Characterizing meteorological and hydrological droughts: A case study of the Gediz River Basin, Turkey

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Abstract
The determination of the drought characteristics of a basin that feeds a reservoir and provides water for agricultural irrigation or energy production is important for the sustainable management of reservoirs. In the present study, the meteorological and hydrological droughts of the upper basins feeding the Demirköprü Reservoir in the Gediz River Basin of Turkey are examined over one, three, six and 12 month timescales. The methods used include the standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) for defining meteorological droughts, and the standardized runoff index (SRI) method for defining hydrological droughts. The results show that the wet periods are dominant in the water years before 1984, and the dry periods occurred more frequently and were longer after this year in the basin. Owing to a temperature increase, it is determined that the effect of potential evapotranspiration losses on drought events has increased in the years after 2000, and the droughts that occurred after this year have happened more intensively in the basin. The results also show that both the meteorological and hydrological drought trends of the basin are prone to dry conditions and no that change is expected in these trends in the near future. Considering the predicted global climate changes, the results provide a source for describing the characteristics of the meteorological and hydrological droughts observed in the basins for the sustainable management of reservoirs which have a large irrigation area or energy production.

KEYWORDS
drought indices, Gediz Basin, standardized precipitation evapotranspiration index (SPEI), standardized precipitation index (SPI), standardized runoff index (SRI)

1 INTRODUCTION

The gradual changes in the Earth’s climate have caused changes in the frequency and intensity of many hydro-meteorological processes, such as precipitation, temperature, evaporation and runoff. As a result of these changes, drought constitutes an important boundary for planners in terms of the sustainable management of water resources (Crausbay et al., 2017; Liu et al., 2019). Drought is one of the natural phenomenon related to the water deficit that occurs at different timescales and causes extensive damage on both water resources and...
humanity. Generally, drought is defined as a lack of water over a sustained period, or an amount of water dropping lower than average for a given period in the inspected water cycle system. It can be classified into three groups: meteorological, hydrological and agricultural. Meteorological drought emerges in the consequence of anomalies in precipitation. Hydrological drought refers to a decrease of the available water in the water resources such as streams, reservoirs and is generally caused by meteorological drought. Agricultural drought takes place due to inadequate soil moisture in a specific zone (Oloruntade et al., 2017; Khan et al., 2018). The drought process in meteorological terms can occur in three stages hydrologically and agriculturally: in the short term and with a mild severe manner; as well as in the long term and with a severe manner. Depending on the duration and severity of the drought, aquatic ecosystems and socioeconomic living conditions are negatively affected by drought, as well as groundwater and the surface water resources parallel to the decrease in precipitation. Therefore, in order to plan water resources sustainably, it is of great importance to describe the drought characteristics in a river basin in terms of duration, magnitude and intensity (Hayes et al., 2011; Mo, 2011; Trenberth et al., 2014; Huang et al., 2015).

Many indices have been developed to help define drought (Niemeyer, 2008; Mishra and Singh, 2010; Liu et al., 2019). The standardized precipitation index (SPI) (McKee et al., 1993) and the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010) of the meteorological drought indices, and the standardized runoff index (SRI) (Shukla and Wood, 2008) of the hydrological drought indices are frequently used in the determination of drought characteristics (Oloruntade et al., 2017; Wu et al. 2017a; Tirivarombo et al., 2018). Precipitation data are used for the determination of meteorological droughts using the SPI method (Mo, 2008; Wang et al., 2011; Stagge et al., 2015; Wu et al., 2018). However, in the SPEI method, drought characteristics are determined by using precipitation and potential evapotranspiration data. In the SPEI method, Thornthwaite (1948) or Penman–Monteith (Penman, 1948; Monteith, 1965) models can be used to determine potential evapotranspiration (Tirivarombo et al., 2018). Therefore, the drought determined by the SPEI depends on the method used to calculate the potential evapotranspiration. When the SPEI and SPI usage are compared, the SPI is used more widely because it calculates on the basis of precipitation data only; therefore, it is easier to implement. Shukla and Wood (2008) have proposed using the SRI, which uses runoff data and is analogous to the SPI. The SRI method is also easy to implement and widely used because it explains hydrological droughts using runoff data only.

The determination of drought characteristics at different timescales (e.g. one, three, six, 12 and 24 months) is important as meteorological and hydrological droughts will occur in different periods due to decreases in precipitation (Lorenzo-Moreno et al., 2013; Barker et al., 2016; Chervenkov et al., 2016; Huang et al., 2017; Wu et al., 2018). In addition, drought has been associated with long-term changes in semi-arid regions, as well as with the change in the rate of drought over long periods (Homdee et al., 2016; Huang et al., 2017; Byakantonda et al., 2018). For this reason, it is necessary to investigate the variability in the dynamics of drought characteristics, that is, whether the drought will continue in the long term or a possible change will occur. The determination of the variability in the drought characteristics of a surveyed timescale is defined depending on the Hurst coefficient calculated by the rescaled range analysis (Wang et al., 2013; Byakantonda et al., 2018). In addition, the Run Theory method proposed by Yevjevich (1967) is used to determine the duration (start-to-finish) magnitude and intensity of the drought characteristics (Wu et al., 2017b).

Several studies have been carried out using the SPI, SPEI and SRI methods to evaluate meteorological and hydrological droughts both separately and together in the basins. Montaseri and Amiratæe (2017) compared droughts found with different drought indices for observed precipitation in 12 regions in 10 countries of different continents across the world, and showed that the SPI method was more consistent in defining meteorological droughts than the other methods. Tirivarombo et al. (2018) determined the meteorological droughts of one, three, six and 12 month timescales in the Kafue basin, Zambia, by using the SPI and SPEI methods, and determined that the magnitude and duration of the drought established by the SPEI was higher than those of the other methods. Wu et al. (2017b) identified hydrological drought with the SRI for the Loess Plateau, China, in association with El Niño–Southern Oscillation (ENSO) events. They concluded that seasonal and annual hydrological droughts were more affected by ENSO events in the southeastern part of the plateau than in the northwestern region. Wu et al. (2018) calculated hydrological and meteorological droughts with the SSI and SPI methods on one, three, six and 24 month timescales and examined the effects of drought with the Xinfengjinag reservoir operation. The results showed that hydrological and meteorological drought characteristics were different under normal conditions. Oloruntade et al. (2017) investigated the meteorological and hydrological droughts of the Niger South Basin in Nigeria with the SPI, SPEI and SRI methods at three, six, nine and 12 month timescales, and showed that hydrological droughts were better associated with the SPEI, and that consequently the
hydrological droughts were more affected by the temperature than by rainfall. In addition, similar studies including Turkey cover only the identification of meteorological drought (Gumus and Algin, 2017). Moreover, Gumus and Algin (2017), examined hydrological and meteorological droughts at three, six and 12 month timescales at the Seyhan–Ceyhan River Basin in Turkey together with the SDI and SPI methods. As a result of the study, the basin showed a one year lag correlation between hydrological and meteorological droughts.

Murray-Rust et al. (2003) state that the irrigation water requirement in the Upper Gediz Basin in Turkey, which feeds the Demirköprü Reservoir on the Gediz River, has not been fully met due to the droughts that occurred in the period 1989–1995. Harmancioglu et al. (2008) examined the sustainable management of water scarcity with different scenarios in the Sustainable Management of Scarce Resources in the Coastal Zone (SMART) project, which studied the existing water consumption activities for the Gediz Basin. As a result, it was stated that the demand for irrigation would be affected mostly by future water scarcity in the basin, and also in the case of drought in the basin; industrial water demand could not be met due to the decrease of groundwater levels. Gorguner et al. (2019) investigated the effect of future climate change by using the Coupled Model Intercomparison Project 5 (CMIP5) projection in the Gediz Basin on the precipitation, temperature and the runoffs feeding Demirköprü Reservoir. The study showed that the average annual temperatures during the period would increase up to 2,100, and in parallel with this, evapotranspiration losses would also increase. They also stated that the results show a tendency to decrease the runoffs that feed the reservoir depending on the climate models. For these reasons, in the present study, meteorological and hydrological droughts of the Acisu, Selendi, Deliiniş and Demirci sub-basins of the Gediz River were investigated between the 1970 and 2013 water years. The main objectives of the study are: (1) to define the meteorological and hydrological drought at different timescales (one, three, six and 12 months); (2) to determine the changes in the multi-scale correlation between meteorological and hydrological droughts; (3) to define meteorological and hydrological drought characteristics such as duration, magnitude and intensity; and (4) to determine whether or not certain meteorological and hydrological drought trends will change in future.

2 | MATERIALS AND METHODS

2.1 | Study area and data

The Gediz Basin, which is along the Aegean coast of Turkey, lies between the northern latitudes of 38 ° 04 ′ N and 39 ° 13 ′ N and the eastern longitudes of 26 ° 42 ′ E and 29 ° 45 ′ E. The basin covers an area of 17,500 km² equal to approximately 2.2% of Turkey. The highest altitude of the basin above sea level is around 2,300 m (Figure 1). Shrubs and forested areas constitute the natural vegetation of the basin. The Gediz River, after which the basin is named, is 275 km long and originates in the Murat Mountains in the northeast of the basin, and then discharges into the Aegean Sea from the north city of İzmir.

The climate of the Gediz Basin is typical for the Mediterranean region. Precipitation generally falls between November and April, and peak runoffs occur in February or March. The mean annual temperature, mean annual precipitation and mean annual runoff of the Gediz Basin are 15.6°C, 635 mm and 46 m³ s⁻¹, respectively (Gorguner et al., 2019). Approximately 110,000 ha of the basin are irrigated for agricultural activities by a large irrigation system. Around 75% of the surface waters in the Gediz Basin are used for irrigation. This irrigation water is provided by three important reservoirs: the Demirkopru reservoir, the Avsar reservoir and Gölarmara Lake. The largest reservoir is the Demirkopru with the capacity of almost 1 billion m³, which is fed by inflows of the Acisu, Selendi, Deliiniş and Demirci sub-basins, which all comprise the Upper Gediz Basin. Demirkopru Dam was built between 1954 and 1960 for the purposes of irrigation, energy production and flood control; its drainage area is 5,520 km².

The Demirkopru Reservoir and Gölarmara Lake both supply irrigation water for an area of 96,000 ha by means of three weirs constructed on the Gediz River, namely the Adala, Ahmetli and Emiralem weirs (Karatas et al., 2009). The water use of the irrigation area of 96,000 ha is limited to 75 m³ s⁻¹ (the capacity of three turbines of the power plant) from Demirkopru Reservoir and 15 m³ s⁻¹ from Gölarmara Lake during the peak irrigation season, which is from late June to early September. Therefore, any meteorological and hydrological drought in the Upper Gediz Basin may cause water scarcity throughout the irrigation season and, hence, serious agricultural droughts in the whole basin (Murray-Rust et al., 2003; Harmancioglu et al., 2008).

The runoff data for the Acisu, Selendi, Deliiniş and Demirci sub-basins were obtained from runoff stations at the outlet of the sub-basins used to define the hydrological droughts for the Upper Gediz Basin. The drainage area of the sub-basins and co-ordinates, altitudes above sea level (masl), long-term monthly mean of observed runoff, and long-term standard deviation of the observed monthly runoff and runoff efficiencies for the runoff stations are listed in Table 1. The runoff efficiency co-efficient defined as the runoff per unit area shows the basin yield for rainfall runoff transformation in a specific basin. The rainfall transformation into the runoff is greater in the basins with a greater runoff efficiency, whereas rainfall is more stored otherwise. The runoff efficiency co-efficients given in Table 1 belong to
the same basins under similar meteorological conditions. According to these coefficients, the largest rainfall transformation is observed in Demirci sub-basin, while the least is seen in Delininis. In other words, basin storage is the highest in Delininis and lowest in Demirci. The sub-basins Acisu and Selendi can be stated to show similar runoff efficiency characteristics.

The monthly average temperature and the monthly total precipitation data observed in the Kula, Gure, Gediz, Simav, Selendi, Icikler and Demirci meteorological stations given in Figure 1 were used in the present study. The co-ordinates, altitudes above sea level, long-term monthly mean of the observed precipitation and the long-term standard deviation of the observed precipitation of these stations are listed in Table 2. The meteorological droughts of the sub-basins were calculated based on the areal total precipitation and the areal average temperatures. The areal precipitation of the sub-basins was calculated using a weighted average, with the weights being equal to the percentage of the area established by the Thiessen method for the sub-region of the stations. The weights of the meteorological stations on the sub-basins are shown in Supporting Information Table S1.

2.2 Standardized precipitation index (SPI)

The SPI method was used to determine the meteorological droughts of the region at different timescales (one, three, six, nine, 12 months and so on) by using the long-term monthly precipitation data. The calculation steps of the SPI method, which are used frequently in meteorological drought analysis, are as follows:

- A probability distribution function is fitted to the long-term (minimum 30 years) precipitation data. The gamma distribution function is expressed as the most suitable distribution function of the precipitation data in most of the studies (Niu et al., 2015; Wu et al., 2018).
- Cumulative probabilities are calculated by the fitted probability distribution function. The calculation steps of the parameters and cumulative probabilities of the Gamma distribution function can be found in detail in the relevant study (Gumus and Algin, 2017).
- Cumulative probabilities are converted to SPI values with a mean of 0 and a standard deviation of 1 by using Equations 1 and 2:

\[
SPI = \begin{cases} 
- \left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) & 0 < H(x) \leq 0.5 \\
+ \left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) & 0.5 \leq H(x) < 1 
\end{cases}
\]

where \( H(x) \) is the cumulative probability of observed precipitation according to the fitted probability distribution

![Image](image-url)
function; and $c_0, c_1, c_2, d_1, d_2$ and $d_3$ are the constants with values of 2.515517, 0.802853, 0.010328, 1.1432788, 0.189269 and 0.01308, respectively.

The classification of droughts into eight classes that vary between the extreme wet to the extreme drought corresponding to the SPI values is given in Table 3 (McKee et al., 1993; Gumus and Algin, 2017).

### 2.3 SPEI

The SPEI developed by Vicente-Serrano et al. (2010) examines the soil moisture gap between the investigated timescales and the historical average of the cumulative soil moisture gap (Oloruntade et al., 2017). The values are calculated by adopting the differences between the monthly precipitation and the monthly potential evapotranspiration to obtain a probability distribution function. Since the potential evapotranspiration values are larger than the precipitation values, especially in arid and semi-arid areas or in the summer, the probability function to be used should give the probabilities for these values because the soil moisture gaps can be negative. Therefore, the probability distribution function with three parameters is used while calculating the SPEI values. Generally, when calculating the SPEI values, the three-parameter log-logistic probability function fitted to the soil moisture gap values is used because it gives a better adaptation for the extreme negative values (Hernandez and Venkatesh Uddameri, 2014).

The evapotranspiration values can be calculated by using methods such as the Thornthwaite or Penman–Monteith. The Thornthwaite method requires the monthly mean temperature and latitude of the meteorological station. For the calculation steps of the method, see Vicente-Serrano et al. (2010). In the present study, the PET was examined by using the Thornthwaite method and the log-logistic with a three-parameter probability function that is fitted to the soil moisture gap values based on goodness-of-fit tests. The differences between the precipitation and potential evapotranspiration for the month were calculated using equation 3:

$$D_i = P_i - PET_i$$

where $D$ is the soil moisture gap; $P$ is the precipitation; $PET$ is the potential evapotranspiration; and $i$ is the month.

Once the $D_i$ values are defined, the calculation steps of the SPEI are similar to the SPI's calculation steps. The only difference is the fitted probability function, that is, the three-parameter log-logistic. The SPEI values are obtained by transforming the cumulative probabilities.
with Equations 1 and 2 (Vicente-Serrano et al., 2010; Tirivarombo et al., 2018). The values can be defined at different timescales for the SPI. Therefore, it can be used to compare the other drought events over the timescales. Depending on the SPEI values, the droughts are classified into eight classes from extreme wet to extreme drought, as discussed in Table 3.

### 2.4 SRI

The SRI method developed by Shukla and Wood (2008) is used to identify hydrological drought events over different spatial and timescales. The hydrological drought can be investigated at different timescales for an area. Therefore, it can be useful to compare meteorological drought events simultaneously at the same timescales. The calculation steps for the SRI values are the same as those for the SPI method. Suitable probability functions for the runoff data are investigated using several goodness-of-fit tests and, thereby, the Gamma distribution is chosen as the best among the successful distributions in the present study. The cumulative probabilities and their transformations to the SRI values are calculated using Equations 1 and 2 (Wu et al., 2018). Depending on the SRI values, the droughts are classified into eight classes from extreme wet to extreme drought, as discussed in Table 3 (Gumus and Algin, 2017; Wu et al. 2017).

### 2.5 Drought identification

In the present study, the meteorological and hydrological droughts are examined for the sub-basins of the Upper Gediz Basin at one, three, six and 12 month timescales between the 1970 and 2013 water years. The precipitation ($P_i$) values for the SPI, the calculated soil moisture gap ($D_i$) values and the runoff ($R_i$) values are aggregated at different timescales. For example, the aggregation can be performed by using Equation 3 for one month in a particular year $I$ with a 12 month timescale (Vicente-Serrano et al., 2010; Mouatadid et al., 2018):

$$\sum_{i=13-k}^{12} Y_{i-k} + \sum_{i=1}^{j} Y_{i} \text{ if } j < k$$

$$\sum_{i=j-k+1}^{j} Y_{i} \text{ if } j \geq k$$

where $Y$ denotes precipitation in the SPI, the calculated soil moisture gap in the SPEI and the runoff values in the

### TABLE 2
Geographical information and basic statistics of the observed precipitation of meteorological stations used in the determination of meteorological droughts of the Upper Gediz Basin

| Station  | Latitude (N) | Longitude (E) | Altitude (masl) | Mean precipitation (mm month$^{-1}$) | Standard deviation (mm month$^{-1}$) |
|----------|--------------|---------------|-----------------|--------------------------------------|--------------------------------------|
| Kula     | 38° 52’ 28° 63’ | 720           |                 | 46.3                                 | 44.9                                 |
| Gure     | 38° 40’ 29° 08’ | 574           |                 | 38.1                                 | 31.6                                 |
| Gediz    | 38° 99’ 29° 40’ | 736           |                 | 48.6                                 | 45.3                                 |
| Simav    | 39° 05’ 28° 58’ | 819           |                 | 65.6                                 | 68.3                                 |
| Selendi  | 38° 75’ 28° 86’ | 475           |                 | 41.8                                 | 36.8                                 |
| Icikler  | 38° 79’ 28° 59’ | 710           |                 | 47.1                                 | 45.4                                 |
| Demirci  | 39° 03’ 28° 64’ | 855           |                 | 53.2                                 | 51.3                                 |

### TABLE 3
Classification of droughts for the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) and standardized runoff index (SRI)

| Drought classes | SPI    | SPEI   | SRI    |
|-----------------|--------|--------|--------|
| Extreme wet (EW)| $SPI > 2$ | $SPEI > 2$ | $SRI > 2$ |
| Severe wet (SW) | $1.5 < SPI \leq 2$ | $1.5 < SPEI \leq 2$ | $1.5 < SRI \leq 2$ |
| Moderate wet (MoW)| $1.0 < SPI \leq 1.5$ | $1.0 < SPEI \leq 1.5$ | $1.0 < SRI \leq 1.5$ |
| Mild wet (MW)   | $0 < SPI \leq 1$ | $0 < SPEI \leq 1$ | $0 < SRI \leq 1$ |
| Mild drought (MD)| $-1 < SPI \leq 0$ | $-1 < SPEI \leq 0$ | $-1 < SRI \leq 0$ |
| Moderate drought (MoD)| $-1.5 < SPI \leq -1$ | $-1.5 < SPEI \leq -1$ | $-1.5 < SRI \leq -1$ |
| Severe drought (SD)| $-2 < SPI \leq -1.5$ | $-2 < SPEI \leq -1.5$ | $-2 < SRI \leq -1.5$ |
| Extreme drought (ED)| $-2 \leq SPI \leq -2$ | $-2 \leq SPEI \leq -2$ | $-2 \leq SRI \leq -2$ |
SRI. The \( Y_{i,j}^k \) in a given month \( j \) and year \( i \) depends on
the chosen timescale \( k \).

The classification of droughts for the SPI, SPEI and SRI are shown in Table 3 (Gumus and Algin, 2017; Wu et al., 2017). The droughts are classified into eight classes that vary from extreme wet to extreme drought, as shown. The negative indices show periods of drought and the positive indices show wet periods. The present study emphasizes the mild to extreme droughts, while defining the drought characteristics.

2.6 Run theory

The drought characteristics, including duration, magnitude and intensity, are defined by the run theory proposed by Yevjevich (1967). This theory says that the drought indices are either below (negative run) or above (positive run) a selected truncation level for a certain period (Figure 2). Depending on the drought level classifications shown in Table 3, the three-run theory threshold levels were set \((-1, 0, 1)\) to define the duration and magnitude of the meteorological and hydrological droughts in the present study. The drought duration \((D)\) was the period where the drought indices (SPI, SPEI, SRI) are continuously \(< 0\). The magnitude of the drought \((M)\) was calculated by the aggregation of all negative drought indices for the duration of the drought. The intensity of the drought \((I)\) is defined as a ratio of magnitude to duration. Four drought events are shown in Figure 2. If a drought event takes place in a one month duration \(D_0\) and its magnitude \(M_0\) or its length continued for several months as \(D_1\) and \(M_1\), then these drought events are defined as a single drought event. In addition, if the duration of the drought event has two branches such as \(d_0\) and \(d_2\), and the intervention period \(d_1\) is less than six months, then these months are defined as a single drought event and its duration was calculated by the sum of \(d_0\), \(d_1\) and \(d_2\). The magnitude of this drought is calculated by the aggregation of \(m_0\) and \(m_1\) (Wu et al., 2017).

2.7 Rescaled range analysis (R/S)

The R/S analysis proposed by Hurst (1951) was extensively used to examine the extent of variability in drought dynamics (Byakantonda et al., 2018; Wu et al., 2018). The variability and different trends of the drought index series are explained by the Hurst co-efficient \((H)\) calculated by using the R/S analysis. The co-efficient ranges are from 0 to 1. In the case of \(H = 0.5\) that shows the randomness in the data series when \(H < 0.5\), the future trend is opposite the past trend, and the smaller the \(H\) values (close to 0) the stronger the variability in the trend. If \(H > 0.5\), the future trend is similar to the past trend and the approximation of \(H\) to 1 indicates that the trend is stable. The evaluation steps of the R/S analysis are as follows:

1. The drought indices (SPI, SPEI, SRI) \(X_i\) of the drought type at the investigated timescales, with \(i = 1, 2, \ldots, N\), where \(i\) is the period (months) of \(N\).
2. The \(X_i\) data set is divided into a sub-series with varying length \((I = 1, \ldots, n)\). In the present study, the data sets of the SPI, SPEI and SRI were divided into six sub-series as \(n_1 = N/1; n_2 = N/3; n_3 = N/6; n_4 = n/12; n_5 = N/24\) and \(n_6 = N/48\).
3. The mean of each sub-series \((\bar{X}(n))\) is determined by Equation 4:

\[
\bar{X}(n) = \frac{1}{n} \sum_{i=1}^{n} X_i
\]

4. The cumulative deviation of each sub-series is calculated by Equation 5:

\[
F(t,n) = \sum_{k=1}^{n} (X_k - \bar{X}_n)
\]

5. The range sequence is calculated by subtraction of the minimums and maximums of the cumulative deviation of the sub-series using Equation 6:

\[
R(n) = \max F(t,n) - \min F(t,n)
\]

6. The standard deviation of each sub-series is then determined by Equation 7:
\[ S(n) = \left[ \frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})^2 \right]^{1/2} i = 1,2,...,n \]  

7. The rescaled ranges of each sub-series are determined by Equation 8 and the rescaled range of the series is computed by taking the average of \((R/S)\):

\[ (R/S)_i = \frac{R(n)}{S(n)} i = 1,2,...,n \]  

8. The correlation of \(R/S\) between the \(H\) co-efficient is as follows (Equation 9):

\[ R/S = an^H \]  

9. The \(H\) co-efficient can be obtained by a linear logarithmic regression of Equation 9 (Equation 10):

\[ Ln(R/S) = Ln(x) + H Ln(n) \]  

10. Finally, the slope of the regression line gives the \(H\) co-efficient.

### RESULTS AND DISCUSSION

#### 3.1 Temporal variation of meteorological and hydrological droughts

The SPI, SPEI and SRI values were calculated to describe the temporal variations of meteorological and hydrological droughts of the Acisu, Selendi, Deliinis and Demirci sub-basins of the Upper Gediz Basin. Figure 3 demonstrates the temporal variations of all drought indices at one, three, six and 12 month timescales between the 1970 and 2013 water years. The meteorological and hydrological drought values show the similar pattern of temporal variability for each timescale at all sub-basins of the Upper Gediz Basin, but they differ in the dynamics of the drought characteristics such as duration, magnitude and intensity. For example, for the long term of 12 months, the meteorological and hydrological droughts in all sub-basins generally showed wet and dry events between the 1970 and 1978 water years; wet events occurred between 1979 and 1984, 1998 and 1999 and 2011 and 2013 water years; and dry events between 1985 and 1997 and 2000 and 2010 water years.

When the temporal variability of the drought indices were examined in terms of timescales, it was seen that the variability of the drought event frequency changes less from the short term (one month) to the long term.

According to the SPI and SPEI values for the meteorological droughts, wet and dry periods were observed in turn in all the sub-basins at the one and three month timescales. However, the wet and dry periods of hydrological droughts within the same timescales were more evident with respect to the SRI values in all sub-basins. The wet periods were more dominant between the 1970 and 1984 and 2010 and 2013 water years. The dry periods were markedly significant between the 1985 and 2009 water years. The six month timescale of the SPI and SPEI values showed wet and dry periods more obviously, which were unclear at the one and three month timescales in all the sub-basins. For example, the dry period observed between the 1973 and 1975 and the 1985 and 1997 water years were identified with the SPI and SPEI values in all the sub-basins more clearly. The SRI values at the six month timescale showed similar results as the three month timescale in all the sub-basins. This conveyed that there were no significant changes in the runoff conditions. The meteorological and hydrological droughts at the 12 month timescale, according to the SPI, SPEI and SRI values, demonstrated significant wet and dry periods in all the sub-basins. For the period under consideration (1970–2013), the most common meteorological and hydrological wet periods were seen between the 1978 and 1983, 1998 and 1999, and 2010 and 2013 water years, and the most common dry periods during 1973–1974, 1985–1995, 2000–2002 and 2006–2009 water years.

According to recent drought research of Turkey, the droughts occurred in the early 1970s and the 1980s, 1990s and 2000s (Akbaş, 2014). In the studies carried out on the Gediz Basin, it was stated that the drought occurred in the basin between 1988 and 1995, and as a result of this, the agricultural irrigation provided by Demirköprü Reservoir was restricted between 1989 and 1998 (Murray-Rust et al., 2003; Akkuzu et al., 2008). These drought events were understandably identified using the SPI, SPEI and SRI methods in the present study.

#### 3.2 Classifications of meteorological and hydrological droughts

Based on the classes given in Table 3 which were calculated with the SPI, SPEI and SRI at a 12 month timescale, the occurrences of meteorological and hydrological drought events for the dry periods are shown in Table 4 and the occurrences of drought events at other timescales are shown in Supporting Information Table S2. The meteorological and hydrological droughts at the 12 month timescale occurred generally in the moderate drought (MoD) class in the Upper Gediz Basin.
Extreme drought events with regard to meteorological droughts took place most frequently in the Acisu sub-basin and the least in the Demirci sub-basin according to both the SPEI and SPI values. The occurrence of the extreme drought events was mostly seen in the Acisu sub-basin according to the SPEI, but in terms of the SPI this happened in the Selendi, Deliinis and Demirci sub-basins. This shows that the Acisu sub-basin meteorological droughts with respect to other sub-basins were affected more than the soil moisture gap defined by the rainfall and potential evapotranspiration due to covering the biggest drainage area of the Upper Gediz Basin. In addition, through the large area of the sub-basin, it may be because the rainfall that occurred on the sub-basin could be more regional and not able to close the soil moisture gap. It was observed that the droughts found by the SPEI method were more frequent when the total meteorological droughts occurred between 1970 and
2013. Although precipitation is an important concept in determining meteorological droughts, the inclusion of the soil moisture gap being dependent on the potential evapotranspiration for determining droughts causes changes in drought experiences.

In terms of hydrological droughts, extreme drought events occurred mostly in the Demirci sub-basin, and the least in the Deliinis sub-basin. Although extreme drought events in the Deliinis sub-basin were few, the highest number of drought events out of the four sub-basins occurred in this basin. Although extreme drought events in the Deliinis sub-basin are few, more drought events in total have occurred in the basin with respect to others. Regarding the runoff efficiency co-efficients given in Table 1, the envisaged reason for the observation of fewer extreme drought events in Deliinis is feeding from soil storage in seasons with no precipitation. This is compatible with its having the lowest runoff efficiency co-efficient, which shows the highest basin storage. Unlike Deliinis, the extreme drought events are observed more frequently in the Demirci sub-basin because of the decrease in precipitation. This is also compatible with the higher runoff efficiency co-efficient of the sub-basin. The higher runoff efficiency co-efficient in the basin indicates that the basin is not fed much by soil storage. Therefore, the hydrological droughts in the sub-basin are more affected by meteorological droughts. Similar runoff efficiency characteristics of the Acisu and Selendi sub-basins are also reflected in extreme drought events.

### 3.3 Identification of meteorological and hydrological drought characteristics

The meteorological and hydrological drought characteristics including the duration, magnitude and intensity of dry periods of the Acisu, Selendi, Deliinis and Demirci sub-basins during the period 1970–2013 at the 12 month timescale were found by using the run theory. The meteorological and hydrological drought characteristics of all the sub-basins are shown in Tables 5 and 6, respectively.

The characteristics of the meteorological droughts found by the SPI and SPEI in the Upper Gediz Basin between 1970 and 2010 were similar in terms of magnitude and intensity compared with the droughts. However, it was seen that the magnitude and intensity of the meteorological droughts found with the SPEI method calculated after 2000 were higher than those calculated by the SPI method. The increase in magnitude and intensity of the droughts observed in SPEI is evident because evapotranspiration has become more dominant than precipitation in the sub-basins droughts after the 2000s since the temperature increase in this region shown by Gorguner et al. (2019).

The hydrological drought characteristics are shown in Table 6. All the sub-basins of the Upper Gediz Basin suffered from droughts between 1988 and 1997; the droughts were experienced uninterruptedly in the Acisu and Selendi sub-basins, while the Deliinis and Demirci sub-basins experienced these droughts in two parts. In the

| TABLE 4 | Occurrences classification of drought events according to the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) and standardized runoff index (SRI) at 12 month time scale in the Upper Gediz Basin |
| --- | --- | --- | --- | --- | --- |
| **Meteorological drought** | **Extreme drought (ED)** | **Severe drought (SD)** | **Moderate drought (MoD)** | **Mild drought (MD)** | **Total** |
| **SPI** | | | | | |
| Acisu | 22 | 18 | 26 | 185 | 251 |
| Selendi | 18 | 25 | 43 | 166 | 252 |
| Deliinis | 20 | 25 | 39 | 155 | 239 |
| Demirci | 15 | 30 | 43 | 160 | 248 |
| **SPEI** | | | | | |
| Acisu | 25 | 21 | 28 | 184 | 258 |
| Selendi | 9 | 28 | 48 | 173 | 258 |
| Deliinis | 10 | 26 | 47 | 177 | 260 |
| Demirci | 9 | 26 | 47 | 176 | 258 |
| **Hydrological drought** | | | | | |
| Acisu | 16 | 19 | 45 | 186 | 266 |
| Selendi | 16 | 21 | 35 | 192 | 264 |
| Deliinis | 9 | 19 | 35 | 215 | 278 |
| Demirci | 21 | 27 | 39 | 160 | 247 |
| Meteorological drought | Acisu sub-basin | Selendi sub-basin | Delinis sub-basin | Demirci sub-basin |
|------------------------|-----------------|-------------------|-------------------|-------------------|
| **Standardized**       | **Start-end**   | **D**  | **M**  | **I**  | **Start-end**   | **D**  | **M**  | **I**  | **Start-end**   | **D**  | **M**  | **I**  |
| precipitation index    | December 1972–  | 15    | 9.39  | 0.78  | August 1972–   | 17    | 11.85 | 0.70  | June 1972–     | 20    | 15.75 | 0.79  |
|                        | February 1974   |       |       |       | January 1974   |       |       |       | January 1974   |       |       |       |
|                        | December 1982–  | 7     | 4.73  | 0.68  | December 1982– | 11    | 7.90  | 0.72  | December 1982– | 11    | 8.61  | 0.78  |
|                        | June 1983       |       |       |       | October 1983   |       |       |       | October 1983   |       |       |       |
|                        | March 1985–     | 74    | 61.86 | 0.84  | November 1984– | 18    | 12.33 | 0.69  | November 1984– | 18    | 15.02 | 0.83  |
|                        | April 1991      |       |       |       | May 1986       |       |       |       | May 1986       |       |       |       |
|                        | December 1991–  | 61    | 43.09 | 0.71  | December 1987– | 85    | 93.50 | 1.10  | December 1987– | 85    | 94.94 | 1.12  |
|                        | July 1997       |       |       |       | December 1994  |       |       |       | December 1994  |       |       |       |
|                        | January–        | 11    | 15.84 | 1.44  | February–July  | 6     | 1.66  | 0.28  | December 1999– | 24    | 23.61 | 0.98  |
|                        | November 2001   |       |       |       | 1997           |       |       |       | November 2001   |       |       |       |
|                        | April 2004–     | 15    | 11.14 | 0.74  | November 1999– | 25    | 24.02 | 0.96  | April 2004–    | 15    | 11.29 | 0.75  |
|                        | June 2005       |       |       |       | November 2001  |       |       |       | April 2005      |       |       |       |
|                        | July 2006–      | 30    | 43.43 | 1.45  | April 2004–    | 18    | 11.83 | 0.66  | December 2006– | 26    | 32.97 | 1.27  |
|                        | January 2009    |       |       |       | September 2005 |       |       |       | January 2009    |       |       |       |
|                        | December 2006–  | 26    | 35.49 | 1.37  | December 2006– | 26    | 35.49 | 1.37  | December 2006– | 26    | 30.95 | 1.19  |
|                        | January 2009    |       |       |       | January 2009   |       |       |       | January 2009    |       |       |       |
| **Standardized**       | **Start-end**   | **D**  | **M**  | **I**  | **Start-end**   | **D**  | **M**  | **I**  | **Start-end**   | **D**  | **M**  | **I**  |
| precipitation-evapotranspiration index (SPEI) | June 1973– | 8     | 4.49  | 0.56  | August 1972– | 15    | 8.42  | 0.56  | June 1972– | 19    | 11.65 | 0.61  |
|                        | January 1974    |       |       |       | November 1973  |       |       |       | January 1974    |       |       |       |
|                        | April 1985–     | 73    | 50.70 | 0.69  | November 1984– | 18    | 10.93 | 0.61  | November 1984– | 18    | 13.06 | 0.73  |
|                        | April 1991      |       |       |       | May 1986       |       |       |       | May 1986       |       |       |       |
|                        | November 1984–  | 18    | 10.93 | 0.61  | November 1984– | 18    | 13.06 | 0.73  | November 1984– | 19    | 14.03 | 0.74  |
|                        | May 1986        |       |       |       | May 1986       |       |       |       | May 1986       |       |       |       |

(Continues)
| Meteorological drought | Acisu sub-basin | Selendi sub-basin | Delinis sub-basin | Demirci sub-basin |
|------------------------|----------------|------------------|------------------|------------------|
|                        | Start-end D M I | Start-end D M I | Start-end D M I | Start-end D M I |
| December 1991–December 1992 | 13 7.36 0.57 | January 1988–August 1995 | 92 77.12 0.84 | January 1988–August 1995 | 92 78.54 0.85 | January 1988–August 1995 | 92 79.25 |
| June 1993–August 1995 | 25 13.85 0.55 | September 1999–November 2001 | 27 32.90 1.22 | November 1999–November 2001 | 25 30.99 1.24 | December 1999–November 2001 | 24 27.81 1.16 |
| December 2000–November 2002 | 23 25.15 1.09 | September 2003–October 2005 | 25 18.71 0.75 | September 2003–September 2005 | 25 14.41 0.58 | February 2004–June 2005 | 17 11.65 0.69 |
| September 2003–August 2005 | 23 16.71 0.73 | November 2006–January 2009 | 27 45.45 1.68 | November 2006–January 2009 | 27 43.75 1.62 | December 2006–January 2009 | 26 39.68 1.53 |
| June 2006–April 2009 | 35 59.32 1.69 | August 2010–January 2012 | 17 8.91 0.52 | March 2010–January 2012 | 23 15.30 0.67 | February 2010–January 2012 | 24 17.08 0.71 |
| February 2010–November 2012 | 30 22.72 0.76 | December 2012–September 2013 | 10 8.56 0.86 | |

Note: D: The drought duration; M: The magnitude of the drought; I: The intensity of the drought.
| Hydrological drought | Acisu sub-basin | Selendi sub-basin | Deliinis sub-basin | Demirci sub-basin |
|----------------------|-----------------|-------------------|---------------------|-------------------|
|                      | Start–end       | D  | M    | I    | Start–end       | D  | M    | I    | Start–end       | D  | M    | I    | Start–end       | D  | M    | I    |
| Standardized         | April 1972–     | 23 | 12.04 | 0.52 | March 1972–     | 23 | 11.88 | 0.52 | February 1972–  | 25 | 17.61 | 0.70 | August 1972–    | 18 | 7.82 | 0.43 |
| precipitation index  | February 1974   |    |       |      | January 1974    |    |       |      | February 1974   |    |       |      | January 1974    |    |       |      |
| (SPI)                |                 | 119| 95.31 | 0.85 | January 1988–   | 119| 108.20| 0.91 | December 1982– | 14 | 10.05 | 0.72 | January 1988–   | 95 | 97.13 | 1.02 |
|                      | January 1997    |    |       |      | November 1997   |    |       |      | January 1997    |    |       |      | January 1997    |    |       |      |
|                      |                 | 13 | 19.22 | 1.48 | February 2000–  | 26 | 25.94 | 1.00 | January 1988–   | 64 | 74.69 | 1.17 | February 1997–  | 12 | 4.75  | 0.40 |
|                      | February 2002   |    |       |      | March 2002      | 26 | 30.65 | 1.18 | January 1997    | 24 | 39.04 | 1.63 | February 2007–  |    |       |      |
|                      | February 2009   | 61 | 62.41 | 1.02 | December 2002–  | 4  | 1.06  | 0.27 | November 1993–  | 51 | 24.67 | 0.48 | February 2000–  | 25 | 29.89 | 1.20 |
|                      |                 |    |       |      | March 2003      |    |       |      | January 1998    |    |       |      | February 2002    |    |       |      |
|                      | February 2004–  | 24 | 16.40 | 0.68 | February 2000–  | 26 | 30.65 | 1.18 | April 2004–     | 21 | 9.45  | 0.45 | April 2004–     |    |       |      |
|                      | January 2006    |    |       |      | March 2002      |    |       |      | December 2005   |    |       |      | February 2007    |    |       |      |
|                      | January 2007–   | 25 | 35.22 | 1.41 | December 2002–  | 38 | 23.75 | 0.63 | January 2009    |    |       |      | January 2009     |    |       |      |
|                      | January 2009    |    |       |      | January 2006    |    |       |      | January 2009    |    |       |      | January 2009     |    |       |      |

Note: D: The drought duration; M: The magnitude of the drought; I: The intensity of the drought.
sub-basins, dry periods between 2000 and 2002 and between 2004 and 2009 occurred with different durations, magnitudes and intensities in the period after 2000. The intensities of droughts that occurred in this period were greater than in the periods before 2000. These increases in the densities of drought were caused by temperature changes in climate conditions as in meteorological droughts.

When the meteorological and hydrological droughts occurring in the sub-basins were examined together, the hydrological droughts started together with the meteorological droughts, and despite the end of the meteorological droughts, the effects on the hydrological droughts continued for a certain period in the sub-basins of the Upper Gediz Basin at the 12 month timescale (Tables 5 and 6).

### 3.4 Rescaled range analysis of meteorological and hydrological droughts

The linear trends of the meteorological and hydrological drought series of the SPI, SPEI and SRI at the 12 month timescale in the sub-basins of the Upper Gediz Basin are shown in Figure 3; the linear trends of this series stated as a percentage of the $Z$-values are shown in Table 7. The trend in the SPEI and SPI demonstrated an increasing trend towards dry conditions for the meteorological drought of all the sub-basins. The linear trends of the hydrological droughts with respect to the SRI series showed an increasing trend towards dry conditions in the Acisu, Selendi and Demirci sub-basins, while there tended to be wet conditions in the Deliinis sub-basin. The linear tendency of the SRI values towards wet conditions stemmed from the fact that extreme wet events occurred in almost all the periods between the 2009 and 2013 water years.

The Hurst ($H$) co-efficients that determine potential changes in drought trends in a 12 month period for the Upper Gediz Basin in the near future are shown in Table 8 and Supporting Information Figure S1 using a rescaled range analysis. The $H$ co-efficients for the SPI, SPEI and SRI series for all sub-basins were > 0.5 and close to 1. The fact that the trends in the meteorological and hydrological droughts are not expected to change in the near future and that even the $H$-values are close to 1 indicate that the trends in the droughts will continue in a stable manner. Therefore, it can be deduced that the meteorological and hydrological droughts of the sub-basins show a tendency for dry conditions, except for the Deliinis sub-basins according to the SRI series. These results are consistent with Gorguner et al. (2017), who state that the Gediz Basin has an increasing trend for annual temperatures and a decreasing average of runoffs from the Upper Gediz Basin which flows from Demirköprü Reservoir.

### 3.5 Correlation of meteorological and hydrological droughts

In terms of sustainable water resource management, the relation between the meteorological and hydrological droughts occurring in the basins should be successfully defined in the basins such as the Upper Gediz Basin, which flows from Demirköprü Reservoir which supplies irrigation water for approximately 90% of the Gediz Basin and generates energy. Therefore, the correlations between the meteorological and hydrological droughts of the Upper Gediz Basin and sub-basins were investigated using the correlation analysis. The lag times in the drought formation at the 12 month timescales were investigated. A 12 month timescale is preferred to capture the lag time between meteorological and hydrological droughts as the hydrological cycle is a loop of 12 months. The variations in the correlation co-efficients versus the lag times are shown in Figure 4 for (a) SPI versus SRI and (b) SPEI versus SRI. While the lag time for the Acisu sub-basin can be two months, it is definitely one month for the other sub-basins because the correlation co-efficients shown in Figure 4 start decreasing after two months in Acisu and after one month in the other sub-basins. This shows that the drainage areas of the sub-basins affect the lag time as the area of Acisu is larger than those of the others.

### Table 7
Linear trends of the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) and standardized runoff index (SRI) series at a 12 month timescale stated as a percentage of $Z$ values

|       | Acisu | Selendi | Deliinis | Demirci |
|-------|-------|---------|----------|---------|
| SPI   | -0.05%| -0.08%  | -0.08%   | -0.08%  |
| SPEI  | -0.25%| -0.23%  | -0.23%   | -0.21%  |
| SRI   | -0.18%| -0.18%  | 0.11%    | -0.15%  |

### Table 8
Hurst co-efficient of sub-basins of the Upper Gediz Basin at a 12 month timescale calculating with a rescaled range analysis

|       | Acisu | Selendi | Deliinis | Demirci |
|-------|-------|---------|----------|---------|
| SPI   | 0.84  | 0.88    | 0.85     | 0.84    |
| SPEI  | 0.87  | 0.88    | 0.86     | 0.84    |
| SRI   | 0.92  | 0.94    | 0.91     | 0.89    |

Note: SPI: standardized precipitation index; SPEI: standardized precipitation evapotranspiration index; SRI: standardized runoff index.
Figure 4 demonstrates that there was a one month lag time between the meteorological and hydrological droughts; in other words, a hydrological drought occurred within one month after a meteorological drought started. This lag time was important in terms of determining the operating policies of Demirköprü Reservoir, which provides water for both energy generation and irrigation for a large area.

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4 | CONCLUSIONS

In the present study, meteorological droughts, using the standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) methods, and hydrological droughts, using the SRI method, were discovered at one, three, six and 12 month timescales in the period between the 1970 and 2013 water years in the Acisu, Selendi, Deliinis and Demirci sub-basins of the Upper Gediz Basin, which flows from Demirkopru Reservoir. The meteorological and hydrological droughts of the sub-basins at the 12 month timescale were examined in detail for long-term droughts. The main conclusions for the long-term droughts of the sub-basins are as follows:

- The wet periods occurred more before the 1984 water year, but at later years, the dry periods occurred more and for longer in the Upper Gediz Basin.
- The long-term droughts have happened in all sub-basins of the Upper Gediz Basin between 1988 and 1997 and from the 2006–2009 water years in terms of meteorological and hydrological droughts.
- Extreme drought events have occurred more frequently than meteorological drought in the Acisu sub-basin, and hydrological drought in the Demirci sub-basin.
- The effects of the soil moisture gap on the droughts in the Upper Gediz Basin have a more effective role in the years following the 2000s and, consequently, meteorological and hydrological droughts occurred more intensively after this year.
- The trends of the meteorological and hydrological droughts lean towards a tendency for dry conditions, and no change in this trend is expected in the near future.
- There is a one month lag time between meteorological and hydrological droughts in the sub-basins of the Upper Gediz Basin at the 12 month timescale.

As a result, for the precipitation of the Upper Gediz Basin, moderate and higher droughts continue to be seen in the short and long terms with increasing frequency. The Upper Gediz Basin’s precipitation is the main water resource for the Acisu, Selendi, Deliinis and Demirci tributaries of the Gediz River located in the basin and feeding Demirköprü Reservoir. The droughts occurring in the basin’s precipitation significantly affect the runoff amounts and significantly reduce the water supply of Demirköprü Reservoir. Therefore, it is inevitable that the current agricultural droughts will occur more frequently and more violently in future, since sufficient irrigation water is not provided downstream of the reservoir. This result brings the necessity and urgency of drought action plans of the basin to the forefront.

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SUPPORTING INFORMATION
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