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Application and Evaluation of SPI and SPEI Indices in Drought Analysis

Yaser Sabzevari[1*], Saeid Eslamian[2], Saeid Okhravi[3]

[1] Department of Water Science and Engineering, College of Agriculture, Isfahan University of Technology, Isfahan, Iran.
[2] Department of Water Science and Engineering, College of Agriculture, Isfahan University of Technology, Isfahan, Iran.
[3] Institute of Hydrology, Slovak Academy of Sciences, Bratislava, Slovakia

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ABSTRACT

Objective: Drought, recognized as one of the most severe natural disasters, is characterized by a prolonged deficiency in rainfall. This study aims to analyze drought patterns in the Khorramabad region using the Mann-Kendall test.

Materials and Methods: For this purpose, the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI) were applied, utilizing average, minimum, and maximum precipitation and temperature data recorded at the Khorramabad synoptic station from 1999 to 2022.

Results and Discussion: The results of the drought analysis indicate the occurrence of various extreme events over the study period. The findings reveal a general increasing trend in drought severity, moving towards higher positive index values, suggesting a greater prevalence of wet years. However, temporal analysis of drought variations and the Mann-Kendall trend test indicate both positive and negative shifts throughout the study period. A negative and decreasing trend has occurred in both drought indices in the Khorramabad region, which is not statistically significant at any level because SPI Z statistic is -0.8, and SPEI Z statistic is -1.6, less than 1.96. These fluctuations may reflect localized climatic changes, highlighting the complexity of drought dynamics in the region.

Conclusions: This study underscores the necessity for continuous monitoring and adaptive water resource management strategies to mitigate the impacts of climate variability in Khorramabad.

*Corresponding author, Email: Y.sabzevari@ag.iut.ac.ir

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1. Introduction

In recent years, the importance of water has significantly increased due to population growth, global warming, overexploitation of natural resources, and declining rainfall. Reduced precipitation and extreme rainfall variability have exacerbated the ongoing water crisis and the frequency of drought events. Drought, recognized as one of the most critical natural disasters, is defined as a prolonged period of insufficient rainfall (Mokhtar et al., 2021; Razmkhah, 2022). Researchers classify drought into different types based on the parameters studied, including meteorological, agricultural, hydrological, and socio-economic drought (Tigkas et al., 2016; Delpla et al., 2009). Among these, meteorological drought typically precedes other forms of drought and acts as a precursor to agricultural and hydrological drought, with a time-lagged effect in a given region (Wan et al., 2023; Dah Mardeh et al., 2024).

Water evaporation plays a crucial role in intensifying drought conditions, as it significantly influences water availability and contributes to surface water loss. Increased evaporation rates, particularly in arid and semi-arid regions, exacerbate water shortages and accelerate the depletion of reservoirs, lakes, and soil moisture (Karimzadeh et al., 2023; El Kenawy, 2024). Climate change, rising temperatures, and shifting precipitation patterns further amplify this process, leading to more frequent and severe droughts that threaten agricultural productivity, ecosystems, and water security (Salarijazi et al., 2024). Given the growing environmental concerns and increasing pressure on global water resources, understanding the interconnections between evaporation and drought is essential for developing sustainable water management strategies, enhancing drought resilience, and ensuring long-term adaptation to changing climatic conditions (Sabzevari et al., 2022).

A fundamental step in drought studies is the identification of reliable indicators to assess the severity and persistence of drought conditions. However, conventional indicators, such as the Standardized Precipitation Index (SPI) and the Effective Drought Index (EDI), primarily rely on daily or monthly precipitation data. These indicators are based on two key assumptions: first, that precipitation variability is more significant than other climatic factors, such as temperature and evapotranspiration; and second, that non-precipitation climate variables do not exhibit a time trend. However, numerous studies have highlighted the critical role of temperature in influencing drought conditions (Knapp et al., 2024). Over the past 150 years, global temperatures have increased by approximately 0.5 to 2°C, a trend well-documented by climate change models (Jiang, 2023). Rising temperatures increase drought frequency and intensity, as higher temperatures lead to greater evapotranspiration rates, ultimately escalating water demand (Peng et al., 2023). To address these limitations, a new drought index that integrates both precipitation and temperature—along with evapotranspiration calculations—was introduced: The Standardized Precipitation-Evapotranspiration Index (SPEI) (Özçelik & Akkuzu, 2023). This index provides a more comprehensive assessment of drought conditions by incorporating temperature-driven changes in water balance, making it a valuable tool for climate impact studies and water resource management.

Ozçelik and Akkuzu (2023) assessed drought conditions in the Aegean region of Turkey using the Standardized Precipitation-Evapotranspiration Index (SPEI). Their findings indicated that SPEI effectively identifies long-term drought periods, while its performance diminishes at shorter time scales, where drought events are more frequent and of shorter duration. Careto et al. (2024) evaluated drought using the Generalized Drought Index (GDI), incorporating a multi-scale daily approach. Their results demonstrated that GDI, along with SPI and SPEI, followed the standard normal distribution, confirming their statistical robustness. Additionally, GDI provided improved performance and greater accuracy in capturing short-term drought dynamics at a daily time step, offering added value to existing indices. Possega et al. (2023) analyzed agricultural drought at multiple spatial and temporal scales in the Iberian Peninsula using non-parametric indices. Their study confirmed that agricultural indices are effective in assessing plant stress, and they developed a new composite drought index that integrates multiple factors. This index enhances drought monitoring and could serve as a valuable tool for future research. Sabzevari et al. (2022) assessed temporal changes of meteorological drought using SPI index in the west of Iran. The results showed that the west of Iran faced drought in 1987 and 1978. Moradi et al. (2023) investigated temporal and spatial changes of meteorological drought (SPI) in Karun watershed. This study's findings revealed that in the year 2008 most stations were involved in very severe drought, and in the year 2000, most stations were involved in a severe drought.

A review of these studies underscores the critical importance of drought assessment in improving resilience and management strategies. However, before, studies usually used one drought index in their study. Applying and comparing different drought indices is essential that is considered in this study. Accurate and region-specific assessments are essential for informed decision-making. Consequently, this study investigates drought patterns in the Khorramabad region using the SPEI and SPI indices, ensuring a more comprehensive evaluation of climate variability and water resource challenges.

2.Materials and Methods

2.1. Study Area

The Khorramabad Plain is situated in the central region of the Zagros Valley in the west of Iran, covering an area of approximately 2,500 km² at an elevation of 1,147.8 meters above sea level. It is located at 48°21′ east longitudes and 33°29′ north latitudes, in the center of Lorestan Province (Figure 1). Climatically, the region is classified as semi-arid according to the Dumartin coefficient and as a cold semi-humid zone based on the Amberjeh climogram. The average annual precipitation in Khorramabad is approximately 508 mm, with 54% occurring in winter, 28.5% in autumn, and 17.3% in spring (Azizi, 2000). Table 1 presents the latitude, longitude, altitude, long-term meteorological averages, and climate classification of the Khorramabad synoptic station, while Figure 1 illustrates the geographical location of Khorramabad and its meteorological station.

Table 1- Geographical location of Khorramabad synoptic station

Station name	Elevation (m)	Latitude	Longitude	Amberjeh	Precipitation
Khorramabad	1147.8	33 26 N	48 17 E	Wet cold	500.1

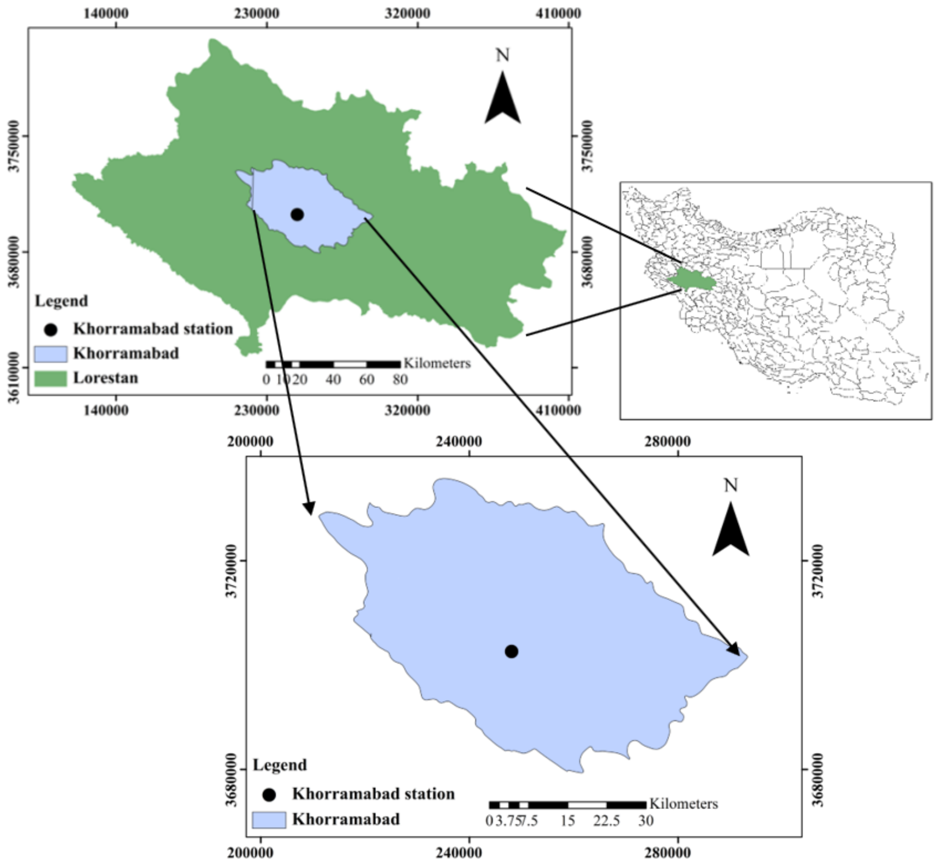

Figure 1-Location of Khorramabad station in Lorestan province and the country

This study conducted drought analysis and assessment using the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI). For this purpose, precipitation and temperature data (including average, minimum, and maximum values) from the Khorramabad synoptic station were utilized. The study period covered 1999 to 2022.

The SPEI is computed across different timescales using a simple water balance equation, which measures the difference between precipitation (P) and potential evapotranspiration (PET) (equation 1). The PET is estimated based on the Thornthwaite method, which incorporates temperature-based calculations (Vicente-Serrano et al., 2010).

$$D_i = P_i - PET_i \quad (1)$$

The values of *D* at different timescales are calculated using Equation (2) (Vicente-Serrano et al. 2010):

$$D_n^k = \sum_{n=0}^{k-1} P_{n-1} - PET_{n-i} \quad (2)$$

where k is the selected timescale in months, and n is the number of months. A three-parameter distribution function is applied to account for negative values of D. Among the tested distributions, the log-logistic distribution showed the best fit for time-series data.

The cumulative probability function for the D data series is calculated in equation 3:

$$F(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)\right]^{-1} \quad (3)$$

where α, β, and γ are scale, shape, and location parameters, respectively, for the values of D. After calculating the cumulative distribution function and converting it to normalized values, the SPEI is extracted.

SPEI values can be calculated for timescales such as 1-month, 3-months, 6-months, 9-months, 12-months, and 18-months. In this study, only 1-month SPEI is calculated. Positive SPEI values indicate a water surplus, while negative values indicate a water deficit. This index is suitable for monitoring dry and wet periods. Drought begins when the SPEI falls below -1 and ends when it becomes positive.

The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993) to monitor drought conditions in Colorado. McKee and colleagues set up a classification system to determine drought and wetness at each station, and the values obtained (SPI) indicate different intensities of drought in an area. Another feature is that, based on this method, the drought threshold can be determined for each time period. Therefore, in addition to the severity of the drought, its duration can also be determined based on this index. The standardized rainfall index is based on the probability of rainfall for each time period. This index is designed to minimize the lack of rainfall in multiple time periods. These different time scales express the special effects of drought on access to different water resources. Equation 4 shows the calculation of SPI index.

$$SPI = \frac{X_i - \bar{X}}{S_X} \tag{4}$$

Where:

X_i= Rainfall per month.

$\bar{x}$= Average rainfall on a time scale.

S_X= is the standard deviation of rainfall on a time scale.

The classification of SPEI and SPI values is shown in Table 2.

Table 2- Classification scale of SPEI and SPI values (McKee et al. 1993)

class	SPEI values
Extreme drought	<-2
Severe Drought	-1.99 to -1.49
Mild Drought	-1 to -1.49
Normal	-0.99 to 0.99
Mild wet	1 to 1.49
Severe wet	1.5 to 1.99
Extreme wet	>2

2.2. Man-Kendall Test

The Mankendall test is used to check the time trend for each set of data. This test is based on non-parametric linear regression logic. The results of this test show whether there is a significant increase or decrease trend in a certain level of confidence in the time series trend of the parameter under study. Using Mankendall non-parametric test is not sensitive to the normality of the data. The Mann-Kendall test was first proposed by Mann (1945) and then developed by Kendall (1975). The use of this method was recommended by the World Meteorological Organization. One of the strengths of the Mankendall method is that it is suitable for time series that do not follow a specific distribution.

This method is used to examine the trend of data. In this method, the S statistic for the g th month and the k th station is calculated as equation 5:

$S_{gk} = \sum_{i}^{n-1} \sum_{j=i+1}^{n-1} sgn(\text{Xjgk} - \text{Xigk}), \forall \leq \text{i<j} \leq \text{n}$ *(5)*

Where n is the number of series data and sgnθ is a function of the sign and θ is the difference between the two observations in each of the studied parameters in different years i and j, which are as in equation 6:

$$\text{Sgn}(\theta) = \begin{cases} 1 \ \ if \quad \theta > 0 \\ 0 \ \ if \quad \theta = 0 \\ -1 \ \ if \quad \theta < 0 \end{cases} \tag{6}$$

Kendall and I showed that when n≥ 10, the S statistic is distributed almost normally and has a mean of 0 and the following standard deviation (equation 7):

$$(\sigma_{gg})_k = \frac{[n(n-1)(2n+5) - \sum d(d-1)(2d+5)]}{18} \tag{7}$$

Where d is the same number of data points in the time series. In this method, Sgk is normalized as equation 8:

$$S'_{gk} = S_{gk} - \text{sgn}(S_{gk}) \tag{8}$$

Then the standardized test statistic or Z, which has a standard normal distribution with a mean of 0 and a variance of 1, is obtained as equation 9:

$$Z_{gk} = \frac{S'gk}{(\sigma_{gg})^{1/2}} \tag{9}$$

If the value of Z is greater than ± 1.96, the data has a trend and the null hypothesis is rejected; otherwise, it has no trend. Z is the standard normal distribution statistic and is used in a two-domain test, depending on the confidence levels of the item The test can take different values and: S is a parameter of the Mankendall method which is calculated It was mentioned above. The value of Z statistic for 95% and 99% confidence levels the percentages are considered to be 1.96 and 2.58, respectively.

Figure 2 shows a summary of the processing steps of the study.

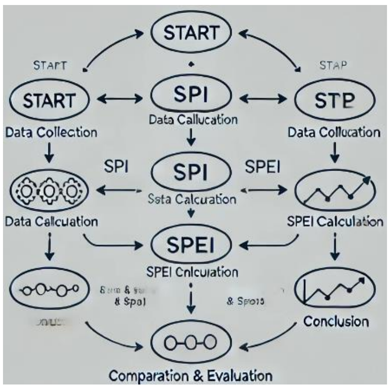

Figure 2- processing steps of the study

3.Results and Discussion

In this section, and in alignment with the research objectives, drought conditions in Khorramabad meteorological station were evaluated using the Standardized Precipitation-

Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI). To achieve this, monthly time series variations of these indices were analyzed at the Khorramabad synoptic station, and the results are presented continuously.

The time series graph of the SPEI index (Figure 3) illustrates the temporal variability of drought conditions in Khorramabad meteorological station. The results indicate significant fluctuations in drought intensity over the study period. Notably, drought conditions deviated from the normal range at both the beginning and end of the study period. In particular, severe drought events were observed in 2021 and 2022, whereas 1999 experienced a wet year, highlighting the region's dynamic nature of climatic variability.

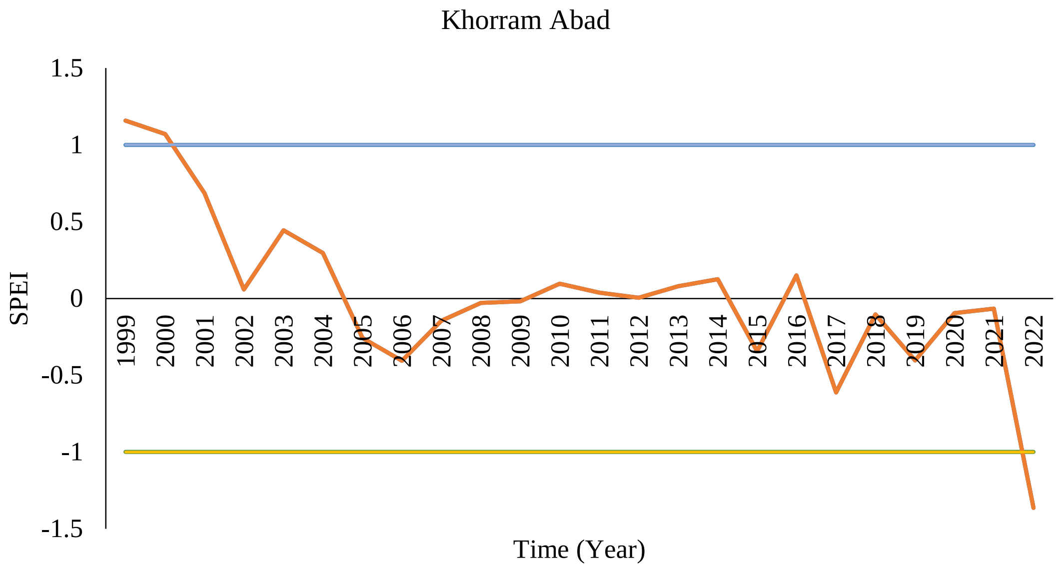

Figure 3- Time series of monthly SPEI in Khorram Abad station

Figure 4 presents the SPI time series variations at the Khorramabad study station, illustrating the temporal changes in drought conditions. The results indicate that at the beginning of the study period, drought conditions deviated from the normal range. Specifically, drought events were recorded between 2001 and 2003, while 1999 also experienced a drought, highlighting significant fluctuations in precipitation patterns over time. In Laimighofer and Laaha (2020), and Bera et al. (2021), increasing trends are reported in their studied area.

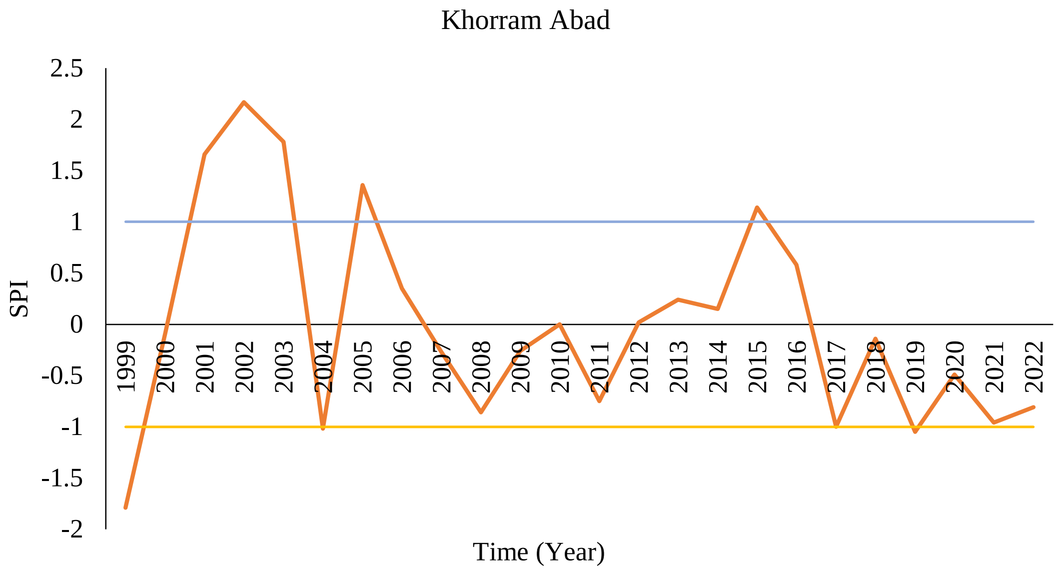

Figure 4- Time series of monthly SPI in Khorram Abad station

3.1. Examining the Trend of Time Changes with the Mann-Kendall Test

A non-parametric Mann-Kendall analysis was used to investigate the trend of temporal changes with the Mann-Kendall test in order to investigate the trend of changes in the drought time series of the study area. Table 3 shows the value of the Mann-Kendall statistic for the drought time series of the SPEI index and the SPI index in Khorramabad. According to this table, a negative and decreasing trend has occurred in both drought indices in the Khorramabad region, which is not statistically significant at any level because the Z statistic is -0.8, which is less than 1.96. The trend resulting from the SPEI drought index decreased more than the SPI index. The decrease resulting from the SPEI index, with a statistic of -1.6 was not statistically significant. A similar study by Nejadrekabi et al. (2022) on trend analysis of SPEI using the Mann-Kendall test showed significantly higher impact of temperature increase than precipitation reduction.

Table 3- Mann-Kendall statistic values at the study station

Mann-Kendall Statistic	SPEI	SPI
Z	-1.6	-0.8

Figures 5 and 6 illustrate the temporal trends of the SPEI and SPI drought indices in the Khorramabad region over the study period. These graphs depict the variations in the selected indices, with the vertical axis representing the variable values (U) and the horizontal axis corresponding to U'. The U' values are derived by arranging the variable values in descending order of the respective years. A significant jump point occurs when the U and U' curves intersect, indicating a notable shift in drought intensity for that year. Conversely, if the two curves remain parallel, it suggests no significant change during the study period. The results presented in Figure 5 align with the Z-statistical analysis, confirming a decreasing trend in drought conditions at Khorramabad station. Additionally, Figure 6—which illustrates the SPEI index trend—reveals a sharp increase in drought intensity in 2012, followed by a decrease in 2015. In contrast, the SPI index trend (Figure 6) does not exhibit any significant jump points, suggesting a more stable pattern. Each identified jump point substantially impacts the overall drought trend, influencing water resource availability and climate variability in the region. The observed shifts provide valuable insights into the long-term dynamics of drought events, emphasizing the need for continuous monitoring and adaptive management strategies.

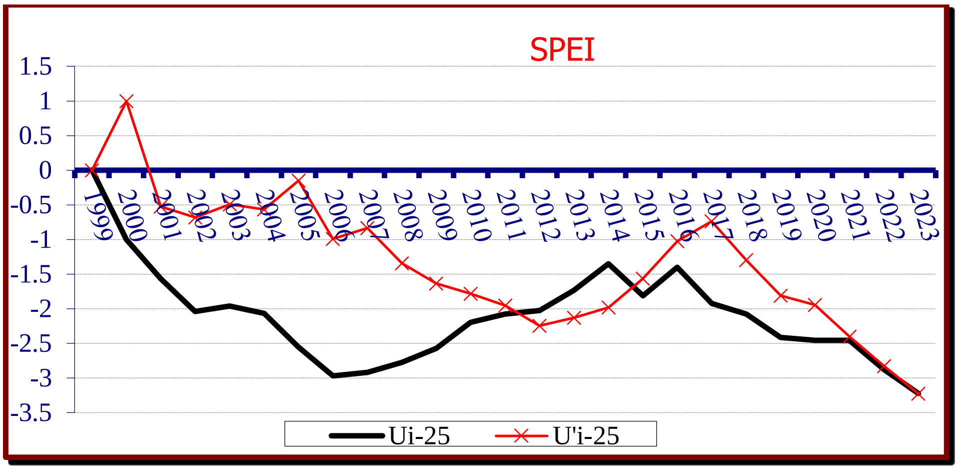

Figure 5- Mann-Kendall graph of SPEI in Khorram Abad station

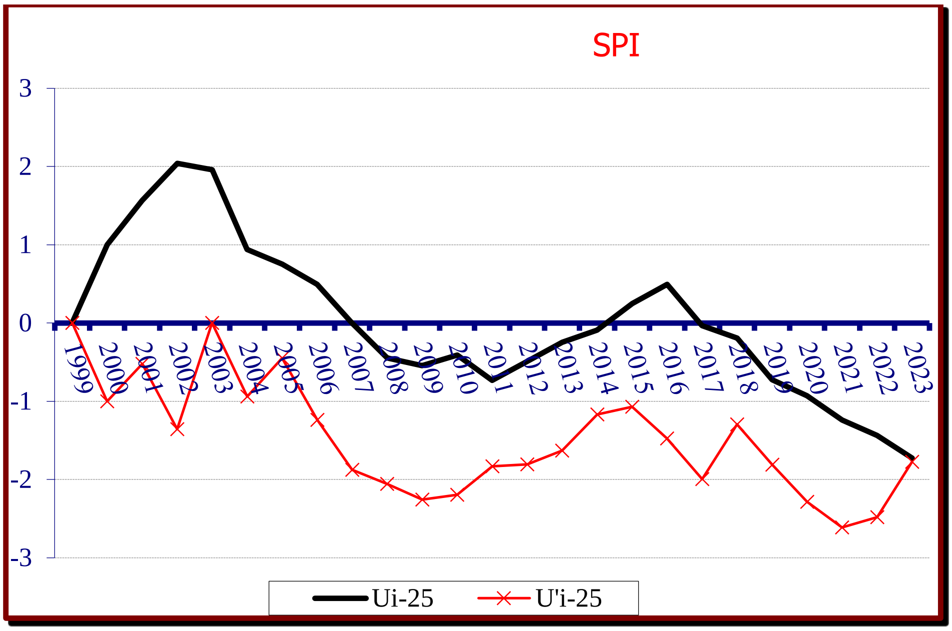

Figure 6- Mann-Kendall graph of SPI in Khorram Abad station

Table 4 presents the frequency of different drought categories at the selected station, providing a comprehensive overview of the drought conditions based on the SPEI and SPI indices during the study period. The findings indicate that the SPEI index classifies drought conditions in Khorramabad as more severe, recording 1 year of extreme drought, 4 years of severe drought, and 2 years of mild drought. In contrast, the SPI index depicts a less intense drought pattern, identifying 3 years of severe drought and 3 years of mild drought. These results suggest that drought events in the region have predominantly occurred on a smaller scale, with variations in intensity depending on the selected index. The differences between the SPEI and SPI classifications highlight the importance of incorporating multiple drought indices for a more comprehensive assessment of drought variability and severity.

Table 4- Number of different drought categories for the selected station

index	Acute wet	Very wet	Moderately wet	Normal	Moderately dry	Very dry	Acute dry
SPEI	٠	٠	1	13	2	4	1
SPI	٠	2	٠	13	3	3	٠

Based on the results of the drought analysis in the Khorramabad region using the SPEI index, it can be concluded that this temperate, mountainous area has experienced various extreme weather events. Over different years, drought conditions have generally followed a declining trend, shifting toward more negative index values, which signifies increased drought occurrences. However, an examination of temporal drought variations and the Mann-Kendall graph at the study station revealed fluctuations, with both positive and negative shifts over time. Additionally, the trend of changes in the SPI drought index suggests a relatively stable drought pattern, indicating that climate variations in the region may be occurring on a micro-scale.

3.2. Limitations

The SPI and SPEI indices rely on climate variables—precipitation for SPI and both precipitation and potential evapotranspiration (PET) for SPEI—whose nonstationarity poses significant challenges in accurately capturing drought trends. This study utilized the Thornthwaite method for PET estimation and SPEI computation, which may introduce biases in the studied area climate where PET is influenced by factors beyond temperature, such as wind speed and solar radiation. Changes in precipitation patterns due to climate variability and anthropogenic influences can lead to shifts in the statistical distribution of precipitation.

4.Conclusion

This study used the SPEI and SPI drought indices to analyze drought conditions in the Khorramabad region. The Khorramabad synoptic station was selected as the representative station for this analysis. The results were evaluated and interpreted after calculating the SPEI and SPI indices. Findings revealed that the study area has experienced several extreme drought and wet weather events. An analysis of temporal drought variations over a 25-year period indicated a general decline in drought conditions in Khorramabad, though this trend was not statistically significant. Over the years, drought severity has generally increased, as reflected by a shift toward more negative index values. However, examining drought trends and the Mann-Kendall graph at the study station revealed fluctuations, with positive and negative shifts occurring over time. These variations may indicate microscale climate changes within the region. Furthermore, the results suggest potential differences between the two regions at a smaller spatiotemporal scale. Therefore, future studies are recommended to conduct comparative evaluations of these regions, considering key parameters influencing drought on both spatial and temporal scales.

Author Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical Considerations

The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

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