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Research Article

Comparison of Drought Indices in the Case of the Ceyhan Basin

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Abstract

The issue of mitigating the expected effects of drought has become quite prominent within the scope of planning, development, and management of water resources affected negatively by climate change. An integrated management approach must be planned primarily for sustainable water management. To conduct drought risk analyses, a sufficient amount of data must be available. The historical process of the basin must be known, and there must be a plan that is assessed with several indices. In this study, we carried out drought risk analyses on the Ceyhan Basin using meteorological, hydrogeological, and hydrological data to determine indices and indicators available in the literature. We compared indices, examined the correlations among them, and reached an outcome. All of the study's indices showed that the drought was in the same periodicity in the basin, and a slow progressing drought occurred in the basin. When the trend of the last 50 years of precipitation in the basin is analyzed, it is evident that there is a general decrease. It has been calculated that there is an extreme drought threat for the basin in the 20-year return interval. In a general view, decision-makers shall provide drought management plans for the basin.

Keywords: Basin, water resources, threshold value, drought index, drought analysis

Introduction

In the aftermath of the effects of global warming, potential drought periods shall make sharing and management of several national and local water resources even harder, including rivers that exceed the borders of cities and countries (Dikici, 2013). Management of the increasing risk of drought and adaptation to this risk may only be achieved by developing sustainable and effective drought risk management strategies that adopt integrated approaches. Drought management is part of disaster management (Wilhite, 2000; Menteş et al., 2019).

Drought Risk Management is the concept and study of preventing the negative results of the hazard of drought and potential effects of disasters by activities and measures directed towards protection, damage reduction, and preparedness (UNDP, 2016). Drought Risk Management constitutes a critical part of water resources management policies and strategies. National drought policies play a critical role in managing drought risk (Wilhite et al., 2014). To decrease the detrimental effects of drought, Drought Management Plans must be prepared based on the legislation of the respective country and drought characteristics and effects specific to the basin (Europian Commission: EC, 2007).

Drought risk management covers the stages of hazard, exposure, impact assessment, and affectability, drought monitoring and early warning system, including forecasts, preparedness, and damage mitigation (Wilhite, 2000; Global Water Partnership: GWP, 2015; Ülker et al., 2018). Early drought warning systems aim to monitor, assess, and present information on the climate, hydrological characteristics, conditions, and water supply (World Meteorology Organization (WMO), 2016). It is critical to monitor and analyze drought since it is a hydrological event that slowly progresses. Drought is monitored and analyzed by various indicators and indices. These indicators and indices provide information about the severity, location, duration, and timing of droughts for determining, classifying, and monitoring drought conditions. Specific indicators and indices may also be used to validate modeled, assimilated, or remotely sensed indicators of drought (WMO, 2016).

The advent of geographic information systems and increasing computing and display capabilities have increased the capacity to overlay, map, and compare various indicators or indices (WMO, 2016; Gorji et al., 2019). There are too many indicators and indices used within the scope of the drought analyses. The issue is particularly expected within the scope of drought analyses in determining the duration, size, and recurrence interval of drought. Therefore, it is exceptionally critical to determine in detail the various characteristics of drought such as duration, severity/size, frequency of drought, and the affected area, and implement the necessary work in consideration of the issues mentioned above. Various characteristics such as drylands, distribution of drought, dry periods, and recurrence frequency may be determined using daily, monthly, and annual climate elements and various relationships that include long-term standards (Ogallo and Gbeckor-Kove, 1989). It is critical for drought indices to accurately reflect and represent the effects that occurred in the drought period. As drought develops, its effects may vary by region and climate. Monitoring different aspects of the hydrological cycle may require various indicators and indices (WMO, 2016; Das et al., 2016; Kütükçü, et al., 2015; Kalubarme e tal., 2019). Various approaches and methods are developed to examine and monitor drought events that may be effective in different time zones.

Indicators are variables or parameters used to describe drought conditions. Drought indicators include the variables such as climate variables or meteorological parameters (precipitation, temperature, relative humidity, evaporation, evapotranspiration, solar radiation, wind, etc.), reservoir, lake, and dam level values, properties of soil (field capacity, soil water holding capacity or available soil water content, etc.) groundwater (groundwater level, reserve change, etc.) (Jehanzaib et al. 2020), snow cover and its thickness, streamflow, vegetation properties, remote sensing instruments (satellite products etc.), and seasonal and long-term model forecasts.

Various drought indices provided above are used globally to determine the characterization of droughts. (severity, frequency, and duration). Hydroclimatic conditions and physical structures of basins affect the performances of drought indices. Quantitative index values are necessary for proper and accurate assessment of drought severity, early drought warning systems, or establishing a comprehensive drought plan (WMO, 2016). Selection of the indicators and indices that shall be used for drought monitoring and analysis must be made considering experiences of the experts and requirements who will make the study related to each application area and sector, availability of relevant data, and as the required equipment and software. The critical issue in selecting indicators and indices is selected indicators/indices to sufficiently represent and reflect drought conditions.

Wable et. Al. (2019) worked with several indices using 25 years in Semi-Arid River Basin, India and concluded that the more indices can be used, the more accurate determinations can be made about drought characteristics. Ryuet al. (2002) used 21 meteorological observation stations' data to monitor drought evalution in Nakdong River Basin and found good correlation with the indices and the drought records. Jehanzaiba and Kim (2020a) researched multi-model ensemble projections using hydro-meteorological variables, drought characteristics, and the propagation process of drought in historical and future periods using RCP 8.5, which was developed by the authors. Mainly they focused on the effects of climate change on induced drought propagation on wetlands were investigated. Jehanzaiba et al. (2020b) analyzed two meteorological drought indices (SPI and SPEI), and a hydrological drought index (SRI) were used to represent drought and the future period according to climate change scenarios. Lee et al. (2019) studied feasible ranges of runoff curve numbers in the case of Korean Watersheds. The estimated confidence intervals were highly significant and strongly recommended for Korean watersheds. Jehanzaiba et al.(2020c) investigated the influence of natural events and anthropogenic activities on hydrological drought in South Korea. Bayissa et al. (2018) compared the performance of six drought indices in characterizing historic drought for the Upper Blue Nile Basin in Ethiopia. Dikici and Aksel (2021) pointed drought risk for the nearby basin, Asi using different types of indices.

Drought studies have been conducted for different regions using various indices to detect drought and make a prediction. The main aim of the study was to answer the following questions based on drought analysis.
- What is the frequency of the drought in the basin?
- What is the future drought severity for the region?

In this study, 41 types of drought indices were used to detect and predict the drought in the Ceyhan Basin using 46 years of measurement data.

Material and Method

Study Area

Ceyhan River Basin is located between latitudes of $35^{0}30'$ - $36^{0}00'$ North and longitudes of $35^{0}30'$ - $37^{0}50'$ East in the eastern Mediterranean region of Turkey. The Seyhan Basin surrounds the Ceyhan Basin in the west and northwest, the Asi Basin in the south, and the Fırat Basin in the east and northeast. Ceyhan River discharges into the Mediterranean Sea at the coastal side of Adana. The climate of the basin is under the control of the Mediterranean climate, which is a mostly dry climate. Almost no rain falls during the summer, and most of the rain falls during the winter. The upstream of the basins are affected by the transition from the Mediterranean to continental climates. Maximum rainfall is observed in the winter, and the average annual rainfall is 540 mm upstream and 780 mm downstream. Minimum rainfall in the basins is observed in summer, and the average annual rainfall is approximately between 5 - 9 mm. The two basins experience significant summer drought due to low rainfall and high temperatures. Mainstream in the basin, which is called the Ceyhan River, has a length of 509 km. (Bayer Altın and Barak, 2012, 2017; Simav et al., 2013; Uzunkol and Kızılelma, 2016).

Indicators and Indices

Indicators and indices used in intra-basinal drought analysis of the Ceyhan Basin, which has a precipitation area of 20,000 km^2, were selected to consider the issues stated below.

- the diversity of data in the basin, length, reliability, and availability of data series,
- meteorological, hydrological, and hydrogeological properties specific to the basin.

Indicators and indices determined within the scope of the study are listed below;

- Percentage of Normal Index (PNI – for 1, 3, 6, 9, 12, 18, 24, 48 months)
- Decimals Index (DI)
- Standardized Precipitation Index (SPI – for 1, 3, 6, 9, 12, 18, 24, 48 months)
- Standardized Precipitation and Evapotranspiration Index (SPEI – for 1, 3, 6, 9, 12, 18, 24, 48 months)
- Standardized Runoff Index (SRI – for 1, 3, 6, 9, 12, 18, 24, 48 months)
- Groundwater Index (GWI)
- Palmer Drought Indices
- Palmer Drought Severity Index (PDSI)
- Self-calibrating Palmer Drought Severity Index (scPDSI)
- Palmer Hydrological Drought Index (PHDI)
- Self-calibrating Palmer Hydrological Drought Severity Index (scPHDI)
- Normalized Difference Vegetation Index (NDVI)
- Vegetation Condition Index (VCI)

Various drought determinations were made using these indices and indicators. These are;

Meteorological drought; is generally analyzed by indicators and indices, in which data on precipitations that take place in a relatively shorter period (1-6 months) is used.

Hydrological drought; is determined by indicators and indices, in which surface and groundwater data are used on precipitations that occur in a relatively more extended period (6-12 months).

Table 1. Indicators and indices used in drought analysis.

Index, Indicator	Meteorological Drought	Agricultural Drought	Hydrological Drought
Percent of Normal Index (PNI) (1, 3, 6, 9, 12, 18, 24, 48 months)	●	●	
Decimal Index (DI) (1, 3, 6, 9, 12, 18, 24, 48 months)	●		
Standardized Precipitation Index (SPI) (1, 3, 6, 9, 12, 18, 24, 48 months)	●	●	●
Standardized Precipitation and Transevaporation Index (SPEI) (1, 3, 6, 9, 12,24, 48 months)	●	●	●
Standardied Flow Index (SRI) (1, 3, 6, 9, 12, 18, 24, 48 months)			●
Groundwater Index (GWI)			●
ıer Drought Severity Index (PDSI)	●	●	
Calibrated Palmer Drought Severity Index (scPDSI)	●	●	
ydrological Drought Index (PHDI)		●	●
Self-Calibrated Palmer Hydrologic Drought Severity Index (scPHDI)		●	●
Normalized Different Vegetation Index (NDVI)		●	
Vegetation Condition Index (VCI)		●	

Agricultural drought; is determined by indices that are calculated based on vegetation and soil moisture data obtained by remote sensing methods. Soil moisture required for plants is below the required value and by meteorological data and vegetative production data.

Indicators and indices used within the scope of the drought analysis of the Ceyhan Basin are provided in Table 1, together with the types of drought they represent, primarily within the scope of this study. Meteorological, hydrological and hydrogeological data were evaluated for 1970-2016 in the Ceyhan Basin drought analysis. The techniques stated in the following subsections were used to complete missing data for the parameters used in calculations (GDWM, 2018).

Meteorological Data

Several meteorological observation stations (MOS) are established in and around the Ceyhan Basin. Some of these stations include long-term observation data; some include short-term, including discontinuous data sets. Some of these stations are closed or in maintenance. In this study, the measurement results of the stations were evaluated according to their data lengths and their characteristics to represent the basin.

Meteorological stations are usually established irregularly. Therefore, direct usage of observation data obtained from these stations in climate studies with the purpose of modeling may cause various problems. Thus, it is ensured that the relative grid points are carried from the stations where meteorological observation data are measured. This is a required and critical procedure. Thus, gridded data sets may allow climate changes to be determined neatly, even in areas away from observation stations (Besselaar et al., 2011). Various methods are applied in transferring observation data to grid points. The Parameter-elevation Relationships on Independent Slopes Model (PRISM) model, which considers the complicated structure of the area used in the interpolation of the observation data, is a good example (Daly et al., 2008). In the procedure performed using the PRISM approach, it is essential to accurately weigh the stations that could be interpolated to the target grid cell. Thus, the stations were weighted based on their distances from each other, their heights, exposures, distances from the sea, and their topographical properties (Daly et al., 2002). In the hydro-meteorological data analysis, the lengths of the series and their continuous nature are significant for the sensitivity and reliability of the results that shall be obtained because of the comparative study.

Rainfall and temperature data that are missing for individual years concerning the meteorological stations, which are used in the drought analysis, were completed by the PRISM approach, where height, exposure, and sea effects.

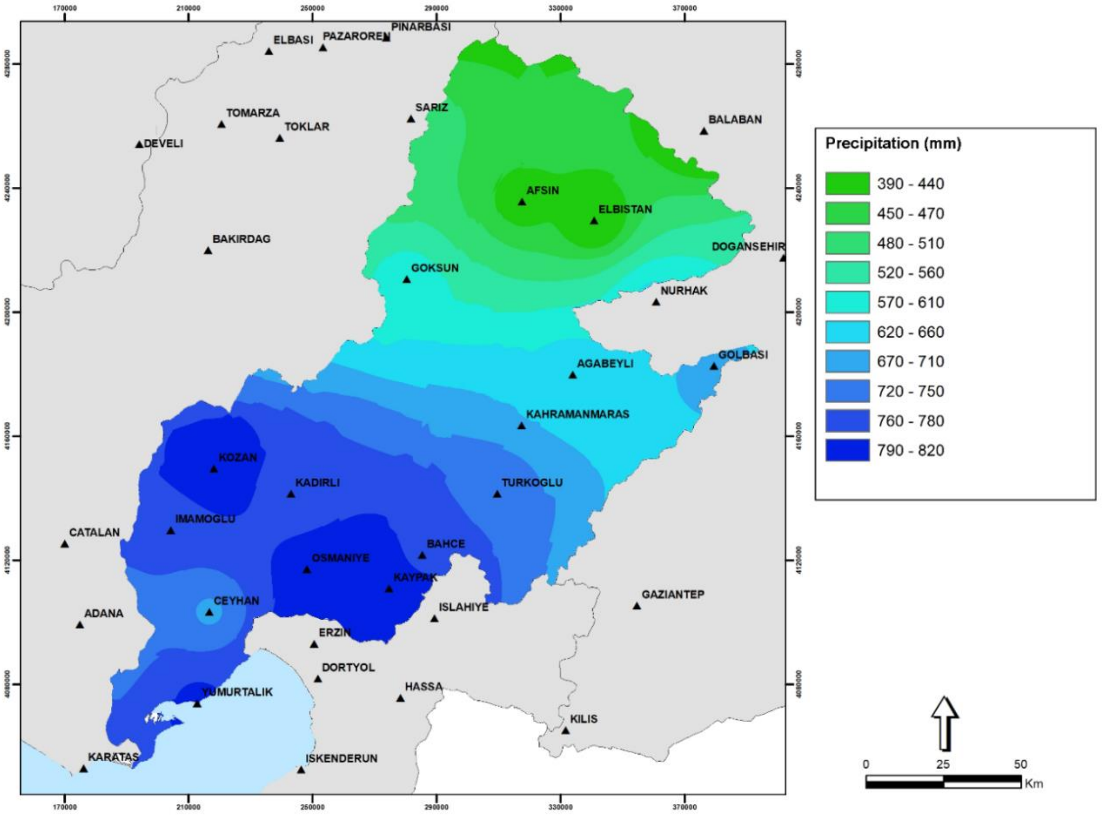

Figure 1. Precipitation distribution map for the Ceyhan Basin.

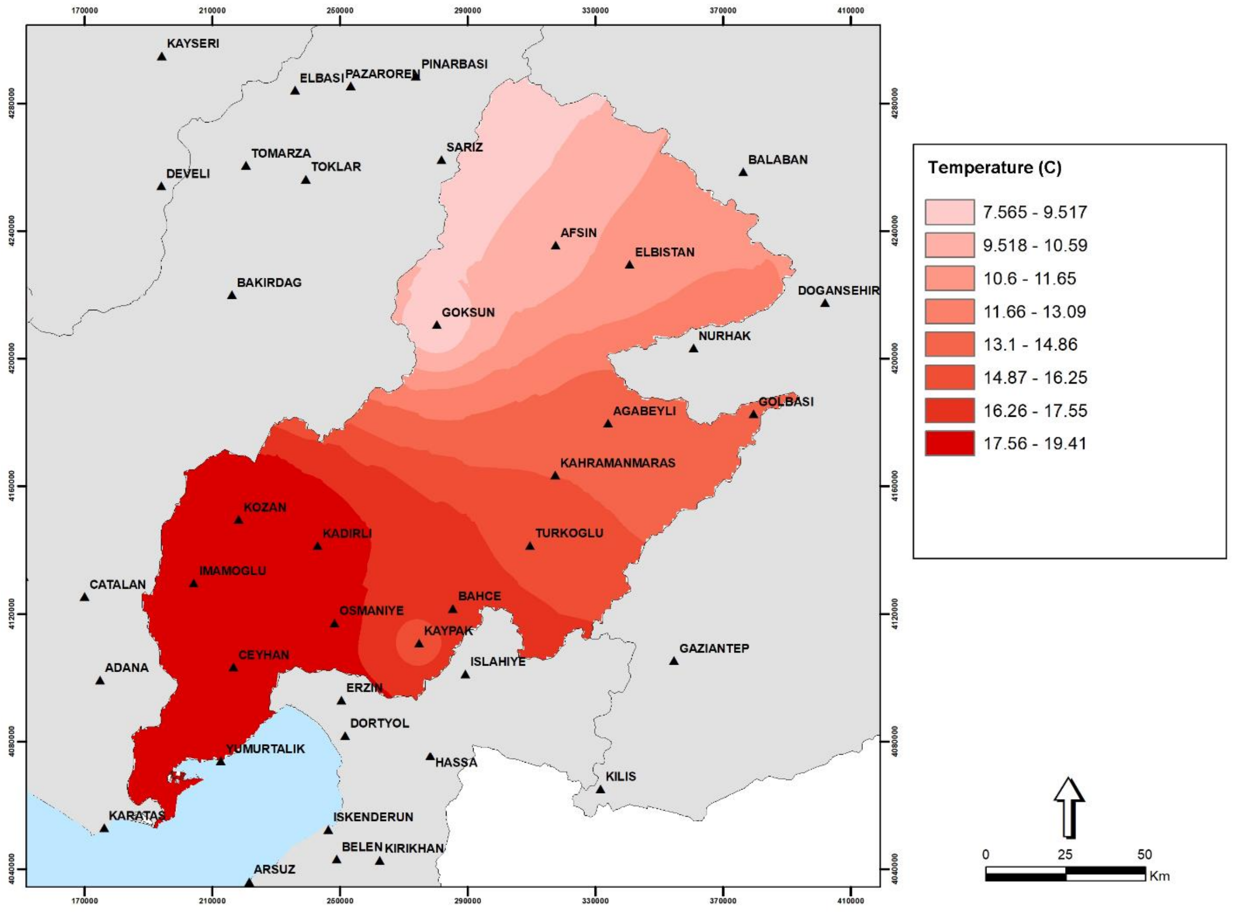

Figure 2. Temperature distribution map of the Ceyhan Basin.

Meteorological Observation Stations

Data obtained from 15 MOSs that remained within the borders of the basin was performed in the Ceyhan Basin drought analysis. Furthermore, the data obtained from 11 MOSs located in neighboring basins close to the Ceyhan Basin borders were used in the drought analyses to consider their effects on the areal analyses.

Precipitation

MOSs data was used to determine the areal distribution of annual average precipitation in Ceyhan Basin, and the result is colored in Figure 1. The dark blue colors in Figure 1 show high precipitation, and the dark green ones show fewer precipitation regions. It has been calculated that the southern part of the basin receives more average rainfall than the north of the basin.

When the mean monthly total rainfall values in the Ceyhan Basin are examined, it is clear that the winter and spring months were rainy and that the early summer and fall months were dry months. While August was the driest month (6.7 mm), December was the wettest month (100.4 mm). The Kaynak station measured the highest amount of rainfall with a mean value of 824.9 mm, and the Elbistan station had the lowest amount of rainfall with 390.7 mm. The long-term mean annual total rainfall of the overall stations in the basin was 691.8 mm.

Temperature

The annual mean temperature distribution is plotted for Ceyhan Basin in Figure 2 by using the meteorological stations available in the basin.

Like many other meteorological parameters, the temperature is sensitive to changes in altitude and continentally. Stations at sea level recorded higher temperatures in comparison to those located in mountainous areas. Exposure is another critical element that determines temperature values. It may be observed that the temperatures were higher at stations in the south-facing areas than those facing north. The highest values were recorded for monthly temperatures in July and August (26.4 °C), and that the lowest value was in January (4.6 °C). In the Ceyhan Basin, the Kozan station had the highest mean annual temperature (19.4 °C). The Göksun station had the lowest average annual temperature values (8.9 °C). The mean annual temperature of the basin was 15.6 °C.

Free Surface Evaporation

When the mean monthly evaporation values in the basin were investigated, the highest value was obtained in July (249.7 mm), and that the lowest value was obtained in January (19.5 mm). For the long-term mean annual total evaporation, the Kozan station had the highest value

(1780.1 mm). The Göksun station had the lowest value (926.6 mm). The mean annual total evaporation value for the basin, in general, was 1421.3 mm.

Hydrological Data

Runoffs must be without any interference (runoffs, in which consumption, storage, and evaporation, etc. are considered) to understand the effects of drought conditions on runoffs within the scope of drought analysis. Otherwise, it becomes indefinite whether any reduction in runoff sources is from human impacts or the impact of drought. Missing data of stations, whose natural runoffs were found was completed by the method of regression analysis, and uninterrupted time series were obtained for the period between 1970 and 2015. Water potential of the intermediary basin (basin area, except for the stations used) shall be obtained by the area ratio method, if any, to determine the water potential of the basin and sub-basins.

Runoff Observation Stations

When PNI results are being assessed, the period when rainfall is lower than the threshold value is defined as the dry period. The first value that falls below the threshold is considered the onset of drought, and the value, in which the index exceeds the threshold, is assessed as the end of the drought (Turkish State Meteorological Service (TSMS), 2017).

Drought Indices

Percent of Normal Index (PNI)

Percent of Normal Index is a commonly used index and a method, calculation of which is rapid and straightforward, and an index, which is quite sufficient for a single area or season. This index may be calculated for daily, weekly, monthly, seasonal, and annual time intervals (WMO, 2016). PNI is obtained in percentage with the division of rainfall for the reviewed time frame to its average. In other words, PNI may be obtained by dividing actual precipitation (Pactual) by average precipitation (Pra) and by multiplying it with 100. 100% is considered normal for anywhere, and average precipitation is obtained by calculating the mean for the minimum last 30 years in general. The frequency of deviations from mean values may not be compared for different areas since the selected average value varies by location and time (Heyes et al., 2011). This situation makes it difficult for any specific value different than average to be correlated with any specific activity. It is not easy to make benchmarking, particularly on different climate regimes that show wet and dry climatic properties. Therefore, PNI is not a useful decision-making tool when used individually in studies on reducing drought risks (Willeke et al., 1994). The series, in which PNI shall be calculated comprises total precipitation values for any specific month(s) in a year based on the time step used. For example, if the time step is selected as one month while calculating PNI for January, the mean value shall be calculated by considering mean rainfall in Januaries. If the time step is selected as three months and if the mean rainfall in Januaries shall be calculated yet again, then the average of the total of November, December, and January in the series shall be calculated (Dikici, 2013). PNI values can be calculated using Eq. 1, where PNIis Percent of normal index value, P_{actual} is amount of rainfall in reviewed time frame and P_{normal} is mean precipitation.

$$PNI_{m,i} = \frac{P_{aactual}}{P_{normal}} = \frac{P_{m,i}}{(\sum P_{m,i})/n} x100 \qquad (1)$$

(m = month; 1, 2, ..., 12; i = year; 1970, 1971, 1972,..., 2016, n = 47 years)

When PNI results are being assessed, the time frame when rainfall is lower than the threshold value is defined as the dry period. The first value that falls below the threshold is considered the onset of drought, in which the index exceeds the threshold, which is assessed as the end of drought (TSMS, 2017).

Decimals Index (DI)

The Decimals Index has an underlying mathematical approach for analyzing droughts in Australia (Gibbs and Maher, 1967). Calculations are based on one parameter, precipitation data, and it does not require any assumption. In this method, long precipitation series are grouped by being divided into decimals, and drought severity level is defined by the decimal segment, in which the precipitation data that are obtained daily, weekly, monthly, or annually are included (Şen, 2015). By the Decimals Index (DI), usage limitations of PNI may be dealt with to a certain degree. The Decimals Index is calculated by dividing cumulative probabilities to equal sub-intervals by listing the precipitation data of the specified meteorological stations for the selected period in ascending order and obtaining empirical cumulative probability distribution (or by calculating a specific probability distribution function) (Şen, 2015).

- Decimals 1–2 (lowest 20%): extremely below normal;
- •Decimals 3–4 (next low 20%): below normal;
- •Decimals 5–6 (in the middle 20%): normal;
- •Decimals 7-8 (next high 20%): above normal;
- •Decimals 9-10 (highest 20%): extremely above normal.

According to the DI approach, it is considered that precipitations that are extremely below normal levels may not be experienced above 20% (Gibbs and Maher, 1967).

Standard Precipitation Index (SPI)

SPI, which is the most commonly used meteorological drought index, is an index where precipitation is taken as a basis for different periods and disregards other effects (McKee, 1993). Negative values of SPI indicate lower than median precipitation, while positive values of SPI indicate higher than median precipitation. SPI values may categorize the intensity of a drought event. SPI drought categories are obtained from precipitation series with the normal distribution. However, the probability distribution function of precipitation series generally fits into a normal distribution, but Gamma distribution. Therefore, when SPI is calculated, probabilities obtained from a probability function of Gamma distribution are normalized using the inverse function of a normal distribution. Thus, the precipitation series is established. The index becomes zero, or its variation becomes one because of this standardization. SPI is calculated using Eq. 2 by dividing the difference of precipitation from average for a specific time scale by the standard deviation of the series.

$$SPI = \frac{x_i - x_j}{\sigma} \quad (2)$$

In Eq. 2, x refers to the precipitation level for the reviewed period, x refers to the mean precipitation level for the series, and σ refers to the standard deviation of the series. By SPI, one may define a lack of precipitation in several time scales. Lack of precipitation may be sufficient on different water resources in different time scales. For example, while soil moisture is being affected by a lack of precipitation in a shorter period, storages may be affected by the same in a more extended period. Therefore, SPI may be calculated in time scales of 3, 6, 9, 12, 18, 24, and 48 months (WMO, 2012). SPI-3 may be used to understand moisture conditions in short and medium terms, SPI-6 may be used to understand precipitation trends in a medium-term, SPI-9 may be used to understand precipitation patterns in a medium-term and SPI-12 may be used to understand precipitation patterns in the long term (Zargar et al., 2011). SPI is calculated for a specific location, and it requires a period based on long-term precipitation observations. A probability distribution that fits relative long-term observations is determined and is transformed into a normal distribution where the mean SPI is “0,” and the standard deviation is “1”. This study used the gamma distribution, which is the best fit probability distribution for climatic precipitation series (Thom, 1958; 1966). and generally preferred in the drought literature (McKee, 1993). The stages that are described below were followed for SPI calculation (Lloyd-Hughes and Saunders, 2002):

1. Transforming the probability distribution function of raw precipitation data to gamma probability distribution function,
2. Calculation of standardized precipitation series, i.e., SPI values, by using the standard normal distribution function for precipitation probabilities obtained from the gamma probability distribution function.

Standardized Precipitation and Evapotranspiration Index (SPEI)

The Standardized Precipitation and Evapotranspiration Index (SPEI) is a newer drought index compared to other indices (Vicente-Serrano et al., 2010). SPEI is based on two fundamental assumptions:

- Precipitation is much more important than other variables that may affect drought severity,
- Drought is only controlled by temporal variations that take place on precipitation. In the calculation of SPEI, the effect of temperature on drought is also considered, based on the principles of SPI, distinctively and superiorly from SPI. Therefore, SPEI is an ideal index that may be used in the examination of climate change by climate model projections.

SPEI is an index that is based on the values of precipitation and potential transpiration and evaporation. Thus, the variations in evaporation values caused by temperature change may be considered. In the calculation of SPEI, complete-time series data are required for both precipitation and potential evapotranspiration temperature when the Thornthwaite method is used. Due to this factor, SPEI may not be calculated in areas that provide insufficient data. The longer the time series of the data is available, the more robust the results will be (WMO, 2016). SPEI considers cumulative climatic water budget (precipitation–potential transpiration and evaporation) anomalies.

In the SPI case, the calculation of SPEI also covers the determination of suitable probability distribution of long-term observations and the transformation of the same to a normal distribution (Van Loon, 2015). The first stage in the calculation of SPEI is the determination of potential transpiration and evaporation. However, it is quite difficult to calculate potential transpiration and evaporation. In the literature, various methods may be used to calculate potential transpiration and evaporation. In this study, the Thornthwaite method (Thornthwaite, 1948) was used to calculate the values of potential transpiration and evaporation. This method only provides monthly mean temperature data. In the second stage, within the scope of the equation below, a simple measure with regards to water surplus or water scarcity. In equation (3); (i) that exists in the reviewed month may be determined by subtracting potential transpiration and evaporation value (Pi) calculated by using the Thornthwaite method from the precipitation value (Pi) for the relative month:

$$Di = Pi - PETi \quad (3)$$

In the third stage, (i) values are transformed into a probability function of the log-logistic distribution. In the fourth and last stage, as in SPI, standardized (Pi) series, i.e., SPEI values, are obtained using the inverse-standard normal distribution function for water surplus or water scarcity (i) probabilities that are obtained from the probability function of the log-logistic distribution. If SPEI is 0, it indicates a value that corresponds to 50% of the cumulative probability of water surplus or water scarcity (i). SPEI is similar to SPI in many ways, such as determining and monitoring dry seasons and calculation methods. As in SPI, SPEI has a severity scale by which both positive and negative values are calculated. Thus, both pluvial periods and dry periods may be determined. Likewise, SPEI values may be applied in any climate regime since they are normalized, and it is a comparable index. As in SPI, since this is a monthly index, this index may not be sufficient to determine developing drought events. SPEI may be calculated for time steps of as little as one month up to 48 months or more. There are drought severity and threshold values that are commonly used in the literature for SPEI.

Standardized Runoff Index (SRI)

SRI is a drought index developed in 2008 as an expression of hydrological drought and based on SPI methodology (Jehanzaib et al. 2020d). Unlike SPI, runoff data are used in the calculation of SRI. SRI is calculated as it is described below by dividing the difference of runoff values from the average for a specific time scale by the standard deviation of the series:

$$SRI = \frac{x_i - x_j}{\sigma} \quad (4)$$

In Eq. 4, x refers to the runoff related to the analyzed period, x refers to the average of the series, and σ refers to the standard deviation of the series. Since SRI only requires the usage of runoff data, like SPI, it is an index that is easy to calculate. Like SPI, SRI may be calculated daily or monthly using runoff data based on both observations and forecasts. Thus, it may provide information on the high and low runoff periods related to floods and droughts. Thanks to SRI, hydrological conditions may be observed over multiple timescales in several areas (WMO, 2016). SRI results may be assessed by being compared with the SPI analysis of the same region. In the studies made to reveal the relationship between precipitation and runoff, it was observed that there is a direct relationship between SPI and SRI. In the calculation of SRI, basins must represent stations, and runoff series are natural. When hydrological drought is examined in drought analyses, SRI results for 9-12 months are preferred since they reflect a complete hydrological precipitation period. Similar threshold values are used since the calculation method of SRI is the same as SPI and SPEI.

Groundwater Index (GWI)

The effects of a drought event may be observed on surface waters, but also groundwater. Changes in groundwater levels measured on groundwater wells may be beneficial in the assessment of groundwater potential in dry periods (Bloomfield and Marchant, 2013). Within the scope of the drought analysis study, the Groundwater Index (GWI) (Mendicino et al., 2008) is used to measure the effect of drought on groundwater. GWI uses groundwater data as an input parameter. Like SPI and SRI, GWI applies a standardization technique but does not use any standardization. The formula of GWI calculation is as Eq 5.

$$GWI = (X_i - \bar{X})\sigma \quad (5)$$

In Eq. 5, (Xi) refers to the level data in the respective time interval, ($\bar{X}$) refers to the mean value of the series in which this level data are included, and (σ) refers to the standard deviation value of the series.

Palmer Drought Indices

Wayne Palmer developed the Palmer drought index (PDI) in 1965 to determine meteorological droughts that are characterized by long-term precipitation scarcity and lack of soil moisture accordingly. The Palmer Drought Severity Index (PDSI), the Palmer Hydrological Drought Index (PHDI) (Palmer, 1965), the Self-Calibrating Palmer Drought Severity Index (scPDSI) and the Self-Calibrating Palmer Hydrological Drought Severity Index (scPHDI) are the Palmer indices that are used commonly in drought studies. Among these indices, PDSI and scPDSI are beneficial in defining meteorological drought, and PHDI and scPHDI are beneficial in defining hydrological drought. The calculation of PDI is based on soil water/moisture balance. Soil water balance is generally based on weekly or monthly total precipitation; weekly or monthly mean temperature, and available water holding capacity (AWHC) data on the studied area or region. The availability and reliability of these indices vary based on accurately obtaining the data and the parameters (e.g., AWHC) that are used as input. Therefore, in calculations, soil moisture must be determined as close to the actual conditions (Palmer, 1965).

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is one of the most frequently used tools in monitoring vegetation using remote sensing data. NDVI is calculated as it is described below based on the observations made on satellite images in near-infrared (NIR) and red (RED) wavelengths:

NDVI=(NIR-RED)/(NIR+RED) (6)

Vegetation Condition Index (VCI)

The vegetation condition index (VCI) derived from remote-sensing data has been widely used for drought monitoring. VCI is calculated for any cell (i) as using Eq. 7 when one considers that the data obtained from satellite data are obtained from several cells spatially.

$$VCI_i = \frac{(NDVI_i - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} x100 \quad (7)$$

Drought Categorization and Threshold Values for the Ceyhan Basin Drought Analysis

Within the scope of the Ceyhan Basin drought analysis, instead of drought severities and threshold values that are preferred to be used in the literature, four main drought severity categories are used for the indices, methods of which are explained in this section, to allow all of the indices to be compared consistently: These categories were determined as Severe Drought, Moderate Drought, Mild Drought, None and Normal/Moisture. The categorization and threshold values that are used within the scope of the drought analysis for Ceyhan Basin are listed in Table 2.

Drought Severity-Recurrence Analysis

This section aimed to determine the level of severity in which drought occurs within specific return periods (once in every 2, 5, 10, 20, and 50 years). Index values that correspond to the selected return periods were determined and localized, and thus, we ensured that the basin was represented. As the first step of this analysis, extreme values were determined for each year when each index was calculated, and the index value of the month, which gave the worst results, was considered for each year. To determine the type of behavior exhibited by the series with 46 formed with an extreme index determined for each year between 1970 and 2016, we determined the probability distribution that each index series fit concerning each station. Kolmogorov-Smirnov test was used to determine the best distribution that fits the values. Regarding the tested distributions, parameters 2 and 3 of Lognormal, Weibull, Pearson Type III (Gamma), and GEV were used from among the probability distributions determined to fit the minimum precipitation low runoff values in the literature (Bayazıt and Önöz, 2008). Index values that corresponded to the return periods (T) of each station were determined with the assistance of the probability distribution intensity function that fits each station. The results were calculated for the return periods of 2, 5, 10, 20, 50, and 100 years. Thus, we compared the affected areas in the basins by the return periods.

Table 2. Drought categorization and threshold values used for Ceyhan basin drought analysis.

SPI, SPEI, SRI GWI	**DI**		**Drought Categories**
> -0.99	> 30		(no drought - normal/moisture))))normal/nemli
-1.49 — -1	20 — 30		(mild drought)
-1.99 — -1.5	10 — 20		(moderate drought)
< -2	0 — 10		(severe drought)
Palmer Index	**VCI**		**Drought Categories**
> -2	> 37.5		(no drought - normal/moisture))))normal/nemli
-3 — -2	25 — 37.5		(mild drought)
-4 — -3	12.5 — 25		(moderate drought)
< -4	0 — 12.5		(severe drought)
PNI1, PNI3	**PNI6**		**Drought Categories**
> 75	> 80		(no drought - normal/moisture))))normal/nemli
65 — 75	70 — 80		(mild drought)
55 — 65	60 — 70		(moderate drought)
0 — 55	0 — 60		(severe drought)
PNI9	**PNI12, PNI24 PNI48**		**Drought Categories**
> 83.5	> 85		(no drought - normal/moisture))))normal/nemli
73.5 — 83.5	75 — 85		(mild drought)
63.5 — 73.5	65 — 75		(moderate drought)
0 — 63.5	0 — 65		(severe drought)

According to the determined return range, the value of the indices in 50% of the basin was determined and how which index gave results in the basin was compared. Thus, it was interpreted which index showed milder drought and which showed more severe.

Results and Discussion

Totally, 41 indices were used to perform agricultural, hydrological, and meteorological drought analyses using data for 46 years between 1970 and 2016.

As a result of the analysis that was carried out in previous sections, the values of SPEI-1, SPEI-6, SPEI-12, SPEI-24, SPI-1, SPI-6, SPI-12, SPI-24, sc-PDSI and sc-PHDI were summarized in Table 3, which may recur by a return period of 5, 10 and 50 years in 50% of the basin spatially, by being colored according to the drought categories.

According to the results provided in Table 3, the primary outcomes can be summarized.

- Every 5 Years; It is expected that Mild Drought may occur in 50% of the basin according to the indices SPI-24, SPEI-12 and SPEI-24, that Moderate Drought may occur in 50% of the basin according to the indices SPI-6, SPI-12, SPEI-1, SPEI-6, sc-PDSI and sc-PHDI, and that Severe Drought may occur in 50% of the basin according to the index SPI-1.
- Every 10 Years; It is expected that Moderate Drought may occur in 50% of the basin according to the indices SPEI-6, SPEI-12, SPEI-24, sc-PDSI and sc-PHDI, and that Severe Drought may occur in 50% of the basin according to the indices SPI-1, SPI-6, SPI-12, SPI-24 and SPEI-1.
- Every 50 Years; It is expected that Severe Drought may occur in 50% of the basin according to all of the indices

Relevant meteorological data and runoff observations that are available in the basin were determined. Missing data were completed using statistical methods. Mann-Kendall-based trend analyses were conducted to detect the temporal change in values for basin and sub basin. As a result of these analyses, a trend of reduction in the annual total precipitation was observed in the Ceyhan Basin. There was a clear increasing trend in annual average temperatures on both sub-basin and basin basis.

Due to the insufficient number of stations making evaporation measurements, spatial evaluation could not be made. In the station-based evaluation, it was seen that there was no significant trend in most of the stations, but an increase. Calculations showed that the flow characteristics of the Ceyhan Basin have a decreasing trend at a 95% confidence level.

Table 3. Index values may recur in 50% of the basin spatially once every 5, 10, and 50 years.

Index	**Turn period (year)**		
	5	**10**	**50**
SPI 1	-2.04	-2,41	-3.21
SPI 6	-1.94	-2.38	-2.38
SPI 12	-1.60	-2.02	-2.69
SPI 24	-1.37	-2.49	-2.49
SPEI 1	-1.83	-2.03	-2.36
SPEI 6	-1.68	-1.95	-2.38
SPEI 12	-1.49	-1.78	-2.29
SPEI 24	-1.35	-1.68	-2.26
sc-PDSI	-3.13	-3.76	-4.82
sc-PHDI	-3.20	-3.86	-4.87

The insufficient number of stations making evaporation measurements caused that spatial evaluation could not be made in station-based evaluations. As a result of the trend analysis performed in the Ceyhan Basin surface runoff series, it has been calculated that the surface flows show a decreasing trend. What is determined regarding the groundwater well level values is that the water level of the wells tends to increase.

The threshold values that corresponded to the categories of average and above, mild drought, moderate drought, and severe drought for each index and all of the analyses were carried out in consideration of these parameters.
The indices that were calculated for the same periods showed a higher correlation in comparison to those that were calculated for different periods. However, the correlation between the VCI and NDVI results and the other indices was low. For a better comparative analysis of the indices calculated values of the relevant indices by years is presented in Figures 3 - 6. While creating temporal graphs, related data and calculated indices are visualized together and SPEI12, SPI12, and SRI12 indices were included in the visualization each time to better monitor the situation in these comparisons.

PDSI, PHDI, SPEI12, SPI12 and SRI12 indices are presented together in Figure 3. Almost all of them follow a similar trend. PDSI and PHDI indices could not only detect the drought in 1972-1973. The temporal variation of SPEI12, SPI12, SRI12 and PNI12 indices is given in Figure 4. As can be seen in Figure 4, the fit between these indices is better than the previous compared indices in Figure 3. In Figure 5, the DI index (green line) is shown together with the SPEI12, SPI12, and SRI12 indices. It has been determined that it exhibits a behavior compatible with the general drought trend of the region.

MODIS and AVHRR3g VCI indices are also processed together and presented in Figure 6. In the calculations made, the correlation of NDVI and VCI indices with other indices does not fit well. However, the values are still within acceptable limits.

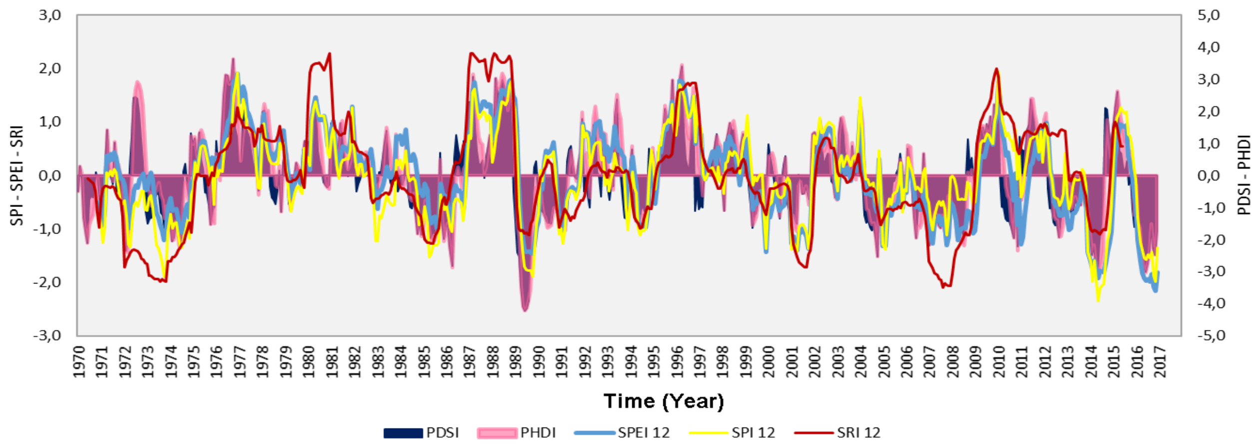

Figure 3. Comparison of PDSI, PHDI, SPEI12, SPI12 and SRI12 indices for the Ceyhan Basin.

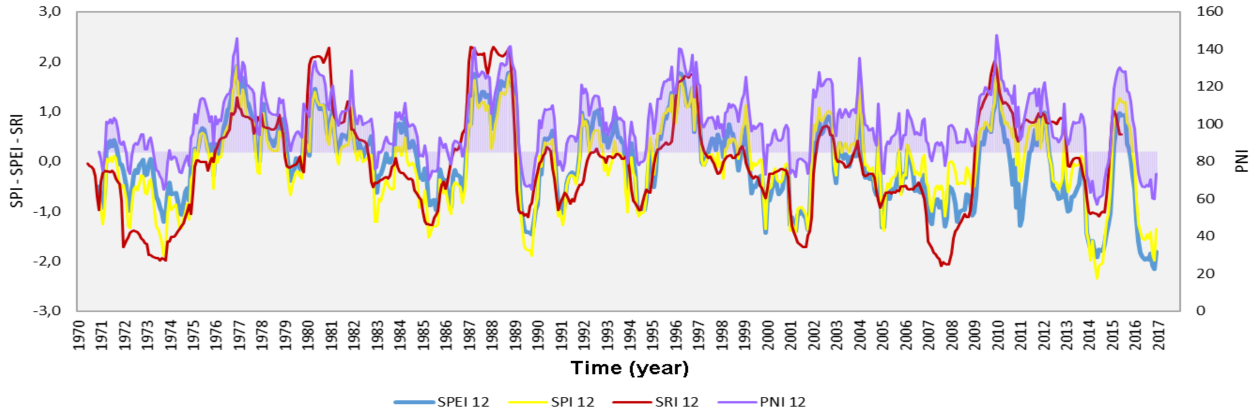

Figure 4. Comparison of SPEI12, SPI12, SRI12 and PNI12 for the Ceyhan Basin.

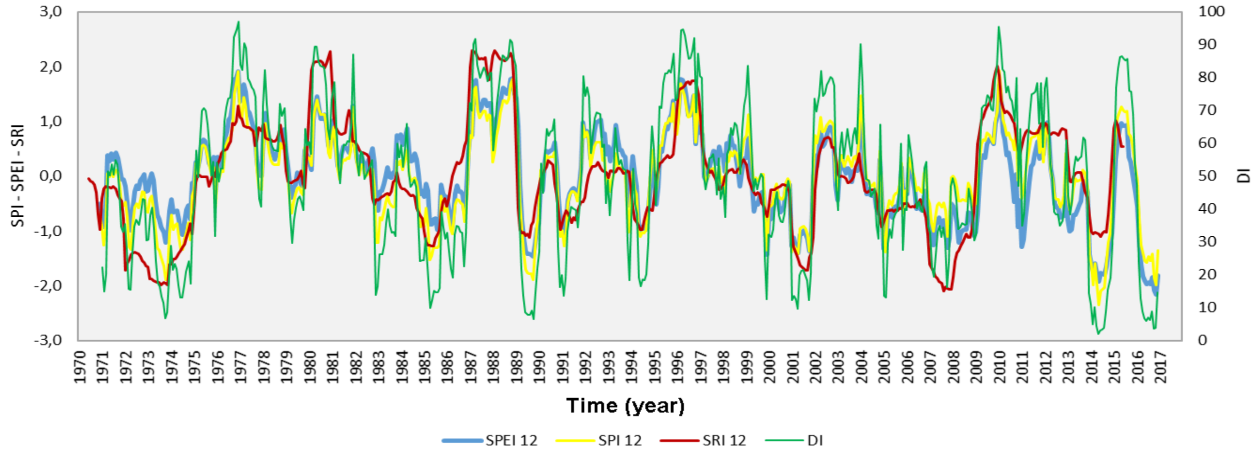

Figure 5. Comparison of SPEI12, SPI12, SRI12 and DI for the Ceyhan Basin.

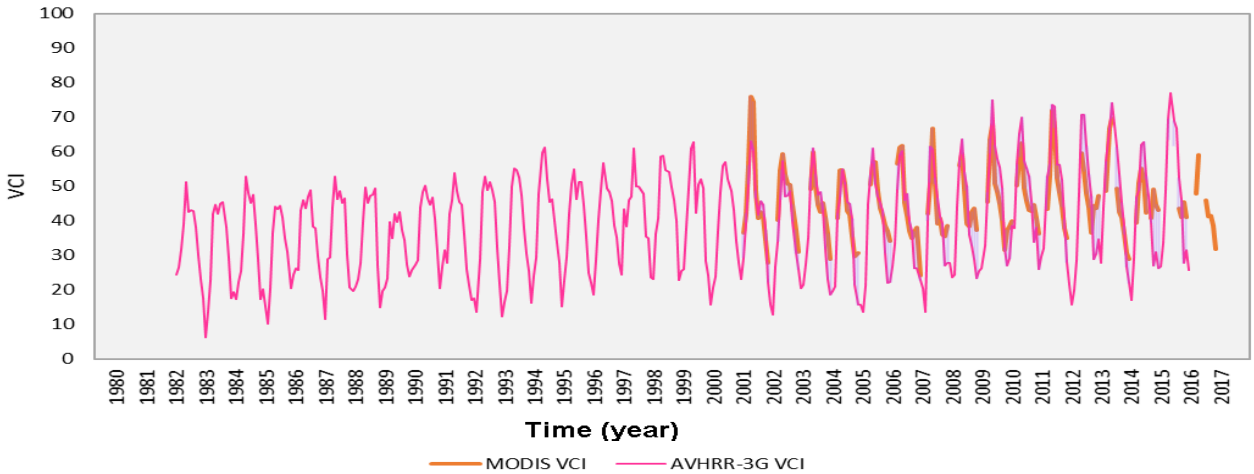

Figure 6. Comparison of MODIS VCI and AVHRR-3G VCI for the Ceyhan Basin.

Conclusion

Droughts with different characteristics were investigated using 41 different indices in this study. It is possible to make the following inferences as a result of analyzing all indices together.

- The periods in which the indices collectively indicate drought for the Ceyhan Basin were determined as 1972-1974, 1984-1986, 1989, 2001, 2007-2008, 2014 and 2016.
- There is a drought risk for Ceyhan basin at 1, 2, 5, 10, 20, 50 and 100 year return intervals, provided that they are in different categories.
- Some indices for the 20-year return period, and all indices for the 50-year yield range show the possibility of extreme drought for more than 50% of the basin.

It is important for decision makers in the region to plan considering the drought situation in the global climate change process, which indices were not detected.

Data Availability

The data used to support the findings of this study are obtained directly from the tests and included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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