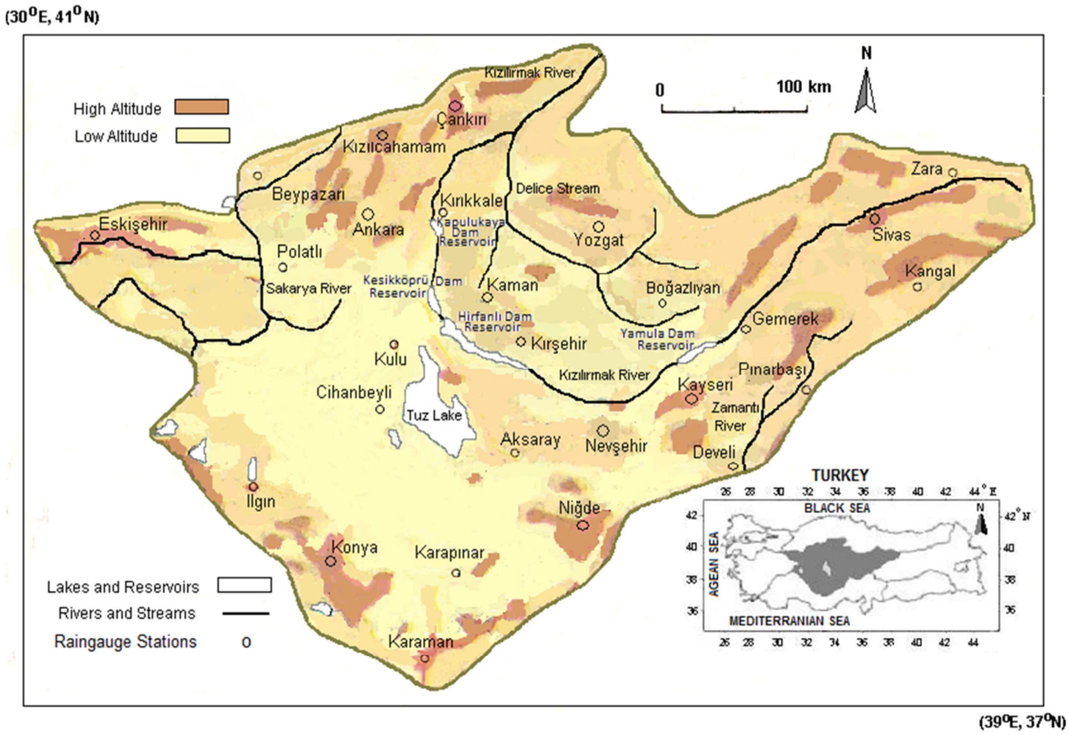

Fig. 1. The Central Anatolian region with raingauge locations and major dam reservoirs.

Two major water resources of the country, the Kızılırmak and Sakarya rivers originate in the region with long term annual average flow rates of 184 m^3/s and 134 m^3/s, respectively, at their outlets to the Black Sea. Fig. 1 depicts the major reservoirs operated for hydropower, irrigation, flood control and domestic water supply purposes in the region (Table 1).

Agriculture is among the major economic sectors in the region where almost one-third of the country's cereal is produced annually. Also, a significant amount of potato and sugar beet across the region are produced. Droughts can cause substantial crop failures in the region. For example, droughts occurred during the periods of 1953-1954, 1956, 1961, 1964, 1969, 1973, 1977, 1984, 1989, 1993-1994, and 1999-2001 resulted in up to 25% decreases in annual cereal production across the region [22].

Table 1. Major dam reservoirs within the region [21].

Name	Reservoir Area (km^2)	Reservoir Volume (hm^3)	Purpose	Hydropower Capacity (MW)	Irrigation Land Area (ha)
Yamula	85.3	2025	Hydropower, irrigation	100	104,000
Hirfanlı	263	5980	Hydropower, flood control	128	-
Kesikköprü	6.5	95	Hydropower, irrigation	76	11,860
Kapulukaya	20.7	282	Hydropower, domestic water supply	54	-

3. HISTORICAL DROUGHTS IN THE REGION

The temporal characteristics of historical droughts in the region were evaluated by the SPI method. Developed by McKee et al. [22] the method is widely used to provide an indicator of drought severity. Based on the probability of the precipitation for a given time period the SPI method is simple and straightforward since precipitation is the only meteorological variable to be utilized. Another advantage of the method is that it provides the utility of various time scales in drought assessments. However, the use of precipitation data alone is also a disadvantage as the data are only recorded at points within the region (interpolation between points is problematic), and examination of groundwater and streamflow data may be more useful.

A standardized precipitation series is calculated using the arithmetic average and the standard deviation of precipitation series. For a given X_1, X_2, X_n series standardized precipitation series, x_i, is calculated from the following equation:

$$x_i = \frac{X_i - \bar{X}}{S_x} \qquad (1)$$

where $\bar{X}$ is the average of precipitation series and S_x is the standard deviation of precipitation series. Negative values obtained from this equation indicate precipitation deficits (drought events), while positive values stand for precipitation excesses (wet events). Four different drought categories are defined by the authors for the SPI ranges given in Table 2.

Table 2. SPI drought categories [22].

SPI Value	Category
(0.0) – (-0.99)	Mild drought
(-1.0) – (-1.49)	Moderate drought
(-1.5) – (-1.99)	Severe drought
≤ -2	Extreme drought

Fig. 2 indicates the regional representative SPI calculated using the areal mean of monthly precipitation data from the meteorology stations across the region. The region has experienced droughts of varying severity and duration during this period of time with 42 months of moderate drought, 18 months of severe drought and 10 months of extreme drought. Major drought events occurred in the region during the periods of 1956, 1961, 1964, 1973, 1977, 1984, 1989, 1993-1994, 1999-2001 and 2004 can be easily detected from Fig. 2.

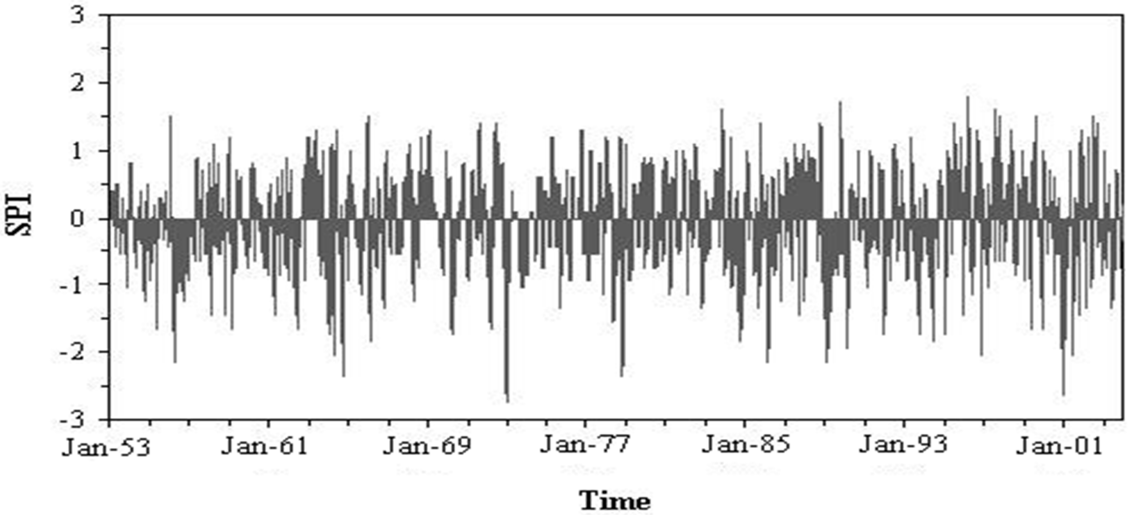

Fig. 2. The spatially averaged monthly SPI for the region (1953-2004).

The influence of precipitation deficits on streamflows over the region was assessed using the streamflow data (between 1950 and 2007) obtained at the inlet of the Hirfanlı Dam Reservoir. The annual flows were normalized by subtracting the long term average value and then dividing by the standard deviation. As shown in Fig. 3 significant decreases in annual flows can be detected during the drought periods of 1950s, 1960s, 1970s, 1990s and 2000s.

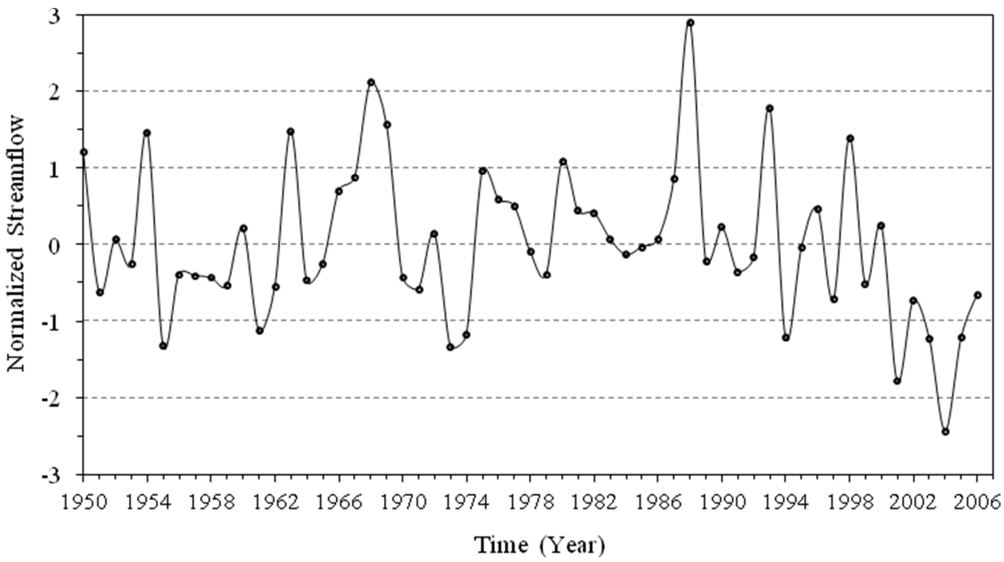

Fig. 3. Normalized annual flows to the Hirfanlı Dam Reservoir between 1950 and 2007.

4. REGIONAL DROUGHT ANALYSIS

Regional drought analysis can provide very useful information for short term or long term water resource management purposes. Proposed by Henriques and Santos [23] the method based on constructing drought intensity-area-frequency curves is one of the most useful regional drought analysis methods to assess drought events in a region. The authors determined the area of influence of each station with the use of Thiessen polygons and developed the drought intensity-area-frequency curves employing the synthetic precipitation series. However, the Thiessen method does not take into account the stochastic characteristics of the precipitation data. Alternatively, Kim et al. [8] proposed the use of geostatistical techniques to obtain regional distribution of precipitation data. They applied the kriging technique to obtain regional precipitation distributions in the Conchos River basin, a semi-arid region under severe drought effects in Mexico. Using the drought intensity-areal extent-frequency curves for the region the authors determined intensity, areal extent and return periods of severe drought events in the 1990s.

This study presents a regional drought analysis in the Central Anatolian region following the method by [8]. Temporal and spatial characteristics of monthly SPI values are used to construct the drought intensity-areal extent-frequency curves in the region. The SPI time series were calculated from the precipitation data between 1953 and 2004 obtained from the Turkish State Meteorology Directorate (www.dmi.gov.tr). 27 meteorology stations across the region were utilized in this study (see Fig. 1).

Following the methodology proposed by [8] temporal and spatial characteristics of monthly SPI values between 1953 and 2004 from 27 meteorology stations within the region were utilized to develop drought intensity-areal extent-frequency curves for the selected return periods in the study area. According to the method, annual drought intensities at each station were calculated by multiplying the annual sum of SPI in dry spells by the probability of drought occurrence which were obtained by dividing the number of months that have a SPI value lower than -1.0 by 12 months for each year. This actually provides the advantages of distributing each drought event evenly for the particular year and of examining the drought with no intermittence.

The spatial distributions of drought intensities for the selected drought years were estimated using the kriging technique and mapped via geographic information systems tools. The drought maps for the selected drought years (i.e., 1956, 1964, 1984, 1989, 1993, 2001 and 2004) are illustrated in Fig. 4 where the spatial variation of SPI as well as temporal evolution of droughts can be detected.

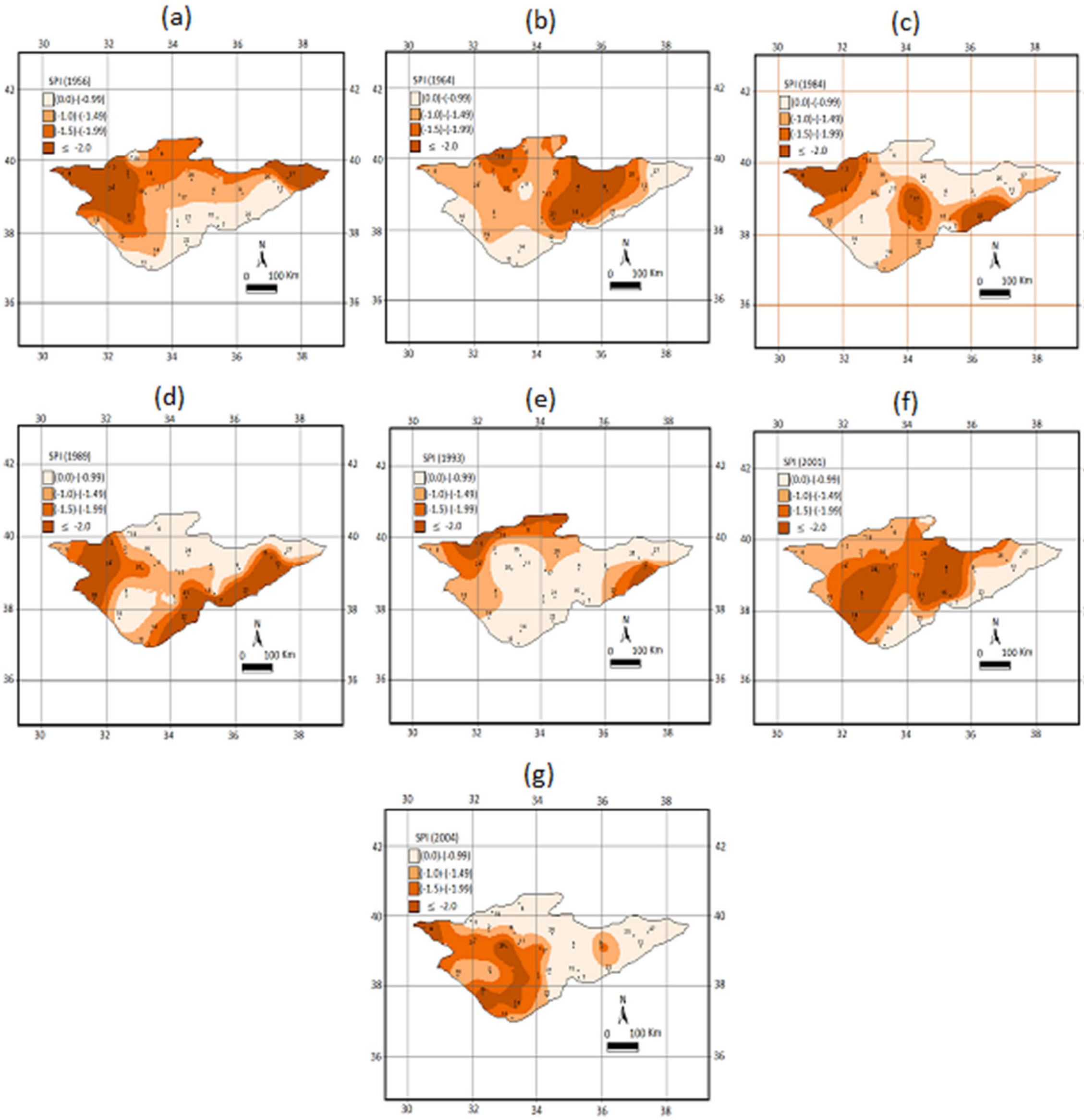

Fig. 4. The spatial distribution of drought intensities for the selected drought years; (a):1956, (b):1964, (c):1984, (d):1989, (e):1993, (f):2001, (g):2004.

After that the drought intensity values associated with the desired percentages of areal extent (5%, 10%, 20%, etc.) were calculated. Negative drought intensity values are converted to positive values for fitting to an available distribution in order to represent the extreme drought and to analyze the risk of the droughts using the exceedance probability. In order to associate the drought intensities with the selected return periods (i.e., 2, 5, 10, 25, 50, 100 years) the frequency analysis for each drought areal extent percentage was performed. The Kolmogorov-Smirnov (K-S) test and the Chi-Square (χ^2) test were applied to the Normal, Log-Normal, Gamma, Extreme Value Type I (EV I), Pearson Type-3 and Generalized Extreme Value (GEV) Distributions. The test results indicate that the selected distributions are appropriate for the drought frequency analysis (Table 3). The EV I was chosen in this study. Although the distribution is usually used to represent precipitation extremes, it was also applied to drought analysis by [23] and [8].

Table 3. Goodness of fit test results (for the areal extent 50%).

Distribution	K-S	Remark 1%	Remark 5%	χ^2	# of D.F.	Remark 1%	Remark 5%	S.L. 1%	S.L. 5%
Normal	0.12	OK	OK	5.21	6	OK	OK	16.81	12.59
Log-Normal	0.14	OK	OK	5.38	6	OK	OK	16.81	12.59
Gamma	0.13	OK	OK	5.22	6	OK	OK	16.81	12.59
Extreme Type I	0.12	OK	OK	6.35	6	OK	OK	16.81	12.59
Pearson Type-3	0.13	OK	OK	5.16	5	OK	OK	15.09	11.07
Generalized Extreme	0.11	OK	OK	1.51	5	OK	OK	15.09	11.07

Significance Level (S.L.) of K-S Test: 1%=0.35 and 5%=0.29

Fig. 5 displays the drought intensity-areal extent-frequency curves obtained for the region under study. The drought intensity, areal extent and return periods for 1956, 1964, 1984, 1989, 1993, 2001 and 2004 droughts in the region are also indicated on the same figure.

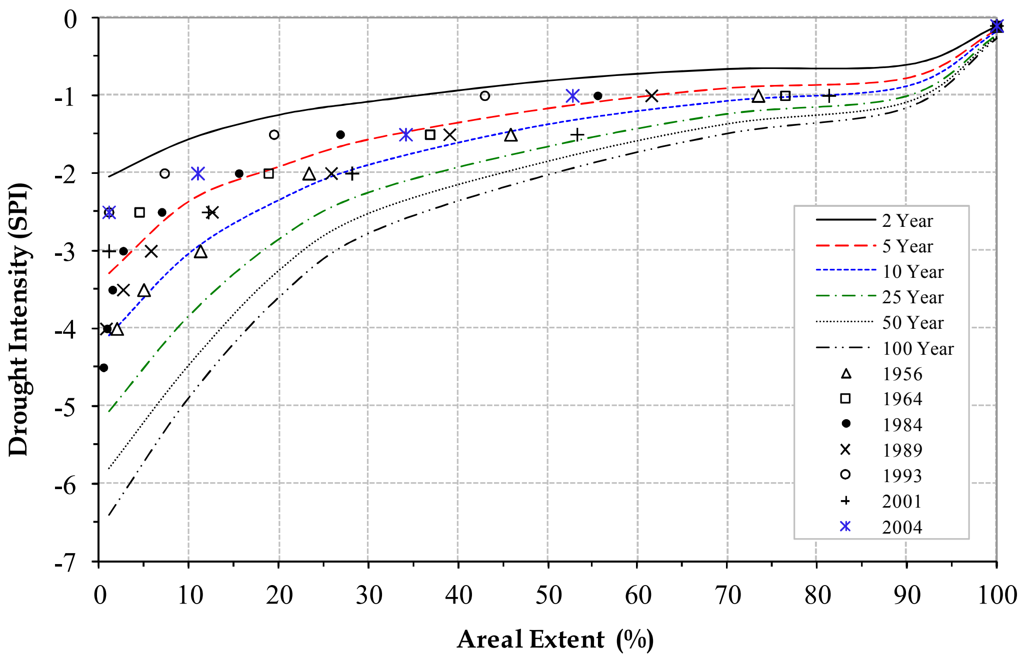

Fig.5. Drought intensity-areal extent-frequency curves for the study area with selected historical droughts.

The selected droughts have a wide a range of return periods from about 2 to 25 years with drought intensities as low as -4.5. As the figure shows the drought severity increases while the areal extent of drought decreases. The droughts of 1956, 1964, 1984, 1989, 1993 and 2004 have relatively low return periods ranging from 2 to 10 years, but the drought of 2001has return periods up to 25 years. During the selected drought years, the areal extent of extreme droughts over the region varies from about 7 to 28% with a return period up to 10 years. On the other hand, nearly 20 to 55% of the region seemed to experience severe drought conditions with a wider range of return periods up 25 years. Moderate droughts seemed to prevail over 45 to 80% of the region with relatively low return periods ranging from 2 to 10 years. As Figs. 4 and 5 indicate about 22 to 28% of the region was subject to extreme droughts (about) during 1956, 1989 and 2001. Above 40% of the region was affected by severe drought conditions during 1956 and 2001. More than half of the region (up to almost 85% in 2001) was under moderate drought effects during all drought years except 1993. Among the selected drought events the drought of 2001 seems to be more widespread with the highest return period in all drought categories. The results show that the region is usually under the influence of droughts with low return periods, that is, high frequency droughts during the study period (from 1953 to 2004). On the other, the areal extent of drought may be significant because of its negative influence on the water resources in the region.

5. SUMMARY AND CONCLUSIONS

A regional drought analysis for the Central Anatolian Region of Turkey was performed in this study. Located in a semi-arid region, the study region is subject to frequent droughts which affect regional water resources and cause substantial agricultural and economic losses. Following the methodology proposed by [8] temporal and spatial characteristics of monthly SPI values were used to construct the drought intensity-areal extent-frequency curve for the region. The historical droughts of 1956, 1964, 1984, 1989, 1993, 2001 and 2004 were evaluated and their spatial and temporal characteristics were quantified. It is shown that the selected droughts have a range of return periods from about 2 to 25 years. The areal extent of extreme droughts reached 28% of the region during 2001. More than 40% of the region was affected by severe droughts during 1956 and 2001. Moderate droughts influenced more than half of the region during all drought years except 1993. It was found that although the region is influenced by droughts with relatively low return periods (i.e., high frequency droughts) the areal extent of droughts can be relatively large and their effect on water resources can be significant as indicated in Fig. 4. The study results suggest that this method can be useful for analyzing regional drought characteristics and can provide valuable information on regional water resource management. Further studies are needed to better understand the impact of droughts on water resources including streamflows, groundwater and reservoirs across the region.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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