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Drought Class Probability Analysis for the Küçük Menderes River Basin

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Abstract

Drought is a complex natural hazard that may take many years to develop and that has significant effects on human life, environmental systems, and the economy. Its impacts may also be serious and costly. This study, considering the fact that drought is a significant natural disaster, aimed to investigate the characteristics of drought in the Küçük Menderes River Basin. Among several drought indices, the Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) were used for drought analysis. SPI and SDI were applied to the monthly precipitation data of Selçuk and Ödemiş meteorological stations with nos. 17854 and 17822, and to the monthly flow data of Selçuk and Bülbüller flow gauging stations with nos. E06A001 and D06A012, respectively. Drought classes for each month were obtained through the referred drought indices. Using the drought classes, meteorological and hydrological droughts were statistically investigated at a regional scale by determining the drought classes' occurrence probabilities, the expected residence time in each drought severity class, the expected first transition time, and the drought class with the highest probability of occurrence in the near future.

Keywords: Drought classes, transition probability, standardized precipitation index, streamflow drought index, Küçük Menderes River Basin

1. Introduction

Drought is a natural event that occurs when the amount of rainfall falls below its normal level, causing serious hydrological imbalances and negatively impacting land resources and production systems. Drought characteristics can be divided into four categories: frequency, severity, duration, and impact area. The drought's main characteristics include the uncertainty of its beginning and end, its cumulative increase in intensity, its impact on multiple resources at the same time, and its significant economic dimension (Turkes, 2010). A universal definition of drought is difficult to come up with. However, drought can be classified into four categories that are widely accepted. Droughts are classified as meteorological, agricultural, hydrological, and socioeconomic (Wilhite & Glantz, 1985). The frequency of possible drought events is of importance in terms of meteorology, hydrology, and agriculture.

In Douro, Portugal, 3- and 6-month scales' Standardized Precipitation Index (SPI3 and SPI6, respectively) values were considered for short-term and medium-term drought analysis. However, for the long-term analysis, the Markov chain approach was used. The expected residence time in each severity class, the expected first transition time, the recurrence time, and the class prediction on a short-term basis were also calculated. When examining the results of a drought event, SPI6 could have been preferred over SPI3, since the first indicated a higher persistence for the same class, being a better guarantee of less water scarcity when adequately managed (Abreu et al., 2008).

In the Eastern Mediterranean region, using the extensive annual and monthly rainfall time series of meteorological observation stations, the distribution among the drought categories of "mild, moderate, severe, and extreme" was determined through the SPI method, and the probability values of drought and deluge in different periods were calculated with the Markov chain. When analyzed spatially, it was determined that as the consecutive periods (1, 3, 6, 12, 24, or 48 months) increased, the probability of drought increased while the probability of deluge decreased in the study area (Fidan, 2011).

Another research aimed to examine and determine drought through the SPI by using monthly total precipitation and probabilities of being dry on the monthly scale with a 2-state first-order Markov chain approach in the Southeastern Anatolia Project (GAP) area. At the regional scale, results showed that a 50% or higher probability of drought was expected 99% of the project area. According to this study and the findings, agriculture-based industries were assessed for risk management (Tonkaz, 2008). In another study by Yildirim and Aksoy (2019), using the SPI, the drought classes' probabilities, the expected residence time in each drought class, the expected first transition time, and the drought class with the highest probability of occurrence in the near future were determined for the Akhisar meteorology station in the Gediz Basin, Turkey.

Nowadays, Turkey is facing problems such as water scarcity, sea level rise, drought, and floods. Droughts are becoming more common in many areas, particularly in areas that are important for national agriculture. İzmir, one of Turkey's major cities, is also at risk, and all cities rely on available fresh water in reservoirs (FAO, 2017; OECD, 2019). Forty-six percent of the İzmir province's surface water presence is in the Küçük Menderes River Basin. In the referred river basin, significant agricultural activities are being carried out with irrigation facilities, which increases water demand. It has therefore been an important study area for which water allocation and drought management plans have recently been prepared by state-owned organizations (TUBITAK, 2010; GDWM, 2016, 2017, Eris et al., 2020). In this study, the Küçük Menderes River Basin was selected as the study area.

Many studies on drought have been conducted in various parts of the world, including Turkey. However, the studies for the determination of transition probabilities from a given drought class to another are limited, particularly for any region in Turkey. The aim of this study was to determine the transition possibilities of drought classes, and thus to make short- and medium-term forecasts of drought transition based on the current state. For this purpose, the Streamflow Drought Index (SDI) was used in addition to the SPI in order to consider both meteorological and hydrological drought. The SPI and SDI were calculated using monthly precipitation for Selçuk and Ödemiş and flow data for Selçuk and Büllbüller, located in the Küçük Menderes River Basin. Drought classes were determined for each month. The drought classes' occurrence probabilities, the expected residence time in each class of severity, the expected first transition time, and the short-term drought class prediction were examined, and the relationship between meteorological and hydrological drought was tried to be determined.

2. Study Area and Method

The Küçük Menderes River Basin, a part of the administrative Küçük Menderes Basin (with no 06 in Figure 1) in the Aegean Region, in the western part of Turkey, was selected for the case study. The river basin has the characteristics of the Mediterranean climate. The winters are warm and rainy, while the summers are hot and dry. The long-term mean annual precipitation is approximately 600 mm, which corresponds to an 11.45 m^3/s annual average discharge at the outlet of the river basin (GDWM, 2016). For the analysis, the monthly precipitation data of Selçuk and Ödemiş meteorological stations (Station Nos. 17854 and 17822) and the flow data of the Selçuk and Bülbüller flow gauging stations (Station Nos. E06A001 and D06A012) located in the basin were obtained from the Directorate General for State Hydraulic Works (DSI) and the Turkish State Meteorological Service (MGM), and their particulars are given in Table 1.

Table 1. Meteorological and flow gauging stations in the Küçük Menderes River Basin

Meteorological station		Flow gauging station	
Station No	17854	Station No	E06A001
Station Name	Selçuk	Station Name	Selçuk
Coordinates	37° 56′ 32″ N,27° 22′ 01″ N	Coordinates	37° 58′ 45″ N, 27° 22′ 46″ E
Elevation (m)	18	Elevation (m)	4
Observation Period*	1964-2018	Observation Period*	1961-2008
Mean precipitation (mm)	570	Mean flow (m^3/s)	9.30
Station No	17822	Station No	D06A012
Station Name	Ödemiş	Station Name	Bülbüller
Coordinates	38° 12′ 57″ N, 27°57′ 52″ E	Coordinates	38° 13′ 54″ N, 27° 50′ 02″ E
Elevation (m)	111	Elevation (m)	130
Observation Period*	1960-2018	Observation Period*	1985-2002
Mean precipitation (mm)	438	Mean flow (m^3/s)	0.23

**Observation period shows the data range used in the study.*

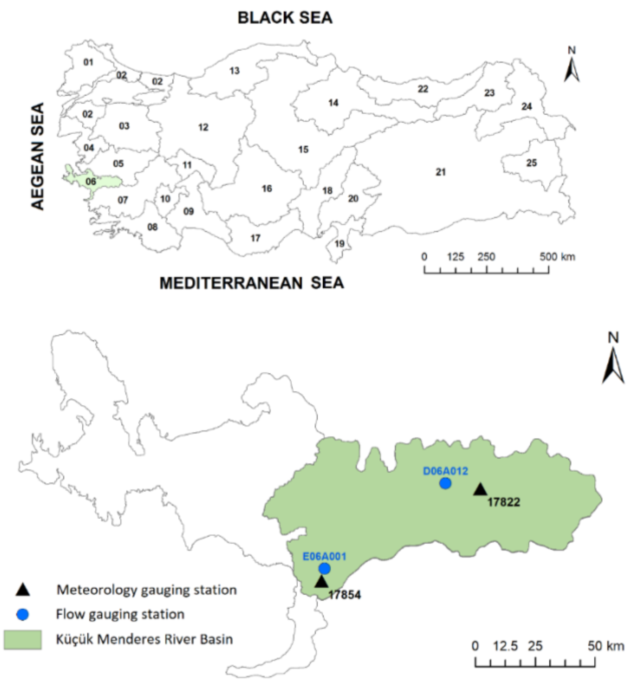

Figure 1. The locations of meteorological and flow gauging stations used in the study

2.1 Standardized Precipitation Index (SPI)

For meteorological drought analysis, the Standardized Precipitation Index (SPI) was used in this study. SPI is the most commonly used index to monitor and characterize meteorological droughts. SPI was developed by McKee et al. (1993), and described in detail by Edwards and McKee (1997). It measures precipitation anomalies for a location based on the comparison of observed total precipitation amount for an accumulation period of interest (e.g. 1, 3, 6, 9, 12, or 48 months) with the long-term historic precipitation record for that period. SPI1 and SPI3 (for 1- and 3-month scales) can be used as an indicator for immediate impacts such as reduced soil moisture, snowpack, and flow in smaller creeks. SPI6 and SPI9 can be used as indicators for reduced stream flow and reservoir occupancy, whereas SPI12, SPI24, and SPI48 can be used for reduced reservoir occupancy and groundwater recharge. Drought classifications based on the SPI values are given in Table 2.

Table 2. SPI/SDI Values of Drought Classifications

SPI /SDI Value	Classification
SPI/SDI≥ 0	Wet
0 < SPI/SDI < -1.0	Mild Drought
-1.0 ≤ SPI/SDI < -1.5	Moderate Drought
-1.5 ≤ SPI/SDI < -1.99	Severe Drought
SPI/SDI ≤ -2.0	Extreme Drought

2.2 Streamflow Drought Index (SDI)

In order to characterize hydrological drought, Nalbantis & Tsakiris (2009) developed the SDI by considering monthly streamflow value (Q_{ij}), where i is the hydrological year and j is the number of months in the hydrological year, based on the concepts of developing the SPI. The cumulative streamflow volume is given in Eq. (1):

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \qquad i=1, 2, \dots \quad j=1, 2, \dots \quad k=1, 2, 3, 4 \tag{1}$$

where Vi,k is the cumulative streamflow volume for the ith hydrological year and for the kth reference period, and k=1 for October-December, k=2 for October-March, k=3 for October-June, and k=4 for October-September (as SDI1, SDI2, SDI3, SDI4).

The *SDI*, based on cumulative streamflow volumes ($V_{i,k}$) for each reference period k of the ith hydrological year, is defined as in Eq. (2):

$$SDI_{i,k} = \frac{V_{i,k} - V_k}{\sigma} i=1, 2, \dots \; k=1, 2, 3, 4 \tag{2}$$

where V_k is the mean and σ is the standard deviation of the cumulative streamflow volumes of the reference period k. The states of hydrological drought based on SDI values are also given in Table 2.

2.3 Drought Class Probability

In determining the probability of drought classes, the following definitions, which were previously proposed and applied to different stations in the South of Portugal by Paulo & Pereira (2007), were used in this study:

Drought class probability is the possibility of occurrence of different drought classes;

Expected residence time in each drought class is the average time spent before transiting from the specified drought class to another class, and it represents the length of such a drought class;

The expected first transition time is the average time elapsed to reach the non-drought (wet) state from the specified drought class;

The drought class most likely to occur in the near future; the drought class most likely to be seen 1, 2, and 3 months following the relevant drought class.

3. Results and Discussion

SPI12 values were obtained for meteorological drought, and SDI4 values were obtained for hydrological drought regarding the Selçuk meteorological and flow gauging stations. Based on the SPI12 and SDI4 time series, the drought class probabilities, the expected residence time in each drought class, the expected first transition time, and the drought class with the highest probability of occurrence in 1, 2, and 3 months following the relevant drought class were determined for each station.

When the SPI12 values (Table 3) were examined, Selçuk meteorological station came up as the one where the highest "mild-drought" was occurring with 245 months, and the probability of occurrence was calculated as 37.8%. "Mild drought" occurred at Ödemiş meteorological station for 237 months, with a probability of occurrence of 34.0%. Since SPI classification is suitable for normal distribution due to its calculation method, the probability of the occurrence of "mild drought" classes close to the average was high. As the drought severity increases, the number of incidents, and therefore, the probability of the occurrence of drought, decreases. The drought class least likely to occur was the "extreme drought" class, with 0.020 and 0.025 for both stations, respectively.

Table 3. Drought class probabilities for SPI12

Drought Class	SELÇUK Station (17854)		ÖDEMİŞ Station (17822)	
	Number of Occurrence	Probability of Occurrence	Number of Occurrence	Probability of Occurrence
Extreme Drought	16	0.025	14	0.020
Severe Drought	30	0.046	42	0.060
Moderate Drought	43	0.066	59	0.085
Mild Drought	245	0.378	237	0.340
Non-Drought	315	0.485	345	0.495

On the other hand, as per SDI4 values (Table 4), "mild drought" class with 164 and 56 months occurred as the drought class with the highest number, and the probability of its occurrence was calculated as 29.0% for Selçuk and Bülbüller flow gauging stations. As SDI is basically the conversion of the streamflow time series to the standard normal distribution, the probability of the occurrence of "mild drought" classes close to average was high. Just like SPI12, as the severity increases, the number of incidents, and therefore, the probability of the occurrence of drought, decreases. The drought classes least likely to occur were the "extreme drought" class with a probability of 0.027 for Selçuk flow gauging station and the "severe drought" class with a probability of 0.026 for Bülbüller flow gauging station.

In terms of expected residence time in each drought class, 12-month droughts tended to take approximately 1.5 and 5.2 months between the "moderate drought" and "mild drought" classes at Selçuk meteorological station (Table 5), and they tended to take approximately 2.0 and 4.6 months between the "moderate drought" and "mild drought" classes at Ödemiş meteorological station.

Table 4. Drought class probabilities for SDI4

Drought Class	SELÇUK Station (E60A001)		BÜLBÜLLER Station (D06A012)	
	Number of Occurrence	Probability of Occurrence	Number of Occurrence	Probability of Occurrence
Extreme	15	0.027	10	0.052
Severe Drought	31	0.055	5	0.026
Moderate	34	0.060	17	0.088
Mild Drought	164	0.290	56	0.290
Non-Drought	321	0.568	105	0.544

Table 5. Expected residence time for SPI12

Drought Class	SELÇUK Station (17854)	ÖDEMİŞ Station (17822)
	Expected Residence Time	
Extreme Drought	3.2	3.5
Severe Drought	2.0	2.2
Moderate Drought	1.5	2.0
Mild Drought	5.2	4.6

In terms of hydrological drought, 12-month droughts generally tend to take quite a long time compared to meteorological droughts. While the residence time in the drought period changed between 3.4-15.0 months at Selçuk flow gauging station, it changed between 1.7-10.0 months at Bülbüller flow gauging station (Table 6). When Tables 5 and 6 are considered together, it can be said that hydrological drought has a more persistent characteristic compared to meteorological drought.

Table 6. Expected residence time for SDI4

Drought Class	SELÇUK Station (E60A001)	BÜLBÜLLER Station (D60A012)
	Expected Residence Time	
Extreme	15.0	10.0
Severe Drought	7.8	1.7
Moderate	3.4	5.7
Mild Drought	9.6	5.1

As seen in Table 7, the first "wet" period was observed in 20.9-41.0 months following a dry period of "extreme drought", "severe drought", "moderate drought", and "mild drought" classes at Selçuk meteorological station. The first "non-drought" period was observed in 16.0-22.9 months following a dry period of "extreme drought", "severe drought", "moderate drought", and "mild drought" classes at Ödemiş meteorological station.

Table 7. Expected first transition time for SPI12

Drought Class	SELÇUK Station (17854)	ÖDEMİŞ Station (17822)
	The Expected First Transition Time	
Extreme Drought	36.6	16.0
Severe Drought	41.0	21.0
Moderate Drought	40.0	22.9
Mild Drought	20.9	17.1

The first wet period was observed in 75 months after a long period following a dry period of "extreme drought" class at Selçuk flow gauging station. In terms of "mild drought" class, the expected first transition time generally increased as the drought severity increased (Table 8). The first wet period was observed in 15 months following a dry period of "extreme drought" class for Bülbüller flow gauging station. For both stations, in terms of "extreme drought" class, the expected first transition time generally decreased as the drought severity decreased. Like the results of "the expected residence time", the results of "the expected first transition time" showed that the transition from a drought class to a wet state takes longer in the hydrological aspect compared to the meteorological aspect. Another conclusion derived from Tables 7 and 8 is that the results of "the expected first transition time" were higher for Selçuk meteorological and flow gauging stations compared to Ödemiş meteorological station and Bülbüller flow gauging station. Selçuk meteorological and flow gauging stations are located at the southwest, whereas the others are at the northeast part of the region. Spatially, these results suggest that the southwestern part of the region transits from a drought class to the wet state in a longer period compared the northeastern part of the region.

Table 8. Expected first transition time for SDI4

Drought Class	**SELÇUK Station (E60A001)**	**BÜLBÜLLER Station (D60A012)**
	The Expected First Transition Time	
Extreme Drought	75.0	15.0
Severe Drought	53.3	7.7
Moderate Drought	55.4	7.0
Mild Drought	34.4	8.4

The aim of the study was also to predict future drought conditions with the help of current drought conditions. Accordingly, the drought class with the highest probability of occurrence in the near future was determined. The drought classes most likely to occur in 1, 2, and 3 months following other drought classes were determined, and they are shown in Tables 9-12 as per SPI12 and SDI4, respectively. In terms of all the drought classes, the most probable classes that occurred in the 1-3 months following them were again the same.

Table 9. SPI12 the drought class most likely to occur in the near future at SELÇUK meteorological station (17854)

	1 Month Later		**2 Months Later**		**3 Months Later**	
Drought Class	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence
Wet	Wet	0.92	Wet	0.87	Wet	0.83
Mild D.	Mild D.	0.81	Mild D.	0.74	Mild D.	0.68
Moderate	Moderate	0.44	Moderate D.	0.51	Moderate D.	0.53
Severe D.	Severe D.	0.50	Severe D.	0.40	Severe D.	0.27
Extreme D.	Extreme D.	0.69	Extreme D.	0.50	Extreme D.	0.31

Table 10. SPI12 the drought class most likely to occur in the near future at ÖDEMİŞ meteorological station (17822)

Drought Class	1 Month Later		2 Months Later		3 Months Later	
	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence
Wet	Wet	0.91	Wet	0.87	Wet	0.84
Mild D.	Mild D.	0.78	Mild D.	0.69	Mild D.	0.64
Moderate	Moderate	0.49	Moderate	0.44	Moderate D.	0.42
Severe D.	Severe D.	0.55	Severe D.	0.43	Severe D.	0.38
Extreme D.	Extreme D.	0.71	Extreme D.	0.57	Extreme D.	0.50

Table 11. SDI4 the drought class most likely to occur in the near future at SELÇUK flow gauging station (E60A001)

Drought Class	1 Month Later		2 Months Later		3 Months Later	
	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence
Wet	Wet	0.97	Wet	0.95	Wet	0.93
Mild D.	Mild D.	0.90	Mild D.	0.83	Mild D.	0.76
Moderate	Moderate	0.71	Moderate	0.56	Moderate D.	0.44
Severe D.	Severe D.	0.87	Severe D.	0.74	Severe D.	0.61
Extreme D.	Extreme D.	0.93	Extreme D.	0.87	Extreme D.	0.80

Table 12. SDI4 the drought class most likely to occur in the near future at BÜLBÜLLER flow gauging station (D60A012)

Drought Class	1 Month Later		2 Months Later		3 Months Later	
	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence	Most Probable Drought Class	Probability of Occurrence
Wet	Wet	0.91	Wet	0.87	Wet	0.81
Mild D.	Mild D.	0.80	Mild D.	0.70	Mild D.	0.61
Moderate	Moderate	0.82	Moderate	0.76	Moderate	0.65
Severe D.	Severe D.	0.40	Severe D.	0.40	Severe D.	0.40
Extreme D.	Extreme D.	0.90	Extreme D.	0.80	Extreme D.	0.70

4. Conclusions

The drought classes' occurrence probabilities, the expected residence time in each drought severity class, the expected first transition time, and the drought class with the highest probability of occurrence in the near future were evaluated for meteorological and hydrological droughts in the Küçük Menderes River Basin. According to the results, the following conclusions can be drawn:

- The probability of drought decreases as the severity of the drought increases during the observation period.
- The probability of "extreme drought" at both stations was 2.0%-2.5% and 2.7%-5.2% for SPI12 and SDI4, respectively. Due to the normal distribution of SPI and SDI,

extreme values were unlikely to be seen. Therefore, a low probability of "extreme drought" was expected.

- The expected residence time in each drought severity class was longer in terms of hydrological drought (SDI4) compared to meteorological drought (SPI12). There was persistent "extreme drought", particularly in terms of hydrological drought. In other words, hydrological drought has a more persistent character compared to meteorological drought. This result is important, and it should be emphasized in terms of measures to be taken against drought.
- The results of the expected first transition time showed that the transition from a drought class to a non-drought state takes longer in the hydrological aspect compared to the meteorological aspect. Due to the location differences of the meteorological and flow gauging stations, spatially, the results showed that the southwestern part of the region transits from a drought class to a non-drought state in a longer period compared to the northeastern part of the region. However, this fact needs to be proven through more stations.
- In terms of all the drought classes, the most probable classes that occurred in 1, 2, and 3 months following them were again the same. When the expected residence times and the first transition times were examined, it was concluded that the hydrological drought lasts longer than the meteorological drought. According to these results, the most likely situations in 1, 2, or 3 months can be considered as drought prediction tools for transitions among drought severity classes.

For future studies, more precipitation and flow data from meteorological and flow gauging stations can be obtained to evaluate the drought characteristics of the Küçük Menderes River Basin accurately. The Markov chain can be used in order to model SPI transition classes for better understanding the drought characteristics of the study region. Drought transition probabilities may also be calculated for different drought indices (Palmer Drought Severity Index, PDSI; Standardized Precipitation Evapotranspiration Index, SPEI, etc.).

Author Statement

The authors confirm their contribution to the paper as follows: study conception and design: E. Eris; data collection: S. Tatar; analysis: S. Tatar; interpretation of results and draft manuscript preparation: S. Tatar, E. Eris. All authors reviewed the results and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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