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Regional Drought Analysis with Standardized Precipitation Evapotranspiration Index (*SPEI*): Gediz Basin, Turkey

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ABSTRACT

In this study, regional drought analysis was performed with the Standard Precipitation Evapotranspiration Index (*SPEI*) and L-moment techniques by using the monthly average temperature and monthly total rainfall amounts collected from five sites in the Gediz basin in Turkey. Using the monthly average temperatures, the Potential Evapotranspiration (*PET*) amounts obtained by the Thornthwaite method and the monthly total rainfall amounts were divided into 5 different reference periods as 1, 3, 6, 9 and 12 months. Expressing the difference between rainfall and potential evapotranspiration amounts, the water balance (D_i) series showed that almost all of the 9 and 12-month periods suffered from water deficiency and the 3-month period was water excessive. After determining the distributions that provide the best adaptation to the water balance series, according to the *SPEI* values obtained, near-normal conditions prevailed in all sites, while moderate and severe arid and humid conditions sometimes occurred, while extremely humid and arid conditions were rarely seen. In the regional drought analysis using L-moment techniques with the *SPEI* values obtained, a region of five sites were accepted and the discordancy and heterogeneity measures showed that the basin was acceptable homogeneous. *SPEI* values are generally the best fit generalized extreme values (GEV) for 1 and 3-month periods, generalized normal (GNO) for 6-month period, generalized logistics (GLO) for 9-month period, Pearson type 3 (PE3) distributions for 12-month period. According to the regional *SPEI* values for reference periods, it has been found near-normal in 1.11, 1.25 and 2 years, moderately humid in 1.04 years, very humid conditions for 1.01 and 1.02 years, moderately dry in 4 and 5 years, severe arid in 10 years, and extremely dry conditions in 20 and longer periods.

Keywords: Potential evapotranspiration, Water balance, *SPEI*, Index-Flood, Regional homogeneity, Drought duration, Drought frequency

1. Introduction

As in the world, the rapid increase in the population in Turkey also causes an increase in the need for water. As a result of incorrectly applied water policies and unconscious water consumption, the amount and quality of water that can be used is decreasing day by day. The effects of global warming, which is the biggest climatic problem of today, are felt every day, and precipitation decreases as the temperature increases, or the irregularity in precipitation is seen in the form of storms, tornadoes and hail that damage agricultural lands. Due to the increase in temperature and the lack of sufficient precipitation, drought is observed in many basins of Turkey or the risk of drought is high. In recent years, there are predictions that the drought will increase gradually and that the 22nd century will be the dry century, and that agricultural production will decrease accordingly. Experts mention that if global warming continues like this, problems will arise in many fields other than agriculture (Redmond 2000). Drought is one of the most important problems for humanity arising from climate change. Although drought does not occur suddenly like other natural disasters (floods, storms, etc.), it is one of the highest cost disasters in the world, threatening more people and nature than other natural disasters, and reaching an annual average of 8-10 million dollars (Wilhite 2000). Drought has been increasing in Turkey in recent years, and it is predicted that there will be a significant lack of precipitation, especially in Southeastern and Central Anatolia regions, and recently Aegean region. Global warming combined with the current lack of precipitation; Agricultural production constitutes an important obstacle to meeting the water required for drinking-use. Located in the Western Anatolia part of Turkey, the Gediz Basin has a semi-arid climate and the decrease in water resources restricts agricultural activities. The dry period, which started in the late 1980s and continued until the mid-1990s, caused many problems in terms of irrigation water. There are approximately 110000 hectares of agricultural land in the basin. Droughts of varying severity and duration in the basin from time to time cause problems in reaching irrigation water and as a result, economic losses (Çetinkaya et al. 2008).

Many indices have been developed to describe drought. The indices, which are made by using some meteorological data, provide short and useful information about drought. Methods such as the Standard Precipitation Index (*SPI*), which are widely used to indicate drought and only consider precipitation, cannot fully explain drought. In recent years, method such as Standard Precipitation Evapotranspiration Index (*SPEI)* has been used, which consider not only precipitation but also precipitation and other important climatic parameters for agriculture. Many studies have been carried out on *SPEI* in recent years. Vicente-Serrano et al. (2010) suggested *SPEI*, which was based on precipitation and temperature data, unlike other drought indices. The biggest advantage of this index is that it can be combined with other data such as precipitation and evapotranspiration, primarily to include the effects of different temperature values in drought forecasts. Potop & Možn (2011) proposed to use the potential evapotranspiration in the study of drought severity in the Czech Republic using drought index, *SPEI*. In the study, they calculated the potential evaporation (ET_0), water balance, D_i (P-ET_0) series at different time scales, and fitted the water balance to the logarithmic logistic distribution to obtain the *SPEI* index series. *SPEI* and water balance series were calculated according to short (1, 3 and 6 months) and long (12 and 24 months) time scales to evaluate the variation of drought conditions over time. Begueria et al. (2014) mentioned that the use of the *SPEI* in climatology and hydrology studies has become widespread. They presented probability distribution parameters to obtain standardized values, ET_0 calculation methods, and methods for estimating probability parameters used in calculating *SPEI* at different time scales. Meixiu et al. (2014) made a drought calculation based on monthly precipitation and air temperature values at 609 points in China during the 1951–2010 period with *SPEI*. They stated that severe and extreme droughts have become more serious for the whole of China since the late 1990s. Stagge et al. (2014) considered whether *SPEI* differed significantly from *SPI* and used five *PET* methods commonly used at 3950 sites in Europe. They found that *SPEI* differed significantly from *SPI*. Li et al. (2015) used *SPEI* to characterize drought conditions in Southwest China between 1982 and 2012 and carried out the calculations using precipitation and temperature data for various periods. Their results showed that Southwest China is prone to drought, and they found that the average *SPEI* values across all five different time scales decreased significantly. Liu et al. (2015) stated in their study that China is one of the countries with the highest drought propensity, and to investigate this, they analyzed the regionalization and spatiotemporal variations of drought based on *SPEI* covering 810 sites in China between 1961 and 2013. Stagge et al. (2015) used the univariate probability distribution to normalize the index for comparison among climates, using *SPI*, a meteorological drought index recommended by the World Meteorological Organization, and *SPEI*, a newer climatic water balance variant. They said that the selection of the inappropriate probability distribution may cause errors in the index values by increasing or decreasing the drought severity. Yang et al. (2015) analyzed the monthly average precipitation and monthly average temperature of 47 meteorological stations in and around the Haihe Basin in the background of climate change, using *SPEI* to obtain the temporal and spatial distribution of different drought levels for the last 50 years with the support of geographic information systems. Anli (2017) explained that the analysis of the temporal variation of reference evapotranspiration (ET_0) is of great importance in arid and semi-arid regions where water resources are limited. *SPEI* method was used with the temporal variation of reference evapotranspiration (ET_0) and L-moment parameter estimation, with parametric and non-parametric tests, and conducted regional drought analyzes in the semi-arid Konya closed basin. Miah et al. (2017), to overcome the lack of long-term climate data in Bangladesh, they conducted an *SPEI* analysis for the years 1901-2011 and found that the frequency and intensity of drought was higher in the northwestern part of the country. This made the region vulnerable to both extreme and severe droughts. Based on the results obtained, *SPEI*-based drought intensity and frequency analyzes were conducted by considering the northwest region of the country to get an idea about drought assessment in Bangladesh. Bae et al. (2018) analyzed the intensity, variability and trends of drought using *SPEI_TH* and *SPEI_PM* in their study in South Korea and compared the results. *SPEI_PM* showed slightly more intense drought than *SPEI_TH* except Chuncheon and Gwangju. At five stations except Cheoncheon, Gwangju and Jinju, the probable cumulative probability increased significantly from 1981-1995 to 1996-2010 with *SPEI_PM* below 1.5 value.

In recent years, significant progress has been made in drought studies on both at-site and regional scales. The spatiotemporal ones of these studies are as follows; Bacanli et al. (2017) precipitation and drought trend analysis in the Aegean region in standard periods, Dikici (2020) drought analysis for different indices and different durations in the Asi basin, Eris et al. (2020) spatiotemporal analysis of meteorological drought in Küçük Menderes river basin in the Aegean region, Aksoy et al. (2021), a new technique with *SPI* method to develop critical drought severity-duration-frequency curves, Katipoğlu et al. (2021) meteorological studies and spatiotemporal analysis of hydrological droughts in the Euphrates river basin, Aksu et al. (2022) using long-term high-resolution Climate Hazard Group Stationary Infrared Precipitation (CHIRPS) data , spatiotemporal drought analysis in the Küçük Menderes river basin and Zeybekoğlu (2022) spatiotemporal analysis of meteorological drought in the Hirfanlı dam basin were performed.

Statistical methods become the most important tool in climatological frequency analyzes to be carried out. Frequency analysis can be defined as specifying the intervals at which a climatological event will occur. The climatological data to be used should cover a long period of time to qualify the event. In frequency analysis studies, it is of great importance to specify the parameter estimation method along with the selection of the probability distribution function. The most commonly used of these methods are moments, maximum likelihood, probability-weighted moments and L-moments (Anlı & Öztürk 2011). L-moments technique gives the characteristics of climatological data and the distribution parameters of these data in a simple and effective way (Greenwood et al. 1979). In some cases, there is not enough data to strongly describe the frequency of an extreme event that may occur at a station, and in some stations, there is no data at all. In addition, in cases where the observation time at a station is shorter than the expected return period, the quantile amounts are not reliable when at-site frequency analyzes are applied (Hosking 1990, Vogel et al. 1993). In this method, which is called regional frequency analysis, the principle is that it should be applied in cases where data from different measurement stations have similar frequencies. Thus, more accurate results are obtained by using regional characteristics at each measuring station, as well as within an appropriately defined region, even in basins with no data and no measuring stations on them (Hosking & Wallis 1993). Most of the studies conducted in Turkey examine the drought as at-site analysis, and there are few regional drought frequency studies. In this study, a period of approximately 27-58 years, collected from five climate stations in the Gediz basin; A regional drought analysis was carried out using the Standard Precipitation Evapotranspiration Index (*SPEI*) and L-moments technique for 5 different reference periods (1-month, 3-month, 6-month, 9-month and 12-month) with monthly total precipitation and monthly average temperature data. The aim of the study is to make an accurate regional estimation of drought in order to minimize the drought conditions that may occur in the basin in the medium and long term. As a novelty in the study, the regionalization of the values obtained by the *SPEI* method was carried out using the index-flood method. Thus, according to the appropriate homogeneity, drought estimation will be made regionally, not on at-site frequency.

2. Study area and the dataset

Located in the Western Anatolia part of Turkey, the Gediz Basin has a semi-arid climate and the scarcity of accessible water resources limits agricultural activities. The dry period, which started in the late 1980s and continued until the mid-1990s, caused significant problems in terms of irrigation water. There is approximately 110000 hectares of agricultural land in the basin (Çetinkaya et al. 2008). In the study, monthly total precipitation amounts and monthly average temperature data given in Table 1 with at least 25 years of observation and collected from non-intervened stations in the Gediz Basin were used as material. In Figure 1, the approximate locations of the meteorological stations in the basin and used for the study were given.

Table 1- Characteristics of stations located in the Gediz Basin

Station	*Code*	*Observation period*	*Number of observations*	*Elevation (m)*	*Latitude*	*Longitude*	*Mean annual rainfall (mm)*
Akhisar	17184	1960-2018	59	92	38.9118	27.8233	576.8
Demirci	17746	1992-2018	27	855	39.0349	28.6482	640.4
Gediz	17750	1972-2018	46	736	38.9947	29.4003	565.2
Manisa	17186	1960-2018	59	71	38.6153	27.4049	735.3
Salihli	17792	1960-2018	57	111	38.4831	28.2340	493.1

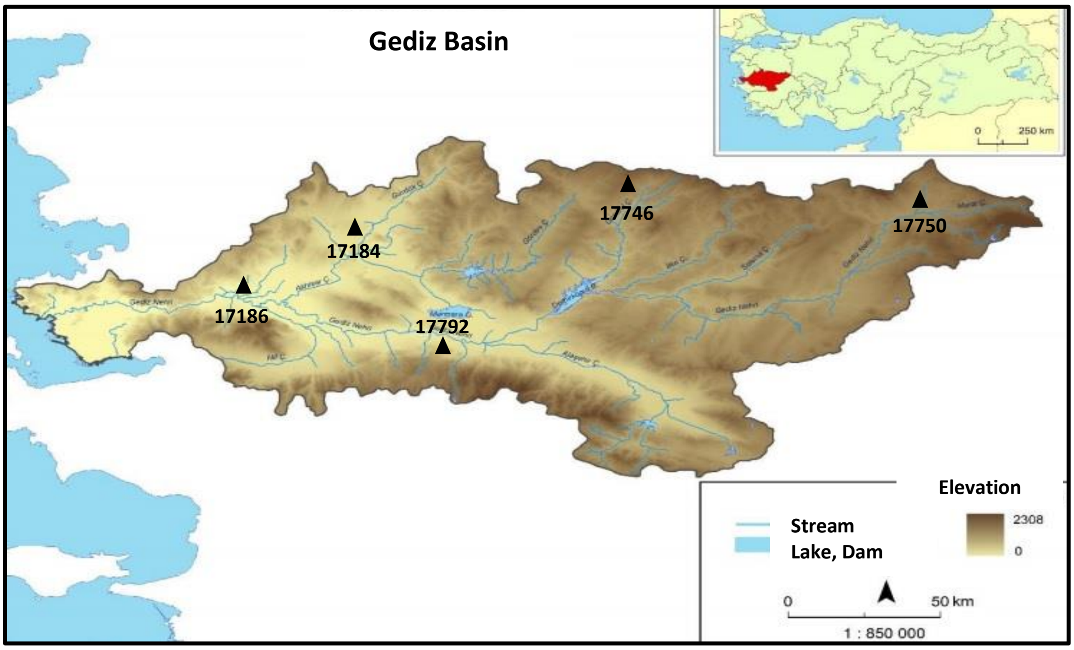


Figure 1- Location of the climate stations in Gediz Basin (SYGM 2016)

3. Methods

3.1. Calculation to SPEI

To calculate *SPEI*, 5 reference periods were determined by taking the 1, 3, 6, 9 and 12-month sums of the monthly total rainfall amounts (P_i). Potential Evapotranspiration (PET_i) amounts were determined by the Equation 1-3 as given in Thornthwaite (1948) and Thornthwaite & Mather (1955, 1957) by using the monthly average temperatures taken from the stations in the Gediz basin.

$$PET_i = 16 \times \left(\frac{10 \times t}{I}\right)^a \times G \quad (1)$$

$$a = 6.7510 \times 10^{-7} \times I^3 - 7.7110 \times 10^{-5} \times I^2 + 1.791210 \times 10^{-2} \times I + 0.49239 \quad (2)$$

$$I = \sum_1^{12} \left(\frac{t}{5}\right)^{1.514} \quad (3)$$

Where; *t*, Monthly average temperature (°C); *I*, Annual temperature index; *G*, Latitude correction coefficient. The latitude correction coefficient (*G*) was taken as 1.04 for Akhisar station, 0.85 for Demirci and Gediz stations, 1.24 for Manisa station and 1.23 for Salihli station (Thornthwaite 1948, Thornthwaite & Mather 1957). Various reference periods of the potential evapotranspiration (PET_i) amounts calculated with the Thornthwaite method using the relevant reference periods of the monthly total rainfall amounts (P_i) measured at the stations used in the study in the Gediz basin for calculating *SPEI*. The difference between the periods (Water Balance, D_i series) showing the excess or lack of water was calculated with Equation 4 (Vicente-Serrano et al. 2010).

$$D_i = P_i - PET_i \quad (4)$$

The most appropriate probability distribution for these series was estimated for D_i series. Normal (N), 3-parameter Normal (N3), 3-parameter Gamma (G3), Logistic (LO) and 3-parameter Logarithmic Logistic (LLO3) distributions were used. The most appropriate distribution was determined by Anderson-Darling (AD) test statistics. The probability of each D_i value was calculated by the cumulative distribution function $F(x)$ of the probability distribution, with the help of the parameters of the most suitable distribution among the distributions that fit the series. By using the standard values of the cumulative distribution functions $F(x)$ and using the Equation 5 and 6, *SPEI* series of 1, 3, 6, 9 and 12-month were obtained.

$$SPEI = W - \frac{(C_0 + C_1 W + C_2 W^2)}{(1 + d_1 W + d_2 W^2 + d_3 W^3)} \quad (5)$$

$$\text{For } P \leq 0.5, \quad W = (-2 lnP)^{0.5}, \quad P = 1 - F(x) \quad (6)$$

If $P>0.5$, the P value changes to 1-P and the sign of the calculated *SPEI* value is inverted.

Where; C_0, 2.515547; C_1, 0.802853; C_2, 0.010328; d_1, 1.432788; d_2, 0.189269; d_3, 0.001308; P, Probability level.

Drought categories for the calculated *SPEI* values were given in Table 2.

Table 2- *SPEI* drought categories (Li et al. 2015)

Moisture category	***Code***	***SPEI***
Extremely wet	EW	$SPEI > 2.00$
Very wet	VW	$1.50 < SPEI < 1.99$
Moderately wet	MW	$1.00 < SPEI < 1.49$
Near normal	NN	$-0.99 < SPEI < 0.99$
Moderately drought	MD	$-1.00 < SPEI < -1.49$
Severely drought	SD	$-1.50 < SPEI < -1.99$
Extremely drought	ED	$SPEI < -2.00$

3.2. Regional analysis

The index-flood method was applied for the regionalization of the *SPEI* series in the Gediz basin (Dalrymple 1960). The basis of index-flood method is that the stations form an approximately homogeneous region and the frequency distribution of the stations in this region is the same except for a certain scale factor belonging to that station (Equation 7).

$$Q_i(F) = \mu_i \, q(F) \qquad i = 1, \ldots, N \quad (7)$$

It is the indicator value representing the average of the frequency distribution at station μ_i. The *q* (*F*) value, which is the same for each station; shows the probability of being exceeded (Wallis & Wood 1985). The regionalization process is generally defined as the determination of climatological homogeneous regions, the selection of the regional frequency distribution and the estimation of the quantiles of indices. In this study, regional drought analysis was carried out with the *SPEI* series obtained by using L-moments. Hosking & Wallis (1993) stated probability-weighted moments in Equation 8, their linear combinations, L-moments, in Equation 9, and L-moment ratios in Equation 10.

$$b_r = n^{-1} \sum_{j=1}^{n} x_{(j)} \frac{(j-1)(j-2)...(j-1)}{(n-1)(n-2)...(n-i)} \tag{8}$$

After finding the probability-weighted moments (b_0, b_1, b_2 and b_3), which are the first four b_r values (r= 0, 1, 2, 3), the first four L-moment statistics, symbolized by ℓ for any distribution, are determined by the equations given below.

$$\begin{aligned} \ell_1 &= b_0 \\ \ell_2 &= 2b_1 - b_0 \\ \ell_3 &= 6b_2 - 6b_1 + b_0 \\ \ell_4 &= 20b_3 - 30b_2 + 12b_1 - b_0 \end{aligned} \tag{9}$$

Dimensionless L-moment ratios (L-coefficient of variation, L-skewness and L-kurtosis) are also estimated as given below.

$$\begin{aligned} t &= \ell_2 / \ell_1 \quad \text{(L-coefficient of variation)} \\ t_3 &= \ell_3 / \ell_2 \quad \text{(L-skewness)} \\ t_4 &= \ell_4 / \ell_2 \quad \text{(L-kurtosis)} \end{aligned} \tag{10}$$

In this study, in the regional analysis of the *SPEI* series; (1) Measures of Discordancy and Heterogeneity to determine climatological homogeneous regions, (2) Measure of Goodness of Fit to select regional frequency distribution, and (3) Regional L-moment algorithm for estimation of quantiles of indices. In this study, five stations located in the Gediz basin were firstly accepted as a single (one) region, and the analyzes were carried out according to this condition.

The discordancy measure (*D*) is the determination of the discordant stations within a region and it is explained by Hosking & Wallis (1997) as in Equation 11.

$$D = \frac{1}{3} N \left(u_i - \bar{u}\right)^T K^{-1} \left(u_i - \bar{u}\right) \tag{11}$$

u_i is the vector of moment ratios of the station *i*, *K* is the covariance matrix of this vector, and the mean of the vector. For a station to be considered discordant, the discordancy measure (*D*) must be greater than the critical table value, which varies depending on the number of stations in the region. Since five stations were considered in this study, the critical value was taken as 1.333 (Hosking & Wallis 1993). After specifying a suitable region according to the discordancy measure, the heterogeneity measure was applied to evaluate whether the region was homogeneous. Heterogeneity measure; It was calculated for three different L-statistics: L-coefficient of variation and H_1, L-coefficient of variation and combination of L-skewness ratios, H_2, and combination of L-kurtosis and L-skewness ratios, and H_3. From here, the *H* statistic for all three cases is written as in Equation 12.

$$H = \frac{\left(V_{obs} - \mu_v\right)}{\sigma_v} \tag{12}$$

V_{obs}; is the weighted standard deviation obtained from the regional data according to the L-moment ratios, μ_v and σ_v; It shows the mean and standard deviation of the number of simulations of the V_{obs} statistics. In this study, the four-parameter Kappa probability distribution, which is a strong distribution, was used while performing the simulation, since it represents many distributions in the frequency analysis of climatological events. In order to estimate μ_v and σ_v values reliably, the number of simulations was considered as 500 for a region. According to this test, the region; if $H < 1$, it is considered to be acceptably homogeneous, if $1 \leq H < 2$, it is probably heterogeneous, and if $H \geq 2$, it is decidedly heterogeneous (Hosking 1994).

The Z^{DIST} statistic, which is determined depending on the L-kurtosis and frequency distribution from the detection of the homogeneous region, was given as in Equation 13.

$$Z^{DIST} = \left(\tau_4^{DIST} - t_4^R + B_4\right) / \sigma_4 \tag{13}$$

t_4^R, regional mean L-kurtosis ratio of sample, B_4, σ_4 regional mean L-kurtosis ratio bias value and standard deviation of sample, respectively, and were expressed in Equation 14 and 15.

$$B_4 = N_{sim}^{-1} \sum_{m=1}^{N_{sim}} \left(t_4^{(m)} - t_4^R\right) \tag{14}$$

$$\sigma_4 = \left[\left(N_{sim} - 1\right)^{-1} \left\{ \sum_{m=1}^{Nsim} \left(t_4^{(m)} - t_4^R\right)^2 - N_{sim} B_4^2 \right\} \right]^{1/2} \tag{15}$$

N_{sim} represents the number of simulations performed with the help of Kappa distribution, and *m* represents the number of simulated regions. In this study, Generalized Logistic (GLO), Generalized Extreme Values (GEV), Generalized Pareto (GPA), Generalized Normal (GNO) and Pearson type 3 (PE3) distributions with three parameters were applied. If absolute $Z^{DIST} \leq 1.64$ in any frequency distribution, this distribution is considered suitable for the regional distribution, but the distribution that provides the absolute Z^{DIST} value closest to zero among the considered distributions is chosen as the most appropriate (best-fit) distribution.

The quantiles of the *SPEI* values were estimated with the regional L-moment algorithm. In a region with *N* stations, an *i* station has n_i data, the sample mean ℓ_1^i, sample L-moment ratios $t^{(i)}, t_3^{(i)}, t_4^{(i)}$ are calculated, and the L-moment regional average ratios t^R, t_3^R, t_4^R are determined as weighted according to the sample size of the stations, and their mathematical explanation has been written in Equation 16-18.

$$t^R = \sum_{i=1}^{N} n_i t^{(i)} / \sum_{i=1}^{N} n_i \tag{16}$$

Regional average ℓ_1^i is 1;

$$t_r^R = \sum_{i=1}^{N} n_i t_r^{(i)} / \sum_{i=1}^{N} n_i \qquad r = 3, 4, \ldots \tag{17}$$

and the regional population (λ_i and τ_i) and sample L-moment ratios (ℓ_i^R, t_i^R) are equalized.

$$\begin{aligned} \lambda_1 &= \ell_1^R \\ \tau &= t^R \\ \tau_3 &= t_3^R \end{aligned} \tag{18}$$

Equation 19, in which regional dimensionless development curves are determined, is written as follows:

$$\hat{Q}_i(F) = \ell_1^i q(F; \ell_1^R, t^R, t_3^R, t_4^R) \tag{19}$$

While performing regional analyzes, routines written by Hosking (2005) with FORTRAN 77 source codes were used. These routines were compiled and run under a main executable program. A basic flow chart of the methodology of the study was given in Figure 2.

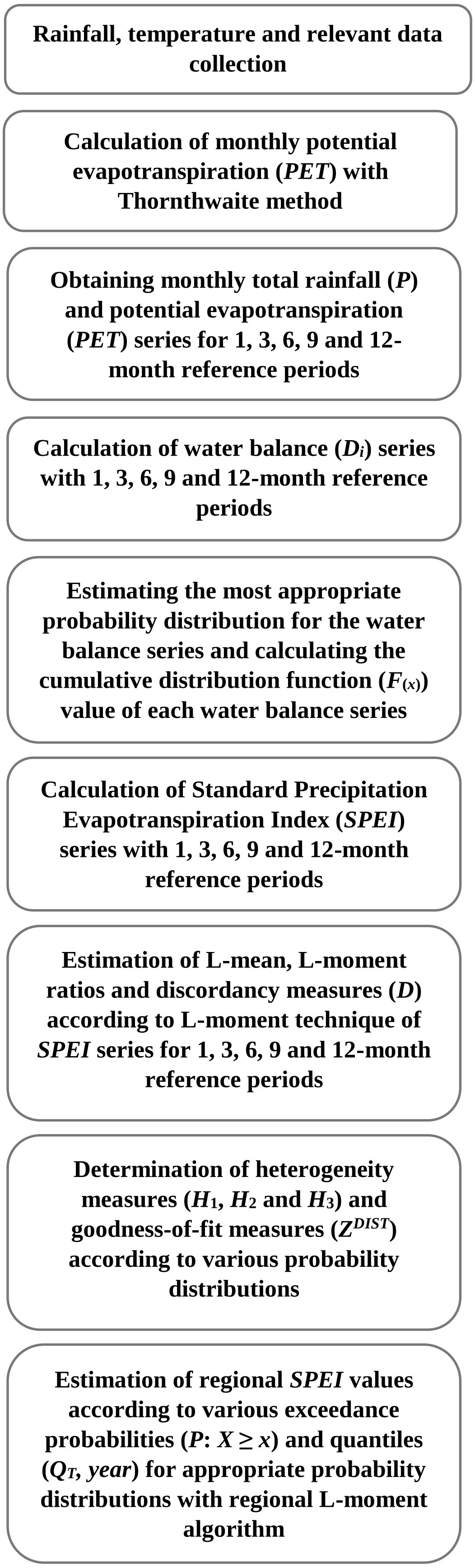


Figure 2- A basic flow chart of the methodology

4. Results and Discussion

As a preliminary information, some descriptive statistics and distribution characteristics of the annual total precipitation and annual average temperature data used in the study, calculated according to L-moment approach, were given in Table 3.

Table 3- Some descriptive statistics and distribution characteristics of annual total rainfall and annual mean temperature data

Site name	*L-mean*	*Standard error of L-mean*	*L-standard deviation*	*L-coefficient of variation*	*L-skewness*	*L-kurtosis*	*Best-fit frequency distribution*
Annual total rainfall (mm)							
Akhisar	576.8	17.4	131.5	22.80	0.42	-0.21	Generalized Pareto
Demirci	640.4	23.2	120.7	18.85	-0.33	-0.88	Log-logistic 3
Gediz	565.2	16.4	111.2	19.67	0.22	-0.36	Log-normal
Manisa	735.3	22.1	169.6	23.06	0.40	-0.06	Generalized gamma
Salihli	493.0	12.2	92.0	18.65	0.29	-0.05	Gamma
Annual mean temperature (ºC)							
Akhisar	16.19	0.09	0.728	4.50	0.31	-0.46	Generalized Pareto
Demirci	13.69	0.17	0.861	6.29	-0.26	-0.16	Generalized extreme values
Gediz	12.72	0.12	0.832	6.54	0.37	0.01	Log-logistic 3
Manisa	16.83	0.08	0.612	3.64	0.30	-0.15	Weibull 3
Salihli	16.26	0.15	1.149	7.07	-1.12	3.11	Log-logistic 3

The water balance series (D_i) obtained by using the monthly total rainfall amounts and the potential evapotranspiration amounts estimated according to the Thornthwaite method were given in Figure 3 for various reference periods.

Water shortages were observed in 1990 and 1992 in the 1-month period, in 1961, 1964, 1966, 1967, 1969, 1972, 1975-1977, 1983, 1985, 1988-1994, 1996, 1997, 2000-2002, 2006-2008, 2011, 2017 and 2018 in the 6-month period. Water deficiency was observed in all years in the 9-month period, and in all years except 1965 and 1981 in the 12-month period at Akhisar station (Figure 3a).

Water shortage has been observed in 1992 and 2001 in the 1-month period, in 2001, 2002, 2007 and 2008 in the 6-month period, in all years except 2016 in the 9-month period, in all years except 1997, 1998, 2005 and 2009 in the 12-month period at Demirci station (Figure 3b). As seen in Figure 3c, water shortage occurred in 2015 in the 1-month period, in 1976, 1977, 1989, 1990, 1992, 2001, 2002, 2007, 2008 and 2014 in the 6-month period. There was water deficiency in all years in the 9-month period, and water deficiency was observed in all years except 1978, 1981, 1983, 2005 and 2009 in the 12-month period at the Gediz station. As seen in Figure 3d, there was a shortage of water in 1989 and 1992 in the 1-month period, and in 1964, 1972, 1977, 1985, 1989-1992, 1994, 1996, 2001, 2002, 2007 and 2008 in the 6-month period. Water deficiency was observed in all years except 1965 and 1978 in the 9-month period, and in all years in the 12-month period at Manisa station. When Figure 3e is examined, water shortage was observed in the year 1992 and 2001 in the 1-month period, and, except for the years 1960, 1962, 1965, 1966, 1968, 1978, 1984, 1993, 2003, 2010, 2012, 2015 in the 6-month period. Water shortage occurred in all years in 9- and 12-months' periods at Salihli station. There was no shortage of water in all stations, and excess water was observed throughout the observation period in the 3-month period. In order to determine the *SPEI* series for various reference periods, the frequency distributions that best fit the water balance (D_i) series were determined.

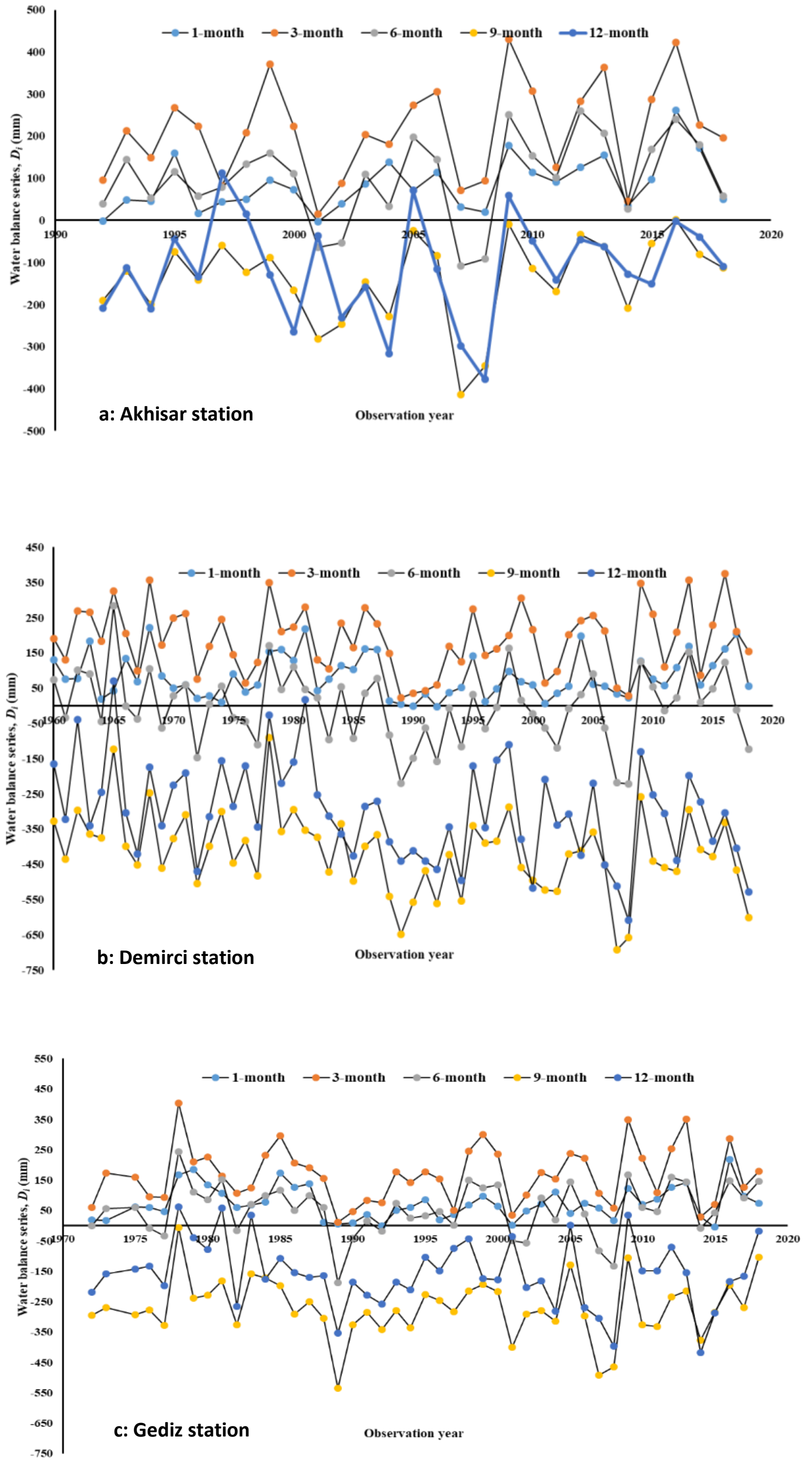
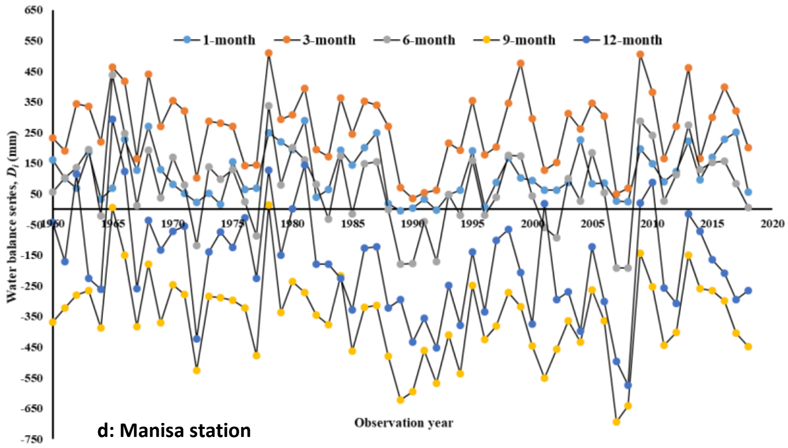


Figure 3- The water balance series (D_i) for stations according to various reference periods



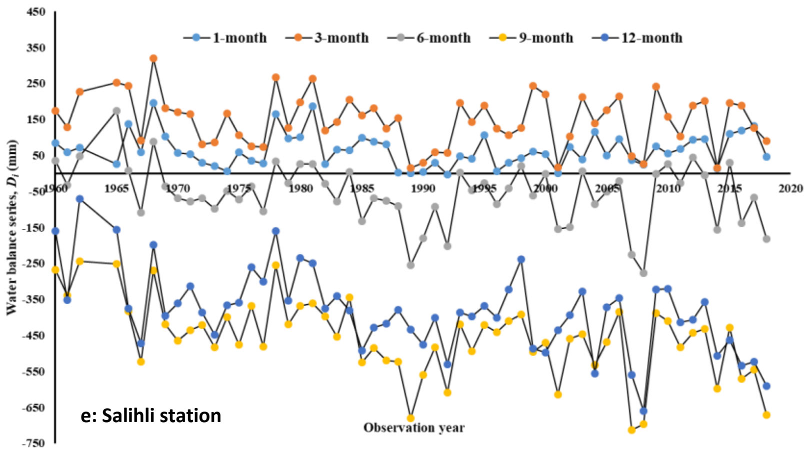


Figure 3 (continued)- The water balance series (D_i) for stations according to various reference periods

Normal (N), 3-parameter Normal (N3), 3-parameter Gamma (G3), Logistic (LO) and 3-parameter Logarithmic (LLO3) distributions were applied and the most appropriate distribution was calculated with Anderson-Darling (AD) test statistic and the results were given in Table 4.

The cumulative distribution functions $F(x)$ of each water balance D_i series were calculated by using the parameters of the frequency distributions selected for the stations according to the reference periods. *SPEI* values were determined for each station and reference periods by using the values corresponding to $F(x)$. The calculated *SPEI* series were given in Figure 4 for Akhisar, Demirci, Gediz, Manisa and Salihli stations, respectively. Moderate drought conditions were observed in 1964, 1972, 1988, 1996, 2008, severe drought in 1974, 1989, 2001, and extreme drought conditions in 1990, 1992 for the 1-month period. Moderate drought was observed in 1972, 1976, 1992, 2001, and severe drought in 1989-1991, 2007-2008 for the 3-month period. When the 6-month period is examined, moderate drought occurred in 1972, 1977, 1990, 1994, 2002, 2018, severe drought in 1992, and extreme drought in 1989, 2007-2008. In the 9-month period, moderate drought occurred in 1988, 1990, 1992, 1994, 2001-2002, severe drought in 2018, and extreme drought in 1989, 2007-2008. In the 12-month period, moderate drought was observed in 1972, 1989, 1991, 1992, 1994, 2016, 2012, severe drought in 2000, 2007, 2018, and extreme drought in 1985 and 1991 (Figure 4a). Moderate drought in 1996, 1998, severe drought in 1992 and extreme drought in 2001 were observed for the 1-month period. Moderate drought occurred in 1992, 1997, 2002, 2007, 2008, 2014, and severe drought in 2001 for the 3-month period. Severe drought was observed in 2001, 2002 and 2008, and extreme drought in 2007 for the 6-month period. Moderate arid conditions were observed in 2002 and 2004, severe arid conditions in 2001 and extremely dry conditions in 2007-2008 for the 9-month period.

Table 4- Frequency distributions applied to water balance (D_i) series for various reference periods and evaluation criteria

Candidate distribution	*Station*	*Evaluation criteria*	*Reference period (month)* 1	3	6	9	12
Normal (N)	**Akhisar**	**AD**	1.321	**0.243**	0.181	0.351	0.237
		P	<0.005	0.758	0.91	0.459	0.778
	Demirci	**AD**	0.479	**0.260**	0.338	0.485	**0.217**
		P	0.217	0.683	0.477	0.209	0.824
	Gediz	**AD**	0.644	0.3	0.296	0.687	0.517
		P	0.087	0.567	0.58	0.068	0.18
	Manisa	**AD**	1.256	**0.263**	0.357	0.408	0.158
		P	<0.005	0.69	0.443	0.336	0.949
	Salihli	**AD**	0.639	**0.199**	0.543	0.576	0.566
		P	0.091	0.881	0.156	0.128	0.136
3-parameter Normal (N3)	**Akhisar**	**AD**	0.370	0.267	0.195	0.346	**0.147**
		P	*	*	*	*	*
	Demirci	**AD**	**0.204**	0.287	0.357	0.499	0.231
		P	*	*	*	*	*
	Gediz	**AD**	0.296	0.201	0.298	0.678	0.509
		P	*	*	*	*	*
	Manisa	**AD**	0.64	0.278	0.38	0.414	**0.108**
		P	*	*	*	*	*
	Salihli	**AD**	**0.237**	0.215	0.565	0.59	0.487
		P	*	*	*	*	*
3-parameter Gamma (G3)	**Akhisar**	**AD**	**0.338**	0.449	0.658	4.078	0.598
		P	*	*	*	*	*
	Demirci	**AD**	0.221	0.299	2.134	14.098	2.918
		P	*	*	*	*	*
	Gediz	**AD**	**0.268**	**0.179**	18.775	13.522	3.623
		P	*	*	*	*	*
	Manisa	**AD**	**0.555**	0.435	0.561	3.609	1.387
		P	*	*	*	*	*
	Salihli	**AD**	0.269	0.447	9.403	4.107	3.998
		P	*	*	*	*	*
Logistic (LO)	**Akhisar**	**AD**	1.208	0.311	**0.155**	**0.151**	0.247
		P	<0.005	>0.25	>0.25	>0.25	>0.25
	Demirci	**AD**	0.429	0.295	**0.288**	**0.339**	0.218
		P	0.243	>0.25	>0.25	>0.25	>0.25
	Gediz	**AD**	0.529	0.299	**0.246**	**0.369**	0.444
		P	0.135	>0.25	>0.25	>0.25	0.228
	Manisa	**AD**	1.279	0.334	**0.307**	**0.285**	0.176
		P	<0.005	>0.25	>0.25	>0.25	>0.25
	Salihli	**AD**	0.461	0.274	**0.368**	**0.345**	0.369
		P	0.21	>0.25	>0.25	>0.25	>0.25
3-parameter Log-Logistic (LLO3)	**Akhisar**	**AD**	0.417	0.316	0.169	0.159	0.202
		P	*	*	*	*	*
	Demirci	**AD**	0.244	0.308	0.3	0.352	0.224
		P	*	*	*	*	*
	Gediz	**AD**	0.335	0.267	0.254	0.373	**0.432**
		P	*	*	*	*	*
	Manisa	**AD**	0.682	0.336	0.326	0.3	0.146
		P	*	*	*	*	*
	Salihli	**AD**	0.277	0.278	0.39	0.361	**0.342**
		P	*	*	*	*	*

AD: Anderson-Darling test statistic; **P:** probability value; *****: indicates non-computable probability level; Bold numbers show the best-fit frequency distributions for D_i series according to Anderson-Darling test statistic.

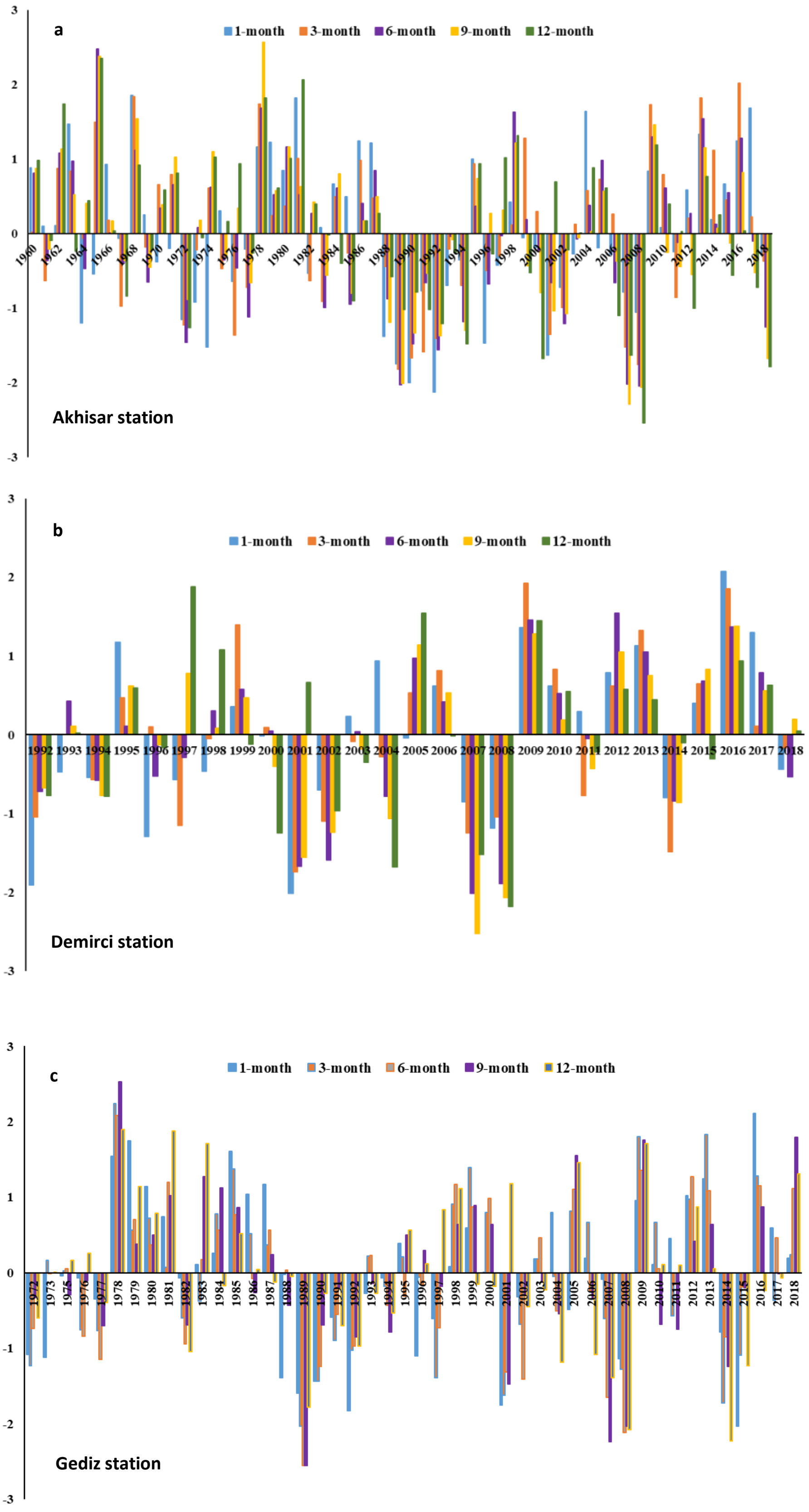
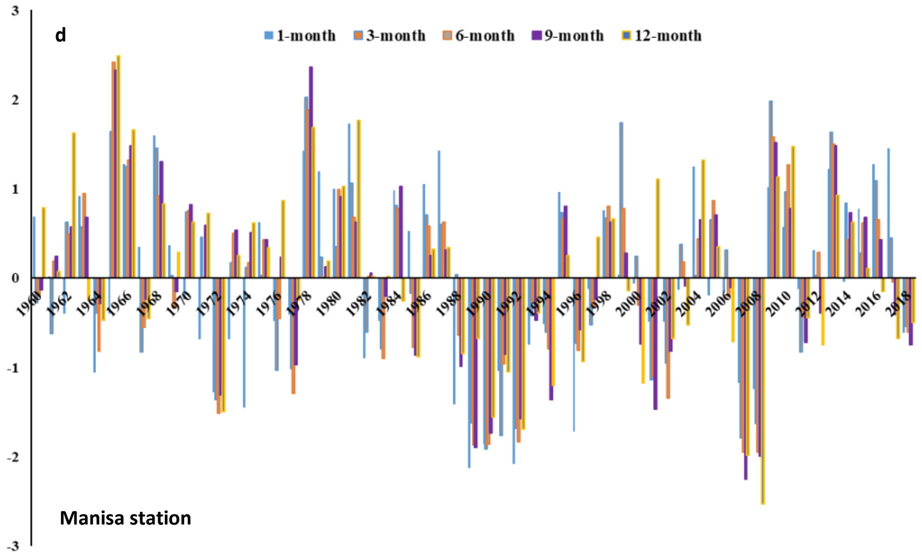


Figure 4- *SPEI* series according to various reference periods



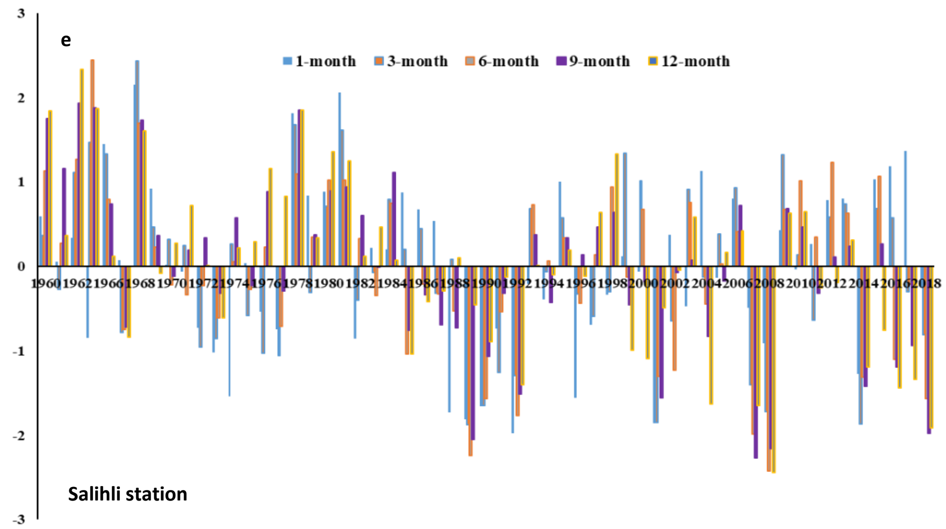


Figure 4 (continued)- *SPEI* series according to various reference periods

There was moderate drought in 2000, severe drought in 2004, 2007, and extreme drought in 2008 for the 12-month period (Figure 4b). Moderate drought was observed in 1972, 1973, 1988, 1990, 1996, 2008 severe drought in 1989, 1992, 2001, and extreme drought in 2015 for the 1-month period. Moderate drought was observed in 1972, 1990, 1992, 1997, 2008, 2015 severe drought in 2001, 2014, and extreme drought in 1989 for the 3-month period. Moderate drought occurred in 1977, 1990, 2001, 2002, severe drought in 2007, and extreme drought in 1989 and 2008 for 6-month period. Moderate drought conditions occurred in 2001, 2014, and extreme drought conditions occurred in 1989, 2007, 2008 for the 9-month period. Moderate drought was experienced in 1982, 2004, 2006, 2007, 2015, severe drought in 1989, and extreme drought in 2008, 2014 for the 12-month period (Figure 4c). Moderate drought occurred in 1964, 1972, 1974, 1988, 1991, 2007, 2008, severe drought in 1990, 1996, and extreme drought in 1989 and 1992 for the 1-month period. Moderate drought was observed in 1972, 1976-1977, 2001, and severe drought in 1989-1992, 2007, 2008 for the 3-month period. Moderate drought conditions were observed in 1977, 2001, 2002, and severe drought conditions in 1972, 1989, 1990, 1992, 2007, 2008 for the 6-month period. Moderate drought was experienced in 1972, 1994, 2001, severe drought in 1989, 1990, 1992, 2008, and extreme drought in 2007 for 9-month period. Moderate drought occurred in 1972, 1991, 1994, 2000, severe drought in 1990, 1992, 2007, and extreme drought in 2008 for the 12-month period (Figure 4d). Moderate drought was observed in 1973, 2014, and severe drought in 1974, 1988-1990, 1992, 1996, 2001 for the 1-month period. In 1976, 1977, 1991, 1992, moderate drought conditions occurred in 2007, severe drought conditions occurred in 1989-1990, 2001, 2008, 2014 for the 3-month period. Moderate drought was observed in 1985, 2001, 2002, 2014-2016, severe drought in 1990, 1992, 2007, 2018, and severe drought in 1989, 2008 for the 6-month period. Moderate drought was observed in 1990, 2014, 2016, severe drought in 1992, 2001, 2018, and extreme drought in 1989, 2007, 2008 for the 9-month period. Moderate drought occurred in 1985, 1992, 2000, 2014, 2016-2017, severe drought in 2004, 2007, 2018, and extreme drought in 2008 for the 12-month period (Figure 4e).

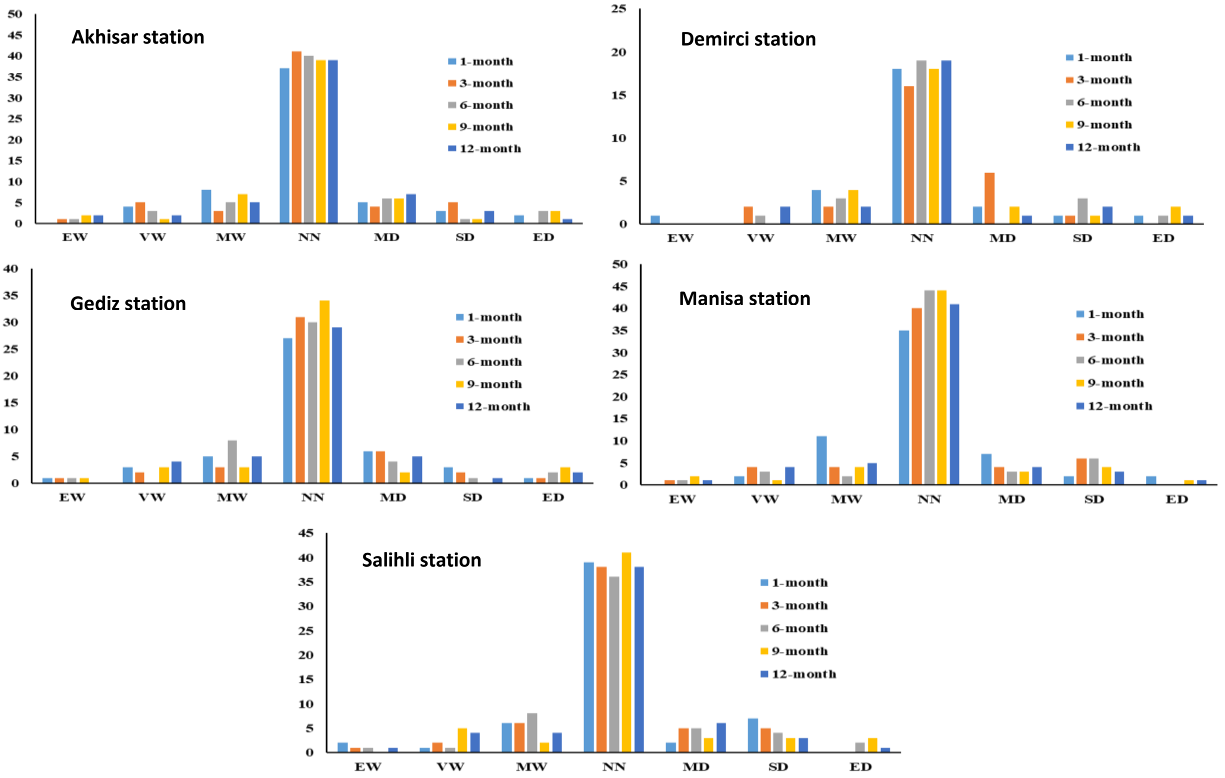


Figure 5- The frequency histograms of dry and wet years according to the *SPEI* series

The frequency histograms of dry and wet years according to the *SPEI* series were also given in Figure 5. It is seen that there are mostly near-normal (NN) conditions in all stations according to the *SPEI* series in Figure 5. For the regional drought analysis of the *SPEI* series, first of all, the five stations used in the study were accepted as a region and the discordancy, heterogeneity and goodness-of-fit measure tests were carried out according to this condition. The mean, L-moment ratios and discordancy measures (*D*) for the stations according to various reference periods were given in Table 5.

Table 5- Mean, L-moment ratios and discordancy measures (*D*) for various reference periods by stations for *SPEI* values

Reference period	*Station*	*L-mean*	*L-coefficient of variation*	*L-skewness*	*L-kurtosis*	*D**
1-month	**Akhisar**	-0.51	0.1288	-0.0006	0.0505	1.09
	Demirci	-0.48	0.1375	0.0279	0.1647	1.33
	Gediz	-0.50	0.1409	-0.0189	0.0640	0.95
	Manisa	-0.54	0.1379	-0.0146	0.0516	0.30
	Salihli	-0.46	0.1202	0.0274	0.1208	1.32
3-month	**Akhisar**	-0.46	0.1168	-0.0098	0.0980	0.56
	Demirci	-0.59	0.1338	-0.0245	-0.0150	1.32
	Gediz	-0.54	0.1291	-0.0424	0.1175	1.27
	Manisa	-0.41	0.1169	-0.0629	0.1094	1.02
	Salihli	-0.49	0.1230	0.0177	0.0766	0.84
6-month	**Akhisar**	-0.54	0.1335	-0.0614	0.1437	0.44
	Demirci	-0.48	0.1230	-0.1221	0.1482	1.13
	Gediz	-0.48	0.1355	-0.0202	0.1289	0.80
	Manisa	-0.49	0.1095	-0.0469	0.1144	1.33
	Salihli	-0.51	0.1362	-0.0512	0.1039	1.31
9-month	**Akhisar**	-0.51	0.1387	-0.0288	0.1516	1.32
	Demirci	-0.56	0.1385	-0.1678	0.1468	1.12
	Gediz	-0.59	0.1275	0.0445	0.2152	1.24
	Manisa	-0.47	0.1170	-0.0078	0.1670	0.68
	Salihli	-0.58	0.1244	-0.1126	0.1406	0.64
12-month	**Akhisar**	-0.47	0.1279	-0.0027	0.1317	1.29
	Demirci	-0.56	0.1256	-0.0478	0.1383	1.21
	Gediz	-0.54	0.1358	-0.0442	0.0858	1.13
	Manisa	-0.42	0.1199	-0.0257	0.1235	1.12
	Salihli	-0.47	0.1260	-0.0457	0.1106	0.24

* *D*, critical value for the discordancy measure: 1.333 (Hosking & Wallis 1997)

The means of *SPEI* values show that the drought status of the basin is Near Normal (NN) from the minus side according to the stations and reference periods. When the L-skewness values are examined, it is seen that there is a left skewness in *SPEI* values in general, but this skewness is not much. When the L-kurtosis values are examined, it is seen that the *SPEI* values are generally flat. When the discordancy measures are examined, although there are stations that are very close to the critical value (1.333) for different reference periods, no discordant stations were found (Table 5). Since no discordant stations were found for the reference periods according to the discordancy measure, the homogeneous region was simulated 500 times using the Kappa distribution, and the regional Kappa probability distribution parameters were determined. By using the calculated Kappa distribution parameters, heterogeneity measures were determined according to the number of 500 simulations for each reference period and are given in the Table 6.

Table 6- Heterogeneity measures for various reference periods

Reference period	*H1*	*H2*	*H3*
1-month	-0.2911	-0.2896	-0.9545
3-month	-0.1912	-0.1881	-0.8758
6-month	-0.2156	-0.2369	-2.1049
9-month	-0.1132	-0.1097	-0.4652
12-month	-0.0882	-0.0869	-2.3861

According to all heterogeneity measures, all reference periods were found to be acceptably homogeneous (Table 6). The fact that the heterogeneity measures in Table 6 have negative values is considered to indicate that the separation between the L-coefficients of variation between stations is less than expected from a homogeneous region and that there is a positive correlation between the data at different stations.

Goodness-of-fit measures were determined after the suggested regions were found to be homogeneous at an acceptable level according to the reference periods. The goodness-of-fit measures (Z^{DIST}) of the frequency distributions applied in the study were given in Table 7.

Table 7- Goodness-of-fit measures (Z^{DIST}) of frequency distributions used in the study for reference periods

Frequency distribution	*Code*	*Reference period*				
		1-month	*3-month*	*6-month*	*9-month*	*12-month*
Generalized logistic	**GLO**	4.84	4.50	2.17	**0.13***	2.61
Generalized extreme values	**GEV**	**1.50***	**1.05***	**-1.08***	-2.73	**-0.63***
Generalized normal	**GNO**	2.37	2.07	**-0.01*#**	-1.82	**0.35***
Pearson type 3	**PE3**	2.35	2.03	**-0.10***	-1.88	**0.31*#**
Generalized Pareto	**GPA**	-4.50	-4.99	-6.60	-7.63	-6.27

*: Suitable distributions; #: The best-fit distribution

Generalized extreme value in 1 and 3-month periods, generalized extreme value in 6 and 12-month periods, generalized normal and Pearson type 3, generalized logistic distributions in 9-month period were determined as appropriate distributions. The general Pareto distribution was not suitable for any reference period. According to the appropriate regional distributions, regional weighted parameters were estimated at 90% acceptance level. The probable regional *SPEI* values obtained for various exceedance probabilities (P: $X \geq x$) and durations (Q_T, year) according to these distributions with the regional L-moment algorithm technique were given in Table 8.

Table 8- Regional *SPEI* values obtained at various return probabilities and periods according to the most appropriate distributions

Exceedance probability (P: X ≥ x)	*Return period (year)*	*Frequency distribution / Reference period*				
		GEV		*GNO*	*GLO*	*PE3*
		1-month	*3-month*	*6-month*	*9-month*	*12-month*
0.99	**1.01**	1.84	1.57	1.62	1.87	1.74
0.98	**1.02**	1.62	1.39	1.41	1.54	1.50
0.96	**1.04**	1.34	1.17	1.16	1.20	1.23
0.90	**1.11**	0.88	0.78	0.76	0.70	0.80
0.80	**1.25**	0.41	0.38	0.37	0.27	0.38
0.50	**2**	-0.51	-0.46	-0.45	-0.49	-0.45
0.25	**4**	-1.23	-1.15	-1.16	-1.14	-1.15
0.20	**5**	-1.40	-1.32	-1.34	-1.31	-1.33
0.10	**10**	-1.86	-1.76	-1.84	-1.81	-1.80
0.05	**20**	-2.22	-2.12	-2.27	-2.29	-2.21
0.01	**100**	-2.87	-2.78	-3.13	-3.40	-2.99

Table 8 shows that the *SPEI* values obtained according to the most appropriate frequency distributions for all reference periods can be very wet conditions in 1.01 years, moderately wet in 1.02 and 1.04 years, and near-normal in 1.11, 1.25 and 2 years. In addition, it is possible to experience moderately dry conditions in 4 and 5 years, severe dry in 10 years, and extremely dry in 20 and longer years in the basin.

5. Conclusions

In this study, a regional drought analysis was carried out with *SPEI* by using monthly average temperature and monthly total rainfall amounts obtained from Akhisar, Demirci, Gediz, Manisa and Salihli meteorological stations with long observation periods in the Gediz basin. The results from these analyzes are summarized as follows:

- The water balance series showed that there was little water deficiency in only a few years in the 1-month period. Water deficiency and excess water conditions in some years in the 6-month period. While there was a shortage of water in almost all of the 9 and 12-month periods, there was no shortage of water at any of the stations in the 3-month period, and excess water condition was detected.

- Anderson-Darling test statistics were applied to determine the distribution that best fits the water balance series. According to the AD test statistics results, the logistic distribution provided the best fit with the water balance series obtained for the 6 and 9-month reference periods at all stations. The dominant distribution adapting to the 3-month period was the normal distribution, 3-parameter gamma and 3-parameter normal distributions for the 1-month period, 3-parameter logarithmic logistic and 3-parameter normal distributions for the 12-month period provided the best fit.

- The cumulative probability distribution function of each water balance variant was determined and *SPEI* values were obtained by using these functions and related equations. According to the *SPEI*, near-normal conditions were the most dominant at all stations, while moderate and severe drought conditions and moderate and very wet conditions were occasionally observed, while extremely wet and dry conditions were rarely observed.

- Regional frequency analysis was carried out by using the *SPEI* values obtained from the points according to the stations and using the L-moment parameter estimation method. The five stations used in the study were accepted as a region and the Gediz basin was determined to be acceptable homogeneous at an acceptable level for these stations, according to the Discordancy and Heterogeneity measure tests applied with L-moment ratios.

- In order to determine the distributions that best-fit the *SPEI* values, 5 regional frequency distributions were applied and according to the results of the Goodness-of-fit Measure test; Generalized Extreme Values for 1 and 3-month period, Generalized Normal for 6-month period, Generalized Logistics for 9-month period and Pearson type 3 for 12-month period provided the best-fit.

- Regional *SPEI* values were obtained according to the parameters of the regional frequency distributions that provide the best-fit for the reference periods, and according to the L-moment algorithm technique, various probability of exceedance and recurrence interval.

- According to the regional *SPEI* values, it can be said that for the reference periods 1.11, 1.25 and 2 years Near Normal, 1.04 years Moderate Wet, 1.01 and 1.02 years Very Wet conditions can occur. It is thought that Moderate Dry conditions may occur within 4 and 5 years, Severe Dry conditions within 10 years, and Extreme Dry conditions for more than 20 years.

The results show that dry conditions will occur from short to long duration Similar results were found in Dikici (2020), Eris et al. (2020) Aksoy et al. (2021) Aksu et al. (2022) and Zeybekoğlu (2022). Establishment of a drought crisis center should be considered as a priority in order to minimize the dry conditions that may occur in the basin in the medium- and long-term period. In addition, the irrigation methods applied in the basin should be switched to mostly advanced pressurized methods, irrigation efficiency rate should be increased and irrigation training courses should be given to farmers. Pipeline conveyance systems should be used and land consolidation techniques should be done in order to minimize the losses in the conveyance of water from the water source to the agricultural land. A plant pattern should be created according to the climatic and water resources conditions of the region. The water obtained by macro basin water harvesting techniques should be used for irrigation purposes for dry periods. Water pricing should be planned according to water volume, not irrigation area. By not allowing construction and buildings around water resources, easier collection and protection of water should be ensured, and all the suggestions should be sustainable.

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