Earth Science Informatics (2025) 18:273
https://doi.org/10.1007/s12145-025-01797-x

RESEARCH

Drought assessment in the northeastern Aras Basin using multi-parameter aggregate drought index and innovative polygon trend analysis

Emre Topçu[1] · Fatih Karaçor[1] · Burak Çırağ[2] · İlteriş Taşkolu[3] · Reşat Acar[2]

Received: 8 November 2024 / Accepted: 16 January 2025 / Published online: 19 February 2025
© The Author(s) 2025

Abstract

Drought is a climate phenomenon that can have serious consequences for all living things. The widespread occurrence of extreme drought and extreme precipitation conditions in recent years has increased the importance of drought studies. This study aims to conduct a comprehensive drought analysis using 11 meteorological parameters for the period 1970–2023 at Ardahan, Iğdır, and Kars meteorological stations in the region of Türkiye, which is located in the Northeast of the Aras Basin and known for its harsh winter conditions. Drought analysis was carried out with the Aggregate Drought Index (ADI) method and the effects of climate change on parameters such as temperature, precipitation, snow water equivalent (SWE), and streamflow in the region were analyzed. As a result of the study, with the use of ADI and IPTA methods, drought trends in Aras Basin, especially in the winter and summer seasons, were clearly seen. It can be said that near-normal conditions are experienced the most with a frequency of approximately 20%. In addition to the ADI analysis, Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI), and Reconnaissance Drought Index (RDI) methods were also applied; however, it was observed that these indexes do not always show full agreement with the ADI and exhibit similar trends in some drought periods. These results show that choosing the right indexes is of great importance for drought analysis and that indexes suitable for regional climate characteristics will give more reliable results.

Keywords Aggregate Drought Index · Aras Basin · Drought · Innovative Polygon Trend Analysis · Reconnaissance Drought Index · Standardized Precipitation Index

Communicated by: Hassan Babaie

✉ Emre Topçu
emretopcu01@gmail.com

Fatih Karaçor
fatihkaracor@gmail.com

Burak Çırağ
burak.cirag@atauni.edu.tr

İlteriş Taşkolu
ilteristaskolu@esenyurt.edu.tr

Reşat Acar
racar@atauni.edu.tr

[1] Civil Engineering Department, Kafkas University, Kars, Türkiye

[2] Civil Engineering Department, Ataturk University, Erzurum, Türkiye

[3] Vocational School Construction Technology Program, Istanbul Esenyurt University, Istanbul, Türkiye

Introduction

Drought, one of the most influential extremes of the water cycle, is a natural disaster caused by the abnormal behavior of hydro-climatic variables (West et al. 2019; Arias et al. 2024; Li et al. 2024). Severe drought has negative impacts on water resources, ecosystems, agricultural production, drying up of rivers, which can affect human health (Park et al. 2017; Cao et al. 2022; Shi et al. 2023). Drought can occur anywhere in the world at any time and is always likely to recur. It occurs more slowly and over a longer period than other disasters (Topçu and Seçkin 2022). However, it can cause major negative consequences as its intensity and duration gradually increase. In this respect, it is one of the costliest natural disasters (Mukherjee et al. 2018). The negative impacts of drought are more severe in regions where livelihoods depend on water (such as agriculture) and where access to water resources is limited (Lin et al. 2021; Santos et al. 2021; Zarei 2022; Wang et al. 2022; Zarei et al. 2023).

In recent years, the effects of global climate change have intensified, notably the marked rise in the frequency of diverse extreme weather and climatic events (Qi et al. 2023; Chen et al. 2024; Jiao et al 2024). Moreover, topography will significantly influence future climate change, as diverse topographic environments exhibit distinct reaction mechanisms to global temperature increases (Tian et al. 2023; Chen et al. 2024). Understanding and addressing the vulnerability to drought hinges on establishing links between indicators of drought and actual impacts experienced in real-world scenarios (O'Connor et al. 2023). Drought is usually analyzed using remote sensing data (Rousta et al. 2017, 2020, 2022, 2023; Omidvar et al. 2024) or various indices. In this context, several indexes have been developed worldwide that measure and assess the level of drought, considering its complex nature. Drought indexes based on specific input parameters are primarily tools that aim to analyze the duration, intensity, severity, and spatial extent of drought (Mishra and Singh 2010; Esfahanian et al. 2017). Examples of these indexes are the Standardized Precipitation Index (SPI) (McKee et al. 1993), the Streamflow Drought Index (SDI) (Nalbantis and Tsakiris 2009), the Deciles Drought Index (DDI) (Gibbs and Maher 1967), the Palmer Drought Severity Index (PDSI) (Palmer 1965), and the Aggregate Drought Index (ADI) (Keyantash and Dracup 2004).

The mathematical approach of ADI can analyze agricultural water shortage, and hydrological and meteorological droughts from a broad perspective with collective perspectives (Faiz et al. 2021). Wang et al. (2018) aimed to develop an ADI using seven drought indexes to monitor agricultural drought in North China Plain and analyze its spatiotemporal variations. As a result of the study, they stated that ADI showed that it could capture wide area droughts between 1996 and 2012. Topçu et al. (2022) conducted a meteorological and agricultural drought analysis using ADI with total monthly precipitation, monthly average temperature, monthly average relative humidity, number of sunny days in a month, and number of overcast days in a month data from 35 meteorological stations located in 4 basins in Türkiye. As a result, they reported that a mild drought prevailed throughout the region. Abbasi (2024) presents monitoring and assessment of drought based on the use of the soil and water assessment tool (SWAT) hydrological model and the ADI (rainfall, evapotranspiration, river flow, reservoir storage, and moisture data) for the Urmia Lake basin in Iran. They also compared ADI values with the SPI over the study period. As a result of the study, they stated that ADI shows drought more clearly than SPI.

This study aims to conduct a comprehensive drought analysis by using monthly total precipitation, monthly average soil temperature of 20 cm, monthly average relative humidity, monthly average wind speed, monthly average temperature, monthly total evaporation, the monthly number of frosty days, the monthly number of snow-covered days, the monthly number of snowy days, the monthly maximum snow water equivalent (SWE), monthly average snow height and monthly average streamflow data obtained from Ardahan, Iğdır, and Kars meteorological stations located in the northeastern most of Türkiye between 1970 and 2023. In the Aras Basin, there are 115,907 ha in the preliminary study or master plan stage, 48,431 ha in the planning stage, 46,600 ha in the project stage, 81,353 ha under construction, 99,208 ha irrigation areas in operation. There are many hydroelectric power plants in the Aras Basin. There are a total of 50 private and public sector hydroelectric power plants in operation. (T. C. Tarım ve Orman Bakanlığı 2022). The reduction or depletion of fresh water resources (surface and groundwater) in the basin due to drought will adversely affect drinking water, ecosystem needs and agriculture, livestock, tourism, mining, industry and the lives of people and living things within the boundaries of the Aras Basin. The scarcity of drought studies in the Aras Basin has led to focus on this region. One of the studies conducted in the region was carried out by Topçu (2022). In this study, drought analysis was performed using climatic oscillations and the Agricultural Standardized Precipitation Index (a-SPI). Unlike the aforementioned study, in this study, the Aggregate Drought Index (ADI), which can operate independently of the units of parameters, was preferred as a drought analysis method. In the second stage of the study, the Innovative Polygon Trend Analysis (IPTA) method was applied to the monthly average temperature, monthly total precipitation, monthly maximum snow water equivalent, and monthly average flow values, which are the most important meteorological parameters in terms of climate change for the Aras Basin, to determine the trend. Finally, the study compared the ADI with the widely used SDI, SPI, and RDI and examined whether there was a compatibility between them. The novel part of the present paper stands out, especially in the type and number of parameters used in the Aggragate Drought Index method, which are considered to be important for the hydrological cycle of the Aras Basin. This undoubtedly makes this study more original, more reliable, and more robust than other studies that have been conducted in the Aras Basin.

Study area

The Aras Basin is one of the 25 basins in Türkiye, located in northeastern Türkiye and covering approximately 3.57% of Türkiye's surface area with a watershed area of 28,114 km^2. It is between 41° 10′ 12″- 44° 49′ 38″ East Longitude and 41° 20′ 30″- 42° 36′ 36″ North Latitude. Together with Ağrı, Kars, Ardahan, Iğdır and Erzurum, it includes five provinces in total. It is also a neighboring basin to the Çoruh and Fırat-Dicle basins. With a drainage area of

28,037 km^2, average annual precipitation of 432.4 mm/m^2, average annual runoff of 4.63 km^3, and average annual yield of 5.3 l/sec/km^2, the Aras basin has a very important place both for the living creatures in the region and for Türkiye (T.C. Tarım ve Orman Bakanlığı 2019). In this study, the Ardahan, Kars, and Iğdır provinces located in the east of the Aras Basin were determined as the study area due to the data obtained from the central stations of these provinces. The geographical view of the Aras Basin is shown in Fig. 1.

The provinces in the Aras Basin, which have high altitudes, experience heavy rain and snowfall throughout the year. Turkish State Meteorological Service (MGM) reported that for Ardahan province, the highest daily total rainfall was 75.8 mm and the highest snow height was 113 cm between 1958 and 2022; for Kars province, the highest daily total rainfall was 71.7 mm and the highest snow height was 120 cm between 1931–2022; for Iğdır province, the highest daily total rainfall was 41.6 mm and the highest snow height was 38 cm between 1941–2022 (MGM 2024). Geographical

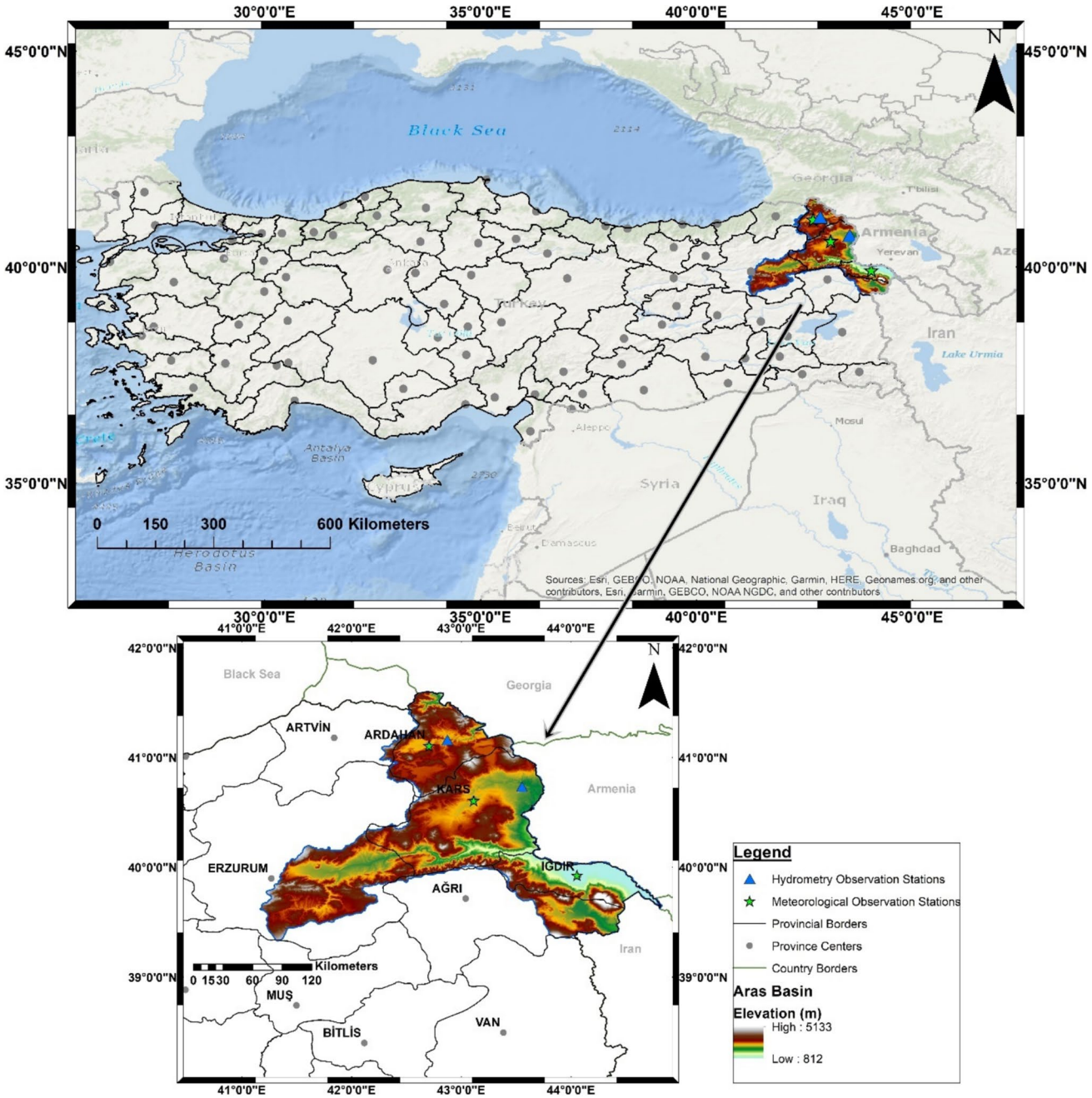


Fig. 1 Geographic location of Aras Basin, showing studied station and elevation of the area

characteristics, Köppen climate classes (MGM 2016), and population information of the provinces covered by the Aras Basin are given in Table 1.

Material and method

Material

11 different meteorological parameters were used in the study. In Ardahan and Kars stations, the data of the nearest streamflow observation station could also be used, whereas the Iğdır streamflow observation station was not used because it was considered to give biased results since it was far from Iğdır meteorological station. The parameters and period ranges used are given in Table 2.

Method

In this paper, drought classification methods that analyze drought by using hydrological parameters for which data are easily available in the Aras Basin were preferred. The choice of methods and parameters used in drought calculation is vital in classifying the drought of a region. Precipitation in the Aras Basin falls in the form of snow, especially in winter. In this study, considering the presence of rivers in the basin, methods that use parameters such as snow water equivalent, frost days, streamflow in addition to rainfall data in a practical way were selected. Using these methods will both save time for decision-makers and analyze the drought of the region in the best way by giving the most accurate analysis results. The selected methods are well-accepted in the drought literature, using multiple or single hydrological parameters. The reason for choosing more than one method is that each drought classification method has different or more parameters than the other. In this way, it should be taken into consideration that drought classification methods that use a large number of parameters better analyze the parameters that make up the hydrological cycle.

SWE values at Iğdır station start in 2002 and end in 2023. However, in order not to cause data loss in drought analysis, SWE values before 2002 were derived by regression analysis. Snow depth values obtained from Iğdır station were used to derive data for regression analysis. For the regression analysis, the ground snow load was first calculated. The ground snow load can be calculated using Eq. 1. In this equation, P_{Ko} is the ground snow load, h is the depth of snow on the ground (m), and ρ is the average snow density (kN/m^3).

$$P_{Ko} = h\rho \tag{1}$$

The value of snow density is determined by its water equivalent (Q' Rourke et al. 1982).

Snow density varies with depth and time; as the snow depth increases, snow density increases as the upper snow layer compresses the lower snow layer. Furthermore, snow density increases over time due to the melting and refreezing

Table 1 Social and characteristic features of the Aras Basin

Provinces	Elevation (m)	Surface area (km^2)	Köppen climate classification	Population
Ardahan	1,900	4,934	Dfb (Snow-fully humid-warm summer)	98,907
Kars	1,756	9,594	Dfb (Snow-fully humid-warm summer)	288,878
Iğdır	850	1,479	BSk (Ardi-summer dry-cold arid)	197,456

Table 2 Parameters used in the study

Parameters	Period	Ardahan	Iğdır	Kars
Monthly precipitation total (mm = kg/m^2)	1970–2023	✓	✓	✓
Monthly average 20 cm soil temperature (°C)	1970–2023	✓	✓	✓
Monthly average humidity (%)	1970–2023	✓	✓	✓
Monthly average wind velocity (m/sn)	1970–2023	✓	✓	✓
Monthly average temperature (°C)	1970–2023	✓	✓	✓
Monthly total evaporation (mm)	1970–2023	✓	✓	✓
Number of monthly frost days	1970–2023	✓	✓	✓
Number of snow-covered days	1970–2023	✓	✓	✓
Number of snowy days	1970–2023	✓	✓	✓
Monthly max. SWE (mm = kg/m^2)	1970–2023	✓	✓	✓
Monthly average snow depth (cm)	1970–2023	✓	✓	✓
Monthly average streamflow (m^3/sn)	1970–2015	✓	X	✓

of the snow mass on the ground. The empirical formula in Eq. 2 is used to express the relationship between snow thickness h (m) and snow density ρ (kg/m3) (Durmaz and Daloğlu 2006; Ghiocel and Lungu 1975)

$$\rho = 300 - 200.e^{-1.5h} \quad (2)$$

As a result of the regression analysis, an equation with an R^2 value of 0.9258 was obtained. SWE values were found with the help of Eq. 3. In this equation y stands for snow water equivalent and x demonstrates $\rho * h$.

$$y = 0.017x + 0.9726 \quad (3)$$

Aggregate Drought Index (ADI)

ADI is a multivariate drought index that includes meteorological, agricultural, and hydrological drought types and combines several input variables (e.g., precipitation, evaporation, soil moisture, and streamflow) that represent these drought types (Keyantash and Dracup 2004). ADI also assesses drought status by examining the relationship between meteorological parameters. This index considers the effect of one meteorological variable on another, especially considering the hydrological cycle (Topçu and Karaçor 2021).

Principal Component Analysis (PCA) is used to calculate the ADI. Principal Component Analysis is a transformation technique that helps to reduce the size of related parameters in the data set to fewer dimensions while preserving their size. This method aims to make the data set expressible with fewer variables (Alkan 2008). Principal Component Analysis requires the creation of a square symmetric correlation matrix that expresses the relationship between the variables in the original data set. For the calculation of principal components:

1. A data matrix is created with the parameters obtained for each month of each hydrological year. In this matrix, each column represents data (precipitation, evaporation, runoff, etc.). This matrix contains the observed values.
2. In the second step, the data in each column are standardized by subtracting their mean and dividing by their standard deviation (obtaining the X matrix). This is to ensure that the observed values used are not weighted in the results.
3. In the third step, the correlation matrix (R) of the matrix created from the standardized data set is calculated. In this way, the relationship of each parameter with the others is determined. For each month, 12 different correlation matrices need to be created.
4. Finally, PCA is performed on the obtained correlation matrix (R). Through this analysis, the eigenvectors and eigenvalues of the matrix are found. Eigenvectors allow the calculation of uncorrelated principal components representing the standardized linear combination of the original variables. The eigenvalues measure the amount of variation explained by each principal component. Since the correlation matrix is used to construct the ADI, the index values are not affected by the units of the parameters. Each parameter can be used in its unit.

If we call the principal component matrix Z, the standardized observation data matrix X, and the eigenvector matrix E obtained from the correlation matrix (R), Z = XE. For ADI, the value for the kth month of year i, Z_{ik} is the first principal component and σ is the standard deviation of the first principal component of the kth month in all hydrological years. Therefore, it is calculated by the formula $ADI_{ik} = (Z_{ik}) / \sigma$. For detailed information on ADI, please refer to (Topçu et al. 2022).

ADI does not have specific thresholds; instead, it is calculated using an empirical cumulative distribution function. In this study, thresholds were calculated for each station to classify drought conditions.

After obtaining the ADI_{ik} values, ADI values are obtained by sorting for each month of the hydrological years. In this way, ADI values are calculated for a period of 12 months. The obtained ADI values are classified in a certain interval and drought degrees are obtained.

Innovative Polygon Trend Analysis (IPTA)

In the Innovative Trend Analysis (ITA) method proposed by Şen (2012), the values of hydro-meteorological data set at a certain time interval are used. It allows visual interpretation of the trends in the "High", "Medium" and "Low" classes of the region determined as the study area (Şen et al. 2019). Unlike the ITA method, it is possible to obtain more accurate trend results by calculating the first-order moment, cross-correlation coefficient, variance, and standard deviation values and testing for significance.

The Innovative Polygon Trend Analysis (IPTA) method proposed by Şen et al. (2019), like the ITA method, determines the trend of a time series by using data from a time series. In this method, which can be applied to different time scales such as daily, weekly, and monthly, parameters such as skewness, standard deviation, maximum, minimum, and average are used as data inputs. In the ITA method, the data sets are divided into two equal time intervals and then sorted in descending order, with the first half-time series (X_i) placed on the x-axis and the second half-time series (X_j) placed on the y-axis (Taşkolu 2023). The same steps in the ITA method are also applied to the IPTA method. The ordered values are plotted in the Cartesian coordinate system

and the plotted points are connected to form a polygon and then a 1:1 (x = y) line is drawn (see Fig. 2).

The more dynamic and complex the hydro-meteorological event under study, the more complex the resulting IPTA polygons. If the lengths and slopes between consecutive points of the polygon are equal, a relatively narrow polygon is formed and the studied variable exhibits an isotropic, uniform variation behavior, indicating that the intrinsic variation is quite homogeneous (Şen et al. 2019; Koycegiz and Buyukyildiz 2024). In the Cartesian coordinate system, if the density of the marked values remains in the upper triangular area of the 1:1 line, an increasing trend can be interpreted, and if it remains in the lower triangular area, a decreasing trend can be interpreted. The slope and trend length of the obtained trend are given in Eqs. 4 and 5, respectively. For detailed information, please refer to (Şen et al. 2019).

$$|AB| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{4}$$

$$s = (y_2 - x_2)/(y_1 - x_1) \tag{5}$$

Other indexes used to compare ADI's results

Standardized Precipitation Index (SPI)

The SPI is calculated by an analysis method based on the cumulative probability of precipitation data at a station. This method works on the principle of normalizing the precipitation value over a given period, then subtracting this value from the mean over the same period and dividing the difference by the standard deviation (McKee et al. 1993).

For the analysis of precipitation data, the gamma distribution is a suitable model and its parameters are estimated by the maximum likelihood method. If zero values are present in the precipitation data, Thom's mixed distribution method (Thom 1958) can be used to calculate zero and non-zero probabilities. SPI is useful in determining drought categories; negative SPI values indicate drought conditions and lack of precipitation, while positive values indicate adequate precipitation. Drought frequency is calculated by dividing by the total number of observations at the station, and this ratio reveals how often drought conditions are experienced at that station during the specified period (Topçu 2013).

Reconnaissance Drought Index (RDI)

The RDI was initially developed for agricultural and meteorological drought monitoring (Tsakiris and Vangelis 2005). This index is widely used, especially in arid and semi-arid regions. The main data needed to calculate the RDI are cumulative precipitation (P) and potential evapotranspiration (PET) values. Four different methods such as Hargreaves, Thornthwaite, Blaney-Criddle, and Penman–Monteith can be used to obtain evapotranspiration data.

In this study, Thornthwaite's potential evapotranspiration method was preferred for RDI calculation. This method, developed by Thornthwaite in 1948, works on the

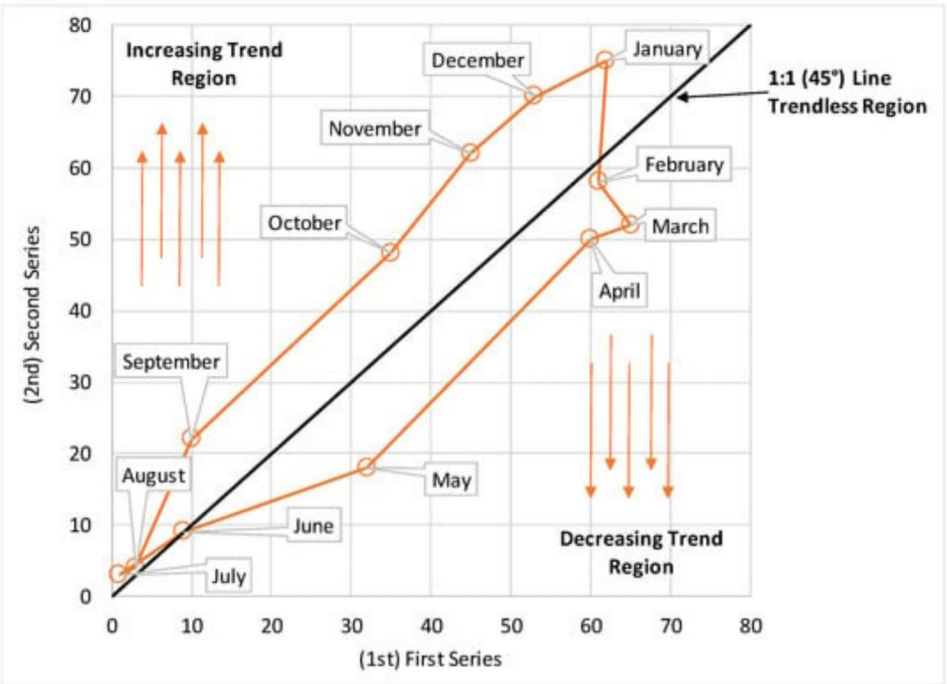


Fig. 2 Hypothetical Innovative Polygon Trend Analysis template (Achite et al. 2021)

assumption that temperature does not cause evapotranspiration at 0℃ and below (Thornthwaite 1948).

Streamflow Drought Index (SDI)

The concept of SDI was proposed by (Nalbantis 2008) to analyze the characteristics of hydrological drought such as duration, severity, and intensity at different time scales. The SDI calculation method follows a similar method to the SPI (McKee et al. 1993) except that precipitation data are replaced by streamflow data. SDI values are calculated as the difference of each month's streamflow data from the mean of all streamflow data divided by the standard deviation of the streamflow data (Malik et al. 2019).

Results

ADI results

Drought and wet thresholds obtained according to the cumulative probability values of the stations are shown in Table 3. Cumulative probability values were used as in the Standardized Precipitation Index (SPI) method (McKee et al. 1993), which is widely used worldwide. Using 11 different meteorological parameters, these drought and wet thresholds determine arid or wet conditions for the station. For example, an ADI value between −1.34 and −2.27 for Ardahan station indicates that Ardahan station is severely drought. The more meteorological parameters are added when calculating the ADI, the stronger the ability to reflect drought or wet conditions. Of course, this also changes the ADI thresholds. The streamflow value added in the ADI calculation for Ardahan and Kars at the end of Table 3 is a good example of this.

While the ADI extreme drought value for Kars without streamflow is −2.24, it becomes −2.18 when streamflow is considered. Similarly, while the extreme wet value is 1.84, it takes the value of 1.69 when streamflow is used. Near-normal values represent normal conditions without drought or wetness. After these values, we can talk about the onset of drought or wet. For example, for Iğdır station, between −0.11 ADI value and −0.26 ADI value represent near normal conditions while between −0.26 ADI and −0.55 ADI values indicate slightly drought conditions. According to Table 3, Ardahan station has the lowest ADI value (−2.27) while Iğdır station has the highest ADI value. However, it should not be ignored that each station is categorized within itself.

Figure 3 shows the change in ADI values at Ardahan, Iğdır, and Kars stations on a monthly basis over the years. In Ardahan and Kars stations, ADI values obtained by taking streamflow into account are also included. The ADI analysis with 11 meteorological parameters and the extra streamflow used, revealed different drought and wet conditions. For example, for Ardahan station, while the minimum value in ADI values without flow is −3.87, the minimum value in ADI values with flow is −4.19. While the maximum ADI is 3.86 in the no-flow calculation, it is 2.86 in the flow calculation. In the ADI graphs for Ardahan, the values have changed in the direction of drought in recent years.

Table 3 ADI thresholds according to drought category for stations

Cumulative Probability	Drought Category	ARDAHAN ADI	IĞDIR ADI	KARS ADI
0.0228	Extreme Drought	−2.27	−1.38	−2.24
0.0668	Severly Drought	−1.34	−1.04	−1.32
0.1587	Moderate Drought	−0.70	−0.55	−0.65
0.3085	Slightly Drought	−0.28	−0.26	−0.24
0.5	Near Normal	−0.08	−0.11	0.10
0.6915	Slightly Wet	0.28	0.08	0.30
0.8413	Moderate Wet	0.77	0.42	0.74
0.9332	Severly Wet	1.24	1.04	1.13
0.9772	Extreme Wet	1.71	2.26	1.84
Cumulative Probability	Drought Category	ARDAHAN ADI with Streamflow	KARS ADI with Streamflow	
0.0228	Extreme Drought	−2.09	−2.18	
0.0668	Severly Drought	−1.23	−1.15	
0.1587	Moderate Drought	−0.76	−0.63	
0.3085	Slightly Drought	−0.28	−0.27	
0.5	Near Normal	0.03	−0.09	
0.6915	Slightly Wet	0.31	0.28	
0.8413	Moderate Wet	0.77	0.77	
0.9332	Severly Wet	1.18	1.22	
0.9772	Extreme Wet	1.61	1.69	

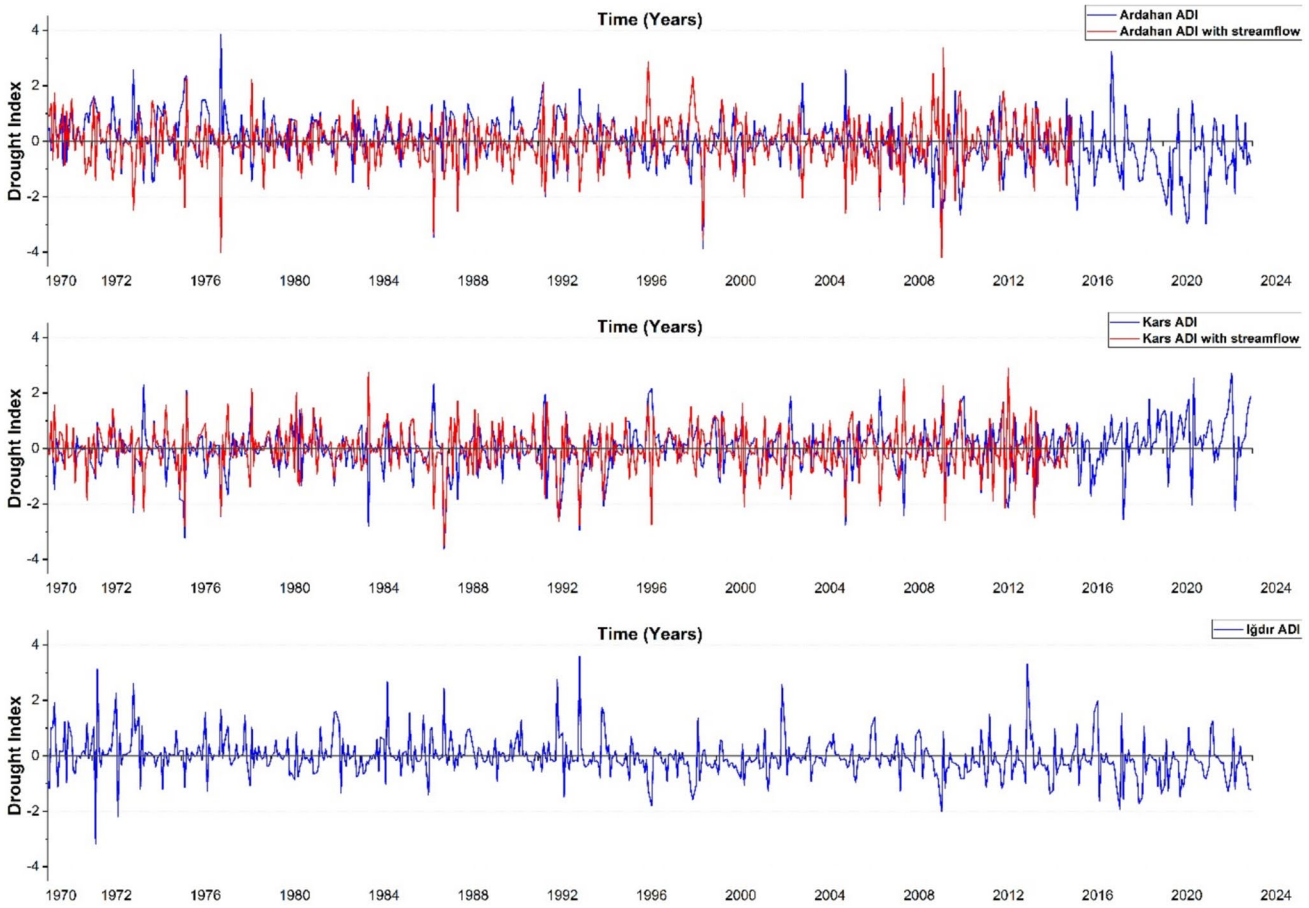


Fig. 3 ADI graphs for Ardahan, Iğdır and Kars

In Iğdır station, which has a lower altitude than the other two stations, the frequency of wet events has decreased in recent years and the values have shifted towards drought. In Kars station, while the frequency of wet events has increased in recent years, severe and moderate drought has also been observed. When the stations are compared with each other, it can be said that more severe drought events were observed in Ardahan and Kars stations than in Iğdır.

In Table 4, the year and month in which the minimum and maximum ADI values of all stations were observed are tabulated. For example, in Iğdır station, the minimum ADI was observed in February 1972 with a value of −3.17. While the maximum ADI was observed in November 1993 with a value of 3.60, the lowest ADI was experienced in February 1972 with a value of −3.17. Table 4 shows that the maximum and minimum values change when the flow parameter is taken into account. While the maximum ADI at Kars station was observed in January 2023 with a value of 2.72, when the streamflow is considered, the maximum ADI was observed in January 2013 with a value of 2.90.

Figures 4 and 5 show drought frequency values corresponding to drought thresholds. These values represent

Table 4 Min. and Max. ADI values for stations

	Value	Year	Month
ARDAHAN			
Min. ADI	−3.87	1999	May
Max. ADI	3.86	1977	October
IĞDIR			
Min. ADI	−3.17	1972	February
Max. ADI	3.60	1993	November
KARS			
Min. ADI	−3.62	1987	October
Max. ADI	2.72	2023	January
ARDAHAN with Streamflow			
Min. ADI	−4.19	2010	January
Max. ADI	2.86	1996	December
KARS with Streamflow			
Min. ADI	−3.52	1987	October
Max. ADI	2.90	2013	January

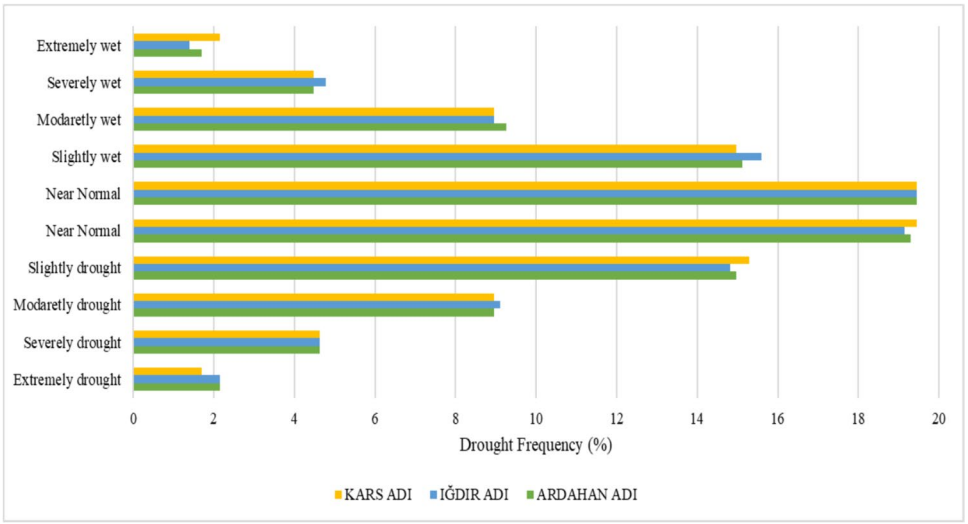


Fig. 4 Drought frequency values for stations

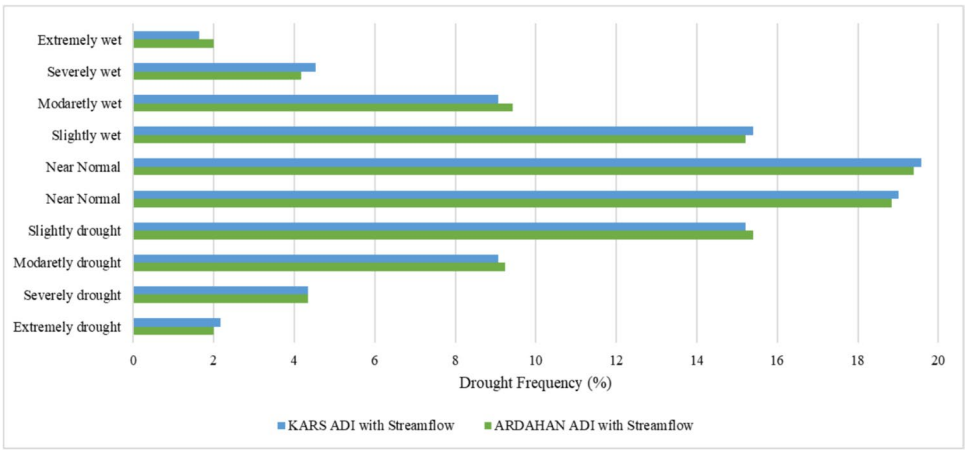


Fig. 5 Drought frequency values with streamflow data

how often drought/wet conditions are experienced. Figure 4 shows the drought frequency values without flow, while Fig. 5 shows the drought frequency values obtained by taking flow into account. After near-normal conditions, slightly drought/wet conditions are observed the most, and extreme drought/wet conditions are observed the least. If we look at the frequency values obtained using streamflow in Fig. 5, it can be seen that they are almost similar to the frequency values without streamflow.

The addition of streamflow data to the ADI for Kars station and Ardahan station resulted in changes in the drought frequency value. Although there were no major changes in terms of overall results, there were changes in important drought frequency values such as 'extremely drought' (Figs. 4 and 5). The results obtained in this study once again emphasize the importance of seasonal variability in assessing drought conditions in Ardahan, Kars, and Iğdır provinces.

IPTA results

In the second part of the analysis, the IPTA method was applied to determine whether there is a trend in temperature, precipitation, SWE, and current values of Ardahan, Iğdır, and Kars stations. Figure 6 shows the IPTA plots for 4 different parameters at Ardahan station. Figure 6 shows that all months are located in the increase trend region for mean temperature values at Ardahan station. For standard deviation (S.D.), it can be said that July, October, April, and November are located in the decrease trend region and March is on no trend line. For the mean SWE values, it can be observed that January, February, and March are in the decreasing trend line, while April, November, and December are in the increasing trend line. In addition, there is a transition from a decreasing trend to an increasing trend from March to April. In the standard deviation

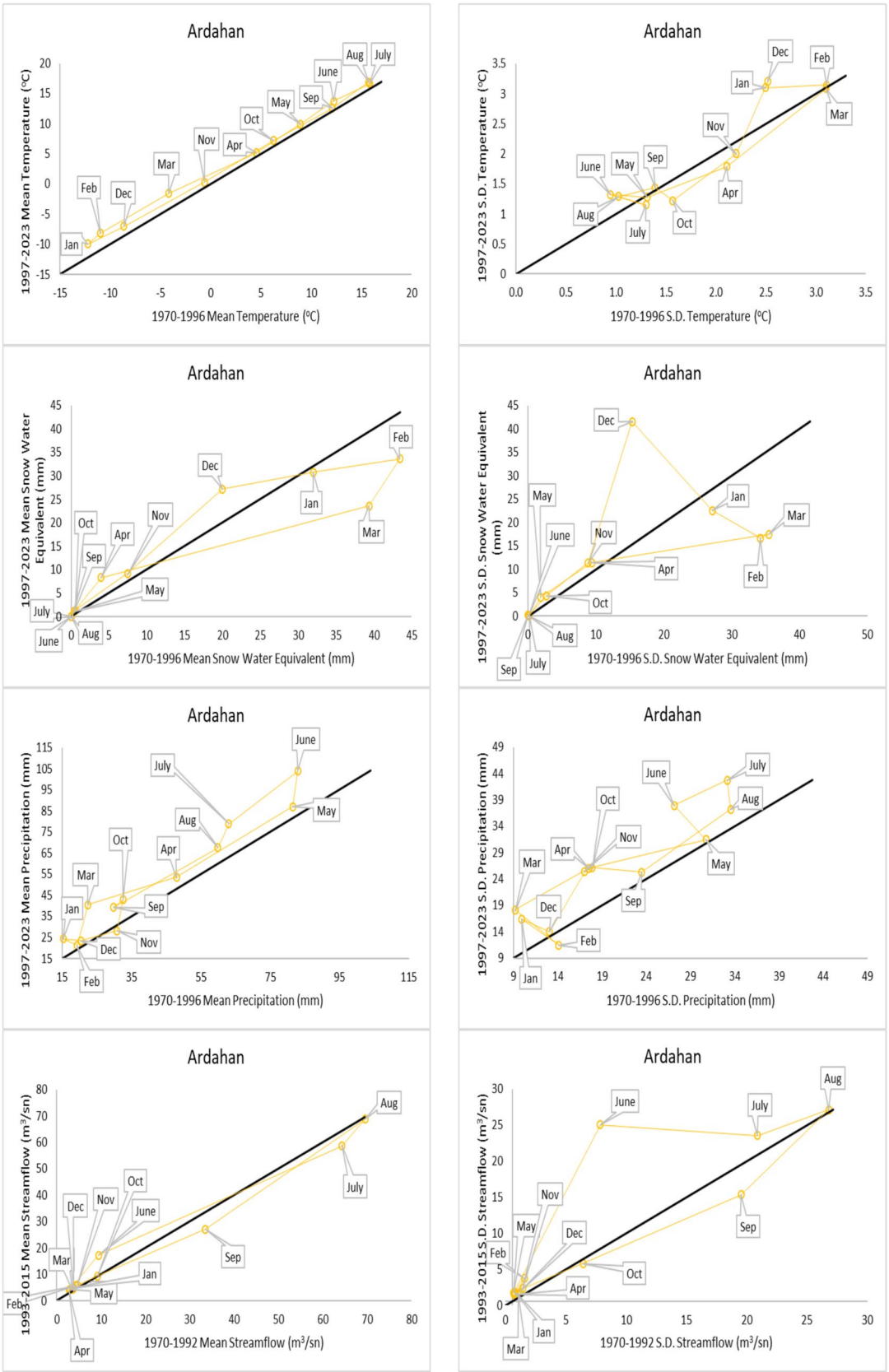


Fig. 6 IPTA graphs for Ardahan station

SWE values, there is a decrease from an increasing trend to a decreasing trend from December to February.

Among the months for which SWE can be calculated, January, February, and March are in the decreasing trend region while the other months are in the increasing trend region. This may represent a decrease in snowfall during the winter months. When we look at the mean precipitation for Ardahan station, it can be said that except for November, the remaining months are in the increasing trend region. In S.D. precipitation, only February shows a decreasing trend. For mean streamflow, a decreasing trend is observed in July, August, and September when the hydrological year is about to start and precipitation decreases. There is also a sharp transition from an increasing trend to a decreasing trend from June to July. For S.D. streamflow values, September and October are in the decreasing trend region while the other months are in the increasing trend region.

Table 5 shows the arrows indicating whether the trend is decreasing or increasing for the parameters for mean and S.D. of Ardahan station. Arrows in months pointing upwards indicate that there are more parameter values (temperature, precipitation, etc.) than in the first series (1970–1996), and arrows in months pointing downwards indicate that there are more parameter values than in the second series (1997–2023) when analyzing the results in Table 5 for Ardahan. Horizontal arrows indicate no trend. By looking at these arrows, the change in the trend from month to month can be followed. The table also shows the change in min. and max. values. This identifies the trend of extreme conditions. For example, when looking at the mean temperature, the upward arrows represent that all months have an increasing trend. For min. temperature, a decreasing trend is detected in (Jan-Feb), (Aug-Sep) and (Dec-Jan). For max. temperature, a decreasing trend is detected for the months (Oct-Nov) and (Dec-Jan). For SWE values, an increasing trend was observed for min SWE values for (Feb-Mar) and (Dec-Jan), while no trend was detected in the other months. For mean precipitation values, a decreasing trend was detected for (Nov-Dec) while an increase was detected in other months. Finally, for Ardahan station, a decreasing trend is observed for S.D. streamflow values in (Sep-Oct) and (Oct-Nov).

Figure 7 shows the IPTA graphs of 4 different parameters for Iğdır. For mean temperature, there is a shift from an increasing trend to a decreasing trend from May to June. Similarly, for S.D. temperature, there is a decreasing trend from April to May and an increasing trend from June to July. For SWE, both mean and S.D. data show a sharp decrease from increasing to decreasing trend from January to February. For mean precipitation, there is an increasing trend from February to March and a decreasing trend from May to June.

When Table 6 is examined, trend reading can be done in the same way as in Ardahan station. Since there is no current observation station acceptably close to Iğdır station, the trend of the current data could not be analyzed. When Table 6 is examined, the first thing that catches the eye is that no trend can be detected in min SWE values. No trend was found for min. temperature and min precipitation values in (July-Aug), (Sep-Oct) and (Nov-Dec).

Similar to Ardahan station, the mean temperature values at Kars station are also in the increase trend. In other words, all months are in the increase trend region (Fig. 8). In mean SWE values, January, February and March are in the decrease trend region. December is very close to the no trend line. What is interesting for Kars station is that in mean precipitation values, all months except February and November are in the increasing trend region. However, February, November and June are very close to the no trend line. Especially the increase in the transition from February to March is striking. In mean streamflow, July, September and November are in the decreasing trend line.

When Table 7 is examined, the first thing that stands out is the lack of trend in min SWE values. Again, no trend was detected in the transition of min. temperature values (May–June). The change in other months is given in Table 7 with the help of arrows. When Table 7 is analyzed, it can be interpreted that the temperature in the region has increased and SWE values have decreased according to the results of the analyzes.

Comparison of drought indexes with each other

Drought analyses using SPI, SDI, RDI, and ADI for the Kars, Ardahan, and Iğdır regions revealed some inconsistencies between the indexes. In general, the results of ADI are not in a direct correlation with SPI, RDI, and SDI (Fig. 8). The highest correlation value for the Ardahan station was observed between SPI-RDI (0.511). There is no significant correlation between all other indices. For the Kars station, the highest correlation is again between SPI-RDI (0.633). The closest value to this correlation value was 0.064 between ADI-SPI. For the Iğdır station, the highest correlation value is between SPI-RDI (0.659). Like the other stations, there is no significant correlation between the other indices for the Iğdır station. However, when the graphs are analyzed, it is observed that some distinct drought and wet periods show similar trends across all indexes. These common periods reveal that the indexes are sensitive to certain hydrological and meteorological events despite their different measurement and calculation methods.

In the graph for the Ardahan region given in Fig. 9, partial agreement is observed between ADI and other indexes. Especially the severe drought events in the 1990s and early 2000s have negative values in all indexes in the same period, signaling drought. However, in some years (e.g. after 2010), differences between ADI and other indexes were observed, indicating that ADI considers not only precipitation data

Table 5 Trend change indicator table for Ardahan station parameters

Ardahan Temperature		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Trend	S.D	↑	↑	↓	↓	↓	↑	↓	↑	↑	↓	↓	↑
Trend	Min	↓	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑	↓
Trend	Max	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑	↓
Ardahan SWE		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	↓	↓	↓	↑	↑	↓	↓	↓	↑	↑	↑	↑
Trend	S.D	↓	↓	↓	↑	↑	↓	↓	↓	↑	↑	↑	↑
Trend	Min	→	↑	→	→	→	→	→	→	→	→	→	↑
Trend	Max	↓	↓	↓	↑	↑	↓	↓	↓	↑	↑	↑	↑
Ardahan Precipitation		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑
Trend	S.D	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Trend	Min	↓	↓	↑	↓	↓	↓	↓	↓	↑	↑	↑	↑
Trend	Max	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Ardahan Streamflow		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	↑	↑	↑	↑	↑	↑	↓	↓	↓	↑	↑	↑
Trend	S.D	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↑	↑
Trend	Min	↑	↓	↓	↑	↑	↑	↑	↑	↑	↑	↓	↑
Trend	Max	↑	↑	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑

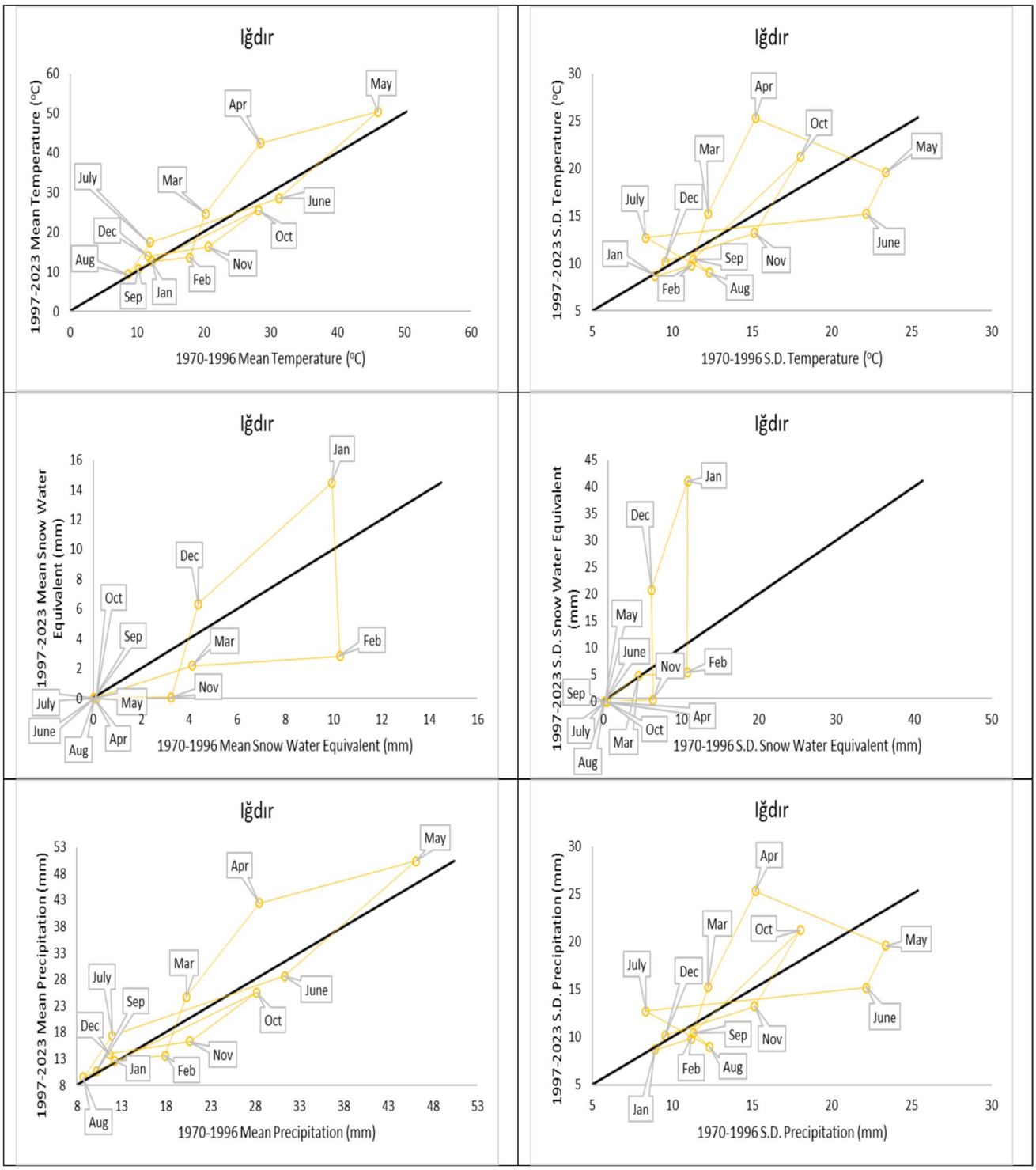


Fig. 7 IPTA graphs for Iğdır

but also other hydrological data. Similarly, in the graph for Kars, common periods of drought and humidity were identified in some years. Especially the drought periods in the late 1980s and early 2000s show that indexes such as SPI, SDI, and RDI move in parallel with ADI. However, there are also some years when ADI shows high values while other indexes remain low. This difference is because the indexes use different parameters to measure drought. Some similar trends were observed in the Igdir graph. While SPI, SDI, and RDI generally follow a parallel movement, ADI deviates

Table 6 Trend change indicator table for Iğdır station parameters

Iğdır Temperature		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	←	→	←	←	←	→	←	←	←	→	→	←
Trend	S.D	→	→	←	←	→	→	←	→	→	←	→	←
Trend	Min	→	→	←	←	→	→	↑	←	↑	←	↑	←
Trend	Mak	→	→	←	←	→	→	←	→	→	←	→	→
Iğdır SWE		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	←	→	→	→	→	→	→	→	→	→	→	←
Trend	S.D	←	→	←	→	→	→	→	→	→	→	→	←
Trend	Min	→	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Trend	Max	←	→	←	→	→	→	→	→	→	→	→	←
Iğdır Precipitation		Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean	←	→	←	←	←	→	←	←	←	→	→	←
Trend	S.D	→	→	←	←	→	→	←	→	→	←	→	←
Trend	Min	→	→	←	←	←	→	↑	←	↑	←	↑	←
Trend	Max	→	→	←	←	→	→	←	→	→	←	→	→

from this trend from time to time. Especially in the 2000s, periods when ADI reached high positive values do not have the same effect on other indexes. This is thought to be due to the ADI's attempt to provide a more holistic analysis by using a wider range of data. However, it has been observed that these differences provide less fit for drought detection in some cases.

Discussion

Drought is a natural disaster and climate-related phenomenon that can occur anywhere in the world. The recent prevalence of both extreme drought and extreme wet conditions has emphasized the increasing importance of drought studies. In this context, this study analyzed the drought in the Aras Basin, which is located in the coldest region of Turkey, has many dams and hydroelectric power plants, and is a basin with high demand for livestock and agricultural irrigation (Topçu and Karaçor 2023). The direct mathematical approach of ADI used in the study allows for an integrated consideration of the agricultural water shortage, and hydrological and meteorological drought in aggregate perspectives (Faiz et al. 2021). Çelik et al. (2018) also determined the seasonal drought conditions of these provinces in their study and stated that the drought trends seen in Kars and Iğdır, especially in summer, are in harmony. The present paper provides a more detailed assessment by integrating the ADI with a wider set of meteorological parameters. This shows that the combination of different indexes used in drought detection will provide more reliable and comprehensive results in accordance with regional climate characteristics. However, indices need different input parameters and therefore the availability of data is important in drought studies. Since this study does not have streamflow data for Iğdır province, ADI could not be analyzed together with streamflow data. Likewise, SDI indice could not be included in the study for Iğdır station for the same reason. The fact that Iğdır, which is located at a lower altitude than Ardahan and Erzurum, was not analyzed with indices based on streamflow can be said as a missing aspect of this study. In addition, a comparison was made in the study to identify and understand the relationship between ADI and other indices. Waseem et al. (2015) proposed a Multivariate Composite Drought Index (CDI) that considers all possible variables related to individual types of drought. In this study, they compared CDI with ADI, SPI, and SDI. In the study, both indexes (CDI and ADI) considering all of the physical themes of water balance gave similar results. CDI gave significant results in indicating drought or wet conditions when compared with SPI and SDI. In this respect, the results of the study were similar to the results of the present study.

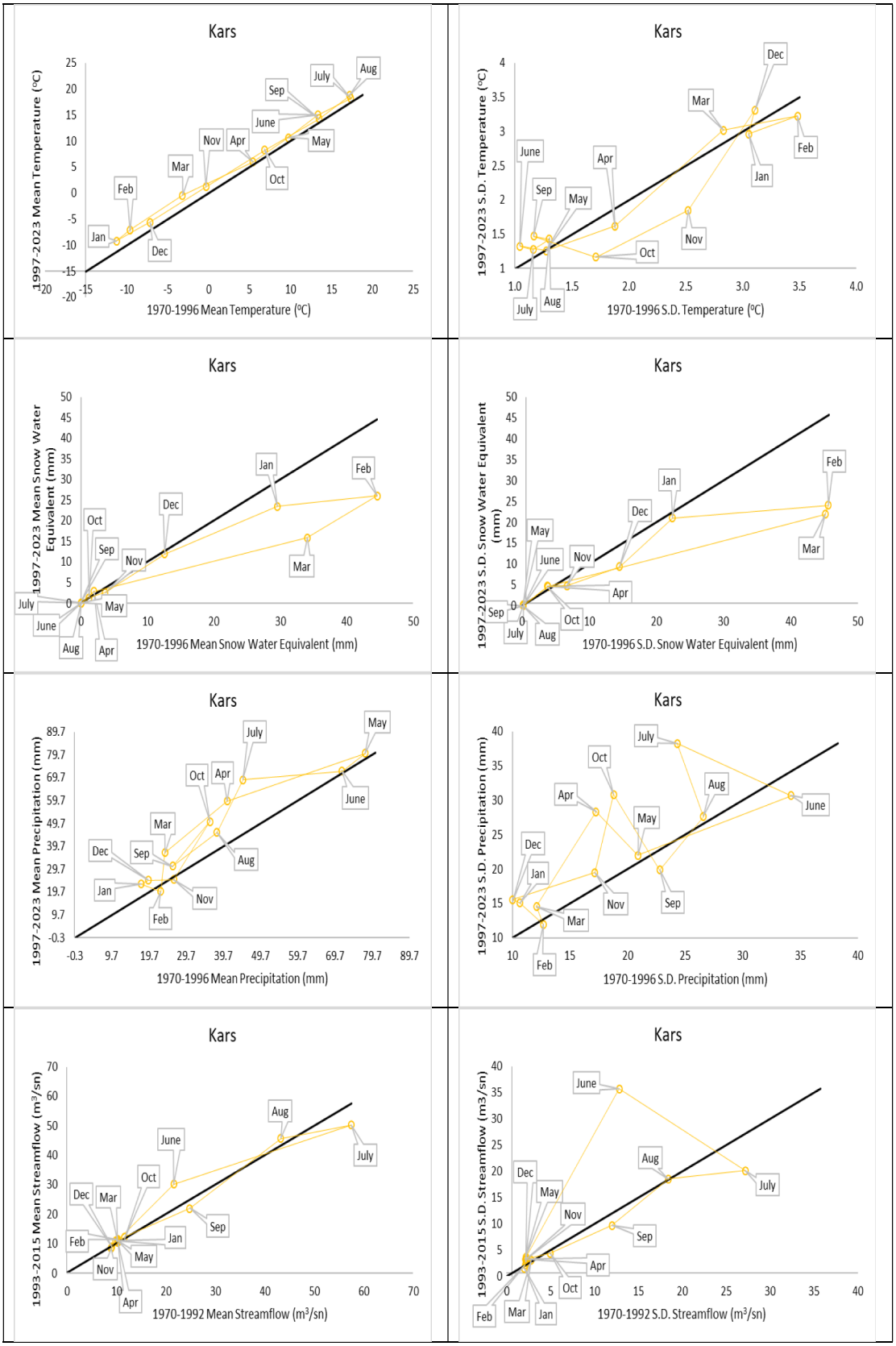


Fig. 8 IPTA graphs for Kars

Table 7 Trend change dashboard for Kars station parameters

Kars Temperature			Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Trend	S.D		↓	↓	↑	↓	↓	↑	↑	↑	↑	↓	↓	↑
Trend	Min		↓	↑	↑	↑	→	↑	↑	↓	↓	↑	↑	↑
Trend	Max		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓
Kars SWE			Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend		Mean	↓	↓	↓	↑	→	↓	↓	↓	↓	↑	↓	↓
Trend		S.D	↓	↓	↓	↑	→	↓	↓	↓	↓	↑	↓	↓
Trend		Min	→	→	→	→	→	→	→	→	→	→	→	→
Trend		Max	↓	↓	↓	↑	→	↓	↓	↓	↓	↑	↓	↓
Kars Precipitation			Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend		Mean	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑
Trend		S.D	↑	↓	↑	↑	↑	↓	↑	↑	↓	↑	↑	↑
Trend		Min	↑	↓	↑	↑	↓	↑	↑	↓	↓	↓	↓	↑
Trend		Max	↑	↓	↑	↑	↓	↓	↑	↑	↓	↑	↑	↑
Kars Streamflow			Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May–June	June-July	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
Trend	Mean		↑	↑	↑	↑	↑	↑	↓	↑	↓	↑	↓	↓
Trend	S.D.		↓	↑	↑	↑	↑	↑	↓	↑	↓	↓	↑	↑
Trend	Min		↑	↑	↑	↓	↓	↑	↓	↓	↑	↓	↓	↓
Trend	Max		↑	↑	↑	↑	↑	↑	↓	↑	↓	↑	↑	↑

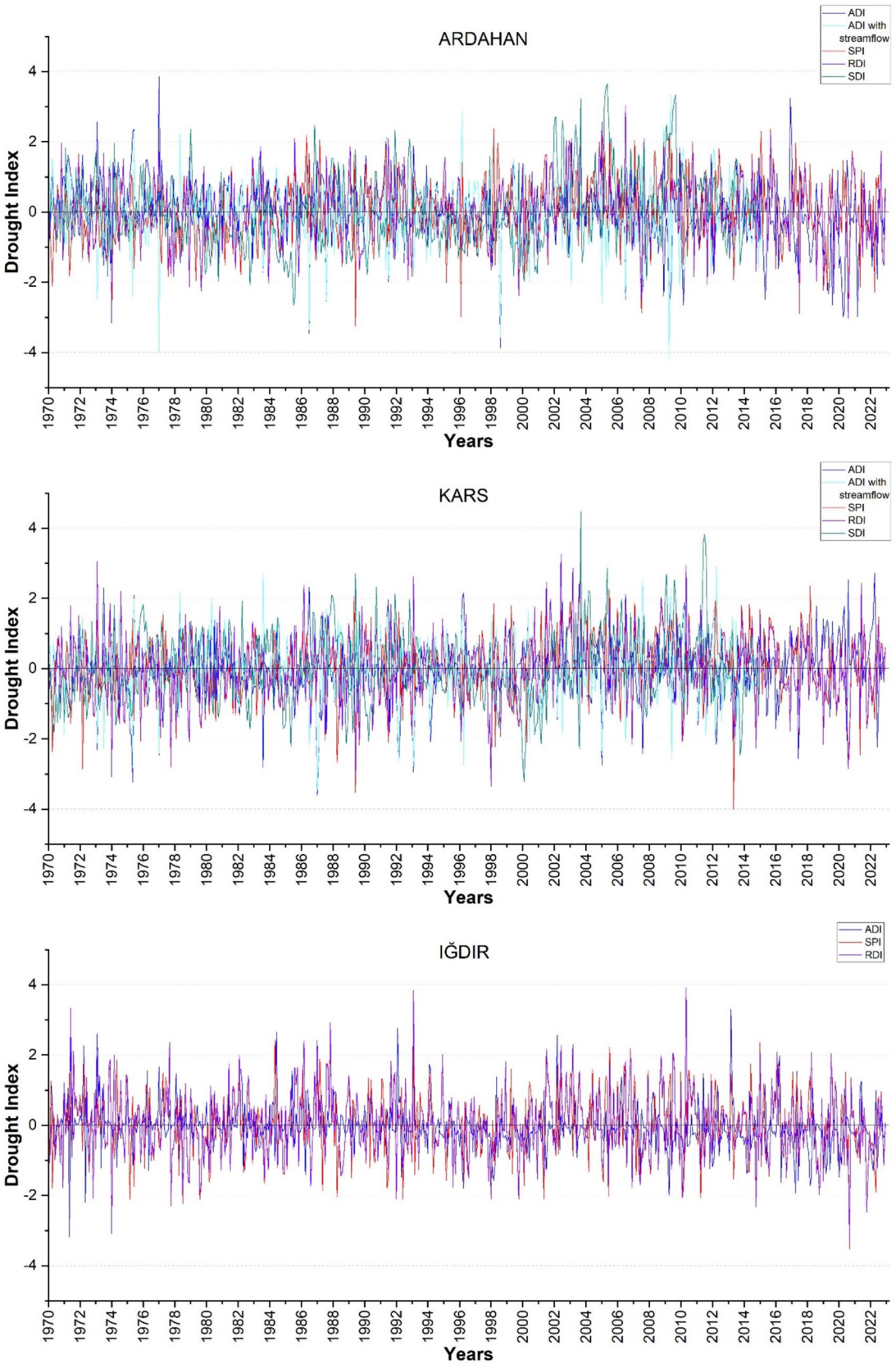


Fig. 9 Comparison of the results of different drought indexes for Ardahan, Kars, and Iğdır

Determining the trend of precipitation and temperatures together with drought analyses is one of the most used methods to understand the climatic characteristics of a region (Taşkolu et al. 2024). In this study, it was stated that the temperature showed a significant increase in the region with the trend analysis performed using IPTA. Keskin and Saplıoğlu (2023) analyzed the temperature trends in the Eastern Anatolia Region by using Innovative Trend Analysis and Mann–Kendall methods. A remarkable parallelism was observed between the findings of this study and the results of Keskin and Saplıoğlu. In both studies, it was determined that the temperature trends in Ardahan, Kars, and Iğdır provinces are consistently increasing. In addition, it is understood that temperatures show an upward trend throughout the Eastern Anatolia Region. However, unlike the other provinces, the temperature trend in Erzurum is in the direction of decrease. This situation reveals that regional temperature changes can show spatial diversity.

Conclusion

This research focuses on drought analysis using various hydrological parameters in Ardahan and Kars, the coldest provinces in Türkiye, as well as in Igdir, which has a milder climate. The drought analysis for these regions identified drought and wet conditions based on predefined drought thresholds. The IPTA method applied to key hydrological parameters such as temperature, precipitation, SWE, and runoff also revealed the impact of climate change on these parameters in the period from 1970 to 2023.

According to the results of the ADI analysis, near-normal conditions are frequently observed in the Aras Basin. However, extreme drought and wet conditions also occur with significant frequency. IPTA plots showing month-to-month changes in hydrological parameters indicate various trends. In particular, temperature has shown a clear upward trend in the region. SWE, on the other hand, generally shows no trend in most months. Precipitation showed an increasing trend in certain months and a decreasing trend in other months. Reflecting the trend in precipitation, streamflow also showed a decreasing trend in the summer months, typical of continental climates.

The last part of the study investigated the agreement of ADI with other indexes. The results revealed that ADI is not always perfectly correlated with other drought indexes such as SPI, SDI, and RDI. This shows that the choice of drought indexes is very important for drought analysis. The lack of perfect correlation between ADI and other indexes suggests that different indexes may reflect regionally and seasonally varying drought conditions. However, some important drought and wet periods show similar trends in all indexes, indicating the existence of common criteria for defining drought events. The graphs obtained as a result of the analysis for the study region will shed light on future research and water resources management studies in the region. The results of this study, which show that periodic droughts occur, can be useful in mitigating droughts and their impacts, promoting more efficient water use, and raising awareness of water sustainability to increase users' understanding of the value of water, planning to provide the necessary infrastructure for efficient management of water resources, and developing a resilient, sustainable, and reuse-oriented water management approach to cope with changing climate, population, and economic conditions. We expect that our study will support the establishment of time-based planning to reduce the impact of drought on land use, the dissemination of sustainable agricultural techniques that also take into account adaptation to climate change, the planning of agricultural planting patterns according to arid conditions, the determination of measures to be taken against forest fires on a basin basis and the sensitization of local people, and studies to reduce the impact of drought on aquaculture.

Author's contribution This study was conceived by E.T. All analyses were performed by E.T, F.K, B.Ç and İ.T. All of the authors were involved in the writing of the article. R.A also proofread the article and reviewed it for the academic language.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). There is no funding for this research study.

Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Ethics approval There are no ethical issues in this study.

Consent to participate This research has been approved by authors and signed on the signature.

Consent for publication The authors agree to the publication of this research and the copyright statement.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abbasi A (2024) Drought assessment and monitoring using a combination of the ADI and SWAT model. Arab J Geosci 17(3):85. https://doi.org/10.1007/s12517-024-11887-7

Achite M, Ceribasi G, Ceyhunlu AI, Wałęga A, Caloiero T (2021) The Innovative Polygon Trend Analysis (IPTA) as a simple qualitative method to detect changes in environment-example detecting trends of the total monthly precipitation in semiarid area. Sustainability 13(22):12674. https://doi.org/10.3390/su132212674

Alkan Ö (2008) Temel Bileşenler Analizi ve Bir Uygulama Örneği, Atatürk Üniversitesi, Sosyal Bilimler Enstitüsü, İşletme Anabilimdalı, Yüksek Lisans Tezi, Erzurum, 125s (In Turkish)

Arias PA, Rivera JA, Sörensson AA, Zachariah M, Barnes C, Philip S et al (2024) Interplay between climate change and climate variability: the 2022 drought in Central South America. Clim Change 177(1):6. https://doi.org/10.1007/s10584-023-03664-4

Cao S, Zhang L, He Y, Zhang Y, Chen Y, Yao S et al (2022) Effects and contributions of meteorological drought on agricultural drought under different climatic zones and vegetation types in Northwest China. Sci Total Environ 821:153270. https://doi.org/10.1016/j.scitotenv.2022.153270

Çelik MA, Kopar İ, Bayram H (2018) Doğu Anadolu Bölgesi'nin mevsimlik kuraklık analizi. Atatürk Üniversitesi Sosyal Bilimler Enstitüsü Dergisi 22(3):1741–1761

Chen L, Wang Q, Zhu G, Lin X, Qiu D, Jiao Y, Lu S, Li R, Meng G, Wang Y (2024) Dataset of stable isotopes of precipitation in the Eurasian continent. Earth Syst Sci Data 16:1543–1557. https://doi.org/10.5194/essd-16-1543-2024,2024

Durmaz M, Daloğlu A (2006) Frequency analysis of ground snow data and production of the snow load map using geographic information system for the Eastern Black Sea Region of Türkiye. J Struct Eng 132(7):1166–1177. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:7(1166)

Esfahanian E, Nejadhashemi AP, Abouali M, Adhikari U, Zhang Z, Daneshvar F, Herman MR (2017) Development and evaluation of a comprehensive drought index. J Environ Manage 185:31–43. https://doi.org/10.1016/j.jenvman.2016.10.050

Faiz MA, Zhang Y, Ma N, Baig F, Naz F, Niaz Y (2021) Drought indices: aggregation is necessary or is it only the researcher's choice? Water Supply 21(8):3987–4002. https://doi.org/10.2166/ws.2021.163

Ghiocel D, Lungu D (1975) Wind, snow and temperature effects on structures based on probability. Abacus Press Turbridge Wells, Kent

Gibbs JW, Maher VJ (1967) Rainfall deciles as drought indicators. Bureau of Meteorol Australia 48:33s

Jiao Y, Zhu G, Lu S, Ye L, Qiu D, Meng G, et al. (2024) The cooling effect of oasis reservoir-riparian forest systems in arid regions. Water Resour Res 60:e2024WR038301. https://doi.org/10.1029/2024WR038301

Keskin ME, Saplıoğlu K (2023) Türkiye'nin Doğu Anadolu Bölgesindeki Sıcaklık Eğilimlerinin Yenilikçi Trend Analizi ve Mann-Kendall ile Belirlenmesi. J Innov Civil Eng Technol 5(1):1–16

Keyantash JA, Dracup JA (2004) An aggregate drought index: assessing drought severity based on fluctuations in the hydrologic cycle and surface water storage. Water Resour Res 40(9). https://doi.org/10.1029/2003WR002610

Koycegiz C, Buyukyildiz M (2024) Applications of innovative polygon trend analysis (IPTA) and trend polygon star concept (TPSC) methods for the variability of precipitation in Konya Closed Basin (Turkey). Theoret Appl Climatol 155(4):2641–2656

Li J, Li Y, Yin L, Zhao Q (2024) A novel composite drought index combining precipitation, temperature and evapotranspiration used for drought monitoring in the Huang-Huai-Hai Plain. Agric Water Manag 291:108626. https://doi.org/10.1016/j.agwat.2023.108626

Lin YC, Kuo ED, Chi WJ (2021) Analysis of meteorological drought resilience and risk assessment of groundwater using signal analysis method. Water Resour Manage 35:179–197. https://doi.org/10.1007/s11269-020-02718-x

Longhu C, Guofeng Z, Qin QW, Linlin Y, Xinrui L, Siyu Lu, Yinying J, Rui L, Gaojia M, Yuhao W, Jiangwei Y, Chen J (2024) Influence of mountain orientation on precipitation isotopes in the westerly belt of Eurasia, global and planetary change, volume 240, 2024, 104543, ISSN 0921-8181.https://doi.org/10.1016/j.gloplacha.2024.104543

Malik A, Kumar A, Singh RP (2019) Application of heuristic approaches for prediction of hydrological drought using multi-scalar streamflow drought index. Water Resour Manage 33:3985–4006

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 vol 17, no. 22, pp. 179–183

MGM (2016) Köppen iklim sınıflandırmasına göre Türkiye iklimi. https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/koppen.pdf (In Turkish) (Access Date 22.02.2024)

MGM (2024) https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m (Access Date 22.02.2024)

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391(1–2):202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mukherjee S, Mishra A, Trenberth KE (2018) Climate change and drought: a perspective on drought indices. Current Climate Change Reports 4:145–163. https://doi.org/10.1007/s40641-018-0098-x

Nalbantis I (2008) Evaluation of a hydrological drought index. Eur Water 23(24):67–77

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

O'Connor P, Murphy C, Matthews T, Wilby RL (2023) Relating drought indices to impacts reported in newspaper articles. Int J Climatol 43(4):1796–1816. https://doi.org/10.1002/joc.7946

Omidvar K, Nabavizadeh M, Rousta I, Olafsson H (2024) Remote sensing-based drought monitoring in Iran's Sistan and Balouchestan Province. Atmosphere 15(10):1211. https://doi.org/10.3390/atmos15101211

Palmer WC (1965) Meteorological drought (vol 30). US Department of Commerce, Weather Bureau

Park S, Im J, Park S, Rhee J (2017) Drought monitoring using high resolution soil moisture through multi-sensor satellite data fusion over the Korean peninsula. Agric for Meteorol 237:257–269. https://doi.org/10.1016/j.agrformet.2017.02.022

Q' Rourke MJ, Redfield R, Bradsky PV (1982) Uniform snow loads on structures. J StructDiv ASCE 108(ST12):2781-2798

Qi X, Qian S, Chen K, Li J, Wu X, Wang Z, Deng Z, Jiang J (2023) Dependence of daily precipitation and wind speed over coastal areas: evidence from China's coastline. Hydrol Res 54(4):491–507. https://doi.org/10.2166/nh.2023.093

Rousta I, Nasserzadeh MH, Jalali M, Haghighi E, Ólafsson H, Ashrafi S, Doostkamian M, Ghasemi A (2017) Decadal spatial-temporal variations in the spatial pattern of anomalies of extreme precipitation thresholds (case study: Northwest Iran). Atmosphere 8(8):135. https://doi.org/10.3390/atmos8080135

Rousta I, Olafsson H, Moniruzzaman M et al (2020) The 2000–2017 drought risk assessment of the western and southwestern basins in Iran. Model Earth Syst Environ 6:1201–1221. https://doi.org/10.1007/s40808-020-00751-8

Rousta I, Sharif M, Heidari S et al (2023) Climatic variables impact on inland lakes water levels and area fluctuations in an arid/

semi-arid region of Iran, Iraq, and Turkey based on the remote sensing data. Earth Sci Inform 16:1611–1635. https://doi.org/10.1007/s12145-023-00995-9

Rousta I, Mansourmoghaddam M, Olafsson H, Krzyszczak J, Baranowski P, Zhang H, Tkaczyk P (2022) Analysis of the recent trends in vegetation dynamics and its relationship with climatological factors using remote sensing data for Caspian Sea watersheds in Iran. Int Agrophys 36(3):139–153. https://doi.org/10.31545/intagr/150020

Santos CAG, Neto RMB, do Nascimento TVM, da Silva RM, Mishra M, Frade TG (2021) Geospatial drought severity analysis based on PERSIANN-CDR-estimated rainfall data for Odisha state in India (1983–2018). Sci Total Environ 750:141258. https://doi.org/10.1016/j.scitotenv.2020.141258

Şen Z (2012) Innovative trend analysis methodology. J Hydrol Eng 17(9):1042–1046. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000556

Şen Z, Şişman E, Dabanlı I (2019) Innovative polygon trend analysis (IPTA) and applications. J Hydrol 575:202–210

Shi X, Chen F, Shi M, Ding H, Li Y (2023) Construction and application of optimized comprehensive drought index based on lag time: a case study in the middle reaches of Yellow River Basin China. Sci Total Environ 857:159692. https://doi.org/10.1016/j.scitotenv.2022.159692

T. C. Tarım ve Orman Bakanlığı (2022) Aras ve Çoruh Havzalari Kuraklık Yönetim Planlarının Hazırlanması Projesi, https://webdosya.csb.gov.tr/db/scd/icerikler/aras-havzasi-kyp-scd-taslak-kapsam-bel-rleme-raporu-20230113094349.pdf (In Turkish) (Access Date 06.11.2024)

T.C. Tarım ve Orman Bakanlığı (2019) Aras Havzası taşkın yönetim planı yönetici özeti. https://www.tarimorman.gov.tr/SYGM/Belgeler/Taşkın%20Yönetim%20Planları%2026.12.2022/ARAS%20HAVZASI%20TAŞKIN%20YÖNETİM%20PLANI%20YÖNETİCİ%20ÖZETİ.pdf (In Turkish) (Access Date 22.02.2024)

Taşkolu İ, Acar R, Çırağ B (2024) Trend analysis of precipitation and temperatures in the Black Sea Region using the innovative trend analysis. J Stud Adv Technol 2(2):74–82

Taşkolu İ (2023) Güneydoğu Anadolu Bölgesi için kuraklık analizi, Pamukkale University, Denizli (Master's thesis) (In Turkish)

Thom HC (1958) A note on the gamma distribution. Mon Weather Rev 86(4):117–122

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38(1):55–94

Tian Y, Zhao Y, Son SW, Luo JJ, Oh SG, Wang Y (2023) A deep-learning ensemble method to detect atmospheric rivers and its application to projected changes in precipitation regime. J Geophys Res: Atmospheres 128:e2022JD037041. https://doi.org/10.1029/2022JD037041

Topçu E, Karaçor F (2021) Drought analysis of Erzurum Station by using standardized precipitation evapotranspiration index and aggregated drought index. J Polytech 24(2):565–574. https://doi.org/10.2339/politeknik.682168

Topçu E, Karaçor F (2023) A comparative investigation on the applicability of the actual precipitation index (API) with the standardized precipitation index (SPI): the case study of Aras Basin Turkey. Theoret Appl Climatol 154(1):29–42

Topçu E, Seçkin N, Haktanır NA (2022) Drought analyses of Eastern Mediterranean, Seyhan, Ceyhan, and Asi Basins by using aggregate drought index (ADI). Theoret Appl Climatol 147(3–4):909–924. https://doi.org/10.1007/s00704-021-03873-w

Topçu E, Seçkin N (2022) Drought assessment using the reconnaissance drought index (RDI): a case study of Eastern Mediterranean, Seyhan, Ceyhan, and Asi basins of Türkiye. J Eng Res 10(2B). https://doi.org/10.36909/jer.12113

Topçu E (2013) L-Momentler ve standart yağış indeksi (SYİ) yardımıyla Seyhan Havzası kuraklık analizi, Cukurova University (Master's thesis) (In Turkish)

Topçu E. (2022) Drought monitoring using MOWCATL data mining algorithm in Aras Basin, Türkiye. Earth Sci Res J 26(2):183–196. https://doi.org/10.15446/esrj.v26n2.94786

Tsakiris G, Vangelis H (2005) Establishing a drought index incorporating evapotranpiration. European Water Public 9(10):3–11

Wang S, Mo X, Hu S, Liu S, Liu Z (2018) Assessment of droughts and wheat yield loss on the North China Plain with an aggregate drought index (ADI) approach. Ecol Ind 87:107–116. https://doi.org/10.1016/j.ecolind.2017.12.047

Wang Y, Peng T, Lin Q, Singh VP, Dong X, Chen C et al (2022) A new non-stationary hydrological drought index encompassing climate indices and modified reservoir index as Covariates. Water Resour Manage 36(7):2433–2454. https://doi.org/10.1007/s11269-022-03151-y

Waseem M, Ajmal M, Kim TW (2015) Development of a new composite drought index for multivariate drought assessment. J Hydrol 527:30–37

West H, Quinn N, Horswell M (2019) Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future opportunities. Remote Sens Environ 232:111291. https://doi.org/10.1016/j.rse.2019.111291

Ying Z, Haixia W, Bing S, Pengfei X, Wangchen Z, Stephan P, Robert LH, Rainer H (2023) Characterizing uncertainty in process-based hydraulic modeling, exemplified in a semiarid Inner Mongolia steppe. Geoderma 440(2023):116713. ISSN 0016–7061. https://doi.org/10.1016/j.geoderma.2023.116713

Zarei AR (2022) Assessing the importance of climate variables on RDI and SPEI using backward multiple linear regression in arid to humid regions over Iran. Pure Appl Geophys 179(8):2905–2921. https://doi.org/10.1007/s00024-022-03073-1

Zarei AR, Mokarram M, Mahmoudi MR (2023) Comparison of the capability of the meteorological and remote sensing drought indices. Water Resour Manage 37(2):769–796. https://doi.org/10.1007/s11269-022-03403-x

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.