Water Resources Management
https://doi.org/10.1007/s11269-025-04229-z

# Spatio-Temporal Variability of Hydrological Drought and Trends: Implementation of Classical and Innovative Approaches

**Ibrahim Halil Deger**[1] · **Mehmet Ishak Yuce**[2] · **Musa Esit**[3]

Received: 24 January 2025 / Accepted: 25 April 2025


**Abstract**
Drought is known as natural hazard having negative potential effects on water resources, economy, sustainability and energy. Hydrological drought is defined as deficiency of surface or subsurface water. Drought is insidious and potentially harmful to the environment and socio-economy, which motivates researchers to monitor and develop new strategies in order to manage possible negative effects. In this research, a detailed hydrological drought monitoring study considering spatio-temporal variability has been performed by employing Streamflow Drought Index (SDI) and mean monthly streamflow records of 36 stations for the standard time scales of 1-, 3-, 6-, 9- and 12-months in the Euphrates Basin which covers the ∼16% of Turkey is one of the most important basins in the country in care of water resources availability and hosting many production sectors and cultural heritage. Spatial distribution of drought and wet categories have been analyzed by using Inverse Distance Weighting (IDW) approach. Trends in the time scales are observed by Mann-Kendall Test, Spearman's Rho Test, Wilcoxon Test, Innovative Trend Significance Test and Sen's Slope Estimator. Graphical Innovative Trend Analysis are employed to examine temporal trends in drought and wet periods. Results have indicated that the mild drought and wet periods are the most repetitive categories based on percentage of occurrences. Different parts of the basin seem to have experienced droughts on the different standard time scales. Decreasing trends are noted to be widespread across the basin. The findings of this research are expected to contribute a better understanding of hydrological drought dynamics in Euphrates Basin that plays critical role in water resources and the sustainability of life in the region.

**Keywords** Drought · Hydrological drought · Streamflow Drought Index · Trend · Euphrates · Turkey

✉ Ibrahim Halil Deger
ibrahim.deger@hku.edu.tr

[1] Civil Engineering Department, Hasan Kalyoncu University, Gaziantep, Turkey

[2] Civil Engineering Department, Gaziantep University, Gaziantep, Turkey

[3] Civil Engineering Department, Adiyaman University, Adiyaman, Turkey

Published online: 16 May 2025

## 1 Introduction

The global interest to water or water related events such as floods, drought has been increasing since due to vital role of water as an irreplaceable resource for life (Wei et al. 2024; Frade et al. 2024). Besides, fresh water sources are limited and when excessive usage of water, increasing of population are added to water threaten factors, the phenomena which forces to governments and communities to take serious precautions becomes more critical. It is notable to emphasize that water presence and the factors affecting it are not only subject matter of personal consumption such as drinking, washing etc. but also are important for the sectors of energy, agriculture, industry, transportation and sustainable development.

Droughts have been considered as extreme natural phenomena that is characterized with a deficit in water availability and influences different areas globally (Sheffield and Wood 2012; Wei et al. 2024; Frade et al. 2024). It is emphasized (Yin et al. 2022; Singh et al. 2022; Liu et al. 2024) that in the Sixth Assessment Report of Intergovernmental Panel on Climate Change drought has been stated as being more frequent and severe throughout the world over the course of recent decades. Besides, Xu et al. (2024) have reported droughts as a phenomenon occurring globally and a prevalent environmental disaster due to its destructive effects and significant economic difficulties, among all natural disasters. In many research studies (Mishra and Singh 2010; En-Nagre et al. 2024; Feng et al. 2024; Christelis et al. 2024; Liu et al. 2024; Zhang et al. 2024) drought has been clustered into four categories which are meteorological, agricultural, hydrological and socio-economic. Meteorological drought has been defined by Mishra and Singh (2010) as a lack of precipitation in a region for a period of time. It has been stated by Li et al. (2021) and Zhang et al. (2024) that meteorological drought is commonly the primary factor of other drought types. Agricultural drought is decline in soil moisture content (Aon and Biswas 2024). Hydrological drought describes a water deficiency that occurs in surface or subsurface water (Gorugantula et al. 2024). It is reported (Brunner et al. 2023; Gu et al. 2023; Wu et al. 2024) that trends of global hydrological droughts which take substantial interest in the past few years show an upward trend behavior with climate change. Socio-economic drought is defined as unusual water deficit due to a mismatch between available water resources and demands of society and environment (Ma et al. 2025).

Wu et al. (2025) noted that drought indices are commonly utilized in order to detect the drought. Many indices have been suggested for different types of drought and some researchers (Niemeyer 2008; Svoboda and Fuchs 2016) have given a valuable efforts to give detailed information about employed indices. Among indices for analyzing the hydrological drought based on different time scales (1, 3, 6, 9, and 12 month), Nalbantis and Tsakiris (2009) have suggested Streamflow Drought Index (SDI). Recently, SDI has been performed to detect hydrological drought events in many studies (Birimbayeva et al. 2024; Kartal and Emiroglu 2024; Saini and Singh 2024; Leščešen et al. 2024; Niazkar et al. 2024; Jahangir et al. 2024).

Because drought is reported a major natural disturbance with profound effects by (Hanby et al. 2025) and is noted as critical hydro-meteorological catastrophe for recent times by Ionita et al. (2022) and Meilutytė-Lukauskienė et al. (2024), communities are forced to monitor drought comprehensively. An index can give an information about drought events as well as the drought category based on the index evaluation criteria in a time scale however this is not enough as drought event can be effective in a certain area for a specific time.

To do so, drought events can be tracked spatially by interpolation techniques such as Inverse Distance Weighting which has been used effectively in many drought studies (Minh and Dung 2023; Aktürk et al. 2024; Niyonsenga et al. 2024; Taylan 2024; Tegegn et al. 2024).

To investigate the possible droughts in care of temporal variability, many trend techniques such as Mann-Kendall Test (Kendall 1975), Spearman's Rho Test (Spearman 1904), Sen's Slope Estimator (Sen 1968), Innovative Trend Analysis (Şen 2012, 2017), Wilcoxon Test (Wilcoxon 1945) have been used. In recent times in many studies (Demirel et al. 2024; Ozocak et al. 2024; Oubadi et al. 2024; Zarei and Mahmoudi 2024; Kartal and Emiroglu 2024; Yaşa and Partal 2024; Aydin et al. 2024; Meskelu et al. 2024; Swain et al. 2024) at least one of these tests have been utilized for drought variability assessments for different parts of the world.

Turkey has 25 water basins, with the Euphrates Basin (part of the larger Euphrates-Tigris Basin) being the largest at 122,010 km². This southeastern region encompasses numerous rivers, lakes, dams, forests, agricultural lands, wetlands, and diverse ecosystems. The basin supports major economic activities including farming, agriculture, industry, mining, and trade. Additionally, tourism flourishes in the area due to its rich cultural heritage (SYGM 2020). Due to sustainability of live life, socio-economic life and negative impacts of droughts counted, there must be strategies and policies for struggling with these hydrological extreme events.

In the literature, many researchers (Tareke and Awoke 2022; Ashraf et al. 2023; Gonçalves et al. 2023; Senatilleke et al. 2023; Al-Juboori 2023; Fowé et al. 2023; Birimbayeva et al. 2024; Meilutytė-Lukauskienė et al. 2024; Achite et al. 2024; Alimkulov et al. 2024; Habibi et al. 2024; Saha and Chandra Pal 2024; Sajeev and Kundapura 2024; Patidar et al. 2024; Zhang et al. 2024; Nguyen-Minh et al. 2024; Rahmi et al. 2025; Tareke 2025; Zhen et al. 2025; Wambura 2025) have studied for analyzing hydrological droughts for different parts of the world with different methodologies. In Turkey, the topic of hydrological drought monitoring has taken an important interest of researchers (Gumus and Algin 2017; Kumanlioglu 2020, 2023; Simsek 2021; Katipoğlu et al. 2022; Deger et al. 2023b; Yuce et al. 2023; Esit et al. 2023; Gulmez et al. 2023; Kartal and Nones 2024; Kartal and Emiroglu 2024; Tuğrul and Hinis 2024). Particularly, when it comes to Euphrates Basin Turkey the number of research studies based on hydrological drought monitoring is very less. For example, Katipoğlu et al. (2021) have performed a drought monitoring analysis as spatiotemporal and have found that the most of the parts of Euphrates Basin has the risk of hydrological droughts during 12-month period because of severe and extreme droughts. Katipoğlu and Acar (2022) have used the standardized runoff index (SRI) as drought index and the tests of Mann-Kendall and Modified Mann-Kendall for trend detection. They have reported that there has been a decreasing drought trend dominance in Euphrates basin. In recent times, Demirel et al. (2024) have performed a study in order to assess trend stability for Euphrates Basin by benefiting from triple Wilcoxon test and Innovative trend analysis. In the study researchers have utilized standardized streamflow index (SSFI). They have found significantly decreasing trends in one station while other station has demonstrated unstable trends.

In this research, a comprehensive analysis for hydrological drought is conducted considering spatiotemporal variabilities. From this aim, the novelty of this paper is that hydrological drought events are investigated in more than one time scale considering spatio-temporal variabilities by spatial interpolation techniques and both classical and innovative trend approaches for one of the most important basins, Euphrates Basin in Turkey. By benefiting from SDI algorithm and streamflow records of 36 stations in Euphrates Basin of Turkey, drought monitoring analysis are conducted for 1, 3, 6, 9, 12-month time scales. Spatial variability analysis for drought and wet classes in time scales are employed by IDW. Possible trends in selected time series of SDI are investigated by Mann-Kendall Test, Spearman's Rho Test, Sen's Slope Test, Wilcoxon Test, and Innovative trend significance Test. To examine the possible trends in drought and wet categories a developed form of graphical innovative trend analysis in which classical graph of innovative trend analysis by (Şen 2012) has been combined with drought and wet categories by (Yuce et al. 2023) has been utilized. The findings of this research are believed to be helpful for the policy and decision makers in drought action plans and effective water resources management.

## 2 Methodology

In the study, a framework of the methodology has been given in Fig. 1.

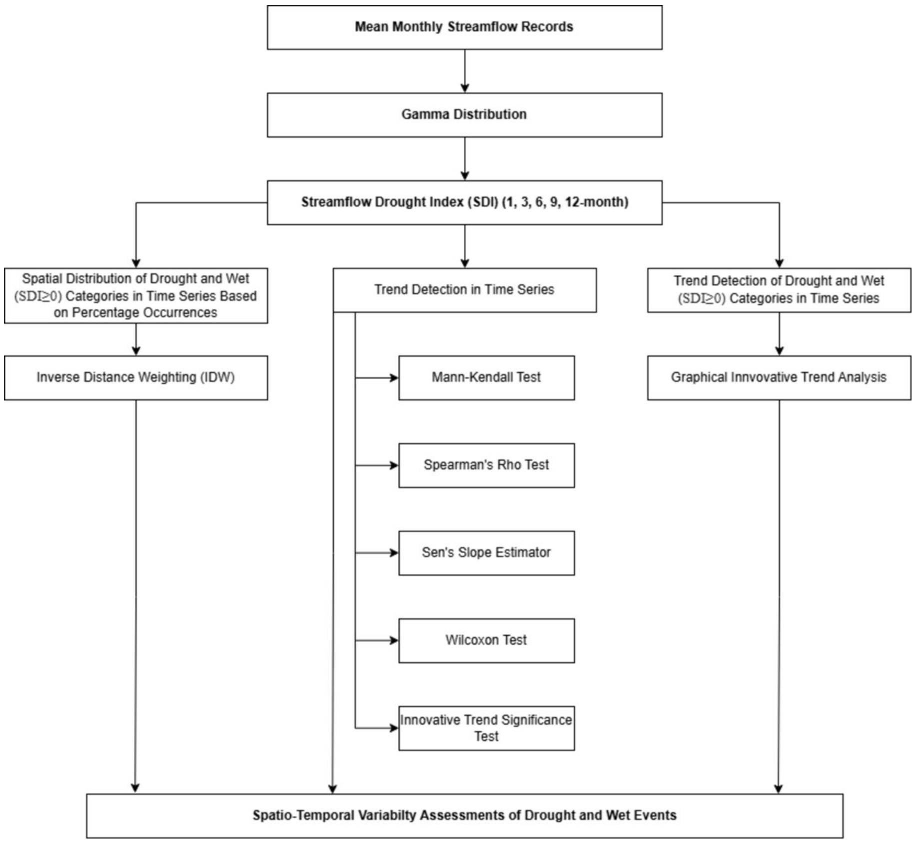


**Fig. 1** Flow chart of the methodology

### 2.1 Streamflow Drought Index (SDI)

The determination of SDI that was introduced by Nalbantis and Tsakiris (2009) and is widely used for hydrological monitoring studies is similar to Standard Precipitation Index (SPI) that was introduced by McKee et al. (1993). Employing mean monthly streamflow data as input data, the total streamflow that is presented by $X_{i,j}^{k}$ in a given month *j* and year *i* depending on the time scale k (1, 3, 6, 9, 12 months) is determined by Eqs. 1 and 2 (Paulo et al. 2003; Hong et al. 2015).

$$X_{i,j}^{k} = \sum_{l=13-k+j}^{12} V_{i-1,l} + \sum_{l=1}^{j} V_{i,l} \ \ if\ j < k \tag{1}$$

$$X_{i,j}^{k} = \sum_{l=j-k+1}^{j} V_{i,l} \ \ if\ j \geq \ k \tag{2}$$

where $V_{i-1,\,l}$ and $V_{i,\,l}$ describe volumes of streamflow in the years of *i-1* and *i*, respectively. Beside of the determination procedure explained above, Nalbantis and Tsakiris (2009) have recommended to apply a gamma distribution to streamflow data before application of SDI because the data records may contain skewness. For this purpose, a gamma distribution application with SDI has been explained in Yuce et al. (2023); Deger et al. (2023a) papers with details. After the determination each SDI values for all-time series each value is associated with a drought or wet categories in Table 1.

### 2.2 Inverse Distance Weighting (IDW)

IDW, as an interpolation method, is widely utilized in spatial data interpolation (Liu et al. 2021). The method states that every identified point produces an impact on predicted point and the weight is directly related to the p-th power of the distance (Hao and Chang 2013; Katipoğlu and Acar 2022). In this research, IDW is employed for the spatial distribution investigation of drought and wet categories that are given in Table 1 for all time scales.

**Table 1** Drought and wet classifications (Hong et al. 2015)

| SDI Value | Category |
|---|---|
| SDI ≥2.00 | Extremely Wet |
| 1.50 ≤SDI <2.00 | Severely Wet |
| 1.00 ≤SDI <1.50 | Moderately Wet |
| 0 ≤SDI <1.00 | Mildly Wet |
| −1 ≤ SDI <0.00 | Mild Drought |
| −1.50 ≤ SDI <−1.00 | Moderate Drought |
| −2.00 ≤ SDI <−1.50 | Severe Drought |
| SDI ≤−2.00 | Extreme Drought |

## 2.3 Trend Detection Techniques

### 2.3.1 Mann-Kendall (MK) Test

The test which has been reported as a rank-based test (Esit et al. 2024; Robleh et al. 2024; Aydin et al. 2024; Meskelu et al. 2024) and proposed by Mann (1945) and Kendall (1975) has been utilized for investigating the trends in time series. In this test the test statistics (Z), slope of the trend and sign equation can be determined by Eqs. 3 and 4 respectively (Ozocak et al. 2024).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right) \tag{3}$$

Where n shows the length of the data, $x_i$ and $x_j$ denote the data points in the years of j and k (j >k) and sign equation is defined as follows.

$$sgn\left(x_j - x_k\right) = \begin{cases} 1 & \left(x_j - x_k\right) > 0 \\ 0 & \left(x_j - x_k\right) = 0 \\ -1 & \left(x_j - x_k\right) < 0 \end{cases} \tag{4}$$

In case of having ties, the variance of S is can be computed from Eq. 5 and in given equation n represents number of data points, $t_i$ is number of ties for i value and m shows the number of tied values (Berhail et al. 2022).

$$Var\left(S\right) = \frac{n\left(n-1\right)\left(2n+5\right) - \sum_i^r t_i\left(t_i - 1\right)\left(2t_i + 5\right)}{18} \tag{5}$$

Then Z is determined from Eq. 6 (Ngwenya et al. 2024; Keskiner and Simsek 2024).

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{6}$$

When interpreting the results based on Z score, Z> 0 indicates a presence of increasing trend while Z< 0 indicates a decreasing trend. Besides of this, trends are associated with a significance cases. In this study, trends have been investigated by considering the significance level of α= 0.01 which corresponds to $Z = \pm 2.576$.

### 2.3.2 Sperman's Rho (SR) Test

This test has been reported as the fastest in care giving the results and one of the most widely utilized methods in literature by Tuğrul and Hinis (2024). SR test value which is denoted by $r_s$ can be calculated from Eq. 7 (Esit et al. 2024).

$$r_s = 1 - \frac{\left[6\sum_{i=1}^{n}\left(Rx_i - i)^2\right)\right]}{n(n^2 - 1)} \tag{7}$$

Where $R_{xi}$ shows the rank of *ith* observation, n represents the length of time series data. If the number of data is bigger than 30 then normal distribution tables can be used and the test statistics can be determined via Eq. 8 (Aydin et al. 2024). Interpretation of the results of z similar to MK test. In the evaluation of the results of this test, the significance level of $\alpha$= 0.01 which corresponds to $Z = \pm 2.576$ has been selected for SDI series.

$$z = r_s\sqrt{n-1} \tag{8}$$

#### 2.3.3 Sen's Slope Estimator

One another trend detection technique used in the study is Sen's slope estimator that has been introduced by Sen (1968) as a non-parametric test. In this technique, the procedure of determination of the trend slope includes ranking the slope pairs from smallest to highest. The next step of the procedure is checking the number of slopes in care of odd or even. When the slope number (n) is odd, the median slope is the slope but when n is even then the average of two median slopes becomes the slope (Esit 2022). The slope (S) of n pair data can be found by approximation of Sen's estimator with Eqs. 9 and 10 (Esit et al. 2024).

$$S = \frac{Q_2 - Q_1}{T_2 - T_1} \tag{9}$$

$$S = \begin{cases} S_{\frac{n+1}{2}} & n = even \\ S_{\frac{n}{2}} & n = odd \end{cases} \tag{10}$$

Where Q shows the data, T denotes the time and n is the length of the data.

#### 2.3.4 Wilcoxon Test

Wilcoxon Test (WT) which aims to determine the scattering of two variables in terms of the being same based on the differences in two-half data has the following determination procedure (Saplıoğlu and Güçlü 2022): At first the difference between halves must be determined by Eq. 11 based on absolute criteria (Eq. 12).

$$D_i = X_i - Y_i \tag{11}$$

$$|D_i| = |X_i - Y_i| \tag{12}$$

where $D_i$ shows the difference between first half which is $X_i$ and second half that is $Y_i$. Secondly the absolute values are sorted from smallest to greatest by giving sequence numbers. Here the summation of marked rows which presents the summation of plus (minus) is considered as $T^+$($T^-$) and can be computed from following Eq.

$$T = T^{+} - T^{-} \tag{13}$$

For identification of the trends in terms significance, the test statistic $Z_w$ can be computed from Eq. 14. In the equation $\mu_T$ is arithmetic mean, $\sigma_T$ is standard deviation of the distribution. Again, similar to Mann-Kendall, Spearman Rho tests the significance level of α= 0.01 which corresponds to $Z = \pm 2.576$ has been selected for SDI series.

$$Z_w = \frac{T - \mu_T}{\sigma_T} = \frac{T}{\sigma_T} \tag{14}$$

$$Z_w = \sqrt{\frac{n(n+1)(2n+1)}{6}} \tag{15}$$

### 2.3.5 Innovative Trend Analysis (ITA)

**Innovative Trend Significance Test** The test is proposed by Şen (2017) for observation of possible trends of time series. Some researchers have benefited from the test recently (Şan et al. 2024; Nath et al. 2024; Hallouz et al. 2024) that test is widely chosen by researchers as the method does not have any assumptions. The application procedure of the test has been given (Şen 2017) paper in detail. In the test, trend slope (s), slope standard deviation ($\sigma_s$) and confidence limit can be determined from Eqs. 16, 17 and 18 respectively (Şen 2017).

$$s = \frac{2\left(\bar{y}_2 - \bar{y}_1\right)}{n} \tag{16}$$

$$\sigma_s = \frac{2\sqrt{2}}{n\sqrt{n}}\sigma\sqrt{1 - \rho_{\bar{y}_2 - \bar{y}_1}} \tag{17}$$

where $\bar{y}_1$ and $\bar{y}_2$ indicates the arithmetic averages of first and second halves, n is the number of data points and $\rho_{\bar{y}_2 - \bar{y}_1}$ denotes cross-correlation coefficient between first and second halves. For a designated significance level of α, the upper and lower confidence limit of trend slope are calculated from Eq. 18.

$$CL_{(1-\alpha)} = 0 \pm s_{cri}\sigma_s \tag{18}$$

Where $s_{cri}$ is confidence limits of standard normal probability distribution function having zero mean and standard deviation. In the study the test has been employed for SDI series considering 99% upper and lower confidence limits.

**Graphical ITA** Şen (2012) is introduced ITA approximation in which trends are investigated visually. The methodology's implementation process is thoroughly documented in the existing literature (Şen 2012; Vinod and Mahesha 2024; Meskelu et al. 2024; Akhundzadah 2024; Singh et al. 2024). A typical example of graphical ITA has been given with Fig. 2a. Beside of the increasing, decreasing, no-trend behaviors, a trend of any time series may exhibit a monotonic or non-monotonic cases. Since it is not easy to evaluate trends in care of monotony as well as the trend behaviors in drought categories from Fig. 2a, ITA are devel-

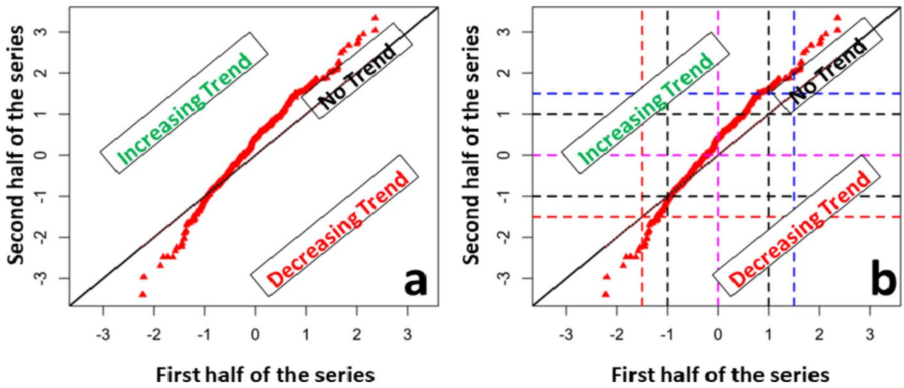


**Fig. 2** Graphical description of **a** ITA method by (Şen 2012) and **b** Developed ITA (Yuce et al. 2023)

oped by Yuce et al. (2023) with 5 vertical lines and 5 horizontal lines added in order to be able to assess trends of time series in detail as it is shown by Fig. 2b. Therefore in this study, unlike the other trend techniques explained above, via Yuce et al. (2023)'s technique trends are evaluated based on drought categories which is compatible with Table 1.

### 2.4 Software Utilized in Calculations

In all calculations of the research, a free version of R studio has been by Team (2022) has been utilized. A licensed version of ArcGIS desktop software was utilized to create detailed maps and implement the IDW technique.

## 3 Data and Study Area

Euphrates Basin which has 40° 20' 26", 36° 39' 17" North latitudes and 36° 46' 36", 43° 48' 10" East longitudes has total area of 122.010 km$^2$ ( ~16% of Turkey) and a part of the Euphrates-Tigris Basin. Sub-basins of the basin are Karasu Stream (37.515 km$^2$), Murat Stream (25.959 km$^2$), Middle Euphrates (16.558 km$^2$) and Lower Euphrates (41.976 km$^2$). The basin has neighbor basins of Yeşilırmak, Kızılırmak, Asi, Tigris, Çoruh and Van. The most important river of the basin is Euphrates River which is the most productive basin of the Turkey (SYGM, 2020). As the basin has a wide area around the Euphrates River, the climate conditions vary from region to region. In the parts of basin in Southeastern Anatolia Region, summers are hot and dry while winters are cold due to continental climate conditions. In the eastern part of region, winters are cold while summers are cool (SYGM, 2020). Besides mean annual precipitation and mean annual temperature have been reported as in Karasu Stream Subbasin 585,2 mm and 10.2 °C, in Murat Stream Subbasin 566,4 mm and 8.2 °C, in Middle Euphrates Subbasin 428,7 mm and 11.4 °C, in Lower Euphrates 547,8 mm and 16.6 °C respectively by (SYGM, 2020). The basin area mainly consists mainly by agricultural areas (43.11%) and forests (53.18%). In the study, mean monthly streamflow data of 36 stations which have taken from General Directorate of State Hydraulic Works (DSI) of Turkey have been used and locations as well as the map of the basin have been given in Fig. 3. Numerical information of used stations has been given in Table 2.

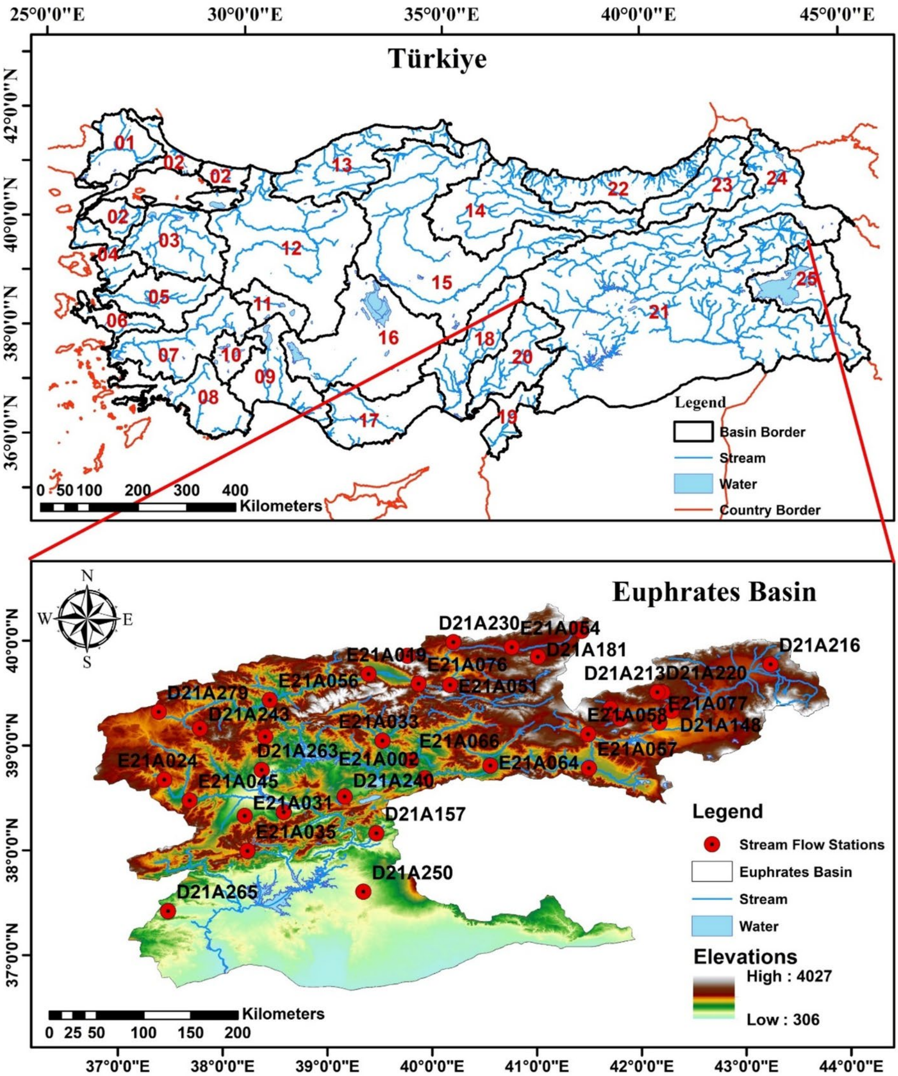


**Fig. 3** The location of selected streamflow station in Euphrates Basin

## 4 Results and Discussion

### 4.1 Assessment of Hydrological Drought in the Euphrates Basin

To comprehensively assess potential hydrological droughts within the basin, SDI were calculated for time scales of 1, 3, 6, 9, and 12 months. To facilitate a visual analysis of SDI values across stations and time scales, diagnostic charts were developed, employing a color scheme with red indicating dry periods and green signifying wet periods. A part of them has been given as examples with Fig. 4 while all of the charts belonging all time scales of all stations have been given in Supplementary. For example, in E21 A045 station (1964–2011),

**Table 2** Information of used stations in Euphrates basin

| Station | Latitude (*N*) | Longitude (E) | Elevation | Data Interval | Min. Flow ($m^3/s$) | Max. Flow ($m^3/s$) | Mean Flow ($m^3/s$) | Std. Deviation | Coefficient of Variance | Kurtosis | Coef-ficient of Skewness |
|---|---|---|---|---|---|---|---|---|---|---|---|
| D21 A001 | 40°6'29" | 41°23'8" | 1830 | 1962–2019 | 0.14 | 19.06 | 2.65 | 2.82 | 1.07 | 5.24 | 2.24 |
| D21 A121 | 38°21'57" | 38°34'58" | 752 | 1986–2019 | 0.00 | 9.95 | 1.27 | 1.65 | 1.30 | 4.26 | 1.95 |
| D21 A148 | 39°19'52" | 42°16'59" | 1465 | 1997–2016 | 0.76 | 80.26 | 15.72 | 15.63 | 0.99 | 2.80 | 1.87 |
| D21 A152 | 40°5'41" | 41°25'32" | 1950 | 1977–2019 | 0.03 | 5.39 | 0.89 | 0.90 | 1.02 | 4.62 | 2.11 |
| D21 A157 | 38°9'48" | 39°28'1" | 657 | 1987–2017 | 0.05 | 54.35 | 6.01 | 7.83 | 1.30 | 5.61 | 2.07 |
| D21 A166 | 39°21'11" | 41°42'6" | 1700 | 1987–2011 | 0.51 | 15.87 | 3.21 | 2.96 | 0.92 | 4.46 | 2.08 |
| D21 A169 | 39°15'24" | 41°47'37" | 1600 | 1979–2019 | 0.20 | 27.92 | 3.34 | 4.81 | 1.44 | 6.86 | 2.55 |
| D21 A181 | 39°50'49" | 41°0'30" | 1942 | 1983–2019 | 0.00 | 2.78 | 0.27 | 0.35 | 1.30 | 9.71 | 2.84 |
| D21 A193 | 39°5'7" | 38°24'25" | 1000 | 1985–2019 | 0.04 | 63.93 | 6.19 | 7.96 | 1.29 | 11.32 | 2.87 |
| D21 A213 | 39°30'27" | 42°11'52" | 1810 | 1986–2019 | 0.00 | 8.86 | 0.68 | 1.15 | 1.69 | 11.62 | 3.06 |
| D21 A216 | 39°46'32" | 43°13'45" | 1805 | 1986–2019 | 0.00 | 9.20 | 1.09 | 1.47 | 1.35 | 6.48 | 2.51 |
| D21 A220 | 39°30'35" | 42°8'55" | 1749 | 1986–2019 | 0.00 | 15.25 | 2.03 | 2.67 | 1.32 | 6.60 | 2.55 |
| D21 A230 | 39°59'10" | 40°12'10" | 1951 | 1987–2019 | 0.01 | 6.38 | 0.68 | 0.94 | 1.39 | 9.12 | 2.73 |
| D21 A240 | 38°30'46" | 39°9'52" | 975 | 1991–2018 | 0.00 | 17.67 | 0.82 | 1.82 | 2.22 | 41.42 | 5.64 |
| D21 A243 | 39°9'49" | 37°47'2" | 1610 | 1988–2019 | 0.00 | 20.45 | 0.91 | 1.81 | 1.99 | 47.57 | 5.62 |
| D21 A250 | 37°36'19" | 39°20'37" | 735 | 1990–2019 | 0.00 | 9.69 | 0.81 | 1.48 | 1.83 | 11.98 | 3.06 |
| D21 A252 | 39°51'26" | 39°45'56" | 1976 | 1990–2019 | 0.20 | 9.23 | 1.98 | 1.88 | 0.95 | 1.54 | 1.52 |
| D21 A263 | 38°46'0" | 38°22'24" | 831 | 1999–2019 | 0.00 | 6.58 | 0.76 | 1.02 | 1.35 | 6.46 | 2.28 |
| D21 A265 | 37°25'14" | 37°28'46" | 591 | 1992–2018 | 0.00 | 3.80 | 0.37 | 0.54 | 1.48 | 10.12 | 2.87 |
| D21 A279 | 39°19'16" | 37°23'28" | 1488 | 1998–2019 | 0.00 | 8.12 | 0.94 | 1.49 | 1.60 | 5.53 | 2.33 |
| E21 A002 | 38°41'18" | 39°55'52" | 852 | 1968–2011 | 13.98 | 1893.70 | 244.17 | 319.68 | 1.31 | 5.81 | 2.35 |
| E21 A019 | 39°40'57" | 39°23'35" | 1123 | 1995–2019 | 16.86 | 427.74 | 81.52 | 71.17 | 0.87 | 4.55 | 2.14 |
| E21 A024 | 38°40'23" | 37°26'35" | 1193 | 1963–2018 | 0.62 | 36.27 | 6.77 | 4.05 | 0.60 | 9.73 | 2.06 |
| E21 A031 | 38°19'47" | 38°12'38" | 892 | 1957–2018 | 0.17 | 18.07 | 1.55 | 2.02 | 1.31 | 19.93 | 3.94 |
| E21 A033 | 39°2'45" | 39°31'34" | 875 | 1968–2009 | 19.01 | 436.80 | 88.42 | 76.44 | 0.86 | 3.27 | 1.87 |
| E21 A035 | 37°59'38" | 38°14'13" | 1252 | 1961–2019 | 0.00 | 16.93 | 3.68 | 2.47 | 0.67 | 3.47 | 1.66 |
| E21 A045 | 38°28'34" | 37°41'8" | 933 | 1964–2011 | 6.37 | 151.84 | 22.11 | 13.29 | 0.60 | 22.04 | 3.63 |

**Table 2** (continued)

| Station | Latitude (*N*) | Longitude (E) | Elevation | Data Interval | Min. Flow ($m^3/s$) | Max. Flow ($m^3/s$) | Mean Flow ($m^3/s$) | Std. Deviation | Coefficient of Variance | Kurtosis | Coef- ficient of Skewness |
|---|---|---|---|---|---|---|---|---|---|---|---|
| E21 A051 | 39°34’43” | 40°10’12” | 1355 | 1964–2019 | 6.73 | 447.39 | 59.53 | 69.25 | 1.16 | 6.18 | 2.38 |
| E21 A054 | 39°56’20” | 40°45’35” | 1675 | 1969–2010 | 2.01 | 153.08 | 19.65 | 24.13 | 1.23 | 4.62 | 2.16 |
| E21 A056 | 39°26’5” | 38°27’4” | 865 | 1969–2011 | 55.82 | 667.68 | 150.13 | 107.71 | 0.72 | 4.00 | 2.02 |
| E21 A057 | 38°47’2” | 41°29’43” | 1250 | 1969–2007 | 0.77 | 233.50 | 24.97 | 35.65 | 1.43 | 8.07 | 2.65 |
| E21 A058 | 39°6’30” | 41°29’14” | 1310 | 1969–2017 | 1.52 | 133.86 | 18.38 | 25.11 | 1.37 | 4.45 | 2.17 |
| E21 A064 | 38°48’31” | 40°33’17” | 990 | 1969–2018 | 0.72 | 285.57 | 32.23 | 46.95 | 1.46 | 5.67 | 2.35 |
| E21 A066 | 38°51’33” | 39°47’47” | 840 | 1970–2011 | 1.67 | 509.39 | 77.36 | 87.29 | 1.13 | 5.06 | 2.18 |
| E21 A076 | 39°35’24” | 39°52’14” | 1225 | 1984–2019 | 0.00 | 10.86 | 1.61 | 1.66 | 1.03 | 5.97 | 2.29 |
| E21 A077 | 39°13’10” | 42°10’6” | 1452 | 1986–2015 | 1.78 | 197.74 | 28.38 | 35.02 | 1.23 | 6.27 | 2.45 |

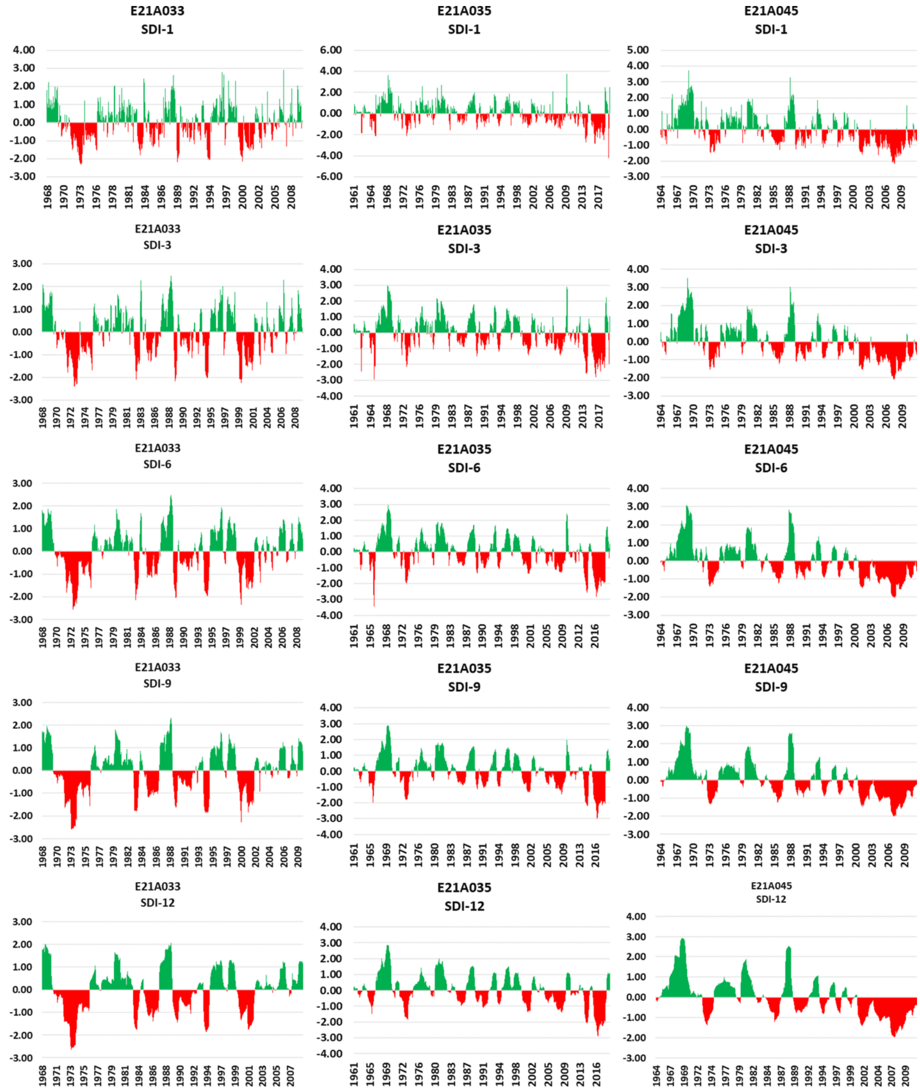


**Fig. 4** Time series of SDI based on dry (red) and wet (green) periods

SDI clearly shows the distinction between dry periods (SDI $<0$) and wet periods (SDI $\geq 0$) throughout the data range. At station E21 A045, located near the central basin area, significant drought conditions have occurred predominantly in the 2000 s, while wetter conditions were primarily observed in earlier time periods. This pattern of increasing drought events in recent years is consistent across all monitoring stations in the region.

According to Table 3, which summarizes the percentage distribution of drought categories and wet conditions (SDI $\geq 0$), mild drought and wet conditions were the most frequently occurring categories across all time scales and stations, consistently showing the highest percentage of occurrences. According to Table 3, it seems that Mild drought has got its

**Table 3** Statistics of drought and wet categories

| | SDI-1 | SDI-3 | SDI-6 | SDI-9 | SDI-12 |
|---|---|---|---|---|---|
| Minimum Percentages of Drought and Wet (SDI ≥ 0) Categories | | | | | |
| Mild | 15.625 | 16.071 | 16.369 | 16.220 | 16.369 |
| Moderate | 4.000 | 4.583 | 3.750 | 4.167 | 2.206 |
| Severe | 0 | 1.235 | 1.667 | 0.450 | 1.006 |
| Extreme | 0 | 0.556 | 1.075 | 1.563 | 1.882 |
| Wet (SDI ≥ 0) | 25.000 | 36.937 | 40.476 | 39.583 | 39.881 |
| Stations of Minimum Percentages | | | | | |
| Mild | E21 A024 | E21 A024 | E21 A024 | E21 A024 | E21 A024 |
| Wet (SDI ≥ 0) | D21 A181 | D21 A181 | D21 A240 | D21 A241 | D21 A240 |
| Maximum Percentages of Drought and Wet (SDI ≥ 0) Categories | | | | | |
| Mild | 64.414 | 51.802 | 47.619 | 46.726 | 44.643 |
| Moderate | 11.905 | 11.828 | 14.773 | 16.333 | 15.530 |
| Severe | 12.054 | 12.649 | 12.500 | 12.202 | 12.054 |
| Extreme | 5.000 | 6.111 | 6.944 | 9.069 | 11.275 |
| Wet (SDI ≥ 0) | 71.389 | 62.054 | 61.607 | 62.202 | 62.054 |
| Stations of Maximum Percentages | | | | | |
| Mild | D21 A181 | D21 A181 | D21 A240 | D21 A240 | D21 A240 |
| Wet (SDI ≥ 0) | D21 A250 | E21 A024 | E21 A024 | E21 A024 | E21 A024 |

minimum (15.625%) in SDI-1 while reaches its maximum in SDI-1 (64.6414) among all time scales. When all time scales are compared, moderate drought has been observed with its smallest in SDI-12 (2.206%) while the highest of it can be observed as 16.333% in SDI-9. Severe droughts are detected with its minimum as 0% in SDI-1 and its maximum has been recorded as 12.649 in SDI-3. The extreme drought category showed its lowest occurrence at 0% in SDI-1, while reaching its maximum at 11.275% in SDI-12. Wet conditions (SDI ≥0) ranged from a minimum of 25% in SDI-1 to a maximum of 71.389%, also in SDI-1. Overall analysis confirms that mild drought is the most frequently occurring drought type across all time scales throughout the basin. When minimum and maximum percentages are investigated only extreme drought class shown a constant behavior in which percentages are increasing with the increment of time scale.

Another assessment by considering categorization criteria has been done based on dry (SDI < 0) and wet (SDI ≥ 0) category in Fig. 5. When SDI values are classified as dry (SDI < 0) and wet (SDI ≥ 0), in SDI-1 and SDI-3 dry has a superiority upon wet, while in SDI-6 and SDI-9 wet has the superiority in terms of number of stations. In SDI-12 both groups have equal magnitude. From this point of view, in SDI-1 and SDI-3 drought events are more serious than SDI-6 and SDI-9-time scales in which even there is a slight difference between dry and wet.

### 4.2 Spatial Distribution of Drought and Wet Categories

Using IDW interpolation, we analyzed drought categories based on occurrence percentages across different time scales, with results shown in Fig. 6. For SDI-1, mild drought (15.65–64.41%) was highest in upper eastern areas, while moderate drought (4.01–11.89%)

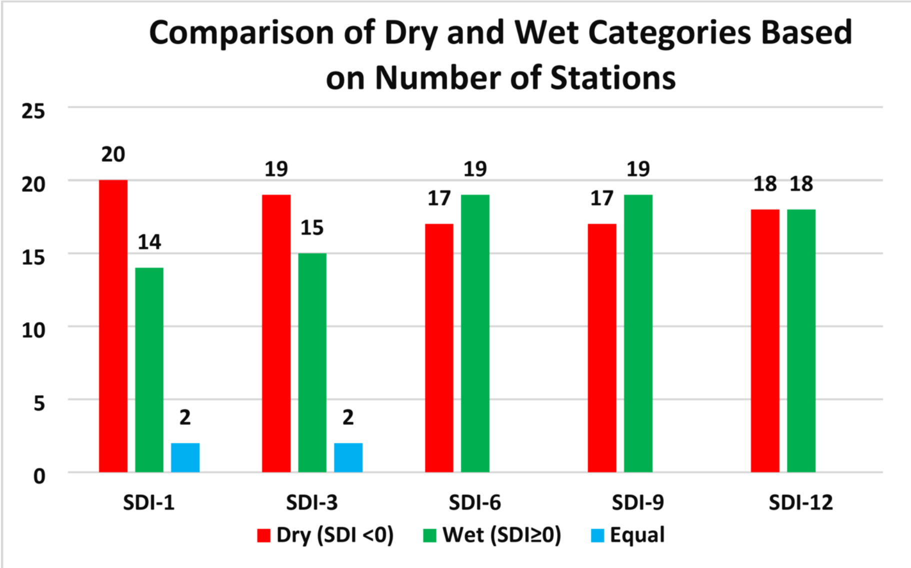


**Fig. 5** Comparison of dry (SDI < 0) and wet (SDI ≥ 0) categories based on number of stations

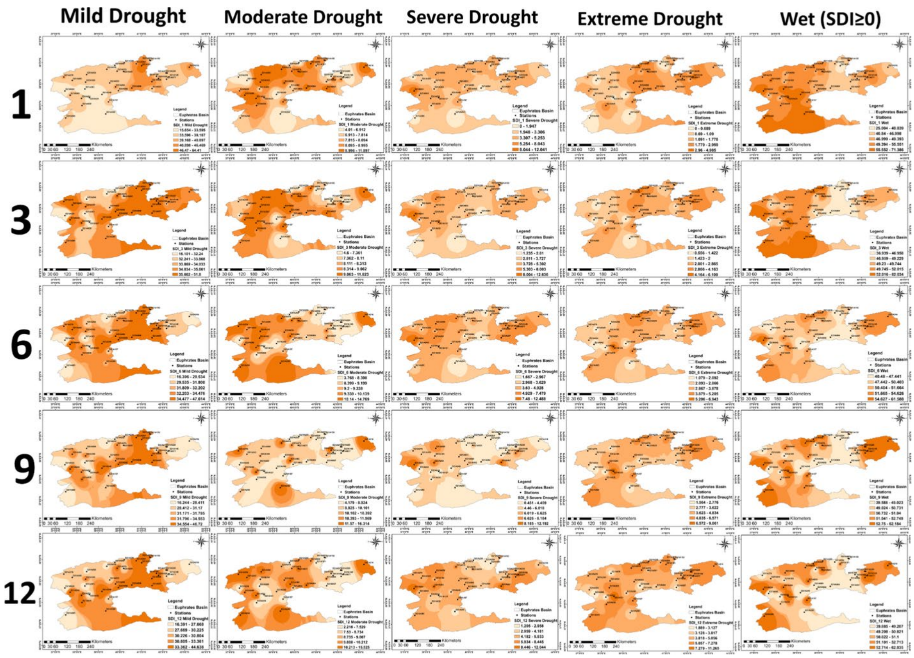


**Fig. 6** Spatial distribution results of drought and wet categories in all time scales

primarily affected northern regions and portions of the middle-west and upper-east. Severe drought (1.94–5.25%) affected nearly the entire basin, with highest intensity in a small western section. Extreme drought (0–4.98%) was most severe in northern and upper eastern areas. Wet conditions (SDI $\geq 0$, 25–71.38%) were predominantly observed in northern regions including upper western areas, and in middle and southern portions of the basin.

For SDI-3, mild drought conditions (16.1–51.8%) were most prevalent in upper regions, parts of upper and lower western areas, middle upper eastern sections, and southeast regions. Moderate drought (4.6–11.82%) was highest in northern areas, the western middle section, and small portions of the upper east. Severe drought (1.23–12.63%) peaked in a small section of the upper east, while most of the basin experienced lower levels of severe drought (2.81–5.3%). Extreme drought (0.556–6.109%) was most intense in northern areas and parts of the upper east. Wet conditions (36.93–62.03%) were primarily observed in upper and lower eastern regions, southern areas, and small northern sections.

For SDI-6, mild drought (16.39–47.61%) extended throughout the basin, with higher concentrations in northern regions including areas near the west and east, the eastern middle section, and the southeast. Moderate drought (3.76–14.76%) showed greatest intensity in portions of the north including the northwest, a small northeastern area, and the lower west and south regions. Severe drought (1.66–12.48%) was most pronounced in upper areas including parts of the upper west and east. Extreme drought (1.07–6.94%) followed a distribution pattern similar to SDI-3 with minor variations. Wet conditions (40.48–61.58%) were most prevalent in a small northern section, a significant portion of the east, and in limited areas of the upper and lower east. Notably, compared to SDI-3, the regions experiencing higher levels of wet conditions decreased.

For SDI-9, mild drought (16.24–46.72%) was most pronounced in northeastern areas, some middle sections, and the southeast region. Moderate drought (4.17–16.31%) showed higher values in small portions of the north, south, northeast, and middle areas, with most of the basin experiencing the lower end of this range (4.17–10.10%). Severe drought (0.451–12.19%) reached peak intensity in small sections of the upper west, north, and upper middle regions, though most areas experienced lower severity levels. Extreme drought (1.56–9.06%) was most significant in small parts of the north, northeast, middle, and lower west. Wet conditions (39.58–62.18%) were concentrated in the north, northeast, a narrow strip of upper west, and small portions of the middle and lower west.

In SDI-12, mild drought (16.39–44.63%) was most severe in the northeastern areas, much of the middle region, and southern areas, particularly the southeast. Central regions showed increased susceptibility to mild drought compared to SDI-9. Moderate drought (2.21–15.52%) exhibited higher intensities in the north (especially northwest), a small northeastern section, parts of the middle, lower east, and south, with affected regions becoming larger and more evenly distributed than in SDI-9. Severe drought (1.20–12.04%) primarily manifested in lower to middle intensity ranges across most of the basin, with highest values in upper regions, parts of the north including northeast. Extreme drought (1.88–11.26%) peaked in portions of the north, northeast, and small sections of the middle and lower west. Wet conditions (39.88–62.03%) were most prevalent in northern, northeastern, and northwestern regions, as well as parts of the middle and lower west.

Overall, the findings of IDW analysis have demonstrated that many portions of the basin are under the risk of hydrological droughts. The spatial distribution of hydrological droughts over the basin changes according to either time scale or drought category.

### 4.3 Trend Detection Tests Results

Obtained SDI series are tested by using MK test for detection of possible trends in time series. Test results are evaluated for significance level of α= 0.01 which corresponds to $Z = \pm 2.576$ and given in Fig. 7. Significant decreasing trends were observed in 14 stations for SDI-1, 18 stations for SDI-3, 20 stations for SDI-6, 19 stations for SDI-9, and 22 stations for SDI-12. This analysis suggests that a substantial proportion of stations (approximately half) exhibited significant decreasing trends across nearly all investigated time scales. Moreover, 12 stations which are D21 A121, D21 A169, D21 A181, D21 A213, D21 A220, D21 A240, D21 A265, E21 A024, E21 A031, E21 A035, E21 A045, E21 A077 have

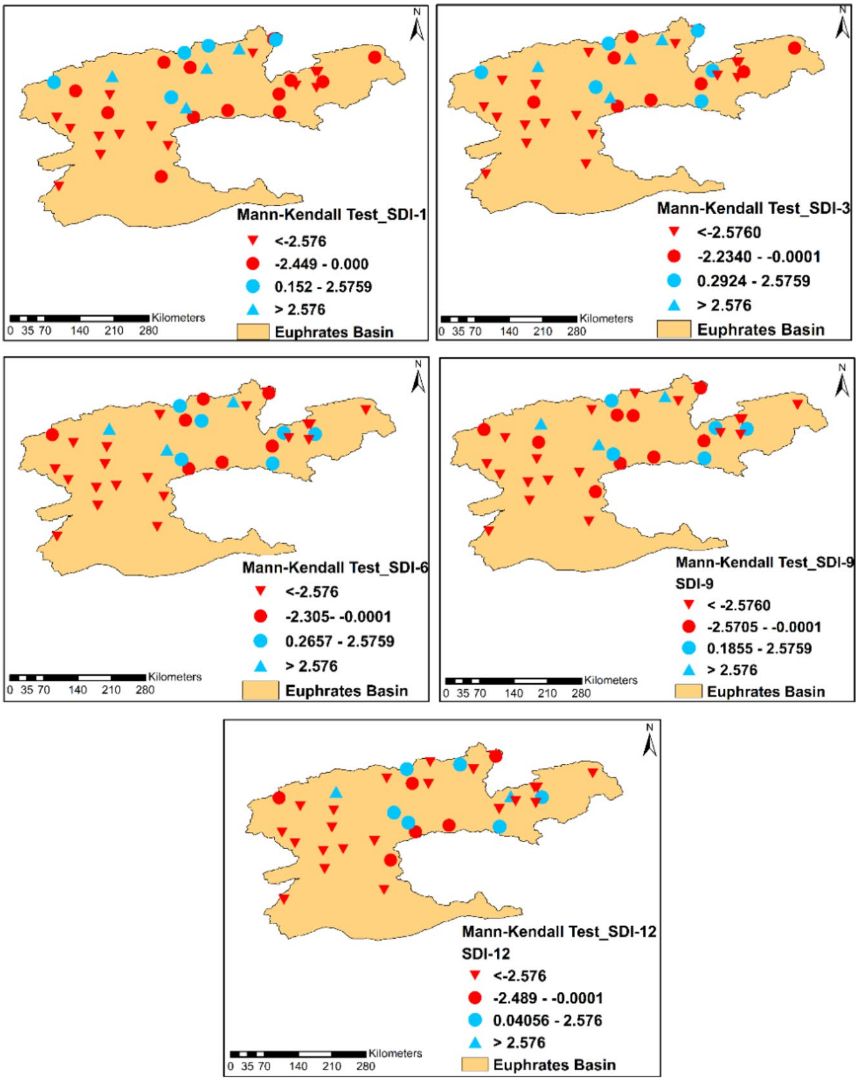


**Fig. 7** Mann-Kendall test results for all time scales over Euphrates Basin

demonstrated significant decreasing trends in all time scales while 5 stations (D21 A001, D21 A193, D21 A243, D21 A250, E21 A019) have significant decreasing trends in four timescales. Figure 7 reveals a spatial concentration of negative decreasing trends primarily within the western and central regions of the study area. Furthermore, significant increasing trends were observed in 4 stations for SDI-1, 4 stations for SDI-3, 3 stations for SDI-6, 3 stations for SDI-9, and 2 stations for SDI-12. Notably, station E21 A056 exhibited significant increasing trends across all time scales, while station E21 A054 demonstrated significant trends in four-time scales. Beside of significant cases, there have been non-significant results. For example, in SDI-1 13(5), in SDI-3 8(6), in SDI-6 7(5), in SDI-9 9(5), in SDI-12 6(6) stations possess decreasing trends (increasing trends). However, these trends are not significant when considering significance level of α= 0.01 ( $Z = \pm 2.576$). But again, superiority of decreasing trends is prevalent in the basin in all time scales except at SDI-12.

Via SR Test SDI series are tested for possible trend detection. Similar to the MK Test, trends are assessed considering significance level of α= 0.01 which corresponds to $Z = \pm 2.576$. Results are illustrated in Fig. 8. The results demonstrate that significant decreasing trends are observed in 14 stations for SDI-1, 17 stations for SDI-3, 20 stations for SDI-6, 21 stations for SDI-9, and 21 stations for SDI-12. In 13 stations which are D21 A121, D21 A169, D21 A181, D21 A193, D21 A213, D21 A220, D21 A240, D21 A265, E21 A024, E21 A031, E21 A035, E21 A045, E21 A077 all time scales have significant decreasing trends while 4 stations (D21 A001, D21 A157, D21 A243, D21 A250) have significant trends in four-time scales. Similar to MK test, significant decreasing trends have been mostly observed in west and middle. Also, In SDI-1 4 stations, in SDI-3 4 stations, in SDI-6 2 stations, in SDI-9 2 stations, in SDI-12 2 stations have shown significant increasing trend behavior. Similar to MK test, only E21 A056 station have shown a significant increasing trend in all time scales while E21 A054 station have significant trends in all time scales. When it comes to non-significant cases, in SDI-1 13(5), in SDI-3 9(6), in SDI-6 6(8), in SDI-9 7(6), in SDI-12 7(6) stations have given non-significant decreasing (increasing) trends. Again, either in significant or non-significant cases, there has been a superiority of decreasing trends over the basin except at SDI-6 in non-significant cases.

In another trend detection test which is Wilcoxon Test, trend results have been illustrated in Fig. 9. The findings have revealed that in SDI-1 15 stations, in SDI-3 17 stations, in SDI-6 17 stations, in SDI-9 16 stations, in SDI-12 20 stations have shown a significant decreasing trend behavior based on significance level of α= 0.01 ( $Z = \pm 2.576$.). In 12 stations that are D21 A121, D21 A169, D21 A181, D21 A193, D21 A213, D21 A240, D21 A265, E21 A024, E21 A031, E21 A035, E21 A045, E21 A077 all time scales have significant decreasing trends while the stations of D21 A243 and E21 A019 have significant decreasing trends in four-time scales. Besides, a significant increasing trend behavior has been observed as in SDI-1 4 stations, in SDI-3 5 stations, in SDI-6 2 stations, in SDI-9 2 stations, in SDI-12 2 stations. In E21 A056 station all time scales have significant increasing trends while D21 A252 there have been four-time scales having significant increasing trends. Similar to Mann-Kendall and Spearman Rho's Test, non-significant trends have been observed. In SDI-1 11(6), in SDI-3 9(5), in SDI-6 8(9), in SDI-9 15(3), in SDI-12 11(3) stations have demonstrated non-significant decreasing(increasing) trends. Again, by this test, it is also very attractive that there has been a superiority of decreasing trends either in significant or non-significant cases, except at SDI-6 of non-significant case which is similar to non-significant case of SDI-6 of Spearman's Rho Test.

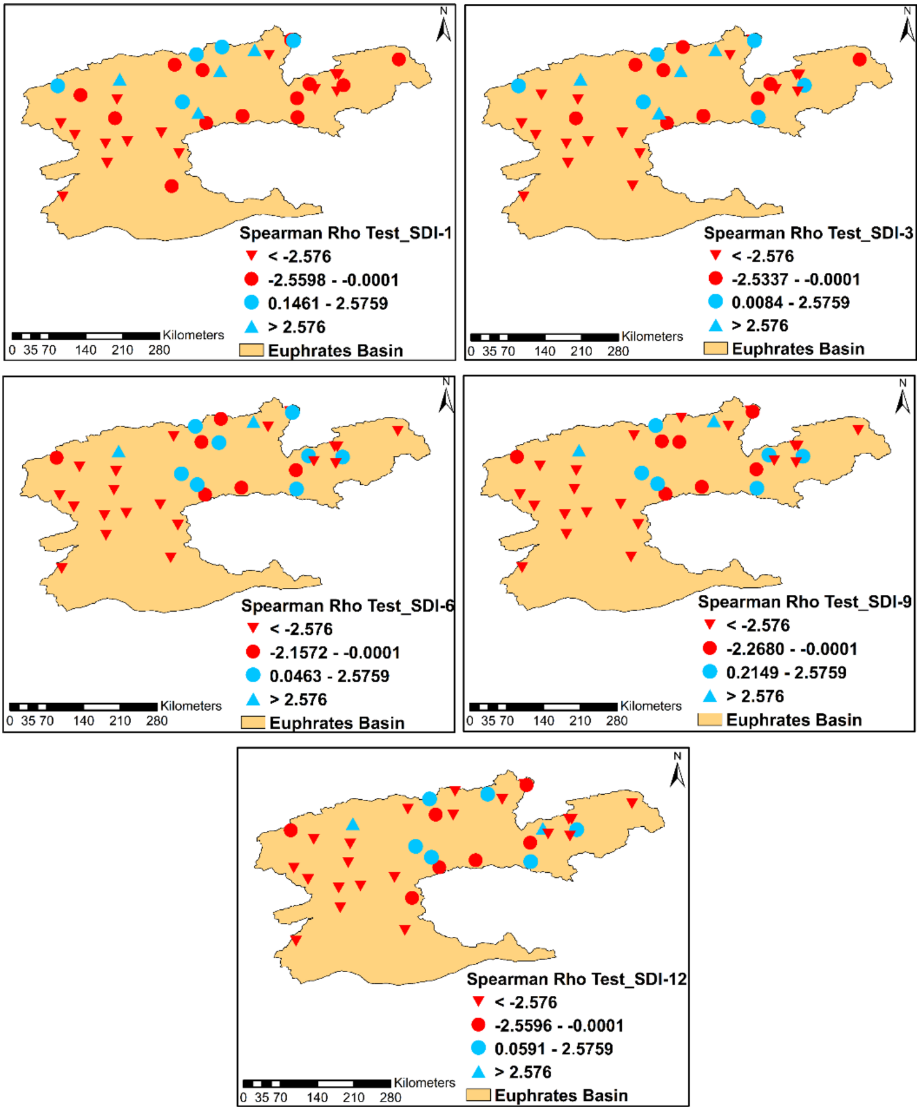


**Fig. 8** Spearman's Rho test results for all time scales over Euphrates Basin

Using Sen's Slope Estimator, trend slopes were calculated, and the results are presented in Fig. 10. The analysis reveals declining trends across multiple time scales: 27 stations in SDI-1, 26 in SDI-3, 26 in SDI-6, 28 in SDI-9, and 28 in SDI-12. Notably, 24 stations exhibit declining trends across all time scales. Conversely, increasing trends were observed in 8 stations for SDI-1, 10 for SDI-3, 9 for SDI-6, 8 for SDI-9, and 7 for SDI-12. Four stations—D21 A252, E21 A033, E21 A056, and E21 A066—show increasing trends across all time scales, while D21 A166 and E21 A057 exhibit increasing trends in four out of five-time scales. Additionally, no trend was detected in specific cases: SDI-12 for D21 A148, SDI-6

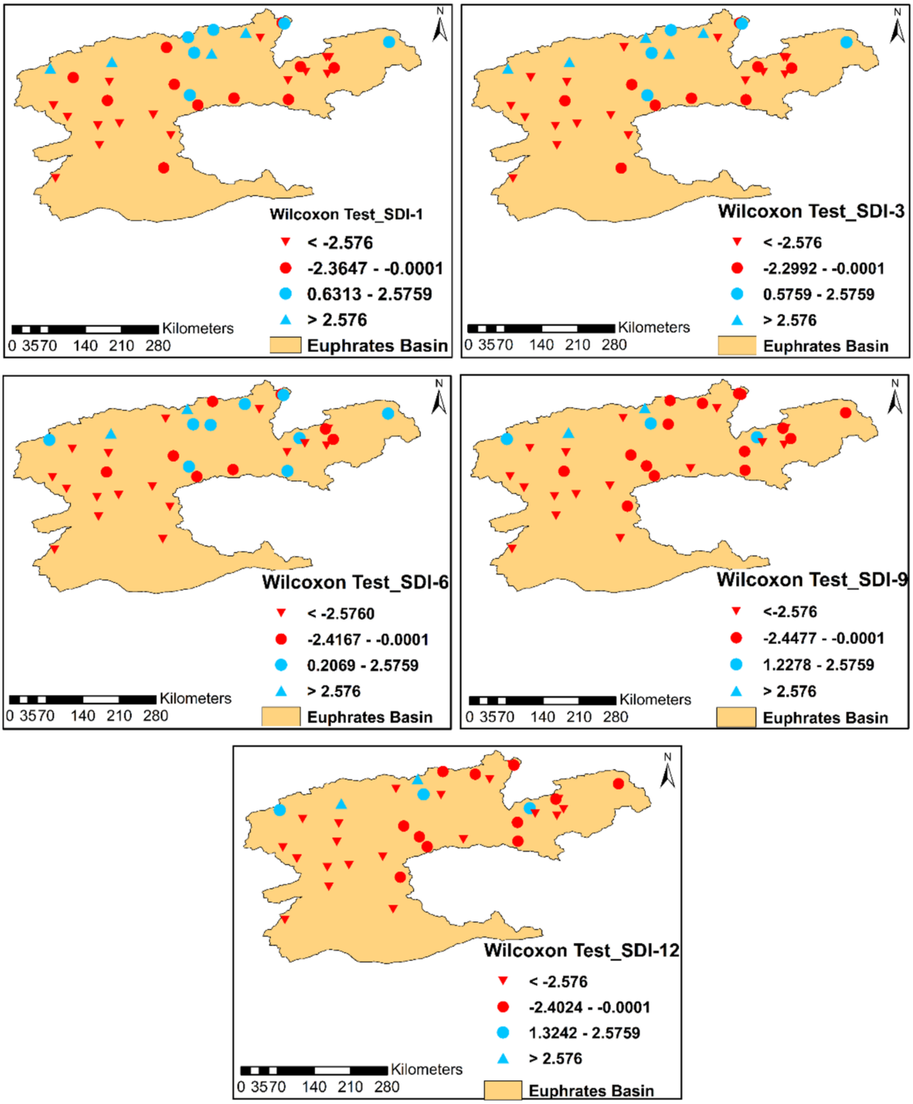


**Fig. 9** Wilcoxon test results for all time scales over Euphrates Basin

for D21 A152, and SDI-1 for D21 A230, as indicated by a trend slope of zero. Similar to the findings of the previous three tests, decreasing trends dominate across the basin.

The ITA significance test results are tabulated in Table 4. In the table, ↓ shows significant decreasing trend, ↑ indicates significant increasing trend and 0 means no significant trend exists for the selected confidence level. The analysis revealed significant decreasing trends in 24 stations for SDI-1, 25 stations for SDI-3, 27 stations for SDI-6, 28 stations for SDI-9, and 29 stations for SDI-12. Notably, 22 out of 36 stations demonstrated significant decreasing trends across all time scales, with stations D21 A001 and E21 A064 exhibiting significant decreases in all time scales. Conversely, significant increasing trends were

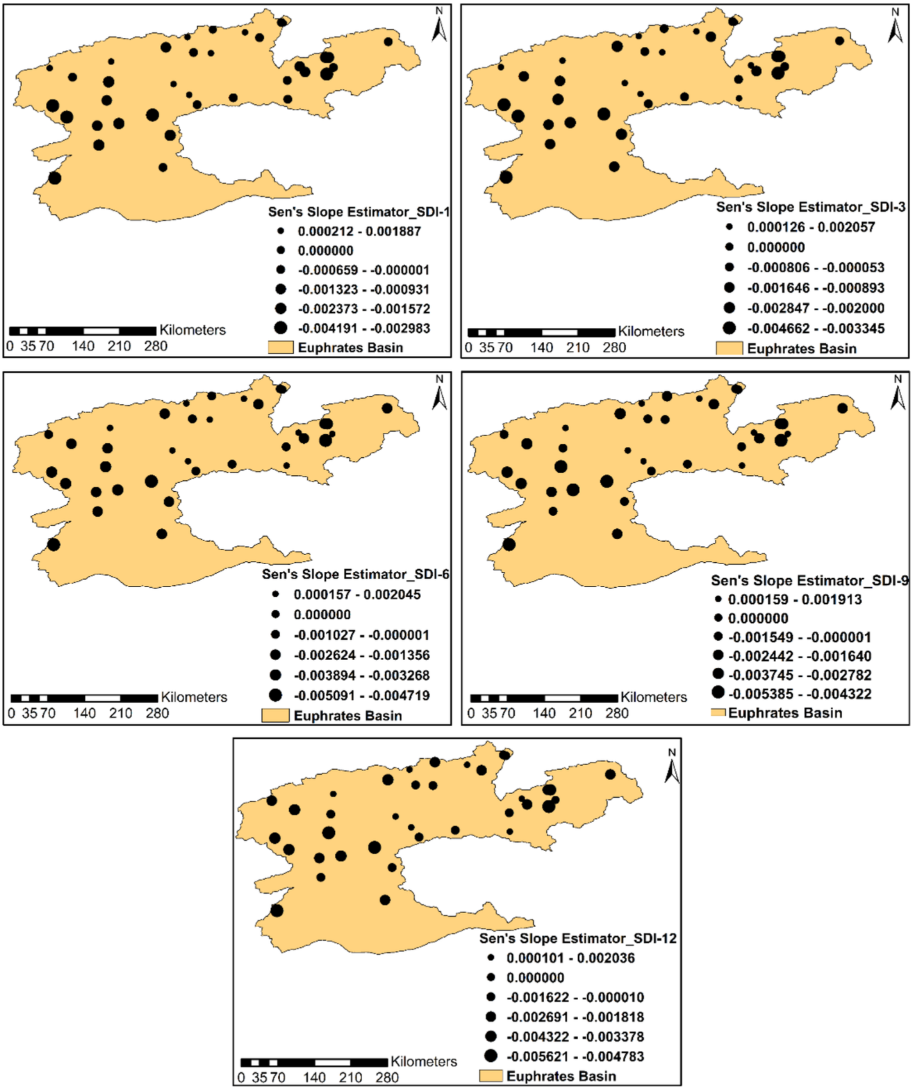


**Fig. 10** Sen's Slope test results for all time scales over Euphrates Basin

observed in 10 stations for SDI-1, 9 stations for SDI-3, 7 stations for SDI-6, 4 stations for SDI-9, and 4 stations for SDI-12. In the stations of D21 A252, D21 A279, E21 A056, E21 A076 all time scales have significant trends. When it comes to no significant trend case it has been recorded that in SDI-1 2 stations, in SDI-3 2 stations, in SDI-6 2 stations, in SDI-9 4 stations, in SDI-12 3 stations no significant trends have been existed. Similar to other tests, it is again very clear that decreasing trends have dominated the basin.

In the graphical ITA assessment groups have been categorized as Mild Drought (MD), Moderate Drought (MOD), Severe and Extreme Drought (SED) which indicates a combination of the last two drought categories (SDI≤−1.5), Mild Wet (MW), Moderate Wet (MOW),

**Table 4** Innovative trend significance test results (↓: significant decreasing trend, ↑: significant increasing trend, 0: no significant trend)

| | Time Scale | | | | | | | | | | | | | | | Type of Trends | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 3 | | | 6 | | | 9 | | | 12 | | | | | | | |
| Station | TS | LCL (99%) | UCL (99%) | TS | LCL (99%) | UCL (99%) | TS | LCL (99%) | UCL (99%) | TS | LCL (99%) | UCL (99%) | TS | LCL (99%) | UCL (99%) | 1 | 3 | 6 | 9 | 12 |
| D21A001 | -0.0000460 | -0.0000537 | 0.0000537 | -0.0001829 | -0.0000602 | 0.0000602 | -0.0004092 | -0.0000701 | 0.0000701 | -0.0005548 | -0.0000697 | 0.0000697 | -0.0006772 | -0.0000627 | 0.0000627 | 0 | ↓ | ↓ | ↓ | ↓ |
| D21A121 | -0.0021690 | -0.0000836 | 0.0000836 | -0.0025171 | -0.0000656 | 0.0000656 | -0.0036244 | -0.0001125 | 0.0001125 | -0.0044684 | -0.0001291 | 0.0001291 | -0.0048289 | -0.0002114 | 0.0002114 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A148 | -0.0026829 | -0.0002848 | 0.0002848 | -0.0028369 | -0.0002473 | 0.0002473 | -0.0033946 | -0.0003701 | 0.0003701 | -0.0034751 | -0.0004532 | 0.0004532 | -0.0035739 | -0.0004469 | 0.0004469 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A152 | 0.0002841 | -0.0000893 | 0.0000893 | 0.0002046 | -0.0001185 | 0.0001185 | -0.0000292 | -0.0001330 | 0.0001330 | -0.0001022 | -0.0001377 | 0.0001377 | -0.0001353 | -0.0001515 | 0.0001515 | ↑ | ↑ | 0 | 0 | 0 |
| D21A157 | -0.0017291 | -0.0000829 | 0.0000829 | -0.0018415 | -0.0000794 | 0.0000794 | -0.0016494 | -0.0001194 | 0.0001194 | -0.0014251 | -0.0001245 | 0.0001245 | -0.0012862 | -0.0001345 | 0.0001345 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A166 | -0.0013279 | -0.0002546 | 0.0002546 | -0.0005123 | -0.0002258 | 0.0002258 | 0.0000303 | -0.0002873 | 0.0002873 | 0.0001567 | -0.0003599 | 0.0003599 | -0.0001374 | -0.0004896 | 0.0004896 | ↓ | ↓ | 0 | 0 | 0 |
| D21A169 | -0.0015239 | -0.0000669 | 0.0000669 | -0.0017949 | -0.0000655 | 0.0000655 | -0.0021223 | -0.0000701 | 0.0000701 | -0.0024484 | -0.0000796 | 0.0000796 | -0.0028775 | -0.0001061 | 0.0001061 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A181 | -0.0019496 | -0.0001996 | 0.0001996 | -0.0021324 | -0.0001452 | 0.0001452 | -0.0026157 | -0.0002166 | 0.0002166 | -0.0031479 | -0.0002077 | 0.0002077 | -0.0037105 | -0.0001580 | 0.0001580 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A193 | -0.0012946 | -0.0001983 | 0.0001983 | -0.0014588 | -0.0001653 | 0.0001653 | -0.0016885 | -0.0000917 | 0.0000917 | -0.0016422 | -0.0001275 | 0.0001275 | -0.0018340 | -0.0001937 | 0.0001937 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A213 | -0.0015225 | -0.0001208 | 0.0001208 | -0.0018057 | -0.0000838 | 0.0000838 | -0.0022540 | -0.0000919 | 0.0000919 | -0.0023975 | -0.0001271 | 0.0001271 | -0.0025359 | -0.0001255 | 0.0001255 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A216 | 0.0002532 | -0.0001038 | 0.0001038 | 0.0000114 | -0.0001168 | 0.0001168 | -0.0003033 | -0.0001083 | 0.0001083 | -0.0005722 | -0.0001160 | 0.0001160 | -0.0006496 | -0.0001399 | 0.0001399 | ↑ | 0 | ↓ | ↓ | ↓ |
| D21A220 | -0.0018215 | -0.0001330 | 0.0001330 | -0.0017945 | -0.0001086 | 0.0001086 | -0.0015699 | -0.0000957 | 0.0000957 | -0.0014205 | -0.0001202 | 0.0001202 | -0.0014472 | -0.0001243 | 0.0001243 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A230 | 0.0004026 | -0.0000889 | 0.0000889 | 0.0001856 | -0.0001497 | 0.0001497 | -0.0002800 | -0.0001873 | 0.0001873 | -0.0007727 | -0.0002260 | 0.0002260 | -0.0011935 | -0.0002792 | 0.0002792 | ↑ | ↑ | ↓ | ↓ | ↓ |
| D21A240 | -0.0027142 | -0.0002088 | 0.0002088 | -0.0043187 | -0.0001693 | 0.0001693 | -0.0057174 | -0.0002318 | 0.0002318 | -0.0060851 | -0.0002730 | 0.0002730 | -0.0064646 | -0.0003232 | 0.0003232 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A243 | -0.0005598 | -0.0000894 | 0.0000894 | -0.0013546 | -0.0001103 | 0.0001103 | -0.0020479 | -0.0001741 | 0.0001741 | -0.0026789 | -0.0002009 | 0.0002009 | -0.0035386 | -0.0002845 | 0.0002845 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A250 | -0.0002855 | -0.0000820 | 0.0000820 | -0.0006376 | -0.0001022 | 0.0001022 | -0.0012937 | -0.0001379 | 0.0001379 | -0.0017670 | -0.0001614 | 0.0001614 | -0.0021763 | -0.0001805 | 0.0001805 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A252 | 0.0016948 | -0.0000989 | 0.0000989 | 0.0021394 | -0.0001474 | 0.0001474 | 0.0024843 | -0.0001919 | 0.0001919 | 0.0024892 | -0.0001910 | 0.0001910 | 0.0025396 | -0.0002075 | 0.0002075 | ↑ | ↑ | ↑ | ↑ | ↑ |
| D21A263 | -0.0006895 | -0.0001471 | 0.0001471 | -0.0006072 | -0.0001522 | 0.0001522 | -0.0013603 | -0.0001532 | 0.0001532 | -0.0021113 | -0.0002269 | 0.0002269 | -0.0027676 | -0.0003372 | 0.0003372 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A265 | -0.0037630 | -0.0001831 | 0.0001831 | -0.0046731 | -0.0001089 | 0.0001089 | -0.0050586 | -0.0001600 | 0.0001600 | -0.0052040 | -0.0002306 | 0.0002306 | -0.0051847 | -0.0002894 | 0.0002894 | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A279 | 0.0025510 | -0.0002540 | 0.0002540 | 0.0026438 | -0.0002716 | 0.0002716 | 0.0026652 | -0.0003149 | 0.0003149 | 0.0024010 | -0.0003223 | 0.0003223 | 0.0022950 | -0.0003496 | 0.0003496 | ↑ | ↑ | ↑ | ↑ | ↑ |
| E21A002 | -0.0006998 | -0.0000772 | 0.0000772 | -0.0007597 | -0.0000858 | 0.0000858 | -0.0007281 | -0.0001167 | 0.0001167 | -0.0006546 | -0.0001318 | 0.0001318 | -0.0007172 | -0.0001721 | 0.0001721 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A019 | -0.0015557 | -0.0001817 | 0.0001817 | -0.0022424 | -0.0001683 | 0.0001683 | -0.0029277 | -0.0002174 | 0.0002174 | -0.0034319 | -0.0002772 | 0.0002772 | -0.0040532 | -0.0003155 | 0.0003155 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A024 | -0.0036880 | -0.0001086 | 0.0001086 | -0.0037327 | -0.0001166 | 0.0001166 | -0.0037609 | -0.0001193 | 0.0001193 | -0.0037782 | -0.0001203 | 0.0001203 | -0.0037954 | -0.0001223 | 0.0001223 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A031 | -0.0011246 | -0.0000217 | 0.0000217 | -0.0013450 | -0.0000297 | 0.0000297 | -0.0016021 | -0.0000336 | 0.0000336 | -0.0018400 | -0.0000321 | 0.0000321 | -0.0019791 | -0.0000366 | 0.0000366 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A033 | -0.0001834 | -0.0000679 | 0.0000679 | -0.0001113 | -0.0000465 | 0.0000465 | -0.0001044 | -0.0000556 | 0.0000556 | -0.0000948 | -0.0000619 | 0.0000619 | -0.0001423 | -0.0000687 | 0.0000687 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A035 | -0.0014391 | -0.0000303 | 0.0000303 | -0.0014528 | -0.0000297 | 0.0000297 | -0.0014749 | -0.0000440 | 0.0000440 | -0.0015999 | -0.0000618 | 0.0000618 | -0.0017278 | -0.0000714 | 0.0000714 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A045 | -0.0030282 | -0.0000574 | 0.0000574 | -0.0030517 | -0.0000580 | 0.0000580 | -0.0029987 | -0.0000676 | 0.0000676 | -0.0029565 | -0.0000713 | 0.0000713 | -0.0029340 | -0.0000648 | 0.0000648 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A051 | 0.0013265 | -0.0000397 | 0.0000397 | 0.0010512 | -0.0000590 | 0.0000590 | 0.0003741 | -0.0000713 | 0.0000713 | -0.0003279 | -0.0000807 | 0.0000807 | -0.0007438 | -0.0000899 | 0.0000899 | ↑ | ↑ | ↑ | ↓ | ↓ |
| E21A054 | 0.0012080 | -0.0000654 | 0.0000654 | 0.0010536 | -0.0000755 | 0.0000755 | 0.0005579 | -0.0000844 | 0.0000844 | 0.0000589 | -0.0000917 | 0.0000917 | -0.0002442 | -0.0001208 | 0.0001208 | ↑ | ↑ | ↑ | 0 | ↓ |
| E21A056 | 0.0017619 | -0.0000595 | 0.0000595 | 0.0017432 | -0.0000991 | 0.0000991 | 0.0015255 | -0.0001411 | 0.0001411 | 0.0013340 | -0.0001742 | 0.0001742 | 0.0012389 | -0.0001957 | 0.0001957 | ↑ | ↑ | ↑ | ↑ | ↑ |
| E21A057 | -0.0003017 | -0.0000696 | 0.0000696 | -0.0000332 | -0.0000735 | 0.0000735 | 0.0002326 | -0.0001000 | 0.0001000 | 0.0000768 | -0.0001206 | 0.0001206 | 0.0000213 | -0.0001486 | 0.0001486 | ↓ | 0 | ↑ | 0 | 0 |
| E21A058 | -0.0007481 | -0.0000588 | 0.0000588 | -0.0008897 | -0.0000474 | 0.0000474 | -0.0009989 | -0.0000620 | 0.0000620 | -0.0009389 | -0.0000800 | 0.0000800 | -0.0011376 | -0.0001100 | 0.0001100 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A064 | -0.0000620 | -0.0000684 | 0.0000684 | -0.0003895 | -0.0000826 | 0.0000826 | -0.0006683 | -0.0000851 | 0.0000851 | -0.0007562 | -0.0000915 | 0.0000915 | -0.0009867 | -0.0001095 | 0.0001095 | 0 | ↓ | ↓ | ↓ | ↓ |
| E21A066 | 0.0002113 | -0.0001005 | 0.0001005 | 0.0001672 | -0.0000825 | 0.0000825 | -0.0000709 | -0.0000660 | 0.0000660 | -0.0003374 | -0.0000538 | 0.0000538 | -0.0005818 | -0.0000799 | 0.0000799 | ↑ | ↑ | ↓ | ↓ | ↓ |
| E21A076 | 0.0001394 | -0.0000778 | 0.0000778 | 0.0001685 | -0.0001271 | 0.0001271 | 0.0003773 | -0.0001105 | 0.0001105 | 0.0005499 | -0.0001284 | 0.0001284 | 0.0005504 | -0.0001364 | 0.0001364 | ↑ | ↑ | ↑ | ↑ | ↑ |
| E21A077 | -0.0032372 | -0.0001222 | 0.0001222 | -0.0037174 | -0.0001171 | 0.0001171 | -0.0040823 | -0.0001303 | 0.0001303 | -0.0042924 | -0.0001572 | 0.0001572 | -0.0046451 | -0.0001849 | 0.0001849 | ↓ | ↓ | ↓ | ↓ | ↓ |

Severe and Extreme Wet (SEW) which also shows a combination of last two wet categories (SDI ≥ 1.5) in SDI series. Some examples of graphical results have been given with Fig. 11 and all of the graphical results have been given in Supplementary. In the related figure, it can be seen that there has been a monotonic increasing trend in SDI-12 of D21 A252 station while a monotonic decreasing trend has existed in SDI-9 of D21 A169. Besides trend behavior of SDI-1 of E21 A064 is a non-monotonic since time series has been in two portions of 45° line.

The types of trends are tabulated in Table 5. In the table increasing trend, decreasing trend and no trend tendency were shown with "↑", "↓", "0" respectively. In SDI-1, 127 times decreasing trends (the fewest across time scales) and 47 times increasing trends (the most) were detected, with 6 stations showing only decreasing trends. Stations D21 A279 and E21 A051 had increasing trends in all groups. SDI-1 also had 42 times no-trend cases, the highest among all time scales. In SDI-3, there were 144 times decreasing, 42 times increasing, and 30 times no-trend cases, with 10 stations showing only decreasing trends. SDI-6 recorded 145 times decreasing, 42 times increasing, and 29 times no-trend cases, again with 10 stations having all decreasing trends. In SDI-9, 148 times decreasing, 43 times increasing, and 25 times no-trend cases were observed, with 9 stations showing consistent

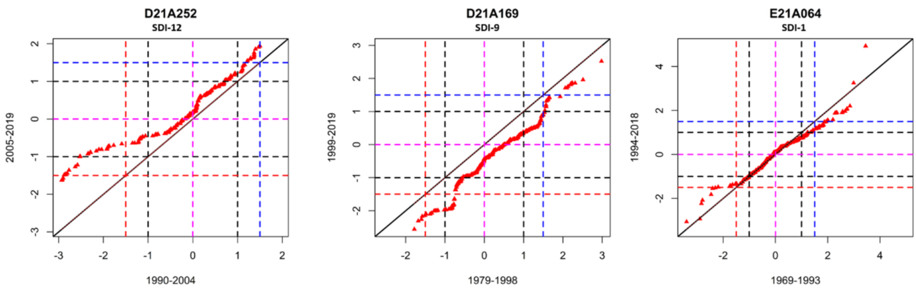


**Fig. 11** Graphical ITA results by some examples

**Table 5** Graphical ITA results of selected stations in euphrates basin based on drought classification mild drought **(MD)**, moderate drought **(MOD)**, severe and extreme drought **(SED)** (SDI≤−1.5), mild wet **(MW)**, moderate wet **(MOW)**, severe and extreme wet **(SEW)** (SDI ≥ 1.5), ↑: increasing trend, ↓: decreasing trend, 0: no trend

| | SDI-1 | | | | | | SDI-3 | | | | | | SDI-6 | | | | | | SDI-9 | | | | | | SDI-12 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | MD | MOD | SED | MW | MOW | SEW | MD | MOD | SED | MW | MOW | SEW | MD | MOD | SED | MW | MOW | SEW | MD | MOD | SED | MW | MOW | SEW | MD | MOD | SED | MW | MOW | SEW |
| D21A001 | 0 | ↑ | ↑ | ↓ | ↓ | ↓ | 0 | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | 0 | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ |
| D21A121 | ↓ | ↓ | 0 | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ |
| D21A148 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A152 | 0 | ↑ | ↑ | 0 | ↑ | ↓ | 0 | ↑ | ↑ | 0 | 0 | ↓ | 0 | 0 | ↑ | 0 | ↓ | ↓ | 0 | ↑ | ↑ | 0 | 0 | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ |
| D21A157 | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | 0 | ↑ | ↑ | ↓ | ↓ | ↓ | ↑ | ↑ | 0 |
| D21A166 | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | 0 | ↑ | ↑ | ↑ | ↓ | ↑ | ↓ | ↑ | ↑ | 0 | ↓ |
| D21A169 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ |
| D21A181 | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ |
| D21A193 | ↓ | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A213 | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ |
| D21A216 | 0 | ↓ | 0 | 0 | ↑ | ↓ | ↑ | ↓ | ↓ | 0 | ↓ | ↓ | ↑ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ |
| D21A220 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | 0 |
| D21A230 | 0 | ↓ | ↓ | ↑ | 0 | 0 | ↑ | 0 | ↓ | ↑ | 0 | ↓ | ↑ | ↑ | ↓ | 0 | ↓ | ↓ | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ |
| D21A240 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ |
| D21A243 | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| D21A250 | ↓ | ↓ | 0 | 0 | ↑ | ↑ | ↓ | ↓ | 0 | 0 | ↑ | ↑ | ↓ | ↓ | 0 | ↓ | ↑ | ↑ | ↓ | ↓ | 0 | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ |
| D21A252 | ↑ | ↑ | ↑ | 0 | 0 | ↓ | ↑ | ↑ | ↑ | ↑ | 0 | ↓ | ↑ | ↑ | ↑ | ↑ | 0 | 0 | ↑ | ↑ | ↑ | ↑ | ↑ | 0 | ↑ | ↑ | ↑ | ↑ | ↑ | 0 |
| D21A263 | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | 0 |
| D21A265 | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↑ | ↓ | ↓ | 0 | 0 | ↓ | ↑ | ↓ |
| D21A279 | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | 0 | 0 | ↑ | ↑ | ↑ | ↑ | 0 | ↑ | ↑ | ↑ | 0 | ↑ | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↓ | 0 | ↑ | ↑ | ↑ |
| E21A002 | 0 | ↓ | ↑ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A019 | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ |
| E21A024 | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ |
| E21A031 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A033 | ↑ | 0 | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↑ | 0 | ↓ | ↓ | ↑ | ↑ | ↑ | ↓ | ↓ | ↓ | ↑ | ↑ | ↑ | ↓ | ↓ | ↓ |
| E21A035 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A045 | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ |
| E21A051 | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ | 0 | ↑ | ↓ | ↓ | ↑ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A054 | ↑ | 0 | ↑ | ↑ | ↑ | ↑ | 0 | 0 | ↑ | ↑ | ↑ | ↑ | 0 | 0 | ↑ | ↑ | ↑ | ↑ | 0 | 0 | ↑ | 0 | ↓ | 0 | 0 | ↓ | ↑ | 0 | ↓ | ↓ |
| E21A056 | ↑ | ↑ | ↑ | ↑ | ↑ | 0 | ↑ | ↑ | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ |
| E21A057 | ↓ | ↓ | ↓ | 0 | ↑ | 0 | 0 | ↓ | ↓ | ↓ | ↑ | ↑ | ↑ | ↓ | ↓ | 0 | ↑ | ↑ | ↑ | ↓ | ↓ | 0 | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ | ↑ | ↓ |
| E21A058 | 0 | 0 | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A064 | 0 | 0 | ↑ | 0 | ↓ | ↓ | 0 | 0 | ↑ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | 0 | ↓ | ↓ | ↓ | ↓ | ↓ |
| E21A066 | 0 | ↓ | ↓ | ↑ | 0 | ↑ | 0 | ↓ | ↓ | ↑ | ↓ | 0 | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | ↑ | ↑ | ↓ | ↓ | ↓ | 0 | ↓ | ↑ | ↓ | ↓ | ↓ |
| E21A076 | 0 | ↓ | ↓ | ↓ | ↑ | ↓ | 0 | ↓ | ↓ | ↑ | ↓ | ↓ | ↑ | 0 | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ | ↑ | ↑ | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↓ | ↓ |
| E21A077 | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | 0 | 0 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |

decreasing trends. SDI-12 had the highest number of decreasing trends (152), but the fewest increasing (40) and no-trend (24) cases. Seven stations had all decreasing trends, while D21 A252 showed increasing trends in 5 groups. Figure 12 illustrates the trend distribution across time scales.

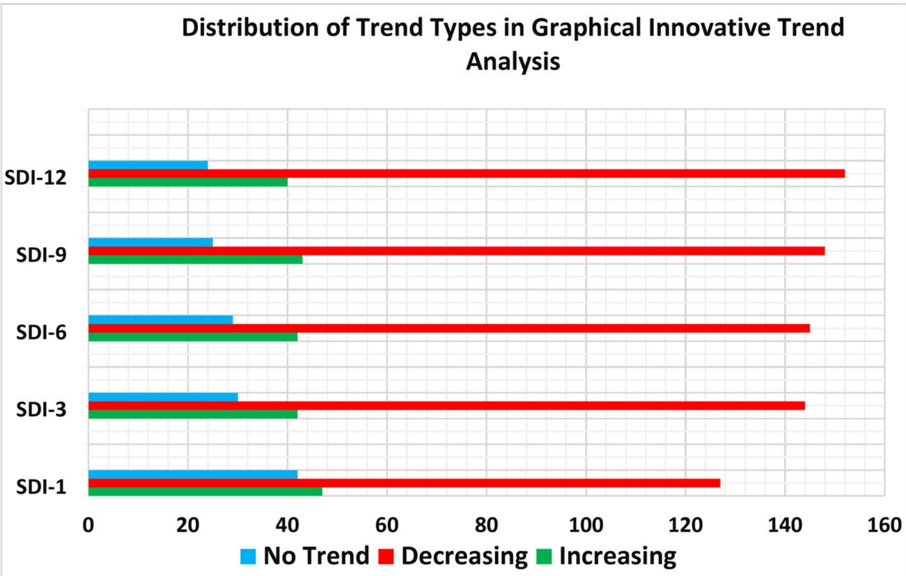


**Fig. 12** Distribution of trend types in graphical ITA test

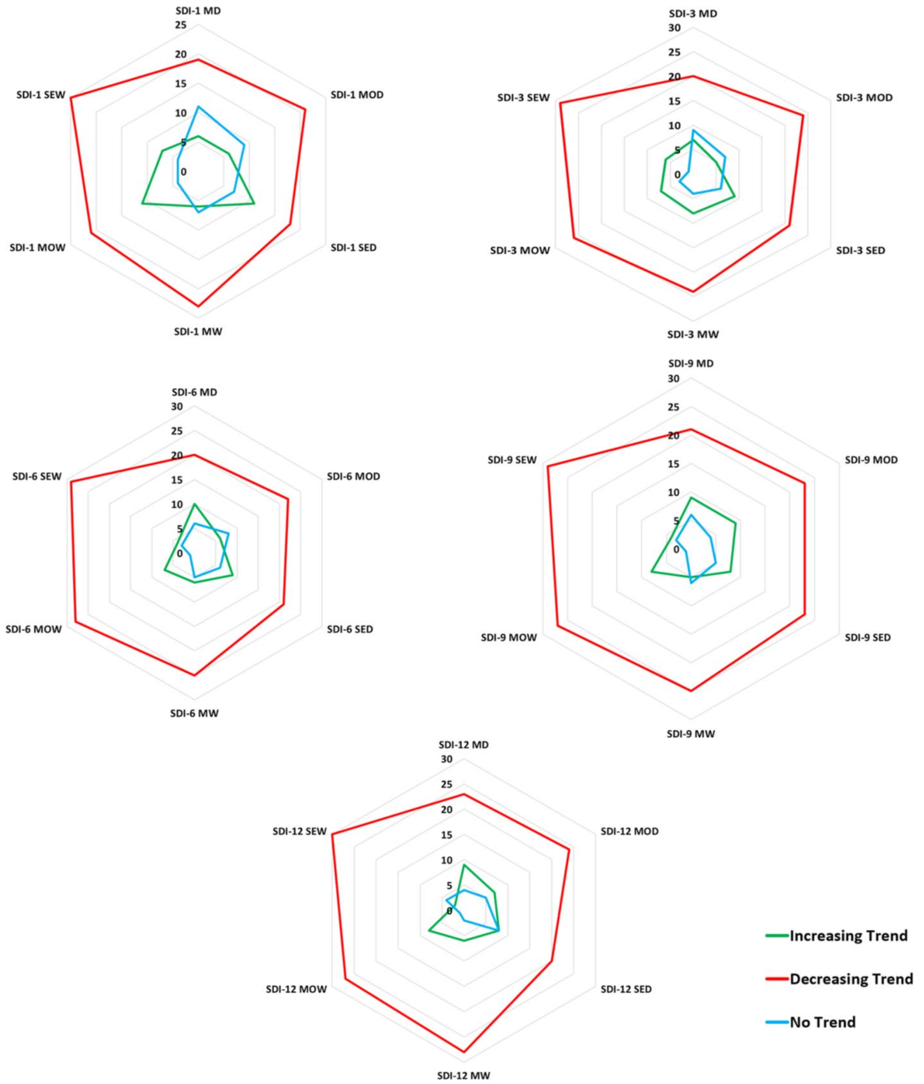


**Fig. 13** Distribution of trend types in Mild Drought **(MD)**, Moderate Drought **(MOD)**, Severe and Extreme Drought **(SED)** (SDI≤−1.5), Mild Wet **(MW)**, Moderate Wet **(MOW)**, Severe and Extreme Wet **(SEW)** (SDI ≥ 1.5) by graphical ITA test

Figure 13 presents the trend patterns for drought and wet categories across time scales. Mild drought (MD) showed decreasing trends in all time scales for 18 out of 36 stations, while stations D21 A252, D21 A279, and E21 A056 showed increasing trends, and E21 A064 and E21 A066 showed no trend. Moderate drought (MOD) had decreasing trends in 14 stations, increasing in D21 A001, D21 A252, and E21 A056, and no trend in E21 A024. Severe and Extreme Drought (SED, SDI ≤ −1.5) showed decreasing trends in 10 stations, increasing in D21 A001, D21 A152, D21 A252, and E21 A054, and no trend in E21 A024. Mild wet (MW) showed decreasing trends in 19 stations, increasing in D21 A279 and E21

A056, and no trend in D21 A216. Moderate wet (MOW) had decreasing trends in 17 stations, and increasing trends in D21 A279 and E21 A057. Severe and Extreme Wet (SEW, SDI $\geq 1.5$) showed decreasing trends in 21 stations and increasing trends in D21 A250.

### 4.4 Discussion

The objective of this research was monitoring hydrological droughts for Euphrates Basin, Turkey, by examining spatiotemporal patterns considering across multiple times scales (1, 3, 6, 9, 12-month). Drought and wet events were predicted by SDI and drought and wet (SDI $\geq 0$) categories were analyzed spatially by IDW for all time scales. Possible trends in time scales were tested with the tests of Mann-Kendall, Spearman's Rho, Wilcoxon Test, Innovative Trend Significance Test considering significance level of $\alpha = 0.01$ and Sen's Slope Estimator. Even trends in drought and wet categories were analyzed by graphical ITA test.

The findings of this study have suggested that mild drought type has been the most repetitive drought type among all drought categories. In many drought monitoring studies (Gumus and Algin 2017; Ozkaya and Zerberg 2019; Altın et al. 2020; Eris et al. 2020; Simsek 2021; Gumus et al. 2021; Akturk et al. 2022; Katipoğlu and Acar 2022; Deger et al. 2023b; Yuce et al. 2023; Keskiner and Simsek 2024) mild droughts have been recorded in Turkey. In the current study except at some cases, more or less all trend techniques have put forth that decreasing trends are prevalent over the basin either in significant cases or non-significant cases. Besides, results of Sen's slope estimator have shown that many trend slopes of time scales are declining which also supports the findings of other tests. The superiority of negative trends have been emphasized by (Katipoğlu and Acar 2022) for Euphrates Basin. Again the presence of decreasing trends have been reported by (Esit et al. 2023) for Tigris Euphrates Basin. Recently, consistent significant negative trends have been reported by (Demirel et al. 2024) for Euphrates Basin. Besides, Gumus et al. (2021) has reported decreasing trends in the majority of Southeastern Anatolia Project (GAP) region. Kartal and Nones (2024) has found that the trend of mean monthly streamflow values of Kızılırmak, Yeşilırmak and Sakarya Basins of Turkey are decreasing trends. In another assessment that has been performed by (Citakoglu and Minarecioglu 2021). The researchers have generally found decreasing trends in flow except at 3 stations stated that generally flow records in Kızılırmak Basin, Turkey. Even (Yuce et al. 2023) has found the decreasing trends in SDI time series by ITA significance test and in drought and wet categories by graphical ITA approximation for Yeşilırmak Basin. Many other studies (Katipoğlu et al. 2022; Robleh et al. 2024) have presented decreasing trends. Therefore, from this point of view the findings of these studies provide a good agreement with the findings of this study for the region.

## 5 Conclusion

In the present research, a detailed study of hydrological drought has been conducted considering spatiotemporal variability patterns for multiple timescales. Overall, via the findings of this study the following conclusions have been reached.

- SDI values have shown that many drought events have formed in the past and near today. From time series given in Supplementary, it is very clear that in some stations, dry (drought) conditions seem critical in the near past.

- Percentage occurrences of drought and wet categories have shown that among drought categories mild drought category is the most frequent. In SDI-1 and SDI-3 dry categories are superior while in SDI-6 and SDI-9 Wet (SDI $\geq 0$) categories are higher with slight differences. In SDI-12 the distribution of stations has become equal. Spatial distribution of drought categories in different time scales have shown that many parts of the basin have experienced with droughts.
- Via Mann-Kendall Test, Spearman's Rho Test, Wilcoxon Test, Innovative Trend Significance Test trends in time scales have been determined. For a selected significance level of $\alpha = 0.01$ many significant trends have been detected. Even these decreasing trends have been seen with negative trend slopes of Sen's Slope Estimator. Besides, graphical ITA results have put forth that trends in drought and wet categories have been decreasing so many times. These negative trends indicate a very critical situation in which the basin may experience with possible droughts with varying intensities or durations in the future as SDI values have continuously decreased within time. Therefore, the basin which is very critical for the country's development, economy, sustainability, water resources management must have a stronger and effective drought action plan. The findings of the study will aid researchers and local authorities, government agencies for monitoring the drought and keeping the water and environment stable.
- The findings of this study have provided significant and updated information which can be used in drought risk management strategies considering hydrological drought monitoring for Euphrates Basin. From this point, in a development of early-warning systems, water related projects and drought management; SDI based monitoring and trend implementation can give beneficial information to policy makers and decision-makers. Besides the findings of this study can be used for social awareness to prevent excessive uses of water.
- Although many valuable insights have been obtained by this research, the research is limited with analyzing hydrological droughts by suggested techniques for Euphrates Basin. Future studies could integrate one or more drought types with different techniques for a detailed assessment of regions.

**Acknowledgements** The General Directorate of State Hydraulic Works (DSI) is to be acknowledged for its contributions for providing streamflow data.

**Author Contributions** Ibrahim Halil DEGER: data gathering, material preparation, data trend analysis, interpretation of the findings, manuscript writing, editing and submission. Mehmet Ishak YUCE: data trend analysis, interpretation of the findings, manuscript writing, supervision and editing. Musa ESIT: data trend analysis, interpretation of the findings, manuscript writing, material preparation, data collection and editing.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).
Not applicable.

**Data Availability** Due to a non-disclosure agreement, the data used in the present study are not publicly accessible.

**Materials Availability** The data related to the study are available upon request.

**Code Availability** Not applicable.

## Declarations

**Ethics Approvals** Not applicable.

**Informed Consent** This study did not include any human participants or animals.

**Consent for Publication** Not applicable.

**Consent to Participate** Not applicable.

**Competing interest** The authors declare no conflict of interest.



## References

Achite M, Simsek O, Sankaran A et al (2024) Analyzing the dynamical relationships between meteorological and hydrological drought of Wadi Mina basin, Algeria using a novel multiscale framework. Stoch Environ Res Risk Assess 38:1935–1953. https://doi.org/10.1007/s00477-024-02663-w

Akhundzadah NA (2024) Analyzing temperature, precipitation, and river discharge trends in Afghanistan's main river basins using innovative trend analysis, Mann–Kendall, and Sen's slope methods. Climate 12:196. https://doi.org/10.3390/cli12120196

Akturk G, Zeybekoglu U, Yildiz O (2022) Assessment of meteorological drought analysis in the Kizilirmak River Basin, Turkey. Arab J Geosci 15:850. https://doi.org/10.1007/s12517-022-10119-0

Aktürk G, Çıtakoğlu H, Demir V, Beden N (2024) Meteorological drought analysis and regional frequency analysis in the Kızılırmak basin: creating a framework for sustainable water resources management. Water 16:2124. https://doi.org/10.3390/w16152124

Al-Juboori AM (2023) Prediction of hydrological drought in semi-arid regions using a novel hybrid model. Water Resour Manage 37:3657–3669. https://doi.org/10.1007/s11269-023-03520-1

Alimkulov S, Makhmudova L, Talipova EK et al (2024) Response of the water level of the Balkash Lake to the distribution of meteorological and hydrological droughts under the conditions of climate change. J Water Clim Change 15:3395–3408. https://doi.org/10.2166/wcc.2024.271

Altın TB, Sarış F, Altın BN (2020) Determination of drought intensity in Seyhan and Ceyhan River Basins, Turkey, by hydrological drought analysis. Theor Appl Climatol 139:95–107. https://doi.org/10.1007/s00704-019-02957-y

Aon S, Biswas S (2024) Bivariate assessment of hydrological drought of a semi-arid basin and investigation of drought propagation using a novel cross wavelet transform based technique. Water Resour Manage 38:2977–3005. https://doi.org/10.1007/s11269-024-03801-3

Ashraf MS, Shahid M, Waseem M et al (2023) Assessment of variability in hydrological droughts using the improved innovative trend analysis method. Sustainability 15:9065. https://doi.org/10.3390/su15119065

Aydin H, Yenigun K, Isinkaralar O, Isinkaralar K (2024) Hydrological low flow and overlapped trend analysis for drought assessment in Western Black Sea Basin. Nat Hazards. https://doi.org/10.1007/s11069-024-06880-y

Berhail S, Tourki M, Merrouche I, Bendekiche H (2022) Geo-statistical assessment of meteorological drought in the context of climate change: case of the Macta basin (Northwest of Algeria). Model Earth Syst Environ 8:81–101. https://doi.org/10.1007/s40808-020-01055-7

Birimbayeva L, Makhmudova L, Alimkulov S et al (2024) Analysis of the spatiotemporal variability of hydrological drought regimes in the lowland rivers of Kazakhstan. Water 16:2316. https://doi.org/10.3390/w16162316

Brunner MI, Götte J, Schlemper C, Van Loon AF (2023) Hydrological drought generation processes and severity are changing in the Alps. Geophys Res Lett 50:e2022GL101776

Christelis V, Mansour MM, Jackson CR (2024) Characterisation of groundwater drought using distributed modelling, standardised indices, and principal component analysis. Water Resour Manage. https://doi.org/10.1007/s11269-024-03997-4

Citakoglu H, Minarecioglu N (2021) Trend analysis and change point determination for hydro-meteorological and groundwater data of Kizilirmak basin. Theor Appl Climatol 145:1275–1292. https://doi.org/10.1007/s00704-021-03696-9

Deger IH, Esıt M, Yuce MI (2023a) Univariate and bivariate hydrological drought frequency analysis by copula functions. Water Resour Manage. https://doi.org/10.1007/s11269-023-03586-x

Deger İH, Yüce Mİ, Eşit M (2023b) An investigation of hydrological drought characteristics in Kızılırmak Basin, Türkiye: impacts and trends. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi 12:126–139. https://doi.org/10.17798/bitlisfen.1200742

Demirel İH, Kesgin E, Güçlü YS et al (2024) Trend stability assessment for hydrological drought in euphrates basin (Türkiye) using triplewilcoxon. Test and innovative trend analysis methods

En-Nagre K, Aqnouy M, Ouarka A et al (2024) Assessment and prediction of meteorological drought using machine learning algorithms and climate data. Clim Risk Manage 45:100630. https://doi.org/10.1016/j.crm.2024.100630

Eris E, Cavus Y, Aksoy H et al (2020) Spatiotemporal analysis of meteorological drought over Kucuk Menderes River Basin in the Aegean region of Turkey. Theor Appl Climatol 142:1515–1530. https://doi.org/10.1007/s00704-020-03384-0

Esit M (2022) Investigation of innovative trend approaches (ITA with significance test and IPTA) comparing to the classical trend method of monthly and annual hydrometeorological variables: a case study of Ankara region, Turkey. J Water Clim Change 14:305–329. https://doi.org/10.2166/wcc.2022.356

Esit M, Çelik R, Akbas E (2023) Long-term meteorological and hydrological drought characteristics on the lower Tigris-Euphrates basin, Türkiye: relation, impact and trend. Environ Earth Sci 82:491. https://doi.org/10.1007/s12665-023-11182-w

Esit M, Yuce MI, Deger İH, Yasa I (2024) Trend and variability analysis in rainfall and temperature records over Van Province, Türkiye. Theor Appl Climatol 155:451–472. https://doi.org/10.1007/s00704-023-04644-5

Feng K, Wang Y, Li Y et al (2024) Three-dimensional perspective on the characterization of the Spatiotemporal propagation from meteorological to agricultural drought. Agric for Meteorol 353:110048. https://doi.org/10.1016/j.agrformet.2024.110048

Fowé T, Yonaba R, Mounirou LA et al (2023) From meteorological to hydrological drought: a case study using standardized indices in the Nakanbe River Basin, Burkina Faso. Nat Hazards 119:1941–1965. https://doi.org/10.1007/s11069-023-06194-5

Frade TG, Santos CAG, da Silva RM (2024) Simulating future hydrological droughts and sediment yield by integrating different climate scenarios for a semiarid basin in Brazil. Stoch Environ Res Risk Assess 38:3677–3693. https://doi.org/10.1007/s00477-024-02777-1

Gonçalves STN, Vasconcelos Júnior F das C, Silveira C da S et al (2023) Comparative analysis of drought indices in hydrological monitoring in Ceará's Semi-Arid Basins, Brazil. Water 15:1259. https://doi.org/10.3390/w15071259

Gorugantula SS, Kambhammettu BP, Lakshmi SJ, Regonda SK (2024) Multivariate drought indices to analyse spatiotemporal drought propagation in a semi-arid river basin. Theor Appl Climatol 156:36. https://doi.org/10.1007/s00704-024-05236-7

Gu L, Yin J, Slater LJ et al (2023) Intensification of global hydrological droughts under anthropogenic climate warming. Water Resour Res 59:e2022WR032997. https://doi.org/10.1029/2022WR032997

Gulmez A, Mersin D, Vaheddoost B et al (2023) A joint evaluation of streamflow drought and standard precipitation indices in Aegean Region, Turkey. Pure Appl Geophys 180:4319–4337. https://doi.org/10.1007/s00024-023-03378-9

Gumus V, Algin HM (2017) Meteorological and hydrological drought analysis of the Seyhan–Ceyhan River Basins, Turkey. Meteorol Appl 24:62–73. https://doi.org/10.1002/met.1605

Gumus V, Simsek O, Avsaroglu Y, Agun B (2021) Spatio-temporal trend analysis of drought in the GAP Region, Turkey. Nat Hazards 109:1759–1776. https://doi.org/10.1007/s11069-021-04897-1

Habibi B, Meddi M, Abdelkader M (2024) The frequency distribution and stochastic analysis of the hydrological drought in Northern Algeria. Ital J Agrometeorol 73–94. https://doi.org/10.36253/ijam-1730

Hallouz F, Meddi M, Ali Rahmani SE, Abdi I (2024) Innovative versus traditional statistical methods in hydropluviometric: a detailed analysis of trends in the Wadi Mina Basin (Northwest of Algeria). Theor Appl Climatol 155:8263–8286. https://doi.org/10.1007/s00704-024-05127-x

Hanby G, Zhai L, Mishra B, Joshi O (2025) A comprehensive outlook on drought caused economic losses and landowner perceptions concerning drought and erratic rainfall patterns. For Policy Econ 170:103405. https://doi.org/10.1016/j.forpol.2024.103405

Hao W, Chang X (2013) Comparison of spatial interpolation methods for precipitation in Ningxia, China. Int J Sci Res India 2:181–184

Hong X, Guo S, Zhou Y, Xiong L (2015) Uncertainties in assessing hydrological drought using streamflow drought index for the upper Yangtze River basin. Stoch Environ Res Risk Assess 29:1235–1247. https://doi.org/10.1007/s00477-014-0949-5

Ionita M, Nagavciuc V, Scholz P, Dima M (2022) Long-term drought intensification over Europe driven by the weakening trend of the Atlantic meridional overturning circulation. J Hydrology: Reg Stud 42:101176. https://doi.org/10.1016/j.ejrh.2022.101176

Jahangir MH, Zarfeshani A, Danehkar S (2024) Numerical comparison of streamflow drought index (SDI) and standardized streamflow index (SSI) for evaluation of Isfahan drought status. Geol Ecol Landscapes 0:1–14. https://doi.org/10.1080/24749508.2024.2359775

Kartal V, Emiroglu ME (2024) Hydrological drought and trend analysis in Kızılırmak, Yeşilırmak and Sakarya Basins. Pure Appl Geophys 181:1919–1943. https://doi.org/10.1007/s00024-024-03499-9

Kartal V, Nones M (2024) Assessment of meteorological, hydrological and groundwater drought in the Konya closed basin, Türkiye. Environ Earth Sci 83:285. https://doi.org/10.1007/s12665-024-11587-1

Katipoğlu OM, Acar R (2022) Space-time variations of hydrological drought severities and trends in the semi-arid Euphrates Basin, Turkey. Stoch Environ Res Risk Assess 36:4017–4040. https://doi.org/10.1007/s00477-022-02246-7

Katipoğlu OM, Acar R, Şenocak S (2021) Spatio-temporal analysis of meteorological and hydrological droughts in the Euphrates Basin, Turkey. Water Supply 21:1657–1673. https://doi.org/10.2166/ws.2021.019

Katipoğlu OM, Yeşilyurt SN, Dalkılıç HY (2022) Yeşilırmak havzasındaki hidrolojik kuraklıkların Mann-Kendall ve Yenilikçi Şen yöntemi ile trend analizi. Gümüşhane Üniversitesi Fen Bilimleri Dergisi 12:422–442. https://doi.org/10.17714/gumusfenbil.1026893

Kendall M (1975) Rank correlation methods. Griffin, London

Keskiner AD, Simsek O (2024) Evaluation of the sensitivity of meteorological drought in the mediterranean region to different data record lengths. Environ Monit Assess 196:602. https://doi.org/10.1007/s10661-024-12726-8

Kumanlioglu AA (2020) Characterizing meteorological and hydrological droughts: a case study of the Gediz River Basin, Turkey. Meteorol Appl 27:e1857. https://doi.org/10.1002/met.1857

Kumanlioglu AA (2023) A new approach for characterization of meteorological and hydrological droughts: cumulative standardized drought index (CSDI). Phys Chem Earth Pt A/B/C 131:103420. https://doi.org/10.1016/j.pce.2023.103420

Leščešen I, Gnjato S, Galinović I, Basarin B (2024) Hydrological drought assessment of the Sava River basin in South-Eastern Europe. J Water Clim Change 15:3902–3918. https://doi.org/10.2166/wcc.2024.157

Li J, Wu C, Xia C-A et al (2021) Assessing the responses of hydrological drought to meteorological drought in the Huai River Basin, China. Theor Appl Climatol 144:1043–1057. https://doi.org/10.1007/s00704-021-03567-3

Liu Z-N, Yu X-Y, Jia L-F et al (2021) The influence of distance weight on the inverse distance weighted method for ore-grade Estimation. Sci Rep 11:2689. https://doi.org/10.1038/s41598-021-82227-y

Liu Q, Yang S, Li S et al (2024) The optimal applications of ScPDSI and SPEI in characterizing meteorological drought, agricultural drought and terrestrial water availability on a global scale. Sci Total Environ 952:175933. https://doi.org/10.1016/j.scitotenv.2024.175933

Ma Y, Ren J, Kang S et al (2025) Spatial-temporal dynamics of meteorological and agricultural drought in Northwest China: propagation, drivers and prediction. J Hydrol 650:132492. https://doi.org/10.1016/j.jhydrol.2024.132492

Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259. https://doi.org/10.2307/1907187

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology. California, pp 179–183

Meilutytė-Lukauskienė D, Nazarenko S, Kobets Y et al (2024) Hydro-meteorological droughts across the Baltic Region: the role of the accumulation periods. Sci Total Environ 913:169669. https://doi.org/10.1016/j.scitotenv.2023.169669

Meskelu E, Ayana M, Birhanu D (2024) Analysis of long-term rainfall trend, variability, and drought in the Awash River Basin, Ethiopia. Theor Appl Climatol 155:9029–9050. https://doi.org/10.1007/s00704-024-05170-8

Minh DT, Dung NB (2023) GIS-based multi-criteria approach for drought hazard modeling in the Ba river basin, Vietnam. Environ Earth Sci 83:30. https://doi.org/10.1007/s12665-023-11337-9

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391. https://doi.org/10.1016/j.jhydrol.2010.07.012

Nalbantis I, Tsakiris G (2009) Assessment of hydrological drought revisited. Water Resour Manage 23:881–897. https://doi.org/10.1007/s11269-008-9305-1

Nath H, Adhikary SK, Nath S et al (2024) Long-term trends and spatial variability in rainfall in the southeast region of Bangladesh: implication for sustainable water resources management. Theor Appl Climatol 155:3693–3717. https://doi.org/10.1007/s00704-024-04843-8

Nguyen-Minh T, Vu-Thanh H, Do-Thanh H et al (2024) Meteorological and hydrological drought characteristics and their relationships in the Central Highlands of Vietnam. Theor Appl Climatol 156:8. https://doi.org/10.1007/s00704-024-05243-8

Ngwenya M, Gidey E, Simatele MD (2024) Agroecological-based modeling of meteorological drought at 12-month time scale in the Western Cape Province of South Africa. Earth Sci Inf 17:1851–1865. https://doi.org/10.1007/s12145-023-01193-3

Niazkar M, Piraei R, Zakwan M (2024) Application of machine learning models for short-term drought analysis based on streamflow drought index. Water Resour Manage. https://doi.org/10.1007/s11269-024-03959-w

Niemeyer S (2008) New drought indices. Options Méditerranéennes Série A: Séminaires Méditerranéens 80:267–274

Niyonsenga S, Eziz A, Kurban A et al (2024) Spatiotemporal analysis of drought characteristics and their impact on vegetation and crop production in Rwanda. Remote Sens 16:1455. https://doi.org/10.3390/rs16081455

Oubadi M, Faci M, Pham QB (2024) Drought and aridity trends on the Algerian steppe. Theor Appl Climatol 155:1541–1551. https://doi.org/10.1007/s00704-024-04865-2

Ozkaya A, Zerberg Y (2019) A 40-year analysis of the hydrological drought index for the Tigris Basin, Turkey. Water 11:657. https://doi.org/10.3390/w11040657

Ozocak M, Akay AO, Esin Aİ et al (2024) A new framework to spatial and temporal drought analysis for 1990–2020 period with Mann–Kendall and innovative trend analysis methods in Turkey. Nat Hazards 120:1463–1517. https://doi.org/10.1007/s11069-023-06258-6

Patidar R, Pingale SM, Khare D, Dayal D (2024) Spatio-temporal assessment of multi-scalar meteorological and hydrological droughts over Bundelkhand, India. Phys Chem Earth Pt A/B/C 136:103729. https://doi.org/10.1016/j.pce.2024.103729

Paulo AA, Pereira LS, Matias PG (2003) Analysis of local and regional droughts in Southern Portugal using the theory of runs and the standardised precipitation index. In: Rossi G, Cancelliere A, Pereira LS et al (eds) Tools for drought mitigation in mediterranean regions. Springer Netherlands, Dordrecht, pp 55–78

Rahmi KIN, Dimyati M, Tambunan MP, Nugroho JT (2025) Spatial modelling of regional drought severity index based on multiple criteria analysis using cloud-based remote sensing data in agriculture land. Model Earth Syst Environ 11:61. https://doi.org/10.1007/s40808-024-02267-x

Robleh HB, Yuce MI, Esit M, Deger IH (2024) Meteorological drought monitoring in Kızılırmak Basin, Türkiye. Environ Earth Sci 83:265. https://doi.org/10.1007/s12665-024-11550-0

Saha A, Chandra Pal S (2024) Spatio-temporal variation of meteorological, hydrological and agricultural drought vulnerability: insights from statistical, machine learning and wavelet analysis. Groundw Sustainable Dev 27:101380. https://doi.org/10.1016/j.gsd.2024.101380

Saini D, Singh O (2024) Comparison of meteorological, hydrological and agricultural droughts for developing a composite drought index over semi-arid Banas River Basin of India. Stoch Environ Res Risk Assess 38:2671–2691. https://doi.org/10.1007/s00477-024-02704-4

Sajeev A, Kundapura S (2024) Comparative evaluation of meteorological and hydrological drought using stationary and non-stationary indices in a semi-arid river basin in India. Nat Hazards 120:13433–13468. https://doi.org/10.1007/s11069-024-06739-2

Şan M, Nacar S, Kankal M, Bayram A (2024) Spatiotemporal analysis of transition probabilities of wet and dry days under SSPs scenarios in the semi-arid Susurluk Basin, Türkiye. Sci Total Environ 912:168641. https://doi.org/10.1016/j.scitotenv.2023.168641

Saplıoğlu K, Güçlü YS (2022) Combination of Wilcoxon test and scatter diagram for trend analysis of hydrological data. J Hydrol 612:128132. https://doi.org/10.1016/j.jhydrol.2022.128132

Sen PK (1968) Estimates of the regression coefficient based on Kendall's Tau. J Am Stat Assoc

Şen Z (2012) Innovative trend analysis methodology. J Hydrol Eng 17:1042–1046. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000556

Şen Z (2017) Innovative trend significance test and applications. Theor Appl Climatol 127:939–947. https://doi.org/10.1007/s00704-015-1681-x

Senatilleke U, Sirisena J, Gunathilake MB et al (2023) Monitoring the meteorological and hydrological droughts in the largest river basin (Mahaweli River) in Sri Lanka. Climate 11:57. https://doi.org/10.3390/cli11030057

Sheffield J, Wood EF (2012) Drought: past problems and future scenarios. Routledge, London

Simsek O (2021) Hydrological drought analysis of Mediterranean basins, Turkey. Arab J Geosci 14:2136. https://doi.org/10.1007/s12517-021-08501-5

Singh J, Ashfaq M, Skinner CB et al (2022) Enhanced risk of concurrent regional droughts with increased ENSO variability and warming. Nat Clim Chang 12:163–170. https://doi.org/10.1038/s41558-021-01276-3

Singh RN, Sah S, Das B et al (2024) Innovative and polygonal trend analysis of temperature in agro climatic zones of India. Sci Rep 14:29914. https://doi.org/10.1038/s41598-024-78597-8

Spearman C (1904) The proof and measurement of association between two things. Am J Psychol 15:72–101. https://doi.org/10.2307/1412159

Svoboda M, Fuchs B (2016) Handbook of drought indicators and indices. Drought and water crises: integrating science, management, and policy 155–208

Swain S, Mishra SK, Pandey A et al (2024) Characterization and assessment of hydrological droughts using glofas streamflow data for the Narmada River Basin, India. Environ Sci Pollut Res 31:54281–54294. https://doi.org/10.1007/s11356-023-27036-8

Tareke KA (2025) Long-term hydrological drought monitoring and trend analysis in Blue Nile River basin. Heliyon 11. https://doi.org/10.1016/j.heliyon.2024.e41161

Tareke KA, Awoke AG (2022) Hydrological drought analysis using Streamflow Drought Index (SDI) in Ethiopia. Adv Meteorol 2022:7067951. https://doi.org/10.1155/2022/7067951

T.C. Tarım ve Orman Bakanlığı, Su Yönetimi Genel Müdürlüğü (SYGM) (2020) T.C. Tarım ve Orman Bakanlığı, Su Yönetimi Genel Müdürlüğü, Fırat Alt Havzası Taşkın Yönetim Planı

Taylan ED (2024) An approach for future droughts in Northwest Türkiye: SPI and LSTM methods. Sustainability 16:6905. https://doi.org/10.3390/su16166905

Team P (2022) RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston. http://www.posit.co/

Tegegn MG, Berlie AB, Utallo AU (2024) Spatiotemporal variability and trends of intra-seasonal rainfall and temperature in the drought-prone districts of Northwestern Ethiopia. Discov Sustain 5:230. https://doi.org/10.1007/s43621-024-00445-6

Tuğrul T, Hinis MA (2024) Trend analysis of hydrological and meteorological drought in Apa Dam, Türkiye. Environ Earth Sci 83:502. https://doi.org/10.1007/s12665-024-11791-z

Vinod D, Mahesha A (2024) Large-scale atmospheric teleconnections and spatiotemporal variability of extreme rainfall indices across India. J Hydrol 628:130584. https://doi.org/10.1016/j.jhydrol.2023.130584

Wambura FJ (2025) From meteorological to hydrological drought: a focus on the characterization of hydrological drought with prediction uncertainty. Water Resour Manage. https://doi.org/10.1007/s11269-025-04138-1

Wei W, Wang J, Wang X et al (2024) The response of global terrestrial water storage to drought based on multiple climate scenarios. Atmos Res 303:107331. https://doi.org/10.1016/j.atmosres.2024.107331

Wilcoxon F (1945) Individual comparisons by ranking methods. Biometrics Bull 1:80–83. https://doi.org/10.2307/3001968

Wu J, Zhang J, Chen X et al (2024) Hydrological drought life-cycle: faster onset and recovery in humid than semi-arid basins in China. J Hydrol 644:132083. https://doi.org/10.1016/j.jhydrol.2024.132083

Wu F, Yang X, Cui Z et al (2025) Comprehensive drought risk assessment of the Yangtze River Basin considering socio-natural systems — based on PCR-GLOBWB model. J Hydrol 646:132315. https://doi.org/10.1016/j.jhydrol.2024.132315

Xu F, Qu Y, Bento VA et al (2024) Understanding climate change impacts on drought in China over the 21st century: a multi-model assessment from CMIP6. Npj Clim Atmos Sci 7:1–12. https://doi.org/10.1038/s41612-024-00578-5

Yaşa İ, Partal T (2024) Drought trend and variability based wavelet transform in Euphrates-Tigris Basin, Türkiye. Atmos Res 302:107291. https://doi.org/10.1016/j.atmosres.2024.107291

Yin J, Slater L, Gu L et al (2022) Global increases in lethal compound heat stress: hydrological drought hazards under climate change. Geophys Res Lett 49:e2022GL100880. https://doi.org/10.1029/2022GL100880

Yuce MI, Deger IH, Esit M (2023) Hydrological drought analysis of Yeşilırmak Basin of Turkey by streamflow drought index (SDI) and innovative trend analysis (ITA). Theor Appl Climatol. https://doi.org/10.1007/s00704-023-04545-7

Zarei AR, Mahmoudi MR (2024) Spatial and temporal assessment and forecasting vulnerability to meteorological drought. Environ Dev Sustain. https://doi.org/10.1007/s10668-024-04776-2

Zhang Y, Li J, Feng P, Tian J (2024) Assessing the spatio-temporal evolution mechanisms from meteorological to hydrological drought in a heavily human-influenced river basin. Water Resour Manage. https://doi.org/10.1007/s11269-024-04049-7

Zhen N, Yao R, Sun P et al (2025) Triggering thresholds and influential factors in the propagation of meteorological drought to hydrological drought. J Hydrology: Reg Stud 57:102184. https://doi.org/10.1016/j.ejrh.2025.102184