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Robust drought trend assessment using multi-index and dual-distribution frameworks in semi-arid climates

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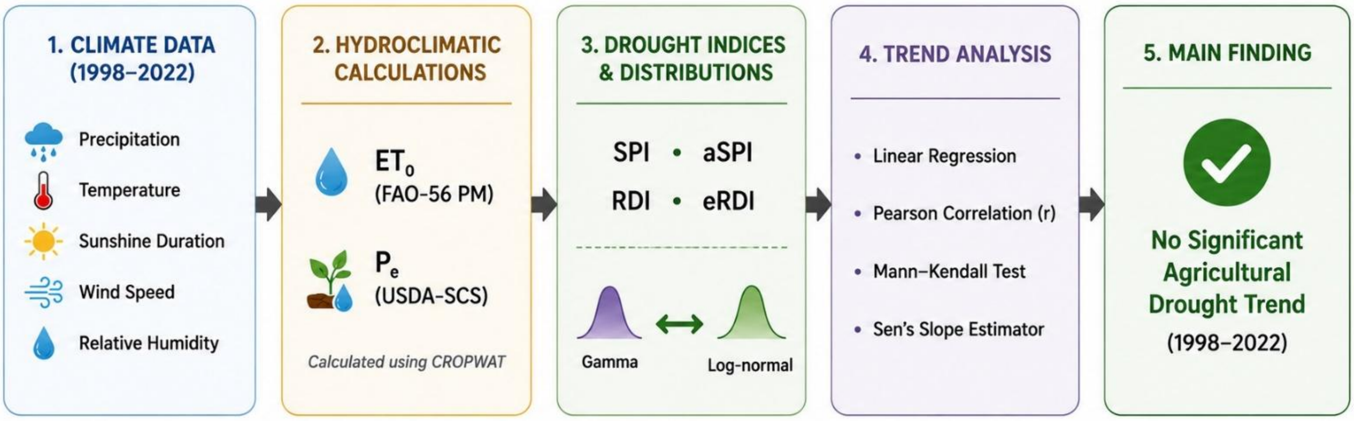
GRAPHICAL ABSTRACT



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ABSTRACT

This study explores agricultural drought variability by applying both classical and rank-based statistical methods within two distinct probabilistic frameworks, aiming to assess how distribution choice affects the interpretation of drought patterns. Monthly meteorological data from 1998 to 2022 were processed into four drought indices: SPI, aSPI, RDI, and eRDI. Effective precipitation was calculated using the USDA method and CROPWAT, and potential evapotranspiration (ET_0) was determined with the FAO Penman-Monteith approach. Each index was standardized with both gamma and log-normal distributions in DrinC to evaluate the influence of distribution choice on trend detection. Trend analysis was conducted using linear regression with Pearson correlation for parametric tests and the Mann–Kendall test with Sen's slope for non-parametric tests. Results from both methods and distributions were consistent: median Sen slopes were within ±0.03 index units per year, and Mann–Kendall Z scores ranged from −0.82 to 0.63, indicating no significant monotonic change. Regression slopes supported this, remaining below 0.03 with p-values above 0.25. The close agreement between parametric and non-parametric results, and between gamma and log-normal distributions, shows that model selection does not bias drought trend analysis. This multi-index, dual-distribution framework provides a robust and transferable methodology for drought monitoring, particularly in data-scarce and semi-arid regions worldwide.

1. Introduction

Human actions, including the burning of fossil fuels and deforestation, are speeding up global warming, which leads to a range of changes in the Earth's climate (Rahmani and Ahmadi, 2024). Climate change is expected to modify regional climatic conditions, including temperature, humidity, and atmospheric pressure, which will subsequently influence precipitation patterns and potentially result in drought conditions (Yu *et al.*, 2021). Drought is a major natural hazard that extensively damages water resources and affects numerous people due to its complexity and wide-reaching nature. This slow and insidious phenomenon impacts both ecosystems and society in various ways (Fathi *et al.* 2025).

Climate change, along with human activities, has been shown in recent studies to profoundly impact hydrological and environmental systems across a range of regions. Amini *et al.* (2009) examined the significant impacts of urbanization on the hydrological processes in the Langat River catchment, highlighting that land use changes led to increased peak streamflow and heightened flood magnitudes. They proposed a method for adjusting historical flood records to account for urbanization. Gharibreza *et al.* (2018) examined how the last Caspian Sea level rise affected Gorgan Bay. They found significant changes in sediment patterns and coastal erosion resulting from climate change related eustatic fluctuations. They found that sea-level rise resulted in severe shoaling, increased coastal flooding, and substantial sediment

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accumulation, leading to a reduction in the bay's water exchange with the open sea. Bharambe *et al*. (2023) examined how climate change has affected drought patterns in the Godavari River Basin in India. Their findings indicated that, over the last ten years, droughts have become more frequent and severe compared to the previous thirty years. Additionally, approximately three-quarters of the region are now more susceptible to drought-related hazards, while the remaining quarter shows comparatively lower vulnerability and risk levels. Wu *et al*. (2023) examined the relationship between climate change, human activities, agricultural drought, and their effects on winter wheat's net primary productivity in the North China Plain. Their findings indicated that climate change contributed more significantly to agricultural drought than human activities. Additionally, longer drought propagation periods were associated with decreases in wheat's net primary production, which was mainly attributed to human interventions. Li *et al*. (2024) studied the way drought characteristics evolve and transfer from meteorological to agricultural phases across China, taking into account both human actions and how climate change affects them. According to their results, when human activities are involved, the time over which drought spreads tends to become longer. In contrast, climate change plays only a small role in reducing this duration. Patel R. and Patel A. (2024) assessed how climate change influences drought susceptibility in the Sabarmati River Basin, India. Their analysis incorporated various data sources such as climate forecasts, geographic information, and environmental factors, revealing that alterations in climate patterns and land utilization have heightened the likelihood of drought in the area.

Together, these studies highlight the complicated relationship among climate change, land use, and human activities as they shape hydrological processes and environmental risks across different geographical contexts. Drought indices provide a standardized method for monitoring drought conditions, enabling consistent assessments over time (Ahmadpari and Khaustov, 2025a). Tigkas, Vangelis, and Tsakiris (2019) compared the effectiveness of the Standardized Precipitation Index (SPI) and its enhanced, agriculture focused version, the aSPI, in linking drought severity to crop yields across four regions in Greece with Mediterranean climates. Their findings demonstrated that the aSPI provides a more reliable indication of agricultural drought than the traditional SPI. Similarly, Sosa, Fernández Long, and Vicente Serrano (2025) evaluated the performance of several drought indices by examining their relationships with rainfed maize yield in Argentina. Their findings showed that drought indices were significantly associated with maize yield across different time scales, although indices incorporating atmospheric evaporative demand generally exhibited stronger relationships with crop productivity than SPI. Overall, their results highlight the value of drought indices for assessing agricultural drought and its effects on crop yield. Eshghizadeh and Esmaeilian (2023) evaluated the trend of agricultural drought in the Gonabad region, Iran, using the Reconnaissance Drought Index (RDI) and its improved version, the effective Reconnaissance Drought Index (eRDI), over a period of 59 years. The results indicated no significant difference between the two indices, although the eRDI was more sensitive and accurate during seasonal periods. The longest drought lasted nine years, while the longest wet period extended for eleven years. Rezaei *et al*. (2024) analyzed drought occurrences in the South Baluchestan sub-basin of Iran by employing the RDI and eRDI indices. Their findings showed that the eRDI values derived from both the USBR and USDA approaches are quite comparable, with the USDA-based eRDI closely matching the RDI more than the USBR-based eRDI. As the time scales extend from 1 month to 3 and 6 months, the eRDI results from different methods tend to converge further. Moreover, the pattern of eRDI fluctuations across the methods more accurately reflects the RDI trend at the 3- and 6-month intervals. These studies show that the most important indices for assessing agricultural drought are the SPI, aSPI, RDI, and eRDI. Probability distribution functions are essential for estimating drought index values, as they provide a statistically sound method for analyzing historical climate data, assessing risks, and predicting future drought conditions (Ahmadpari and Khaustov, 2025a).

Based on the studies conducted, the providers of SPI, aSPI, RDI, and eRDI indices have proposed gamma and log-normal probability distribution functions as appropriate distributions for calculating drought severity (Tigkas *et al*., 2022; Ahmadpari and Khaustov, 2025b). Lee *et al*. (2023) investigated the optimal probability distribution function for daily SPI time series in South Korea. The results of these studies indicated that the gamma distribution is recommended for use across all time scales. Asadi Zarch and Motraghi (2025) performed a global evaluation of optimal probability distribution functions for the RDI, taking into account both historical observed data and future projections. The findings of their study indicated that the gamma distribution is the most suitable distribution for both historical and projected periods.

Examining climate data trends is essential for effective management of water supplies and for gaining insight into the way industrialization influences the hydrological cycle through greenhouse gas emissions (Ghorbani, Vali, and Zarepour, 2019). To identify patterns within time series of climatic and hydrological variables, researchers employ a variety of statistical tests, which are broadly categorized into parametric and non-parametric approaches. In recent years, numerous investigations worldwide have focused on drought trend analysis utilizing both parametric and non-parametric techniques (Zarei, Moghimi, and Mahmoudi, 2016; Ghorbani, Vali, and Zarepour, 2019; Almendra-Martín *et al*., 2021). Findings from these studies suggest that the occurrence and severity of droughts are escalating in various regions as a consequence of climate change (Zarei, Moghimi, and Mahmoudi, 2016; Ghorbani, Vali, and Zarepour, 2019). Understanding drought trends is critical for effective planning and the equitable allocation of water resources. This is especially important in river basins where multiple stakeholders depend on shared water sources for agriculture, domestic consumption, and industrial activities. Analyzing agricultural drought trends in river basins plays a vital role in promoting sustainable water management, ensuring food security, enhancing climate change adaptation, and fostering both economic and environmental resilience. While numerous studies worldwide have investigated drought trends, the majority have concentrated on meteorological and hydrological droughts. In contrast, relatively few have addressed agricultural drought trends. A review of the existing literature indicates a gap in research on agricultural drought trend analysis in the Darreh Dozdan River (DDR) basin, highlighting the need for focused investigation in this context.

This study aims to systematically compare the influence of probability distribution selection and statistical method choice on agricultural drought trend assessment. By applying four widely used drought indices (SPI, aSPI, RDI, and eRDI) standardized with gamma and log normal distributions, and by assessing trends through parametric approaches (linear regression together with Pearson correlation) as well as non-parametric methods (the Mann-Kendall test combined with Sen's slope estimator), we provide a consistent comparative framework for drought analysis in semi-arid, data scarce basins. The primary objective is to clarify whether distributional assumptions and statistical approaches lead to divergent trend interpretations in the Darreh Dozdan River basin. The framework is intended to serve as a practical reference for similar comparative assessments in other regions where methodological transparency and robustness are essential for drought monitoring and water-resources planning.

2. Materials and methods

2.1. Study area

The Darreh Dozdan River (DDR) is located in Lorestan Province, Iran. This river flows within the Karkheh watershed, which is classified as a second level basin (Ahmadpari and Khaustov, 2025a). Along the DDR, only one rain gauge and hydrometric station exist, named Tange Siab. This station measures several variables including precipitation, flow rate, sediment load, as well as the chemical and physical characteristics of the water. It is situated in Kuhdasht County, Lorestan Province, Iran (Ahmadpari and Khaustov, 2025a). To compute agricultural drought indices, evapotranspiration data are required. However, the Tange Siab station lacks the necessary data for estimating evapotranspiration in the DDR basin. Therefore, this study used the Kuhdasht synoptic station, which is the closest meteorological station to Tange Siab compared to all other available stations. The Kuhdasht synoptic station was established and has been operating since 1997 under the Iran Meteorological Organization. Its geographic coordinates are longitude 47°38′52″E and latitude 33°31′27″N, and it sits at an elevation of 1197 meters above sea level (Ahmadpari and Khaustov, 2025b). The location of the study area within Lorestan Province and Iran is illustrated in Fig. 1.

2.2. Agricultural drought indices

The study focused on several indices, including the Standardized Precipitation Index (SPI), the Agricultural Standardized Precipitation Index (aSPI), the Reconnaissance Drought Index (RDI), and the Effective Reconnaissance Drought Index (eRDI). To compute the values of these indices, both gamma and log-normal distribution models were applied using DrinC software (version 1.7). The present study focused on several drought indices, namely SPI, aSPI, RDI, and eRDI. However, because the definitions, mathematical formulations, and computational procedures of these indices have already been well established in the literature, they are not repeated in detail herein.

Instead, readers are referred to the original studies for a complete description of the theory and equations underlying SPI (Tsesmelis *et al*., 2023; Ahmadpari and Khaustov, 2025a), aSPI (Ibrahim, Alghamdi, and Aly, 2024; Saracoglu and Kaynar, 2025), RDI (Yue, Shen, and Wang, 2018), and eRDI (Ahmadpari and Khaustov, 2025b).

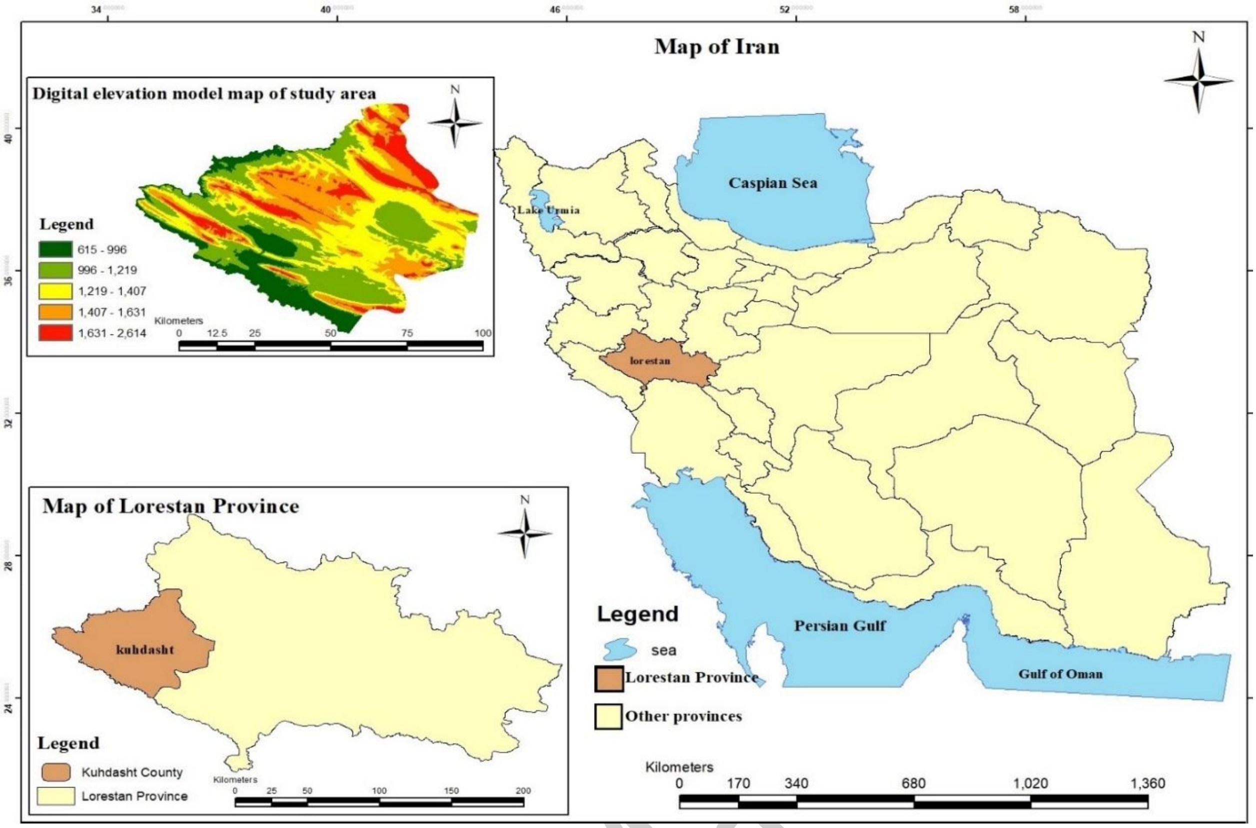


Fig. 1 Map of the study area showing its position in Lorestan Province and Iran.

2.2.1. Potential evapotranspiration and effective precipitation

Effective precipitation was calculated using the CROPWAT 8.0 software, which employs the USDA methodology. Potential evapotranspiration was also estimated with CROPWAT 8.0, based on the FAO-56 Penman-Monteith equation (Iacuzzi *et al*., 2025). CROPWAT is a modeling tool designed to simulate climate variables, effective precipitation, crop water requirements, soil water balance, and irrigation scheduling (Binesh *et al*., 2020). It streamlines the process of calculating reference crop water use, irrigation planning, and crop-specific water needs across different cultivation types (Binesh *et al*., 2020). The software determines reference evapotranspiration using the FAO-56 Penman-Monteith method, which requires input data such as temperature extremes, humidity, wind speed, and sunshine hours. The FAO has endorsed the FAO-56 Penman-Monteith approach as the standard procedure for estimating reference evapotranspiration globally (Ahmadpari, Hashemi Garmdareh, and Ghalehkohneh, 2017). The FAO-56 Penman-Monteith method with all its formulas is described in the study by Ahmadpari, Safavi Gerdini, and Ebrahimi (2019).

2.3. Agricultural drought trends

Two categories of statistical methods were used to assess trends. Parametric methods included regression analysis along with the Pearson correlation coefficient (PCC). Nonparametric methods included the Mann-Kendall (MK) test and Sen's slope estimator (SSE). To perform these tests, we used the MAKESENS 1.0 Excel macro, which the Finnish Meteorological Institute made available as freeware in 2002. Regression analysis and PCC were performed using Microsoft Excel 2019 software. All trend analyses in this study are performed for the 1998–2022 period, corresponding to the full length of available station data, and the reported trends are interpreted strictly within this observational time window.

2.3.1. Complementary roles of the selected statistical methods

Each of the four statistical methods employed in this study serves a distinct and complementary role in drought trend detection:

1. MK: Determines whether a monotonic trend exists. Its key advantage is that it does not assume normality and is robust to outliers.
2. SSE: Quantifies how strong the trend is, providing the slope magnitude in index units per year. Like MK, it is resistant to outliers.
3. PCC: Measures the strength and direction of a strictly linear relationship between time and the drought index.
4. Linear regression (LR): Models the trend as a straight line, providing the best linear unbiased estimate of the slope and the coefficient of determination (R^2).
5. Value of combining all four methods: Agreement between parametric and non-parametric results serves as cross-validation. This consistency confirms that the findings are not artifacts of outlier influence, non-normality, or violations of parametric assumptions. If the methods had disagreed, deeper investigation would have been required. Thus, the multi-method framework enhances the reliability of trend detection.

2.3.2. Preliminary data checks prior to trend analysis

Before applying the MK test and SSE, several preliminary checks were conducted to ensure the reliability of trend detection. Missing data were examined to preserve the continuity of the time series, and appropriate handling procedures were applied where necessary. Potential outliers were identified and evaluated to prevent undue influence on slope estimation. Data independence was assessed through serial correlation analysis, as the MK test assumes independent observations. In addition, data homogeneity was examined to confirm that the time series originated from a consistent generating process without abrupt structural changes. The results of these preliminary assessments confirmed that the time series satisfied the fundamental assumptions required for the application of the MK and SSE methods.

2.3.3. Mann-Kendall test

The MK test is a non-parametric method for detecting trends in time series data. This test calculates a statistic S based on pairwise comparisons of data points, from which a standardized Z value is derived. A positive Z indicates an upward trend and a negative Z a downward trend. At the 0.05 significance level, a trend is considered statistically significant if $|Z| > 1.96$ (Chen *et al*., 2016; Amini, 2020). The Mann-Kendall Jump Test, which computes forward (U_i) and backward (U_i') series, was used to detect sudden shifts; an intersection outside the ±1.96 bounds indicate a significant change point (Amiri *et al*., 2015; Liu and Xu, 2016). The MK test was performed following the procedures detailed in Chen, Ghadami, and Epureanu (2022) and Amini (2020), who provide comprehensive explanations and equations for its application.

2.3.4. Sen's Slope Estimator test

Sen's non-parametric method was applied to estimate the trend slope in the dataset. The calculation procedure is presented in Gocic and Trajkovic (2013). In this method, pairwise slopes are first computed for all possible combinations of data points, and then the median slope (Q_{med}) is taken as the representative estimate of the overall trend. In addition, the upper and lower confidence limits of the slope are determined, denoted as (Q_{max}) and (Q_{min}), respectively, to evaluate the statistical significance of the estimated trend. If both limits have the same sign, the trend is considered statistically significant at the selected confidence level.

2.3.5. Pearson correlation coefficient

The PCC, commonly represented as r, is a statistical metric used to assess the degree and direction of a linear association between two continuous variables. Its values range from -1 to 1. The PCC is calculated according to Eq. 1 (Jiang and Sun, 2025; Tosan *et al.*, 2026).

$$r = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2 \sum_{i=1}^{n}(b_i - \bar{b})^2}} \qquad (1)$$

a_i and b_i are the values of two variables at the i-th observation point, $\bar{a}$ and $\bar{b}$ are the means of the two variables, and n is the number of samples. The comparison of the PCC and correlation strength can be found in Fig. 2.

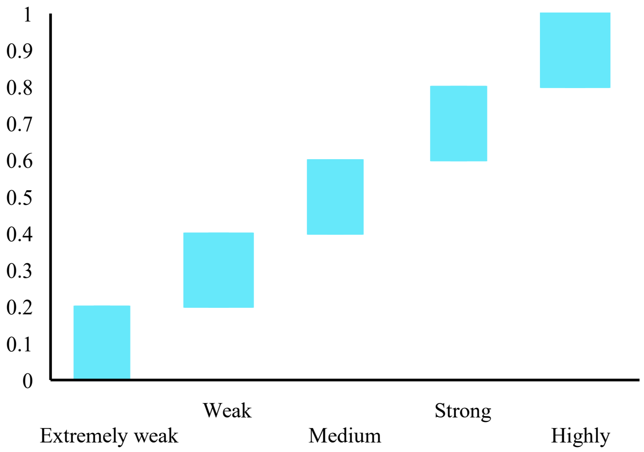


Fig. 2. Pearson correlation coefficient strength classification

The significance of the PCC is evaluated by computing the t-statistic from the sample size and the correlation value, and then obtaining the corresponding p-value using the t-distribution (Yu and Hutson, 2024). The p-value, calculated through the T.DIST.2T function in Excel, represents the probability of observing such a correlation under the null hypothesis (Bonovas and Piovani, 2023). A small p-value (≤0.05) indicates that the correlation is statistically significant. In the study by Ahmadpari, Khaustov, and Amini (2025), the calculation of the t-statistic and the significance testing of the PCC are described in detail.

2.3.6. Regression analysis

This study employed regression analysis as a statistical tool to examine trends in drought indices. In general terms, regression analysis helps to understand how one or more explanatory variables relate to a response variable (Hu *et al.*, 2022). It is commonly applied for detecting patterns, forecasting future values, and interpreting temporal changes in data. For the case involving a single explanatory variable and a single response variable, simple linear regression is appropriate. This method assumes a linear relationship between the two variables, which can be expressed as Eq. 2.

$$\mathrm{Y = a + bX} \qquad (2)$$

where:

- Y = Agricultural drought indices
- X = Year
- a = Y intercept
- b = slope of the line

To determine whether the observed trend is statistically meaningful, the p value was calculated. All regression analyses in this study were conducted using Microsoft Excel 2019, specifically the regression function within the Analysis ToolPak.

2.3.7. Significance level

The significance level, known as the Type I error threshold, is used in hypothesis testing (Maier and Lakens, 2022). Table 1 presents the conventional decision rules.

Table 1 Statistical decision rules based on significance level and p value.

Significance level	Confidence level	p-value condition	Significant
0.05	95%	$p < 0.05$	Yes
0.05	95%	$p > 0.05$	No
0.01	99%	$p < 0.01$	Yes
0.01	99%	$p > 0.01$	No

For further discussion on the interpretation of p-values, see Kwak (2023) and Akobeng (2016).

3. Results and discussion

3.1. The trend of agricultural drought

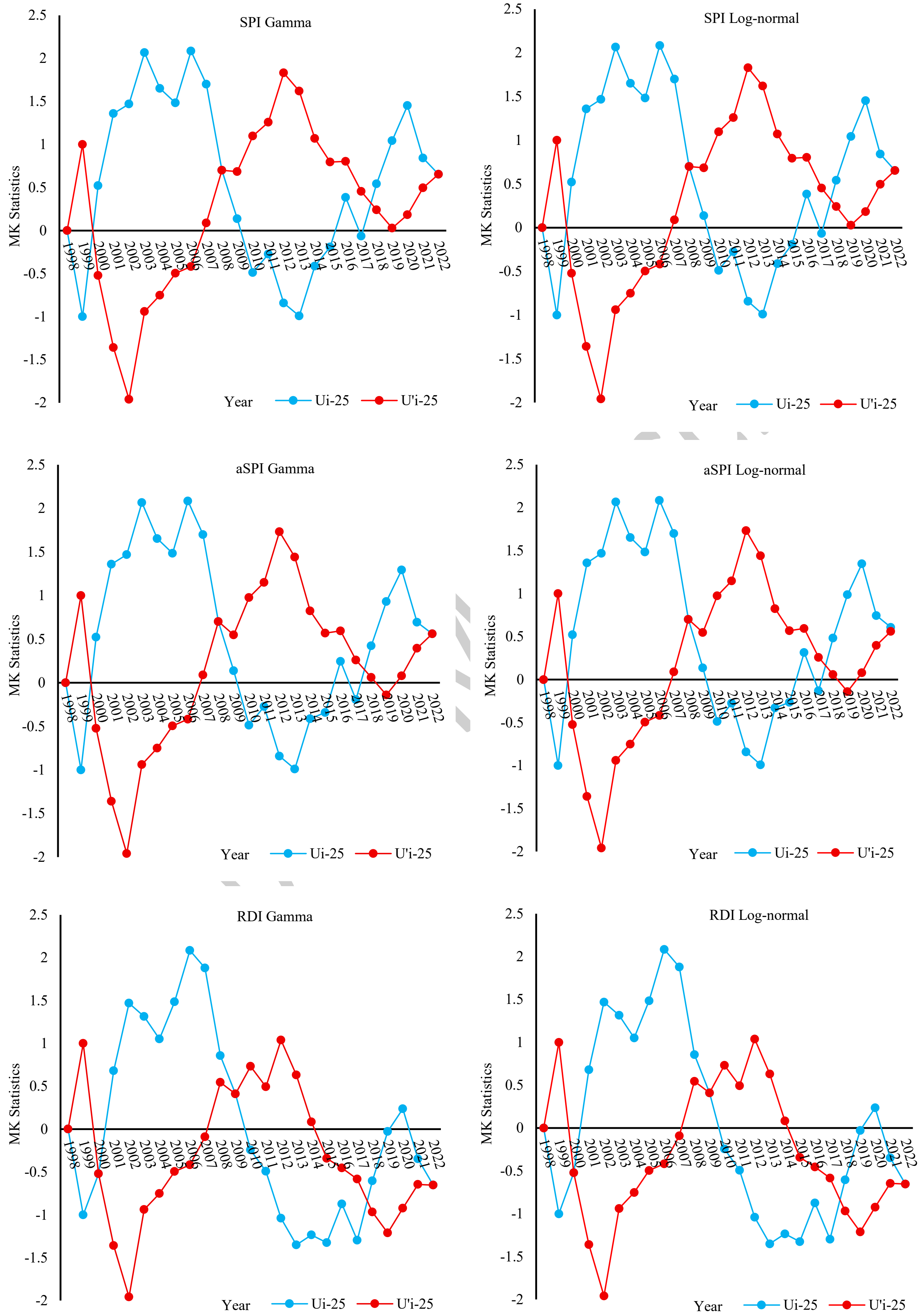
3.1.1. Mann-Kendall test

The results of the agricultural drought trend analysis for the DDR basin from 1998 to 2022 (a 25-year period) are summarized based on the MK, utilizing both gamma and log-normal distributions (GALND). The Z value of the MK for the SPI index in the GALND is equal, and its value is 0.63. This value indicates that the SPI index value has an increasing trend, but this increase is not significant (Z value is between +1.96 and -1.96) at the 5% and 1% levels (Confidence Level = 95%, 99%). The Z value of the MK for the aSPI index in the GALND is 0.54 and 0.56, respectively. These values indicate that the aSPI index has an increasing trend, but this increase is not significant at the 5% and 1% levels. The Z value of the MK for the RDI index in the GALND is equal, and its value is -0.63. This value indicates that the RDI index value has a decreasing trend, but this decrease is not significant at the 5% and 1% levels. The Z value of the MK for the eRDI index in the GALND is equal, and its value is -0.82. This value indicates that the eRDI index value has a decreasing trend, but this decrease is not significant at the 5% and 1% levels. Fig. 3 shows the Mann–Kendall jump test of agricultural drought indices for the DDR basin from 1998 to 2022 with the GALND.

Fig. 3 shows that the U_{i-25} and U'_{i-25} do not intersect outside the ± 1.96 range in all agricultural drought indices modeled with GALND in the DDR basin. Therefore, none of the indices examined with these distributions exhibit a significant trend. According to the presented results, it can be said that during the studied period (1998 to 2022), no significant trends were observed in the various agricultural drought indices. This means that the changes in agricultural drought during this period are not strong enough to be identified as a significant increasing trend or significant decreasing trend. Therefore, further studies may be needed over longer time periods or using other data to better understand the agricultural drought situation.

3.1. 2. Sen's slope estimator test

Table 2 presents SSE results for agricultural drought trends in the DDR basin over 25 years (1998–2022) under the GALND. Table 2 shows that the Q_{med} values of the two indices, SPI and aSPI, are positive in the GALND, so these two indices have an increasing trend. The Q_{min} and Q_{max} values of the two indices, SPI and aSPI, are positive and negative (have not similar signs) in the GALND, so these two indices have a not significant increasing trend at the 95% and 99% confidence levels.


SPI Gamma
MK Statistics
Year
Ui-25
U'i-25
SPI Log-normal
MK Statistics
Year
Ui-25
U'i-25
aSPI Gamma
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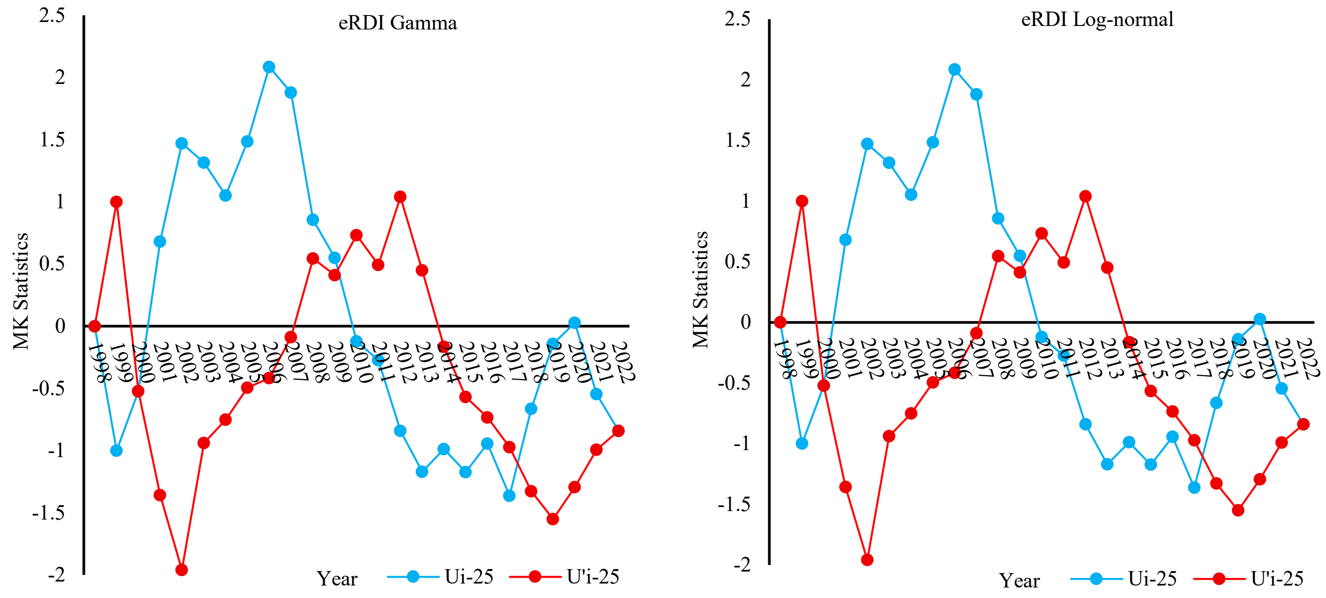


Fig. 3. Mann–Kendall jump test of agricultural drought indices in recent 25 years.

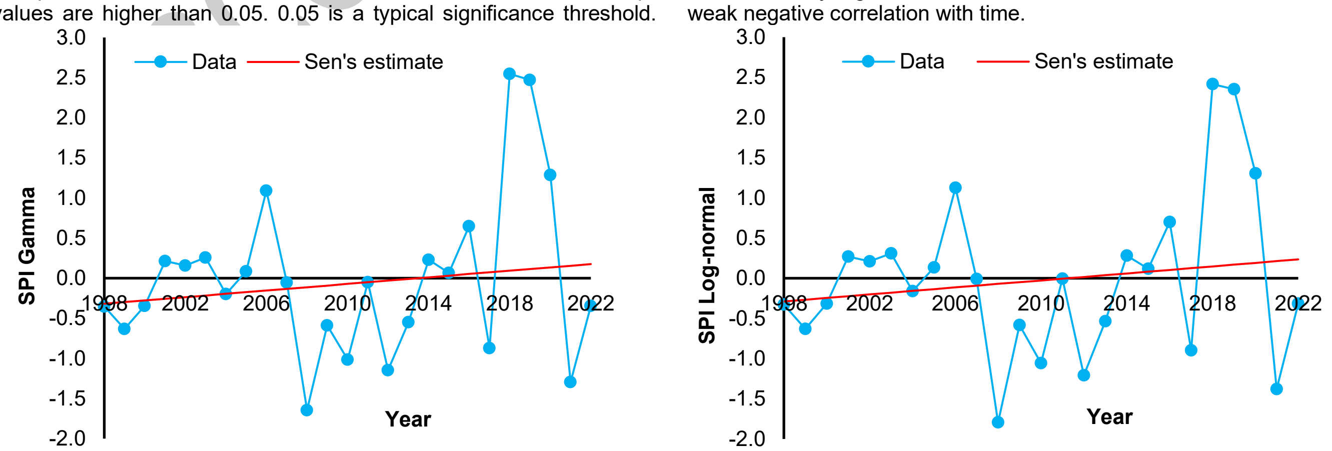
The Q_{med} values of the two indices, RDI and eRDI, are negative in the GALND, so these two indices have a decreasing trend. The Q_{min} and Q_{max} values of the two indices, RDI and eRDI, are positive and negative (have not similar signs) in the GALND, so these two indices have a not significant decreasing trend at the 95% and 99% confidence levels. All results of the SSE test confirm all results of the MK. The results of this study are consistent with the results of Garba and Udokpoh (2023). These researchers analyzed the trend in meteorological and hydrological time series using MK and SSE in Akwa Ibom State, Nigeria. The results of their studies showed that the MK and SSE demonstrated consistent performance in detecting trends for the hydro-meteorological variables. The fitting of Sen's line to the time series of agricultural drought indices data for the DDR basin over the 25-year period from 1998 to 2022 using the GALND is shown in Fig. 4. This figure confirms the results of Table 2.

Table 2. Sen's slope estimator results for agricultural drought trend analysis.

Time series	Q_{med}	Q_{min}	Q_{max}	Q_{min}	Q_{max}	B	B_{min}	B_{max}	B_{min}	B_{max}
Confidence Level	-	99%	99%	95%	95%	-	99%	99%	95%	95%
SPI Log-normal	0.022	-0.062	0.118	-0.039	0.090	-0.29	0.46	-1.28	0.36	-0.82
SPI Gamma	0.021	-0.058	0.122	-0.035	0.085	-0.32	0.39	-1.39	0.30	-0.82
aSPI Log-normal	0.021	-0.057	0.108	-0.041	0.080	-0.26	0.58	-1.27	0.51	-0.68
aSPI Gamma	0.021	-0.055	0.109	-0.039	0.080	-0.29	0.53	-1.32	0.46	-0.70
RDI Log-normal	-0.023	-0.106	0.068	-0.083	0.042	0.35	1.25	-0.65	1.01	-0.37
RDI Gamma	-0.022	-0.101	0.069	-0.076	0.041	0.29	1.15	-0.72	0.87	-0.41
eRDI Log-normal	-0.028	-0.119	0.053	-0.090	0.031	0.50	1.50	-0.50	1.18	-0.24
eRDI Gamma	-0.027	-0.120	0.052	-0.085	0.031	0.44	1.47	-0.54	1.09	-0.29

3.1.3. Pearson correlation analysis

Table 3 presents PCC results for agricultural drought trends in the DDR basin over 25 years (1998–2022) under the GALND. Table 3 shows that the SPI in GALND is positively and weakly correlated with time. Because the PCC of this index in GALND is between 0.21 and 0.23. The p-values for SPI in GALND are between 0.26 and 0.31. The p-values are higher than 0.05. 0.05 is a typical significance threshold. therefore, these increasing trends in GALND are not statistically significant. The aSPI index in GALND shows a very weak positive correlation with time. The PCC in both distributions' ranges from 0.16 to 0.18. The p-values for aSPI in both distributions are between 0.39 and 0.44, which are higher than the conventional significance level of 0.05. Therefore, the observed increasing trends in both distributions are not statistically significant. The RDI index in GALND exhibits a very weak negative correlation with time.



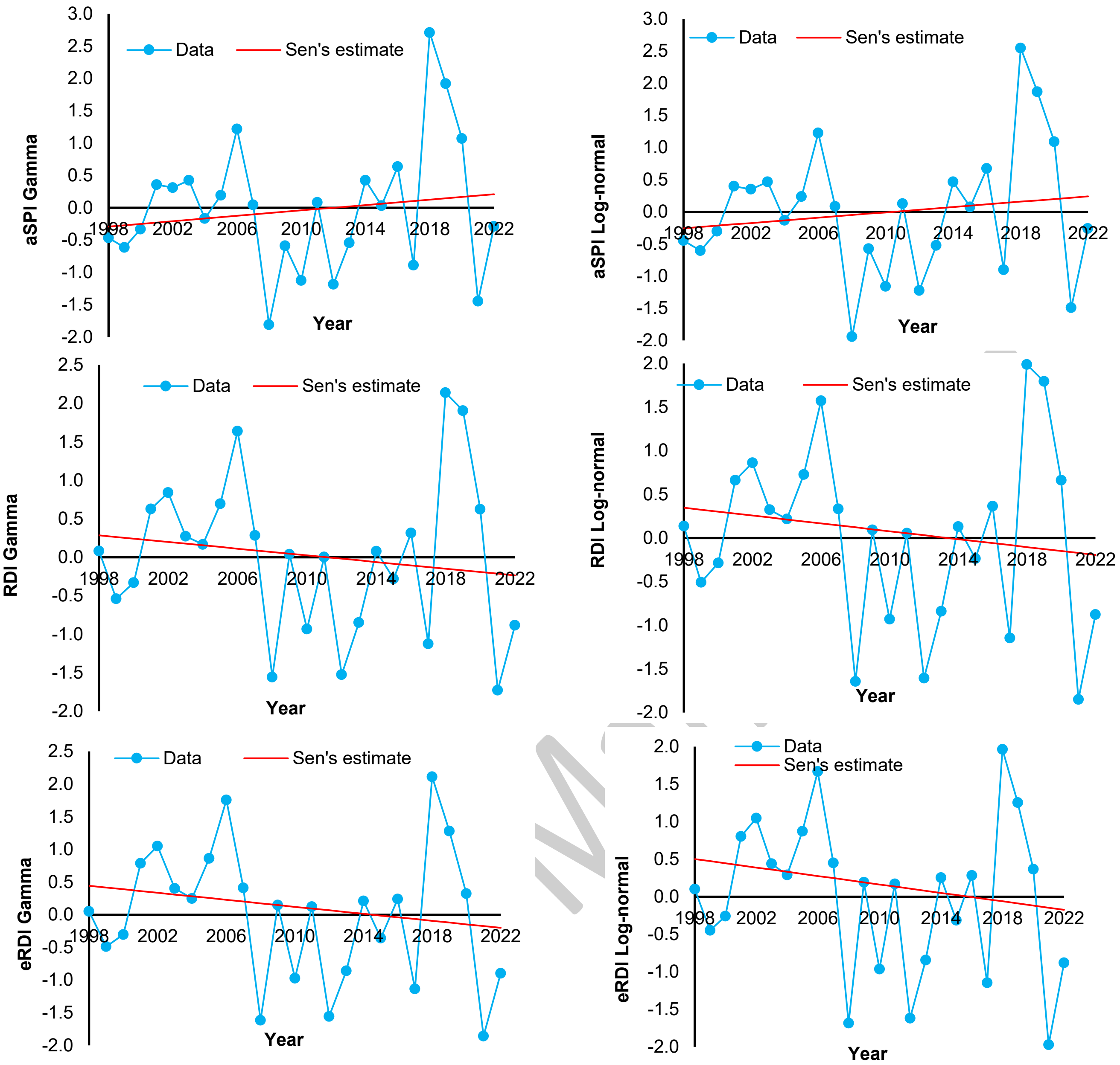


Fig. 4. Sen's line fitted to the time series of agricultural drought index data.

The PCC range from -0.09 to -0.12 in both distributions. The p-values for the RDI in these distributions lie between 0.57 and 0.66, exceeding the conventional significance threshold of 0.05. Consequently, the observed decreasing trends in both distributions are not statistically significant. The eRDI index demonstrates a negligible negative correlation with time across GALND, with PCC ranging from -0.19 to -0.21. The corresponding p-values, spanning from 0.32 to 0.37, substantially exceed the standard significance level of 0.05. Therefore, the apparent decreasing trends in both distributions are not statistically significant. All results of the PCC confirm all results of the MK and SSE. The results of this study are consistent with the results of Polroudimoghadam, Hamzeh, and Vazifehdoust (2016). These researchers analyzed the trend in rainfall and runoff using the MK and the PCC in the Doosti Dam Basin, Iran. The results of their studies showed that both methods provide similar results.

Table 3. Pearson correlation results for agricultural drought trend analysis

Time series	R	n	T	df	p-value	Significant
SPI Log-normal	0.21	25	1.03	23	0.31	No
SPI Gamma	0.23	25	1.16	23	0.26	No
aSPI Log-normal	0.16	25	0.78	23	0.44	No
aSPI Gamma	0.18	25	0.87	23	0.39	No
RDI Log-normal	-0.12	25	-0.58	23	0.57	No
RDI Gamma	-0.09	25	-0.44	23	0.66	No
eRDI Log-normal	-0.21	25	-1.08	23	0.32	No
eRDI Gamma	-0.19	25	-0.92	23	0.37	No

3.1.4. Linear regression

Table 4 presents linear regression results for agricultural drought trends in the DDR basin over 25 years (1998–2022) under the GALND. The slope for SPI in GALND is 0.03. Similarly, the slope for aSPI in both distributions is 0.02. For both SPI and aSPI indices, the slopes are positive and close to zero, which suggests a slight increasing trend over time. The slopes for RDI in GALND are -0.01 and -0.02, respectively. The slopes for eRDI in both distributions are -0.03. For both RDI and eRDI indices, the slopes are negative and close to zero, which suggests a slight decreasing trend over time. The p-values for all agricultural drought indices are above 0.05, indicating that none of the trends are statistically significant at the conventional 5% significance level. The result suggests that there is no strong evidence of a definitive increasing or decreasing trend in agricultural drought indices over the analyzed period. The intercept values are reported in Table 3 for completeness but are not interpreted, as the independent variable represents calendar year. Fig. 5 presents the linear regression fitted to the agricultural drought index time series for the DDR basin over the period 1998 to 2022 using the GALND.

Table 4. Linear regression results for agricultural drought trend analysis.

Time series	a	b	p-value	Significant
SPI Log-normal	-58.63	0.03	0.31	No
SPI Gamma	-65.32	0.03	0.26	No
aSPI Log-normal	-44.69	0.02	0.44	No
aSPI Gamma	-49.67	0.02	0.39	No
RDI Log-normal	33.58	-0.02	0.57	No
RDI Gamma	25.74	-0.01	0.66	No
eRDI Log-normal	57.86	-0.03	0.32	No
eRDI Gamma	52.75	-0.03	0.37	No

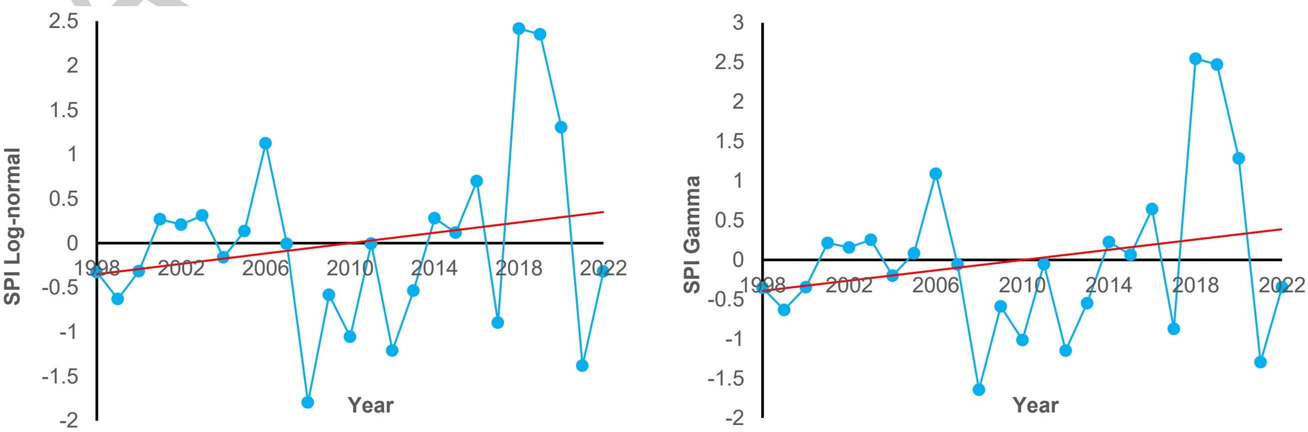
Fig. 5 shows that the SPI and aSPI indices have a slight upward trend, while the RDI and eRDI indices exhibit a slight downward trend. Fig. 5 confirms the results of Table 4. Comparing Fig. 3 and Fig. 4 shows that the graphical representations created with the linear regression and SSE indicate the same visual results. All results of the linear regression confirm all results of the MK, PCC and SSE. The results of this study are consistent with the results of Bararkhanpour *et al*. (2020). These researchers analyzed the trend in seasonal and annual rainfall using the MK and linear regression in the Gorgan Hashem-Abad station, Iran. The results of their studies showed that both methods depict similar variations. The results of this study are consistent with the results of Raeesi *et al*. (2023). These researchers analyzed the trend in the normalized difference vegetation index (NDVI) using SSE and linear regression in Semnan Province, Iran. Their results indicated that the slope obtained from linear regression and that from SSE are nearly identical. The results of this study are consistent with the results of Basati, Yarahmadi, and Nasiri (2014). These researchers analyzed the trends in relative humidity and temperature using regression analysis, the MK, and the PCC at the Kermanshah station, Iran. Their findings indicated that all three methods yielded similar results.

3.1.5. Comparison between gamma and log-normal distributions across all methods

To quantitatively assess the influence of probability distribution choice on drought trend detection, the results obtained from the gamma and log-normal distributions were directly compared for all four drought indices using all four statistical methods. The maximum absolute differences between the two distributions were as follows: for Mann–Kendall Z-values, the difference was 0.02; for Sen's slopes, the difference ranged from 0.001 to 0.002 index units per year; for Pearson correlation coefficients, the difference ranged from 0.02 to 0.05; and for linear regression slopes, the difference was 0.00 to 0.01 index units per year. All these differences are substantially below any practical significance threshold commonly used in monitoring drought (e.g., 0.05 index units per year for slope estimates). The near-identical results from all four methods – both parametric and non-parametric – confirm that the choice between gamma and log-normal distributions does not bias trend detection in this dataset. This robustness can be attributed to two factors: first, both distributions adequately fit the underlying precipitation and precipitation-to-PET ratio data in the semi-arid Darreh Dozdan River basin; second, the estimated trend magnitudes are sufficiently close to zero that even substantial differences in distributional assumptions would not alter the statistical conclusion of no significant monotonic change.

3.2. Comparison with regional climatic trends and interpretation of non-significant results

To better interpret the observed agricultural drought trends, it is necessary to compare them with regional climatic trends, particularly for precipitation and evapotranspiration, which are the primary drivers of drought in semi-arid regions (Amini *et al*., 2019). The SPI and aSPI indices are based solely on precipitation, with total precipitation for SPI and effective precipitation for aSPI. Therefore, their trend behavior directly reflects the trend of precipitation in the region. Regional studies in Lorestan Province have consistently reported no significant precipitation trends. Lornezhad, Ebrahimi, and Rabieifar (2023) analyzed precipitation trends over a 35-year period (1986–2021) using the modified Mann-Kendall test and found no significant decreasing or increasing trend at the 5% confidence level in any of the cities across the province. Nikoo *et al*. (2026) investigated meteorological drought trends using the SPI and Mann-Kendall test, reporting that only Selseleh city showed a significant increasing trend, while the remaining cities, including the area where the Darreh Dozdan basin is located, exhibited no significant trends. The absence of significant trends in SPI and aSPI in the present study, with Z-values between -1.96 and +1.96, p-values above 0.05, and Sen's slopes of 0.021 to 0.022 index units per year, is therefore a direct consequence of the absence of significant precipitation trends in the region. For the RDI and eRDI indices, which are based on the ratio of precipitation (or effective precipitation) to potential evapotranspiration (PET), the interpretation is more nuanced. In this study, PET was estimated using the FAO-56 Penman-Monteith method, which requires meteorological parameters including minimum and maximum temperature, relative humidity, wind speed, and sunshine hours. Although unpublished studies in the Darreh Dozdan basin indicate a significant increasing trend in PET, the influence of precipitation on RDI and eRDI is substantially larger. Approximately 75% of the variance in these indices is controlled by precipitation, while PET contributes only about 25%. This is because precipitation variability in semi-arid regions is typically much higher than PET variability, and the ratio P/PET is dominated by changes in precipitation. Consequently, even though PET shows a significant increasing trend, the lack of significant trends in precipitation combined with the dominant role of precipitation in the P/PET ratio results in non-significant trends in RDI and eRDI. These indices exhibited Z-values of -0.63 and -0.82, Sen's slopes of -0.022 to -0.028 index units per year, and p-values above 0.05. This coherence between agricultural drought trends and underlying climatic drivers, where non-significant precipitation trends directly explain the non-significant results in all four indices with precipitation dominating the P/PET ratio for RDI and eRDI, strengthens the robustness of our findings.



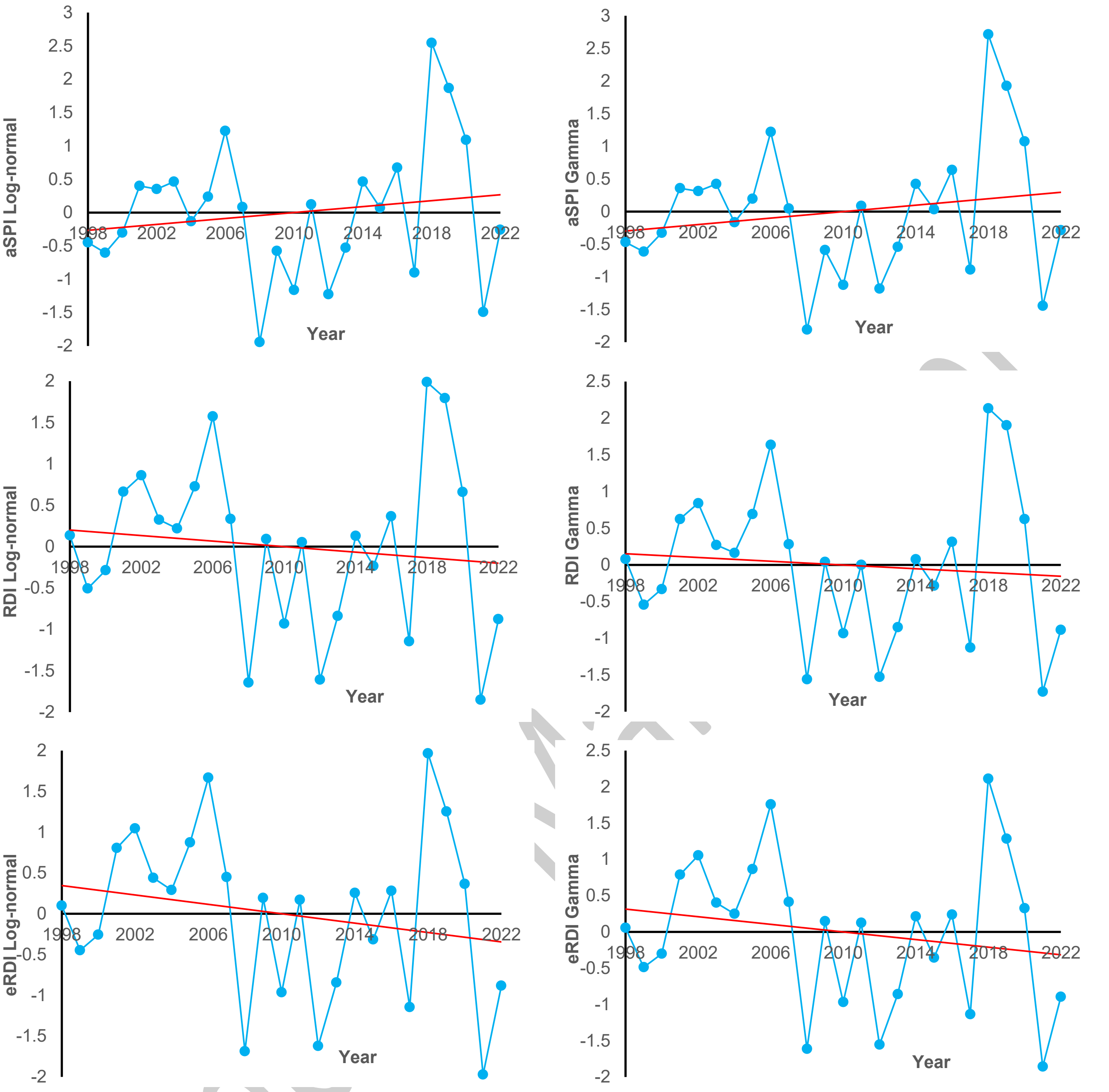


Fig. 5. Linear regression fitted to agricultural drought index time series.

4. Conclusions

Drawing on a 25-year record from the DDR basin, this study combined four drought indices (SPI, aSPI, RDI and eRDI) with two probability models (gamma and log normal) and two complementary statistical toolsets: linear regression with PCC for the parametric perspective and the MK with SSE for the nonparametric perspective. The primary results of this study are presented below.

- Standardising the four drought indices with GALND produced virtually identical trend estimates, showing that the choice of probability model does not bias agricultural-drought assessment in the DDR basin.
- Linear regression and PCC (parametric) reached the same no-trend verdict as MK and SSE (non-parametric), so agreement across statistical families confirms the absence of a monotonic signal from 1998 to 2022.
- Median Sen slopes remained within ±0.03 index units per year, and regression slopes were similarly small with p-values above 0.25, indicating that any shifts in SPI, aSPI, RDI and eRDI are both statistically and practically negligible.
- This multi-index, two-distribution, dual-statistic protocol forms a transferable template for robust drought-trend attribution in data-scarce semi-arid basins, providing reliable evidence for water-resource planning amid climatic uncertainty.

One limitation worth mentioning is that the data came from a single synoptic station inside the DDR basin. Although this record is long and detailed, it only represents a single point in space rather than areal coverage. A more robust statistical outcome and better spatial representation would likely come from incorporating multiple stations with extended, more complete datasets, which could in turn provide a finer picture of agricultural drought behavior across the basin. As for the 25-year study window (1998–2022), it is important to recognize that it does not meet the WMO's recommended 30-year baseline for analyzing climate trends. Shorter time series are more easily influenced by natural climate fluctuations occurring near the start or end of the period, potentially hiding or overstating monotonic trends. Thus, the fact that this study found no significant trends means only that no detectable change occurred between 1998 and 2022; it should not be taken as evidence of long-term stability. That said, the fact that different statistical approaches and distribution assumptions all gave similar results supports the idea that if a genuine trend had existed, the data length would have been enough to capture it. Going forward, researchers should look beyond SPI, aSPI, RDI, and eRDI and include other ground-based indices as well as remote-sensing-based drought indicators, allowing a fuller, multi-scale evaluation of drought dynamics.

Author Contributions

Hedieh Ahmadpari: Undertook the collection and analysis of data, performed the investigation, established the methodology, provided resources and software, and prepared the original draft as well as reviewing and editing the text.
Vitaly Khaustov and Ata Amini: Jointly developed the conceptual framework, ensured validation, oversaw the study as supervisors, and participated in reviewing and editing the manuscript.

Conflict of Interest

The authors declare there is no conflict of interest.

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Data Availability Statement

All data obtained during this research are contained and presented in the present paper.

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