ISSN:2372-0743 print
ISSN:2373-2989 on line
International Journal of Ground Sediment & Water
Vol. 20
2024

◆ Research paper

DOI: 10.5281/zenodo.14025336

Analysis of Hydrological Drought Patterns in the Aras River Basin within the Framework of Transboundary Water Management

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Abstract: This study analyzes drought trends and their effects on water management in the transboundary Aras River Basin, a crucial component of Turkey's annual water resources. Climate change has resulted in diverse water management strategies among the basin-sharing nations—Turkey, Azerbaijan, Iran, and Armenia—each seeking to safeguard its interests. The utilization of the Aras River for agricultural irrigation and energy generation has led to tensions among the nations regarding its shared management. This study utilized monthly average flow data from six streamflow observation stations operated by the Turkish State Hydraulic Works, gathered from 1970 to 2015, to compute standardized streamflow drought indices for 3, 6, 9, and 12-month intervals. The indices were subsequently examined utilizing the Mann-Kendall Trend and Mann-Kendall Regional Trend tests. The results demonstrate a declining trend in drought indices at stations D24029 and D24058 over 3, 6, 9, and 12-month intervals, and at stations D24019 and D24049 over 9 and 12-month intervals, whereas station D24060 showed an increasing trend over the 9 and 12-month indices. The regional trend analysis for the entire basin revealed a consistent decline in the 6, 9, and 12-month indices. These findings underscore the imperative for coordinated and sustainable annual water production and distribution among Turkey, Azerbaijan, Iran, and Armenia to alleviate the risks of prolonged hydrological drought in the Aras River Basin. Determining the annual potential water budget is essential for ecosystem preservation, transparent governance, and attaining sustainable water allocation via an integrated, collaborative water management approach.

Keywords: Aras River, Standardized drought index, Transboundary water, Mann Kendall Trend test, Hydrological drought

Introduction

While the boundaries of numerous countries and regions are delineated by natural features, these natural borders do not always correspond to watershed boundaries, potentially leading to complications in the allocation of transboundary water resources. Currently, conflicts arise in the Nile River in Africa, the Euphrates, and Tigris Rivers in the Middle East, and the Amazon River in South America. Transboundary waters are defined as all water systems that traverse political boundaries between two or more countries (Rivera & Candela, 2018). Transboundary waters are crucial for the livelihoods of individuals globally, particularly in nations that heavily rely on agriculture for their economic sustenance (Gökçekuş & Bolouri, 2023). Climate change alters precipitation patterns, resulting in diminished stream flow and the irreversible depletion of our limited freshwater resources (Impact of Climate Change on Hydrological Processes and Water Resources: Insights, Challenges, and Strategies for Resilience). Climate change, whose effects are presently evident, contributes to various natural destruction processes, including drought and desertification. Furthermore, it indirectly influences hydrological processes due to the degradation of the ecological framework in semi-arid regions (Dölarslan and Gül, 2024), which are delicate ecosystems (Dölarslan et al., 2017; Gül and Dölarslan, 2021; Gül and Erşahin, 2019). The management of transboundary waters involves natural challenges stemming from hydrological uncertainty (Englezos et al., 2023; Mohammed et al., 2022), socio-economic issues resulting from land use changes and intersectoral water allocation (Englezos et al., 2023; Mgala et al., 2024), and political obstacles arising from disparate legal and administrative frameworks among nations (Oybek, 2024; Varady et al., 2023).

Transboundary water sharing presents complex challenges arising from the interplay of ecological, socio-economic, and political factors, which are becoming more critical as the impacts of climate change intensify. These challenges heighten the imperative for international cooperation to manage water resources equitably and sustainably. A multitude of limitations hinders the effective management of transboundary water resources. The primary concerns encompass flood prevention (Rahayu et al., 2024), safeguarding water resource quality (Baten and Titumir, 2016), facilitating equitable water distribution (Khan and Rahman, 2022; Sondermann and de Oliveira, 2021), and establishing multi-agency control over water management (Krengel et al., 2018). In contrast to the limited and under-researched studies on hydrological drought (Kale, 2021), meteorological drought has been extensively examined at local levels (Bacanlı and Kargı, 2018; Batan, 2021; Dursun and Babalık, 2020; Özgün et al., 2020; Partal and Yavuz, 2020; Şener and Davraz, 2021; Taylan and Bahşi, 2021; Uçar et al., 2019), basin-wide (Ediş and Ulas, 2017; Uygur Erdoğan and Ediş, 2023), and across Turkey (Deniz Öztürk and Ünlü, 2022).

The management of transboundary water basins has resulted in the formulation of effective strategies, including fostering cooperation and information exchange (Baten and Titumir, 2016), implementing integrated basin management (Baudry, 2013; Göl et al., 2017; Krengel et al., 2018), establishing a shared database and proactively identifying risks (Wheeler et al., 2018), and enhancing international dialogue through the adoption of a flexible and dynamic management approach (Zeitoun et al., 2013). Furthermore, transboundary water management encompasses challenges and complexities while optimizing stakeholder engagement through political and cultural collaboration with other nations (Johnson et al., 2018; Zeitoun et al., 2013).

Transboundary water basins, accounting for approximately one-third of Turkey's annual gross water potential, are essential for the governance of these rivers, the interests of several stakeholder states, and their sustainable use in light of climate change. Notwithstanding international agreements that mandate the development of riverine structures and the fair allocation of water, each nation experiencing hydrological drought and in need of potable water may choose diverse water management strategies tailored to the interests of its citizens. Therefore, methodical techniques and concrete results are essential for the effective management of common water resources during extreme conditions like drought. Meteorological and hydrological studies have been conducted in the Aras River Basin because Azerbaijan, Iran, and Armenia, which derive from Turkey and are situated in the lower watershed of the Aras-Kura River Basin, utilize the river for agricultural irrigation and energy production, leading to tensions over its management (Coşkun, 2020a; Demir et al., 2014; Topçu and Karaçor, 2023, 2020). The recent study by Coşkun (2020) is inadequate regarding consistency, comparability, sensitivity to extremes, normalization, temporal flexibility, and decision-making processes in assessing hydrological drought, as it solely conducts station-based trend analysis on flow data. This study seeks to deliver a more thorough and comparable examination of hydrological drought progression at both station-based and regional levels through the application of a standardized flow index.

Materials and Methods

Study area

The Aras Basin, one of Turkey's 25 principal basins, was selected as the study area because the upstream section of the river basin is located in Turkey, where water sharing commences. In this context, monthly average flows (m3/sec) recorded at six flow observation stations (D24018, D24029, D24049, D24058, D24060, D24069) of the State Hydraulic Works from 1970 to 2015 were utilized. The Aras River basin encompasses an area of 102,000 km^2 and is situated in eastern Türkiye. Only a small portion of the basin is forested (<10%), predominantly consisting of Scotch Pine. Pastures and agricultural zones comprise the predominant land use. The Aras River basin in Turkey typically receives an average annual precipitation ranging from 400 mm to 600 mm.

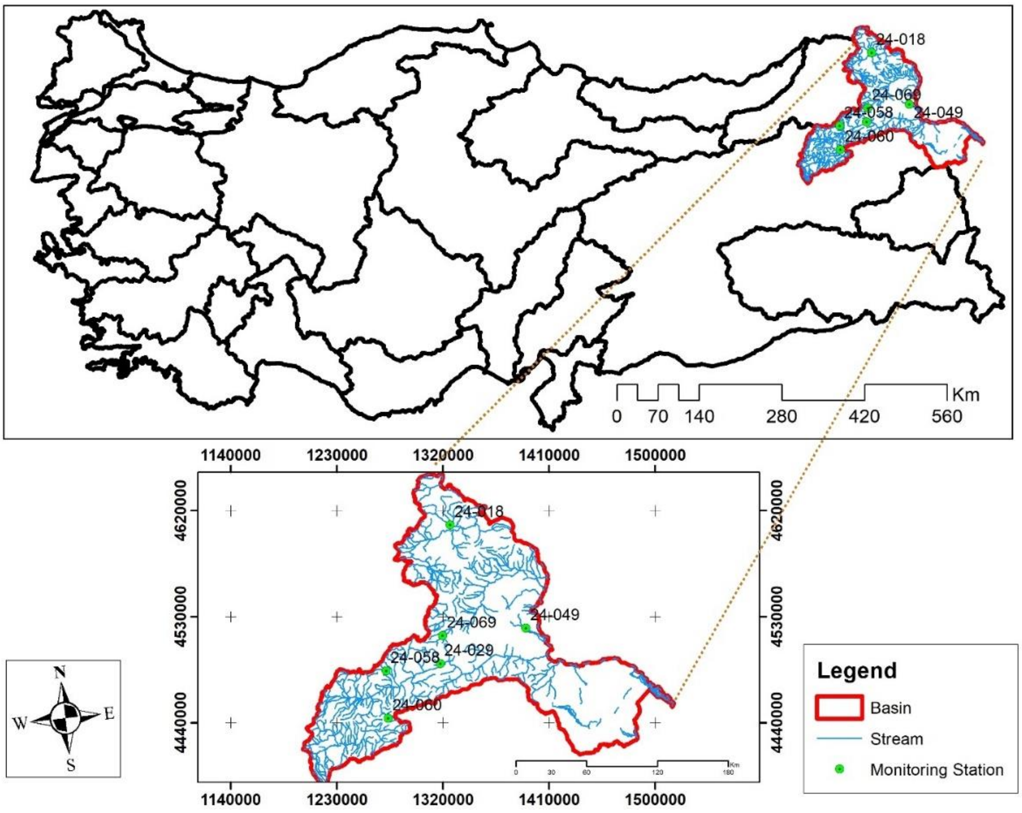


Figure 1. Location map of the study area and distribution of monitoring stations.

Methods

The R package for Windows was utilized to compute monthly average flows from 1970 to 2015 and to standardize flow drought indices of varying durations (3, 6, 9, and 12 months). Let Q denote streamflow data and F(Q) signify the cumulative distribution function (CDF) of the fitted probability distribution; the SSI for a designated period t can be articulated as:

$$SSIT = \Phi^{-1}\left(F\left(Q_t\right)\right) \quad (1)$$

Where $F(Qt)$ is the cumulative probability of streamflow $Qt1$;Φ^{-1} is the inverse of the standard normal distribution function

The SSI value signifies drought conditions: negative SSI values denote below-average flows (drought), whereas positive values signify above-average flows (wet conditions).

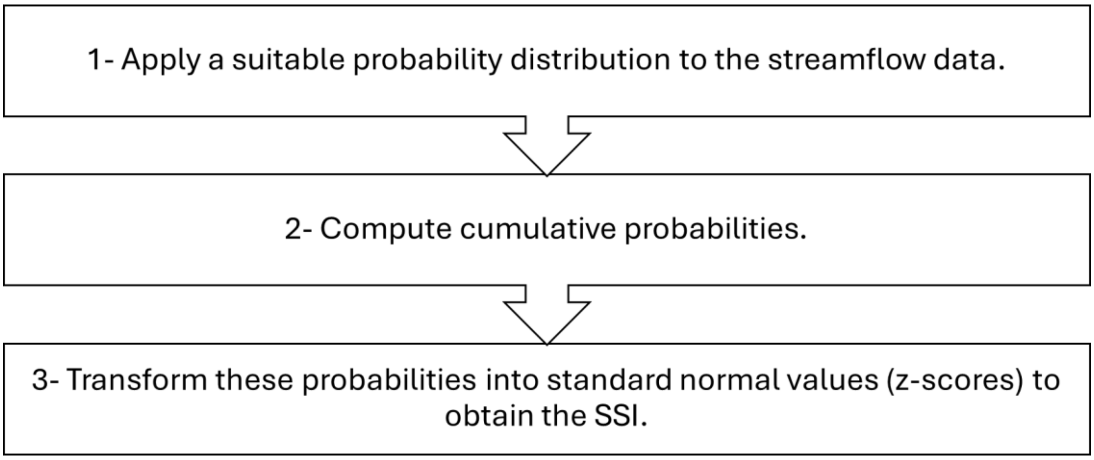


Figure 2. Flowchart of the standardized streamflow drought index

The Mann-Kendall Trend test and the Mann-Kendall Regional Trend test were utilized to ascertain the trends of the indices computed via the same program for each station and the entire basin.

Mann Kendall Trend Test

The Mann-Kendall trend test is a non-parametric method employed to identify trends in a time series without presuming a particular distribution. It is frequently utilized in hydrology, meteorology, and environmental research. The assessment determines the presence of a trend by computing Kendall's S statistic and the Z-score for significance.

For a time series comprising n data points, $x_1, x_2, \ldots, x_n$.

Table1. Formula and Explanations for the Mann-Kendall Trend Test

Step	**Formula**	**Description**
Compute S	$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(xj - xk)$ Where: $sign(xj - xk) = \begin{Bmatrix} +1\ if\ xj > xk \\ 0\ if\ xj = xk \\ -1\ xj < xk \end{Bmatrix}$	For a time series comprising n data points, $x_1, x_2, \ldots, x_n$ S represents the aggregate of the signs of all potential differences between pairs of data points.
Variance of S	$\sigma^2 = \frac{n(n-1)(2n+5) - \sum tt(t-1)(2t+5)}{18}$	When the sample size n exceeds 10, S approximates a normal distribution, and the variance of S is computed as: Where t denotes the quantity of tied groups of identical values within the dataset.
Calculate Z-score	$Z = \begin{Bmatrix} \frac{S-1}{\sigma}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S-1}{\sigma}\ if\ S < 0 \end{Bmatrix}$	The standardized test statistic Z is calculated using S and its variance σ^2
Interpret the Z score.	A positive Z indicates an upward trend, whereas a negative Z signifies a downward trend. The importance of the trend is evaluated by contrasting Z with a critical value from the standard normal distribution (e.g., $Z_{0.05}$ = 1.96 for a 5% significance level). If the computed |Z| surpasses the critical value, a statistically significant trend is indicated.	

The Regional Mann-Kendall Trend Test

The Regional Mann-Kendall Trend Test is an enhancement of the Mann-Kendall test, intended to identify trends across various locations within a region. It evaluates the presence of a significant overarching trend within a regional context by amalgamating trend data from individual stations. The essential steps include computing the Mann-Kendall statistic for each location and subsequently consolidating these results to evaluate a regional trend.

Table 2. Formula and Explanations for the Regional Mann-Kendall Trend Test

Step	Formula	Description
Calculate the Mann-Kendall S Statistic for Each Site:	$Si = \sum_{k=1}^{n-1} \quad \sum_{j=k+1}^{n} sign(xj - xk)$	For each site i, calculate the Mann-Kendall Si statistic according to the conventional Mann-Kendall test.
Variance for Each Site	$\mathrm{\sigma i2} = \frac{\mathrm{n(n-1)(2n+5)} - \sum \mathrm{tt(t-1)(2t+5)}}{18}$	Compute the variance σi^2 for each site's statistic Si. Where t represents the number of tied groups in the dataset for site i
Standardize Each Site's Statistic to Obtain Zi	$Zi = \begin{Bmatrix} \frac{Si-1}{\sigma} \ if\ Si > 0 \\ 0\ if\ Si = 0 \\ \frac{Si-1}{\sigma}\ if\ Si < 0 \end{Bmatrix}$	For each site i, compute the standardized test statistic Zi as follows:
Combine Z-scores for Regional Test	$ZR = 1/m \sum_{i=1}^{m} Zi$	Compute the regional average Z statistic, ZR, by consolidating the individual Z_i values for m sites.
Interpret the Regional Trend	If ZR is markedly distinct from zero, it signifies a regional trend. To ascertain statistical significance, juxtapose ZR with a critical value from the standard normal distribution (e.g., Z 0.05 = 1.96 Z 0.05=1.96 for a 5% significance threshold).	

Results and Discussion

Upon evaluating station 18 solely based on the Mann-Kendall trend test results, no statistically significant trend was identified in short-term hydrological droughts; however, a statistically significant decreasing trend was observed in long-term hydrological droughts. The pronounced declining trend observed over the 12 months indicates that this station is experiencing long-term drought conditions (Figure 3, Table 3).

a

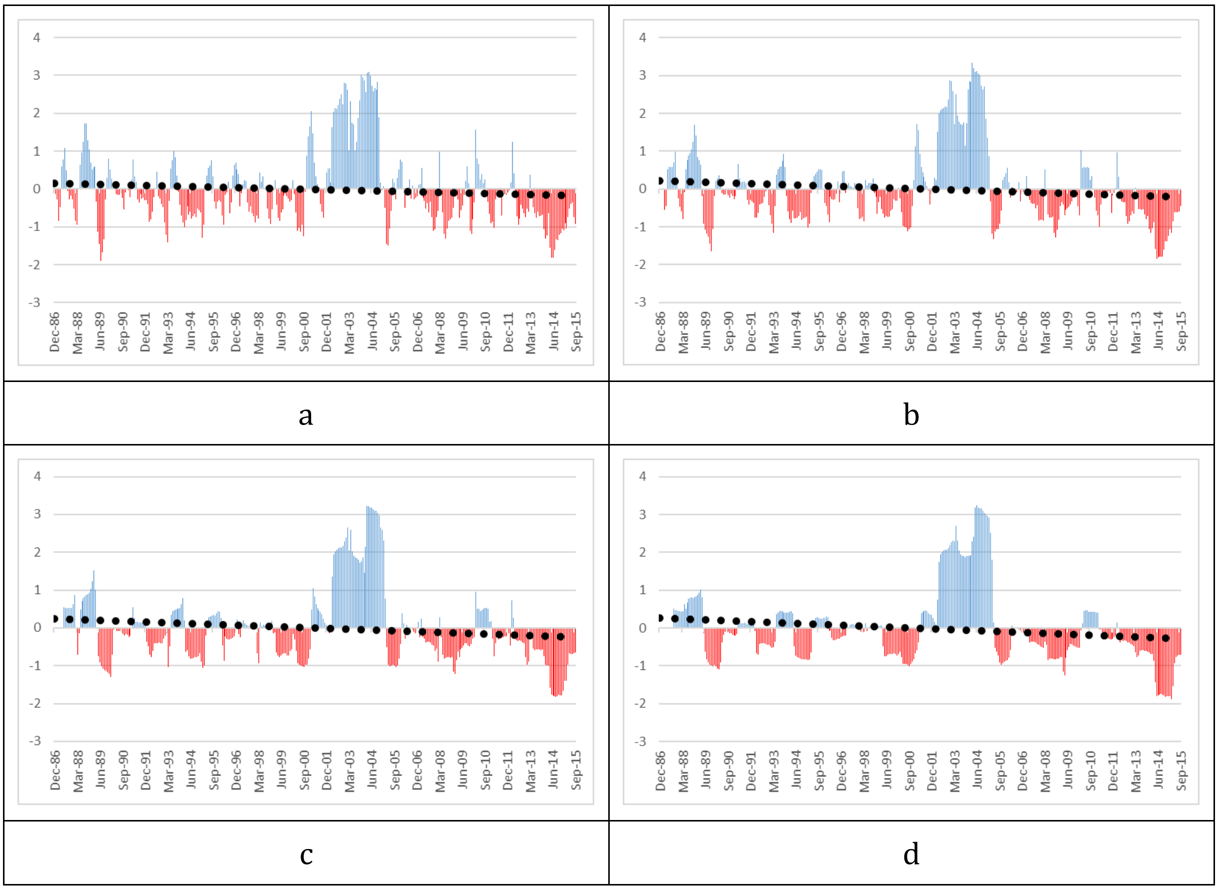
b

c

d

Figure 3. Trends of the standardized streamflow index for station 18: a) 3 months b) 6 months c) 9 months d) 12 months

At Station 29, the standardized stream drought index values for both short-term and long-term periods exhibit a statistically significant declining trend. Alongside a notable reduction in the 3, 6, and 9-month values, the 12-month period exhibited the effects of a persistent and severe drought trend, as evidenced by the Z (-4.760) and p (0.00) values (Figure 4, Table 3).



a

b

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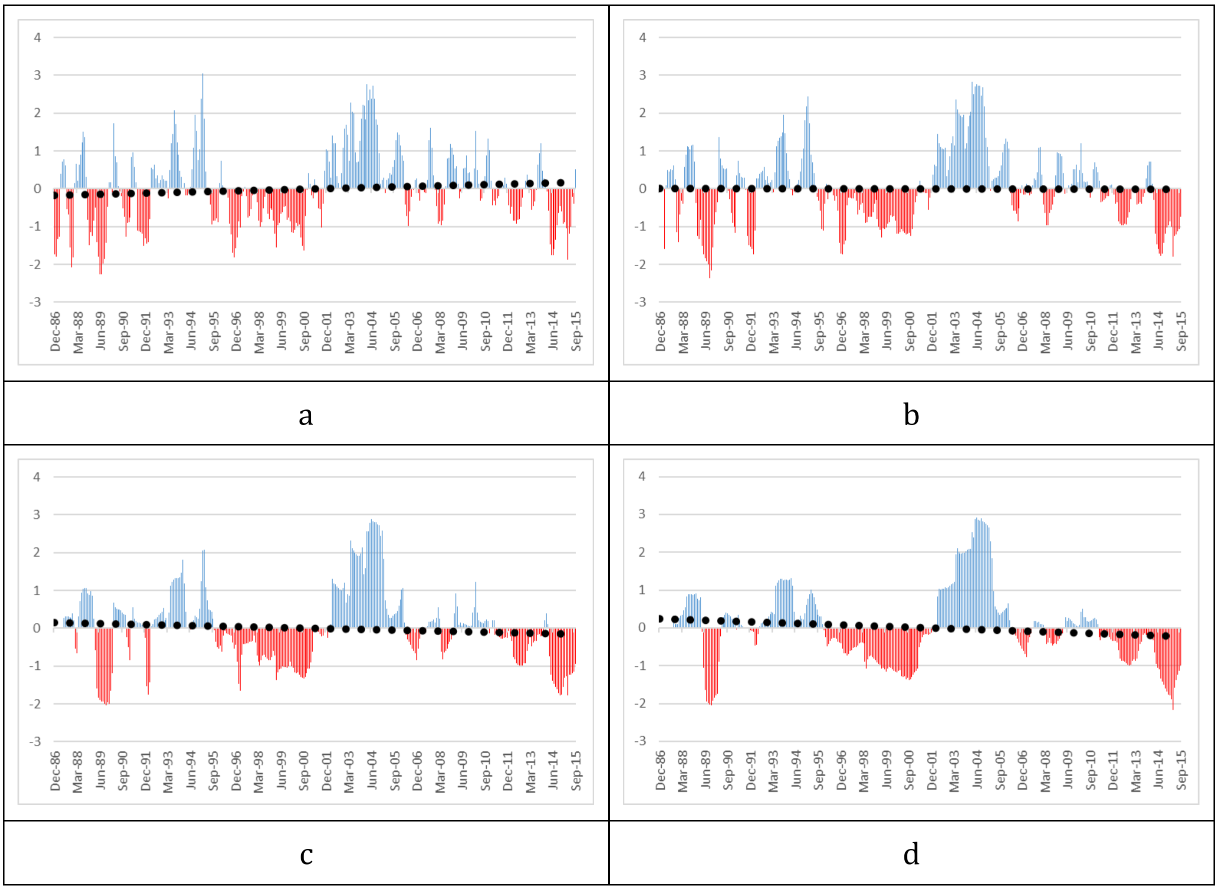
Figure 4. Trends of the standardized streamflow index for station 29: a) 3 months b) 6 months c) 9 months d) 12 months

Station 49, when assessed using the Mann-Kendall trend test, exhibits no statistically significant trend in short-term intervals (3, 6) as observed in station 18, yet demonstrates a statistically significant decreasing trend in long-term intervals (9, 12). As the duration extends from 9 months to 12 months, the intensity of drought escalates, evidenced by Z (-4.543) and p (0.000) values indicating that prolonged drought is more severe at this station (Figure 5, Table 3).



a

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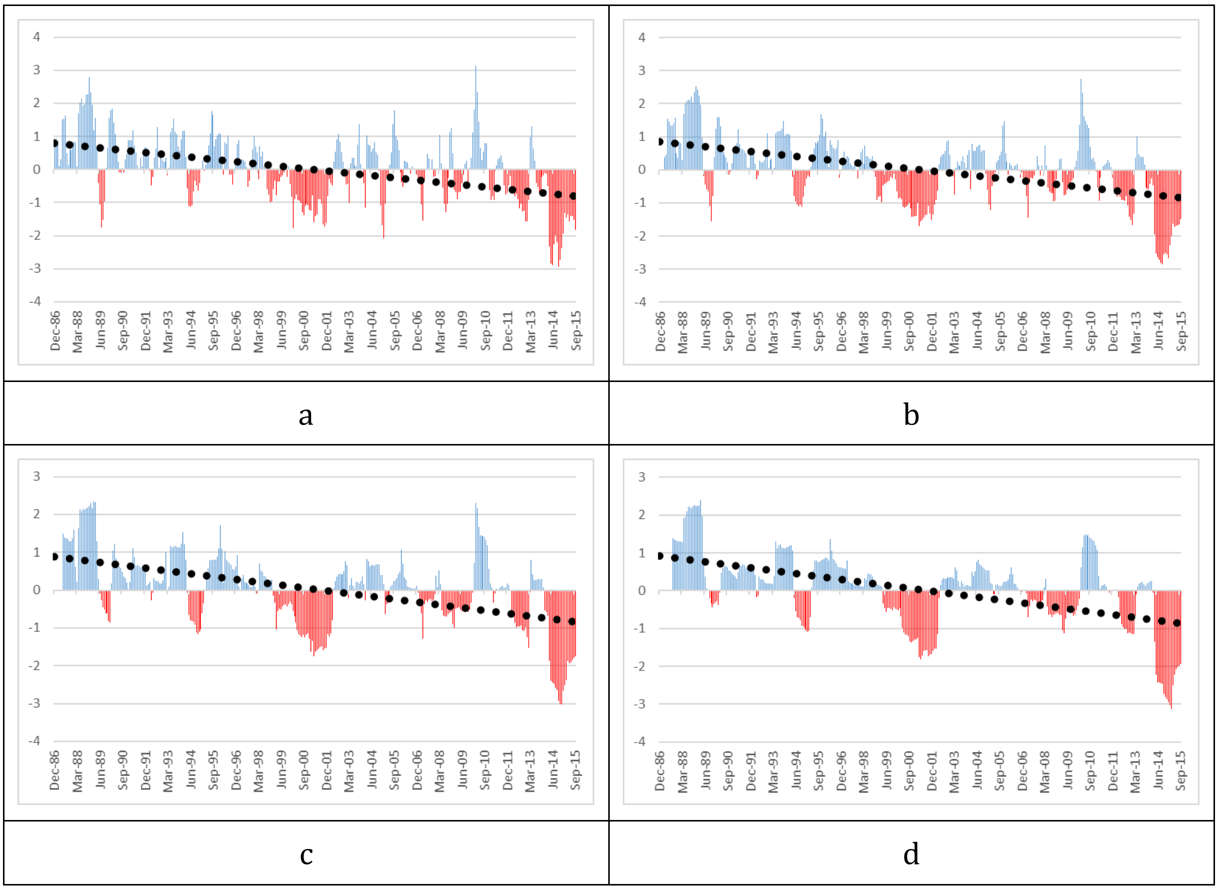
Figure 5. Trends of the standardized streamflow index for station 49: a) 3 months b) 6 months c) 9 months d) 12 months

A statistically significant and pronounced downward trend can be seen in all of the short-term and long-term SSI values at station 58, according to the results of the Mann-Kendall Trend test (Figure 6). The fact that Z-values have been decreasing throughout the period that has been extended from three months to twelve months is evidence that station 58 is experiencing a drought trend that is continuing. It can be seen in Table 3 that the hydrological drought at station 58 is more severe than the droughts at other stations.



a

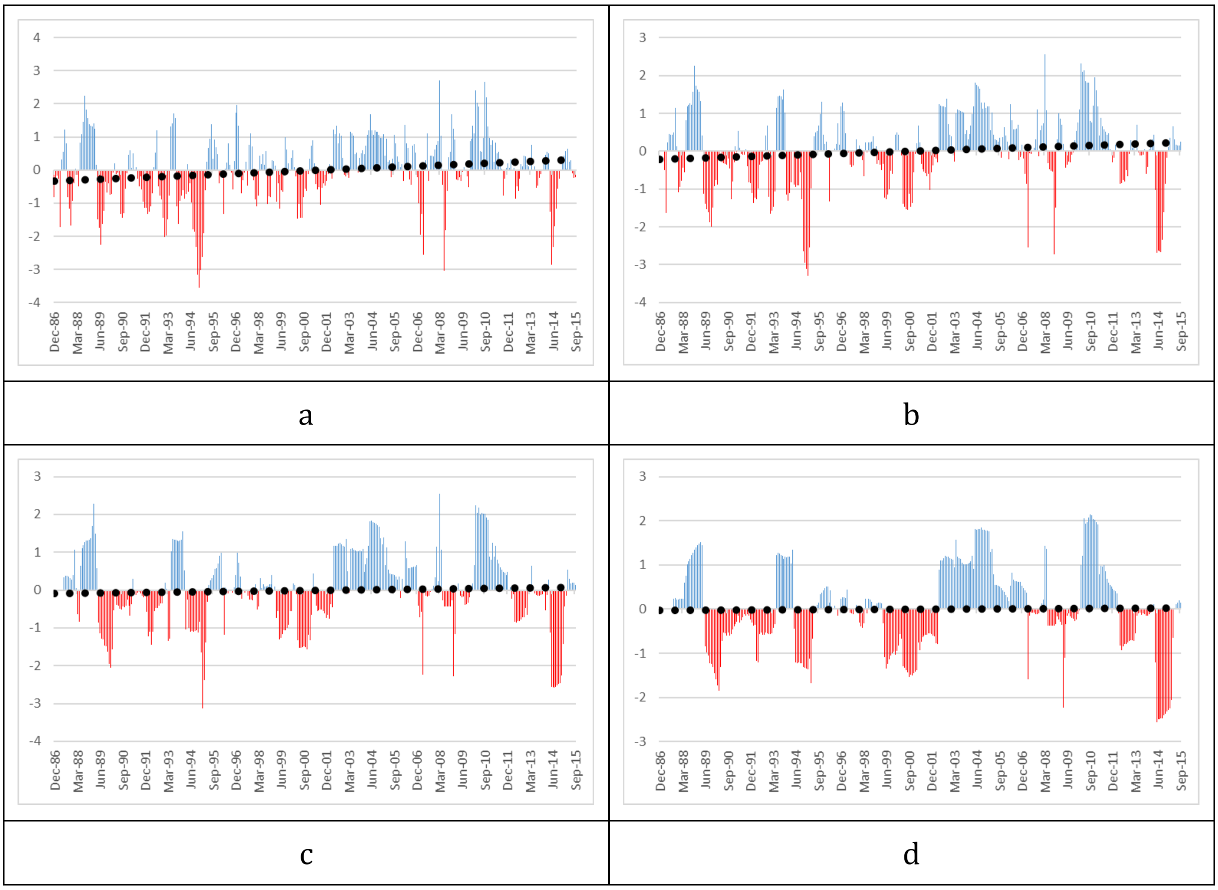
b

c

d

Figure 6. Trends of the standardized streamflow index for station 58: a) 3 months b) 6 months c) 9 months d) 12 months

Station 60 exhibited a unique behavioral pattern in the development of the hydrological drought compared to the other stations. This was quantified by the SSI values. In the short-term values, a statistically significant trend of increase was observed; however, no trend was identified in the long-term values (Figure 7, Table 3). It can be concluded that long-term assessments are necessary to evaluate hydrological drought. Long-term flow conditions are generally more stable than short-term flow conditions. Consequently, it is essential to account for short-term alterations when strategizing for drought in such regions.



a

b

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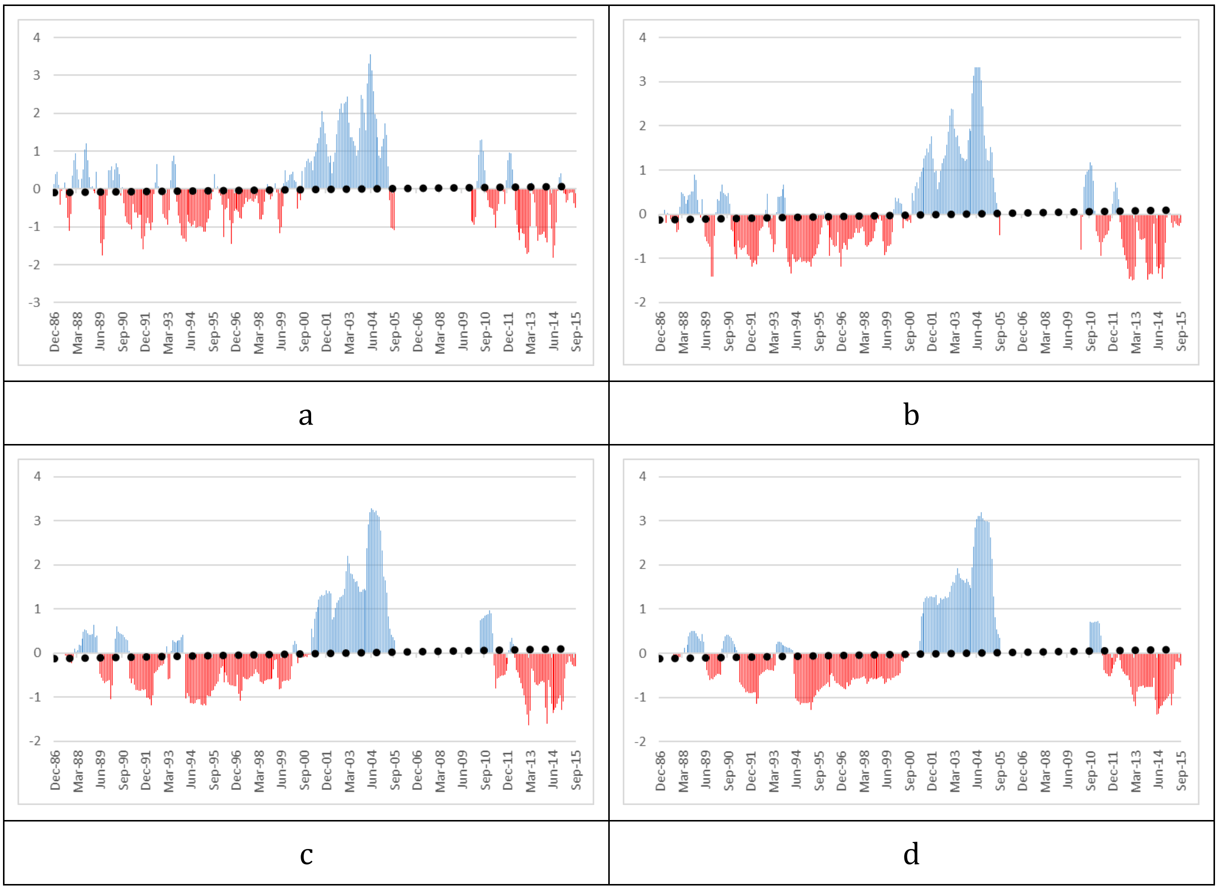
Figure 7. Trends of the standardized streamflow index for station 60: a) 3 months b) 6 months c) 9 months d) 12 months

Analysis of the standardized stream drought index (SSI) values for station 65 reveals that the Mann Kendal trend test demonstrates a statistically significant increasing trend for the three- and six-month intervals; however, no trend is observed for the nine and twelve-month periods (Figure 8, Table 3). Similar to station 60, the rise in short-term SSI values is attributed to the swift influx of water masses into the hydrological processes following abrupt precipitation or snowmelt. This occurs due to the rapid influx of water masses. Considering these findings, long-term hydrological observations must be factored into the development of a drought plan for station 65.



a

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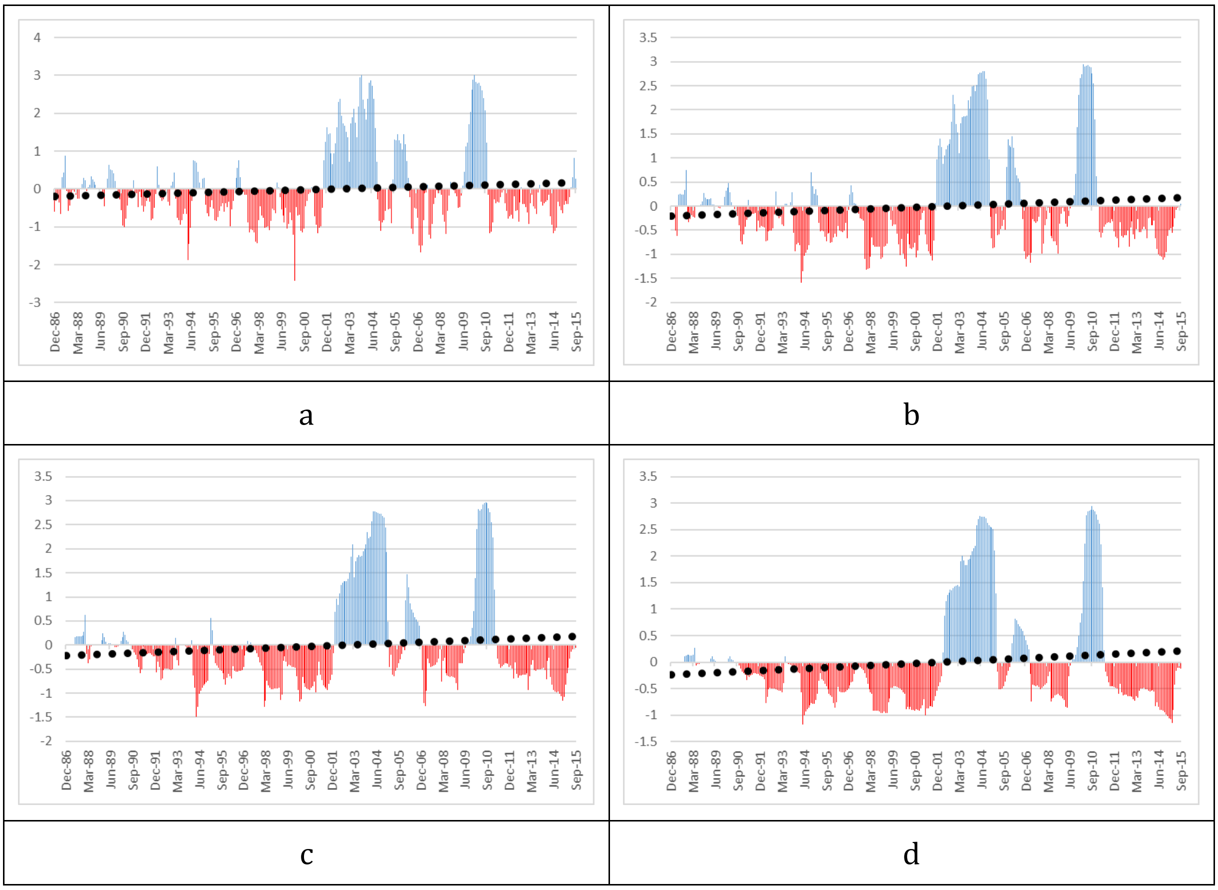
Figure 8. Trends of the standardized streamflow index for station 65: a) 3 months b) 6 months c) 9 months d) 12 months

At station 69, SSI values exhibited trends analogous to those at station 18 (Figure 9). No trend is evident in short-term (3, 6 months) SSI values; however, a statistically significant downward trend is identified in long-term (9, 12 months) values. The p-values indicate that drought severity is greater during extended drought periods (Table 3). These results indicate that hydrological drought conditions at Station 69 are likely to deteriorate over the long term, potentially leading to a significant reduction in river water levels. Consequently, the risks of drought in the basin may escalate, necessitating a revision of water management policies.



a

b

c

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Figure 9. Trends of the standardized streamflow index for station 69: a) 3 months b) 6 months c) 9 months d) 12 months

The regional Mann Kendal Trend test results, based on the SSIs of the Aras River basin, indicate from the p-values in Table 3 that hydrological drought intensifies with prolonged drought periods. The findings suggest that prolonged drought will result in a significant reduction of water resources in the basin. The drought effect, anticipated to intensify with climate change, may yield diverse consequences in this basin, ranging from meteorological drought to socio-economic drought. The trend data also point to increasing stress on water in the region with the recent drought trends in station 58 and station 29 appearing to suggest a decline. This could lead to inter-state tensions about the storage of water in the basin which could compromise the fragile ecosystems of the region.

Furthermore, given that the river's water is shared with neighboring countries, regional water management strategies and agreements should be restructured by the basin's water production capacity.

Table3. Standardized stream drought index (SSI) values for 3, 6, 9, and 12 months from six stream observation stations, along with Mann-Kendall trend analysis results.

Data	**Mann Kendall Statistic (S)**	**Normalized Test Statistic (Z)**	**Probability**	**Tau correlation coefficient**	**Trend (At 95% level of significance)**
S**18**_SSI3	407.	0.189	0.8502	0.007	No trend
S**18**_SSI6	-2742.	-1.292	0.1965	-0.047	No trend
S**18**_SSI9	-6553.	-3.129	0.0018	-0.114	**Decreasing**
S**18**_SSI12	-8278.	-4.005	0.0001	-0.146	**Decreasing**
S**29**_SSI3	-7278.	-3.385	0.0007	-0.122	**Decreasing**
S**29**_SSI6	-8212.	-3.869	0.0001	-0.140	**Decreasing**
S**29**_SSI9	-9112.	-4.350	0.0000	-0.158	**Decreasing**
S**29**_SSI12	-9839.	-4.760	0.0000	-0.174	**Decreasing**
S**58**_SSI3	-19037.	-8.854	0.0000	-0.319	**Decreasing**
S**58**_SSI6	-19362.	-9.124	0.0000	-0.330	**Decreasing**
S**58**_SSI9	-19176.	-9.156	0.0000	-0.333	**Decreasing**
S**58**_SSI12	-19847.	-9.603	0.0000	-0.351	**Decreasing**
S**60**_SSI3	7876.	3.663	0.0002	0.132	**Increasing**
S**60**_SSI6	5958.	2.807	0.0050	0.102	**Increasing**
S**60**_SSI9	2685.	1.282	0.2000	0.047	No trend
S**60**_SSI12	1459.	0.705	0.4805	0.026	No trend
S**49**_SSI3	3010.	1.400	0.1616	0.050	No trend
S**49**_SSI6	-2043.	-0.962	0.3359	-0.035	No trend
S**49**_SSI9	-7259.	-3.466	0.0005	-0.126	**Decreasing**
S**49**_SSI12	-9390.	-4.543	0.0000	-0.166	**Decreasing**
S**69**_SSI3	-695.	-0.323	0.7468	-0.012	No trend
S**69**_SSI6	-2661.	-1.254	0.2100	-0.045	No trend
S**69**_SSI9	-4173.	-1.992	0.0464	-0.072	**Decreasing**
S**69**_SSI12	-4822.	-2.333	0.0197	-0.085	**Decreasing**
RK_TS_SSI3	-123.	-0.889	0.3741	-0.047	No trend
RK_TS _SSI6	-444.	-3.393	0.0007	-0.182	**Decreasing**
RK_TS _SSI9	-473.	-3.615	0.0003	-0.194	**Decreasing**
RK_TS _SSI12	-491.	-3.753	0.0002	-0.202	**Decreasing**

It is understood that regional protocols regarding the conflict over water resources also should cover the emergency and disaster management aspects of the situation. Comprehensive water management agreements should be extended to Azerbaijan, Armenia, and Iran and should provide strategies for water use, protection and rehabilitation of aquatic zones, and even drought management strategies. Collaborating to monitor circumstances and exchange information will enhance the relationships among these nations and facilitate future decision-making. Moreover, it is essential to formulate strategies that enhance resilience in agricultural water management and optimize irrigation systems to address drought conditions.

Given the non-stationarity of climate data, typically employed to evaluate regional drought (Vinnarasi et al., 2023), a standardized index is dependable for assessing hydrological drought, particularly as anthropogenic influences, such as the construction of ponds and dams, can directly or indirectly impact river regimes (Wang et al., 2022).

The varying trends (increase, decrease) and distinctions between short-term (3, 6 months) and long-term (9, 12 months) outcomes in the station-based SSI index assessments of the Aras River basin indicate the presence of diverse hydrological regimes within the basin. Consequently, the response time of each micro-basin must be considered when evaluating potential drought assessments in the Aras River basin's micro-basins and formulating water management policies. Consider short accumulation periods (3, 6 months) in basins with rapid response times and extended accumulation periods (9, 12, 36 months) in basins with slow response times (Baez-Villanueva et al., 2024). The selected temporal scale must encompass the entire hydrological process.

The drought intensity-duration-frequency curves method, which considers precipitation and streamflow deficits, can be employed to evaluate hydrological instability resulting from seasonal effects in the region, in contrast to the preferred SSI method for assessing hydrological drought (Cavus et al., 2023).

Given that the repercussions of drought persist for numerous years, it is imperative to incorporate long-term trends in various short- and long-term drought monitoring indices to the greatest extent possible. Thus, long-term perspectives can be established, particularly in basins with shared water resources, facilitating a unified approach to comprehensive water management (Yu et al., 2015).

Conclusion

It is understood that regional protocols regarding the conflict over water resources also should cover the emergency and disaster management aspects of the situation. Comprehensive water management agreements should be extended to Azerbaijan, Armenia, and Iran and should provide strategies for water use, protection and rehabilitation of aquatic zones, and even drought management strategies. Collaborating to monitor circumstances and exchange information will enhance the relationships among these nations and facilitate future decision-making. Moreover, it is essential to formulate strategies that enhance resilience in agricultural water management and optimize irrigation systems to address drought conditions.

Acknowledgment: A part of this study was published as an abstract text at the 10th National Limnology Symposium between 04-06 September 2023, Çankırı/Türkiye.

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This paper DOI: 10.5281/zenodo.14025336

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