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ORIGINAL RESEARCH PAPER

Quantitative Assessment of Drought Risk in Iran: A Copula-Based Approach Using SPI and SPEI Indices

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ABSTRACT

BACKGROUND AND OBJECTIVES: BACKGROUND AND OBJECTIVES: Drought is one of the most critical climate-related hazards affecting Iran, exerting substantial impacts on agricultural production, water resources, and socio-economic stability. The predominance of arid and semi-arid climatic regimes, coupled with high interannual precipitation variability and sustained warming trends, has intensified both the frequency and severity of drought events nationwide. Traditional drought assessments in Iran have predominantly relied on univariate drought indices and linear correlation measures, which often fail to capture the compound nature of drought processes driven by concurrent precipitation deficits and elevated atmospheric water demand. In recent decades, temperature-driven evapotranspiration has emerged as a key determinant of drought severity under climate change, exposing the limitations of precipitation-only metrics such as the Standardized Precipitation Index (SPI). In this context, the Standardized Precipitation Evapotranspiration Index (SPEI), which explicitly integrates potential evapotranspiration (PET), provides a more comprehensive characterization of drought dynamics. However, robust drought risk characterization requires not only evaluating individual indices but also quantifying their joint behavior and underlying dependence structure. Because interactions among climatic drivers can substantially amplify environmental impacts, recent advances in climate risk assessment emphasize modeling compound extremes—such as concurrent drought and heatwave events—via multivariate frameworks. Accordingly, this study provides a probabilistic, multivariate assessment of drought risk across the major climatic regions of Iran by jointly analyzing SPI and SPEI through copula theory. By modeling the joint dependence structure of these indices, this study captures nonlinear and asymmetric relationships, with particular focus on the tail dependence associated with extreme drought events. Beyond advancing methodological frameworks, this study demonstrates the utility of copula-based drought modeling for drought risk management, climate adaptation planning, and the conceptual formulation of index-based insurance schemes.

METHODS: This study utilized long-term meteorological observations spanning 1981–2020 from synoptic stations across Iran. Monthly precipitation and temperature records were employed to compute SPI and SPEI across multiple accumulation timescales, facilitating the evaluation of both short- and long-term drought conditions. The computation of SPEI integrated PET to account for the impact of rising temperatures on drought intensity. Marginal probability distributions for SPI and SPEI were fitted using the Maximum Likelihood Estimation (MLE). To model the dependence structure between the two indices, several copula families—namely Gaussian, Student-t, Clayton, and Gumbel—were evaluated across diverse dependence behaviors, including symmetric dependence, tail dependence, and asymmetric lower- or upper-tail dependence. Optimal copula models were selected based on the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), and goodness-of-fit (GoF) tests. Lower- and upper-tail dependence coefficients were quantified to evaluate the joint probability of concurrent extreme drought conditions. Furthermore, joint probabilities and bivariate return periods for severe and extreme drought events were derived from the fitted copula models across distinct climatic regions of Iran and subsequently validated against historical drought records.

FINDINGS: The results revealed pronounced spatial heterogeneity in drought characteristics and dependence structures across Iran. Arid and semi-arid regions—particularly the Central Plateau and eastern Iran—exhibited strong lower-tail dependence between SPI and SPEI, indicating a high likelihood of concurrent extreme droughts driven by simultaneous precipitation deficits and elevated evaporative demand. In these regions, the Clayton copula consistently demonstrated the best fit, effectively capturing the asymmetric lower-tail dependence characteristic of severe drought events. Conversely, humid regions along the Caspian Sea coast exhibited weaker dependence structures, negligible tail dependence, and longer drought return periods. Transitional climatic zones were better characterized by the Student-t copula, which captures symmetric tail dependence and intermediate drought dynamics. These probabilistic findings are consistent with major documented drought episodes within and after the study period, particularly those occurring during the late 1990s and late 2010s. Earlier historical drought events, such as those reported during the early 1970s, are considered as contextual evidence from previous studies rather than direct validation cases for the proposed modeling framework.

CONCLUSION: These findings provide a probabilistic characterization of drought risk in Iran and establish a quantitative basis for analyzing compound drought behavior. Although this study does not formulate an actuarial pricing model, the findings provide actionable insights for drought risk management, climate adaptation strategies, and the conceptual design of index-based insurance frameworks. By integrating multivariate drought indices with copula-based dependence modeling, this study demonstrates the necessity of advancing beyond univariate and linear correlation-based paradigms in drought risk assessment. Furthermore, the findings underscore the escalating influence of temperature-driven evapotranspiration under climate change, confirming the critical utility of SPEI in warming environments. Overall, the proposed framework offers a robust, flexible, and policy-relevant tool for assessing drought risk across Iran, establishing a scientific foundation for strengthening climate resilience, enhancing agricultural risk management, and developing innovative risk-transfer mechanisms.

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INTRODUCTION

Drought is one of the most damaging climate-related hazards, particularly in arid and semi-arid regions, where limited water availability severely constrains agricultural production and socioeconomic stability. Unlike sudden-onset hazards, drought develops gradually, exhibits substantial spatial heterogeneity, and generates cumulative impacts, rendering its monitoring and quantitative assessment particularly challenging. Under ongoing climate change, rising temperatures and altered precipitation regimes have increased the frequency and severity of drought events in many regions worldwide (Spinoni et al., 2018).

Iran is among the countries most vulnerable to drought because of its predominantly arid and semi-arid climate, high interannual variability in precipitation, and increasing pressure on limited water resources. Approximately 85% of the country is located within dry climatic zones, and a substantial proportion of agricultural production depends on precipitation or increasingly stressed groundwater systems. Recurring drought events have resulted in considerable crop losses and water shortages, underscoring the need for robust quantitative drought-assessment frameworks to support risk-informed decision-making.

Drought monitoring commonly relies on standardized indices that summarize hydroclimatic anomalies across multiple timescales. The Standardized Precipitation Index (SPI) is widely used because of its conceptual simplicity and minimal data requirements; however, it does not explicitly account for temperature-driven evapotranspiration (Hayes et al., 1999). To address this limitation, the Standardized Precipitation Evapotranspiration Index (SPEI) incorporates both precipitation and atmospheric water demand, thereby providing a more comprehensive representation of climatic water balance and agricultural drought, particularly under warming conditions.

Although SPI and SPEI have been extensively applied, many drought assessments analyze these indices independently or rely on linear correlation, which is insufficient for capturing nonlinear and asymmetric dependence structures during extreme events. In practice, precipitation deficits and elevated evapotranspiration may occur simultaneously, thereby amplifying drought impacts. Copula theory provides a flexible statistical framework for modeling such dependence structures independently of the marginal distributions and enables the quantification of tail dependence and joint extreme behavior.

Although previous studies have examined drought trends and spatial variability in Iran, systematic analyses of the joint behavior of SPI and SPEI and its implications for probabilistic drought-risk assessment remain limited. In particular, the integration of copula-based joint probabilities into frameworks relevant to drought-risk management and index-based insurance design has received insufficient attention.

Against this background, this study aims to quantitatively assess drought characteristics and dependence structures across Iran using SPI and SPEI. Specifically, it (i) computes multiscalar SPI and SPEI values using long-term climatic data; (ii) models their dependence using different copula families; (iii) identifies regional differences in tail dependence and joint drought behavior; and (iv) derives joint probabilities and return periods to support probabilistic drought-risk assessment. By integrating multiscalar drought indices with copula-based modeling, this study contributes to a clearer understanding of compound drought dynamics in Iran and provides a quantitative foundation for climate-informed risk management and index-based insurance applications.

Such probabilistic characterization of compound droughts is essential for reducing basis risk and improving the transparency of index-based insurance schemes in drought-prone regions.

LITERATURE REVIEW

Drought Indices and Their Applications

Drought indices provide quantitative tools for characterizing drought intensity, duration, and temporal evolution, thereby enabling consistent comparisons across regions and timescales. Numerous indices have been developed to monitor meteorological and agricultural drought, with each reflecting different components of the hydroclimatic system and their associated impacts.

Among the most widely used indicators is the Standardized Precipitation Index (SPI), originally proposed by McKee et al. (1993). SPI measures precipitation anomalies over multiple accumulation periods and was developed to support drought monitoring across different timescales (Edwards & McKee, 1997). It has been extensively applied because of its conceptual simplicity, limited data requirements, and flexibility across climatic regimes. In arid and semi-arid regions such as Iran, SPI has been widely employed for drought monitoring and regional assessments (Modarres & Sarhadi, 2009). However, because SPI relies exclusively on precipitation, it does not explicitly account for the influence of temperature-driven evapotranspiration, which has become increasingly important under ongoing climate warming.

The Standardized Precipitation Evapotranspiration Index (SPEI) incorporates evapotranspiration (PET) alongside precipitation and therefore reflects variations in atmospheric water demand. Numerous studies have shown that SPEI provides a more sensitive representation of drought conditions in

warming environments, particularly in agricultural systems. Recent evaluations have further examined the performance of drought indices under climate warming, emphasizing the importance of temperature-sensitive indicators such as SPEI for drought assessment under changing climatic conditions. Empirical evidence from Iran suggests that SPEI is more effective than SPI in capturing drought severity during warm and prolonged dry periods, particularly for temperature-sensitive crops such as wheat and barley (Kheyri et al., 2021). Recent studies have also applied modified SPEI-based approaches to investigate drought trends and temporal variability across different regions of Iran (Rahnama et al., 2023).

In addition to SPI and SPEI, other drought indicators have been developed to capture long-term soil-moisture conditions and vegetation responses. The Palmer Drought Severity Index (PDSI) is commonly used for long-term drought assessment but requires detailed soil and calibration data, which limits its applicability in data-scarce regions. Remote-sensing-based indicators, such as the Normalized Difference Vegetation Index (NDVI) and the Vegetation Health Index (VHI), have also been employed to monitor vegetation stress and the ecological impacts of drought (Tehrany et al., 2014). Although these indices provide valuable complementary information, they primarily reflect vegetation responses rather than atmospheric drought processes.

Overall, SPI and SPEI remain among the most suitable indices for large-scale and long-term drought assessment in Iran because of their data availability, comparability, and flexibility across timescales. Their joint use provides a more comprehensive representation of hydroclimatic variability by capturing both precipitation deficits and atmospheric water demand.

Recent drought episodes in Iran have had substantial and measurable effects on agricultural yields. Empirical studies have shown that severe drought conditions significantly reduce the performance of rainfed crops, particularly strategic cereals such as wheat and barley (Shayeghi et al., 2024). For example, observational analyses across diverse Iranian climatic zones indicate that drought events, particularly those identified by low standardized drought-index values, are associated with notable reductions in rainfed wheat and barley yields, with impacts often exceeding 20–30% in severe drought years relative to average yields (Tehrany et al., 2014). These quantitative effects demonstrate that drought is not only a climatological phenomenon but also a critical driver of agricultural production losses in Iran. Recent studies have further documented significant effects of drought variability on agricultural systems and water availability (Shayeghi et al., 2024). This evidence underscores the practical importance of integrating drought indices such as SPI and SPEI into agricultural risk-assessment and policymaking frameworks.

Copula Models in Drought Analysis

Copula theory provides a flexible statistical framework for modeling multivariate dependence structures by separating marginal distributions from joint behavior. Unlike conventional correlation measures, copulas can capture nonlinear and asymmetric dependence patterns, including tail dependence, which is particularly relevant to the analysis of extreme drought events.

Different copula families exhibit distinct dependence characteristics. The Gaussian copula assumes symmetric dependence and weak tail dependence, which may result in the underestimation of joint extremes. The Student-t copula extends this framework by allowing symmetric tail dependence, making it suitable for modeling concurrent extreme drought conditions. Archimedean copulas provide additional flexibility; for example, the Clayton copula captures lower-tail dependence and is therefore well suited to representing simultaneous low values of drought indices, whereas the Gumbel copula emphasizes upper-tail dependence and is more relevant to wet extremes.

Copula-based approaches have increasingly been applied in hydroclimatology to assess compound and joint drought behavior. Several studies in Iran and neighboring regions have reported pronounced lower-tail dependence among drought-related variables, indicating a high probability of concurrent extreme conditions. For example, Hosseini et al. (2021) identified strong lower-tail dependence in precipitation patterns across central and southeastern Iran, whereas studies in Pakistan and Türkiye reported similar dependence structures using copula-based frameworks. More recent research has shown that of SPI and SPE) and Clayton copulas often outperform Gaussian copulas in modeling the joint behavior of SPI and SPEI (Kheyri et al., 2021).

Beyond descriptive analysis, copula models provide a probabilistic foundation for drought-risk assessment by enabling the estimation of joint exceedance probabilities and return periods. These properties are essential for evaluating the likelihood of compound drought events and supporting quantitative, risk-based decision-making.

In addition to facilitating statistical characterization, copula-based dependence modeling has direct operational relevance to the design of parametric drought-insurance schemes. In such contracts, indemnity payments are triggered when predefined climate indices cross critical thresholds, making accurate representation of joint drought behavior essential for reducing basis risk and ensuring actuarial soundness (Cummins & Weiss, 2009). By explicitly modeling the joint distribution of SPI and SPEI, copulas enable the

Table 1. Annual summary of the national extent of drought in Iran based on SPEI, showing the percentage of the country affected by drought conditions during selected periods[1]

Period / Year	% of Iran under Drought (SPEI-based)	Description / Source
2010–2019 (10-year aggregate)	96.92%	Proportion of the total country affected by moderate to very severe drought during the 10-year SPEI assessment period (2010–2019).
2019 (end of Oct 2019)	87.9%	National drought extent based on the 10-year SPEI summary through 2019.
2023 (one-year SPEI)	86.50%	Percentage of Iran affected by mild to very severe drought based on the 1-year SPEI.
2024 (one-year SPEI)	86.50–91.1%*	National drought extent through early 2024, reported as approximately 91.1% in national open data.

*Note: variation arises by reporting date.

[1] *Data source: Iran Open Data Center (SPEI-based national drought assessments).*

Table 2. Conceptual comparison of commonly used copula families for drought-dependence modeling, summarizing their dependence characteristics and typical applications based on existing methodological and hydroclimatic literature[2]

Copula Type	Dependence Feature	Typical Use	Notes
Gaussian	Symmetric dependence; weak tail dependence	General dependence modeling	Limited suitability for extreme events
Student-t	Symmetric dependence with tail dependence	Assessment of severe drought risk	Suitable for multiregional droughts
Clayton	Lower-tail dependence	Design of drought-payout triggers	Captures simultaneous low SPI and SPEI values
Gumbel	Upper-tail dependence	Analysis of wet extremes	Of limited relevance to arid Iran

[2] *Table entries are synthesized from established copula theory and previous drought dependence studies* (Nelsen, 2006).

estimation of joint threshold-exceedance probabilities associated with compound drought conditions, which can inform the definition of objective triggers. Lower-tail-dependent structures, such as the Clayton copula, are particularly suitable for this purpose because they capture the increased likelihood of simultaneous precipitation deficits and elevated atmospheric water demand—conditions under which agricultural losses may be most severe. Moreover, joint return periods derived from copula models provide a probabilistic basis for calibrating payout schedules and premium levels, allowing insurance pricing to reflect the multivariate risk of extreme drought events rather than relying on single-index metrics. Consequently, copula-based frameworks provide a rigorous quantitative link between hydroclimatic analysis and risk-based financial instruments, supporting the development of more robust and transparent drought-insurance solutions.

Integration of Drought Indices and Copulas in Risk Management

Integrating multiscalar drought indices with copula-based dependence modeling enables a comprehensive probabilistic characterization of drought risk. In this framework, SPI and SPEI are first derived from long-term meteorological observations and subsequently linked through appropriate copula functions to represent their joint dependence structure.

As illustrated in Fig. 1, the resulting joint distributions enable the estimation of key risk metrics, including joint drought probabilities, severity levels, and associated return periods. These metrics provide an analytical basis for identifying regions with elevated exposure to compound drought conditions and comparing drought behavior across different climatic zones.

Such integrated approaches are increasingly being used to support risk-informed decision-making in water-resources management and agriculture. In addition, index-based weather insurance has emerged as an important mechanism for transferring climate-related agricultural risks, particularly in developing regions where conventional loss assessment can be costly and inefficient. Government support mechanisms and institutional frameworks also play important roles in expanding agricultural insurance programs in developing countries (Mahul & Stutley, 2018).

By quantifying the probability of simultaneous precipitation deficits and elevated atmospheric water demand, copula-based frameworks also provide conceptual support for the development of index-based and parametric insurance schemes. Although the present study does not implement a full insurance-pricing model, the derived joint-probability structures provide a necessary statistical foundation for future applications aimed at reducing basis risk, enhancing climate resilience, and supporting broader climate-risk-financing strategies.

Research gap and methodological contribution

Previous drought studies in Iran have primarily

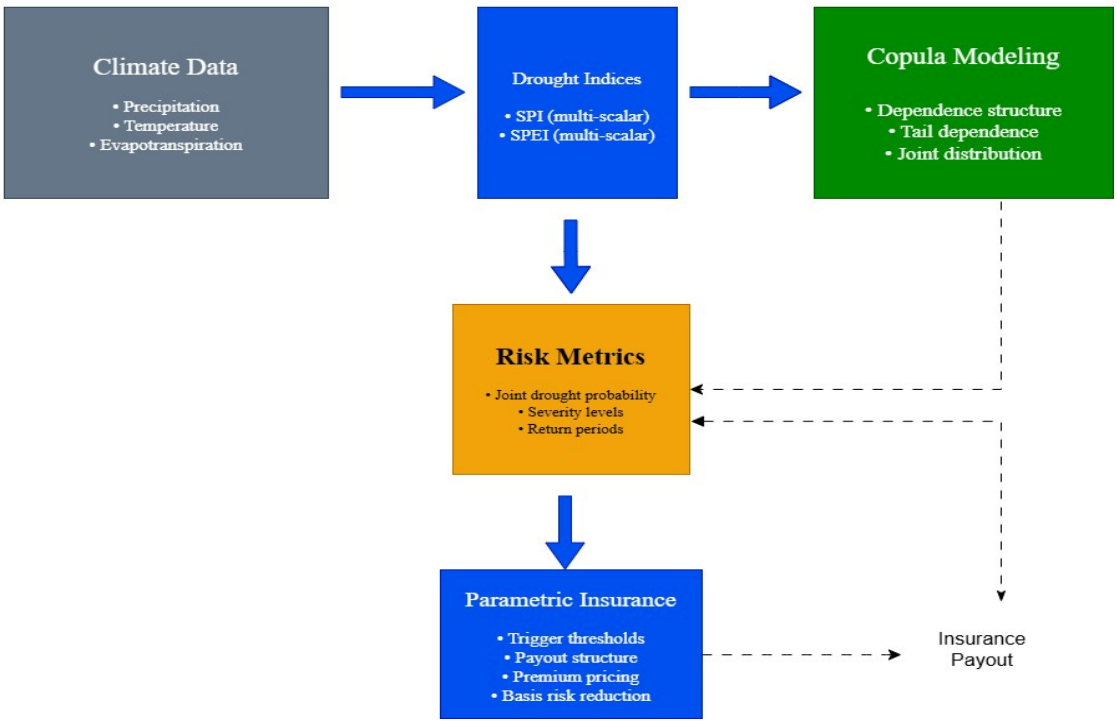


Fig. 1. Conceptual framework illustrating the methodological workflow of the study, linking climate data—precipitation, temperature, and evapotranspiration—to multiscalar drought indices (SPI and SPEI), copula-based dependence modeling, and the derivation of drought-risk metrics for parametric-insurance applications

focused on individual drought indices, temporal trends, and spatial variability using univariate frameworks or linear correlation measures (Farajzadeh & Ahmadian, 2014). These studies have provided valuable insights into the climatology, precipitation variability, and dynamics of drought across different regions of Iran.

More recently, multivariate approaches have gained attention in drought research; nevertheless, systematic applications of copula theory to the joint modeling of SPI and SPEI remain scarce in the Iranian context. In particular, previous studies have not explicitly quantified tail dependence or joint drought probabilities, which are critical for understanding the co-occurrence of extreme droughts and informing probabilistic risk assessment.

The present study addresses this gap by introducing a copula-based framework for jointly modeling SPI and SPEI, thereby enabling the explicit characterization of dependence structures, tail behavior, and joint return periods of drought events. This methodological contribution advances previous drought assessments in Iran by providing a more comprehensive basis for compound-drought-risk analysis and related applications.

EXPANDED DATA AND METHODOLOGY

Study Area

Iran is situated in Southwest Asia between approximately 25°–39° N latitude and 44°–63° E longitude and exhibits substantial climatic heterogeneity owing to its complex topography and geographic setting. The country encompasses diverse climatic regimes ranging from hyper-arid deserts to humid coastal zones, making it particularly well suited for evaluating spatial variability in drought dynamics.

Mean annual precipitation ranges from less than 50 mm in the central and eastern desert basins to more than 1,200 mm along the southern Caspian Sea coast, whereas mean annual air temperature varies from below 10 °C in high-altitude mountainous areas to above 25 °C in southern lowlands. Extreme land surface temperatures exceeding 50 °C have been recorded in parts of the Lut Desert, underscoring the severe thermal stress characteristic of eastern Iran (NASA, 2020).

Based on prevailing hydroclimatic characteristics, Iran can be classified into several major zones: the arid central plateau, semi-arid northwestern regions, humid Caspian coastal areas, the western Zagros Mountains, and the hyper-arid eastern deserts. This pronounced climatic diversity provides an ideal setting for evaluating drought variability and testing probabilistic modeling frameworks under contrasting environmental conditions.

Data Sources and Preprocessing

Monthly and daily meteorological observations

were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO), which maintains the national synoptic station network. To ensure spatial representativeness and statistical reliability, stations were screened according to strict completeness and continuity criteria.

Following established climatological protocols, stations with more than 10% missing daily precipitation records over the study period were excluded to prevent bias in trend and distributional analyses. Following quality control, a total of 49 synoptic stations covering the period 1981–2020 were retained. This set of 49 stations represents an optimal balance between maximizing spatial coverage across Iran and ensuring sufficient data quality and record length for robust statistical estimation. Statistically, the exclusion of stations with substantial data gaps improves the stability of drought index estimation and the reliability of subsequent copula-based dependence modeling. Spatially, the selected stations are distributed across Iran's major hydroclimatic zones, including the arid central plateau, the semi-arid northwestern regions, the humid Caspian coastal belt, the mountainous western regions, and the hyper-arid eastern deserts. This configuration enables the dataset to capture the primary gradients of precipitation, temperature, and atmospheric evaporative demand governing drought dynamics at the national scale, thereby confirming the representativeness of the selected station network for regional and nationwide drought risk assessment.

To address remaining data gaps and ensure temporal continuity, missing precipitation values were complemented using ERA5 reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 integrates in situ observations with satellite data via numerical weather prediction models, providing spatially consistent climate variables at a 0.25° × 0.25° horizontal resolution. Its applicability to hydroclimatic studies over Iran has been extensively validated in previous research.

Potential evapotranspiration (PET) was estimated using the FAO Penman–Monteith formulation, which incorporates air temperature, relative humidity, wind speed, and solar radiation, and is widely recognized as the reference method for evapotranspiration estimation (Allen et al., 1998). Specifically, the FAO Penman–Monteith method estimates reference evapotranspiration by integrating net radiation, air temperature, wind speed, and vapor pressure deficit, providing a physically based representation of atmospheric evaporative demand. Due to its robustness across diverse climatic regimes, this method is recommended by the Food and Agriculture Organization (FAO) as the standard approach for PET estimation and has been widely applied in drought, climate variability, and water resource investigations. Its suitability for arid and semi-arid environments, such as large parts of Iran, has been demonstrated across numerous regional and global assessments.

Prior to drought index calculation, meteorological observations were subjected to standard quality-control procedures, including inconsistency detection, outlier screening, and temporal continuity checks, following classical meteorological data analysis frameworks (Brooks & Carruthers, 1953).

Calculation of Drought Indices

Standardized Precipitation Index (SPI):

$$\mathrm{SPI} = \frac{\mathrm{Xi} - \mu}{\sigma}$$

where Xi is the precipitation in month *i*, μ = long-term mean, σ = standard deviation of the transformed series.

Standardized Precipitation Evapotranspiration Index (SPEI)

P−PET= Di $\mathrm{SPEI} = \frac{\mathrm{DDi} - \mu}{D\ \hat{}\ \phi}$

Both indices were computed across 1-, 3-, 6-, and 12-month timescales using two-parameter gamma and three-parameter log-logistic distributions, respectively.

Drought severity was categorized according to the World Meteorological Organization classification (WMO, 2012):

Mild (-0.5 to -0.99), Moderate (-1.0 to -1.49), Severe (-1.5 to -1.99), Extreme (< -2.0).

RATIONALE FOR DISTRIBUTION SELECTION

The selection of gamma and log-logistic distributions for SPI and SPEI, respectively, is grounded in the statistical properties of the underlying hydroclimatic series and their established suitability for drought monitoring. Precipitation series utilized for SPI computation are strictly non-negative and commonly positively skewed. The two-parameter gamma distribution effectively accommodates this positive skewness, ensuring that extreme wet and dry events are accurately represented while preventing non-physical negative values.

Conversely, for SPEI, which accounts for the climatic water balance ($D = P - \mathrm{PET}$), values can be both positive and negative, particularly during extended dry intervals when atmospheric evaporative demand exceeds precipitation. The three-parameter log-logistic distribution effectively spans this domain, accommodating lower-bound characteristics and capturing both short- and long-term drought variability with higher fidelity.

The choice of these parametric distributions aligns with benchmark literature demonstrating their

operational robustness for meteorological and climatic drought indices (McKee et al., 1995; Vicente-Serrano et al., 2010).

Drought Indices Computation

The SPI was calculated by fitting a two-parameter gamma probability distribution to the precipitation records, whereas the SPEI was derived from the monthly climatic water balance ($P-\mathrm{PET}$) using a three-parameter log-logistic distribution. Both indices were subsequently standardized to a standard normal distribution with a mean of zero and a standard deviation of one.

Timescales:

- SPI (1, 3, 6, and 12 months): capturing short-term meteorological anomalies through long-term hydrological deficits.
- SPEI (3 and 6 months): reflecting agricultural drought conditions sensitive to temperature anomalies and evaporative demand fluctuations.

Table 2. Drought severity classification based on standardized index thresholds (WMO, 2012)[1].

Category	SPI/SPEI Range
Mild	-0.5 to -0.99
Moderate	-1.0 to -1.49
Severe	-1.5 to -1.99
Extreme	< -2.0

This standardized classification ensures analytical consistency across regional and temporal comparisons.

1. Marginal distribution fitting: SPI and SPEI series were fitted via maximum likelihood estimation (MLE).
2. Candidate copula families: Gaussian, Student-t, Clayton, and Gumbel copulas were evaluated.
3. Parameter estimation: Dependence parameters (θ) were estimated via MLE.
4. Goodness-of-fit (GoF) evaluation: Model selection was conducted using the Akaike information criterion (AIC), Bayesian information criterion (BIC), and the Kolmogorov–Smirnov (K–S) test.
5. Tail dependence metrics: Lower-tail (λ_L) and upper-tail (λ_U) dependence coefficients were derived to quantify concurrent extreme events.

Joint Probability Formulation:

$P(y \le x, Y \ge p(x)) = C(FX(x), FY(y); \Theta)$

Bivariate Return Period:

$$T=\frac{1}{P(X \le x, Y \le y)}$$

Scenario analysis incorporates a projected warming of $+2^{\circ}C$ combined with a -10% reduction in precipitation to evaluate hydroclimatic sensitivity under climate change.

Copula Modeling Methodology

To characterize the compound behavior of meteorological and agricultural droughts, a copula framework was implemented to link the marginal distributions of SPI and SPEI into a joint multivariate formulation describing their underlying dependence structure. Marginal distributions were estimated via maximum likelihood estimation (MLE). Several parametric copula families—including Gaussian, Student-t, Clayton, and Gumbel—were fitted to capture distinct dependence structures (e.g., symmetric, asymmetric, and tail-heavy behaviors). Dependence parameters (θ for Archimedean copulas and correlation matrices for elliptical copulas) were likewise estimated via MLE.

To ensure rigorous and transparent model selection, performance was appraised across multiple statistical criteria. Specifically, the AIC and BIC were calculated for each candidate copula, with lower values denoting superior relative fit. Additionally, the bivariate Kolmogorov–Smirnov (K–S) test was conducted to evaluate agreement between empirical and theoretical joint distributions. The final selection of the optimal copula family for each climatic zone was determined through concurrent evaluation of AIC, BIC, and GoF test statistics rather than relying on a single metric.

Tail dependence coefficients were computed to quantify the probability of concurrent extreme drought conditions (λ_L for lower-tail dependence and λ_U for upper-tail dependence).

"A parametric insurance payout threshold was established for conditions where both SPI and SPEI fall below -2, corresponding to extreme drought conditions according to the WMO (2012) classification. This threshold ensures that indemnities are triggered exclusively by extreme compound drought events, mitigating premature payouts during mild or moderate fluctuations."

Empirical analysis reveals that such joint events occur approximately once every 14 years in arid zones, corresponding to a joint occurrence probability of approximately 7%."It should be noted that this probability represents the joint probability of simultaneous SPI and SPEI threshold exceedance derived from the fitted copula model, rather than the marginal probability of an individual drought index."

1 The WMO (2012) drought severity classification is a widely recognized international standard and provides a sufficient framework for assessing drought in most scientific studies, enabling comparisons with global and regional research. While developing a region-specific classification for Iran using long-term precipitation and PET data would be valuable, it requires extensive statistical analysis to define SPI/SPEI thresholds corresponding to observed drought impacts. Such a detailed local classification is beyond the scope of the present study, but future research could refine these thresholds for improved regional accuracy. Although this classification has not been formally validated using impact-based observations specific to Iran, it has been widely adopted in previous drought studies across the country.

The joint probability of extreme droughts was extracted directly from the fitted copulas, reflecting the underlying dependence between SPI and SPEI. Within this probabilistic framework, the Expected Annual Loss (EAL) for insurance pricing was calculated as:

$$\mathrm{EAL} = \mathrm{i}\sum \mathrm{Pi} \times \mathrm{Li}$$

where P_i represents the joint occurrence probability of the i-th drought scenario derived from the copula, and L_i denotes the corresponding average insured loss. This formulation integrates both the severity and joint recurrence interval of compound extremes into the parametric model, ensuring that insurance pricing reflects actuarial risk exposure.

The joint occurrence probability (P_i) was derived directly from the fitted copula as the probability that both indices simultaneously breach the defined threshold ($\mathrm{SPI} \le -1.50$ and $\mathrm{SPEI} \le -1.50$), expressed as:

$$P_i = C(F_{\mathrm{SPI}} \mid (-1.50)\, F_{\mathrm{SPEI}}(-1.50))$$

The average loss (L_i) represents the mean proportional yield reduction associated with severe drought and was defined as a fixed proportion of the total insured value, based on historical drought impact assessments in arid zones of Iran. To maintain analytical generality and avoid dependence on farm-scale financial records, L_i was normalized as a proportional yield loss rather than an absolute monetary value, enabling the EAL to quantify relative risk exposure across regions.

Integration into Insurance and Risk Transfer Frameworks

Joint SPI–SPEI probabilities derived from the fitted copula models were integrated as parametric triggers, establishing an empirical foundation for drought risk transfer and actuarial pricing. "Payouts are triggered when both SPI and SPEI fall below -2, consistent with extreme drought conditions under the WMO (2012) classification." Historical analysis using multi-decadal meteorological records from Iran (1981–2020) demonstrates that such compound events occur with an average probability of approximately 7% in arid zones, corresponding to a return period of approximately 14 years.

These joint probabilities were calibrated against observed climatic records across Iran, while agricultural exposure proxies—such as provincial rainfed crop yields and cultivated area statistics—were incorporated to align model outputs with regional agricultural vulnerability. The Expected Annual Loss (EAL), serving as the baseline for premium determination, was computed as:

$$\mathrm{EAL} = \mathrm{i}\sum \mathrm{Pi} \times \mathrm{Li}$$

where P_i denotes the joint probability that $\mathrm{SPI} \le -1.50$ and $\mathrm{SPEI} \le -1.50$, obtained directly from the fitted copula as:

$$P_i = C(F_{\mathrm{SPI}} \mid (-1.50)\, F_{\mathrm{SPEI}}(-1.50))$$

and L_i represents the normalized proportional loss incurred under severe drought conditions. To preserve broad applicability and eliminate site-specific accounting discrepancies, L_i was parameterized as a normalized fraction of total insured exposure, reflecting empirical yield reductions documented during severe droughts in arid and semi-arid regions of Iran. This formulation links insurance premiums directly to compound hydroclimatic hazard probabilities rather than univariately defined thresholds.

In addition to primary pricing applications, copula-derived dependence structures facilitate risk diversification across reinsurance portfolios by identifying regions with weak spatial or inter-index co-dependence, thereby optimizing capital reserve allocations. However, the operational deployment of parametric drought insurance in Iran faces several structural constraints, including spatial gaps in high-quality meteorological monitoring networks, administrative costs associated with index contracts, spatial heterogeneity of crop exposure, and basis risk stemming from divergences between index triggers and realized on-farm financial losses. Future enhancements may mitigate these limitations by incorporating high-resolution satellite-derived climate products and coupling parametric triggers with empirical damage datasets to improve spatial precision and underwriting efficacy.

RESULTS

Drought Characteristics Across Iran

Spatial analysis of SPI and SPEI series revealed pronounced hydroclimatic variability across the country:

- Arid Regions (Central Plateau): Characterized by persistent moisture deficits, with a mean SPI-12 of -0.45 and a mean SPEI-6 of -0.52.
- Semi-Arid Northwest: Displayed substantial interannual variability interspersed with brief pluvial phases, with SPI-12 values ranging from -2.10 to 1.80.
- Caspian Coastal Zone: Characterized by predominantly mild drought anomalies, with SPEI values rarely falling below -1.00.

Temporal evaluations indicate an intensifying trend in drought severity over the final two decades of the study period, driven primarily by sustained warming

Table 3. Regional comparison of copula model performance and lower-tail dependence () between SPI and SPEI across Iranian climatic zones.

Region	Best-Fitting Copula	AIC	Lower-Tail Dependence (λL)	Hydroclimatic Interpretation
Arid Plateau	Clayton	-212.5	0.45	Strong co-occurrence of extremes
Semi-Arid Northwest	Student-t	-198.2	0.32	Moderate compound dependence
Caspian Coast	Gaussian	-120.5	0.10	Weak tail co-dependence
Eastern Desert	Clayton	-210.3	0.48	High compound vulnerability

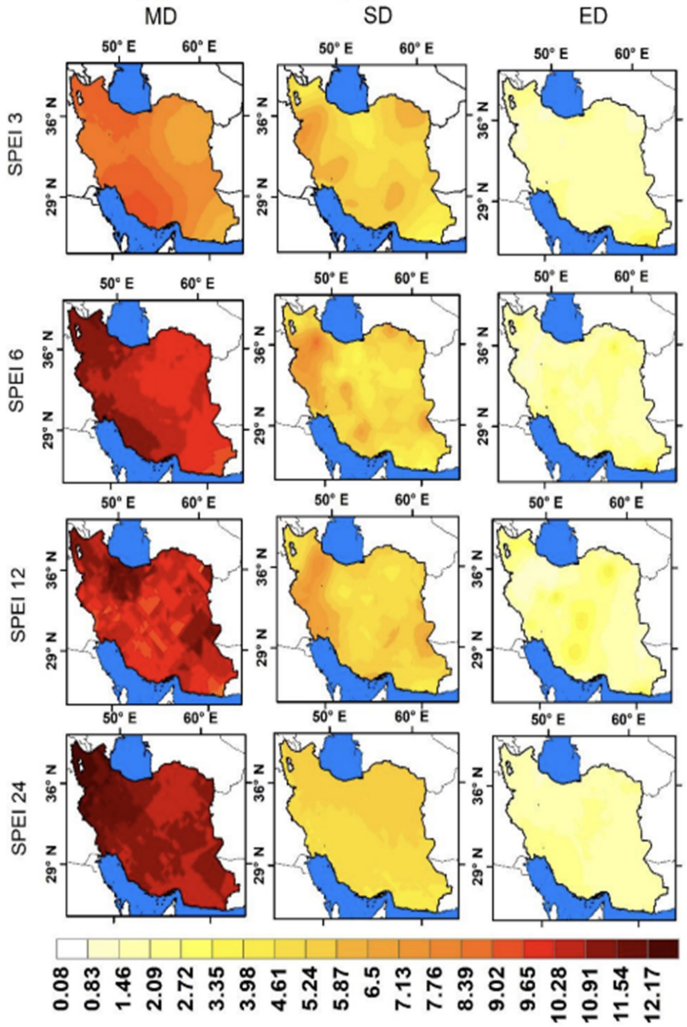


Fig. 2. *Spatiotemporal distribution and multiscalar characterization of drought frequency across Iran based on the Standardized Precipitation Evapotranspiration Index (SPEI).*
The spatial matrix depicts the occurrence frequencies of moderate drought (MD), severe drought (SD), and extreme drought (ED) across four accumulation timescales: SPEI-3 (seasonal moisture anomalies), SPEI-6 (medium-term agricultural stress), SPEI-12 (annual hydrological deficits), and SPEI-24 (extended multi-year drought conditions). The color gradient indicates the percentage frequency of drought months over the observation period. Adapted from Torabinezhad, Zarrin, & Dadashi-Roudbari (2023).

trends and heightened atmospheric evaporative demand.

Copula Model Fitting

- The Clayton copula demonstrated the best overall fit across arid zones ($\mathrm{AIC} = -212.5$, $\mathrm{BIC} = -205.8$), capturing pronounced lower-tail dependence between precipitation deficits and evaporative demand.
- The Student-t copula was selected as the optimal model in semi-arid zones, effectively representing moderate, symmetric tail dependence across SPI and SPEI.
- The Gaussian copula exhibited inferior performance across all evaluated zones, consistently underestimating the joint probability of concurrent extremes.

Tail dependence analysis confirms that compound extreme droughts exhibit significant spatial co-

occurrence across stations within the arid central plateau, highlighting geographic clusters susceptible to severe agricultural failure.

Fig. 3 illustrates the spatial extent and frequency (expressed in percent) of three drought intensity categories—Moderate Drought (MD), Severe Drought (SD), and Extreme Drought (ED)—across different accumulation timescales. The analysis is presented for four distinct Standardized Precipitation Evapotranspiration Index (SPEI) timescales: (a) SPEI-3 (short-term, reflecting seasonal moisture anomalies), (b) SPEI-6 (medium-term, indicating mid-range agricultural moisture stress), © SPEI-12 (long-term, representing annual hydrological deficits), and (d) SPEI-24 (extended-term, capturing multi-year cumulative hydrological drought impacts). The color gradient indicates the proportion of time each grid cell was classified under the respective drought category, ranging from low frequency (yellow) to high frequency (dark red).

(a) Mean Annual Precipitation

The spatial distribution of mean annual precipitation across Iran for the period 2014–2024 demonstrates pronounced climatic heterogeneity. Maximum precipitation values are concentrated along the narrow Caspian Sea coastal plain and the Zagros Mountain range, reflecting moisture advection from the Caspian Sea and orographic enhancement over high terrain. Conversely, the central, eastern, and southeastern regions exhibit persistently low annual totals, characteristic of hyper-arid and arid regimes. This spatial pattern emphasizes structural disparities in water endowment and underscores the acute vulnerability of inland and eastern basins to chronic water scarcity.

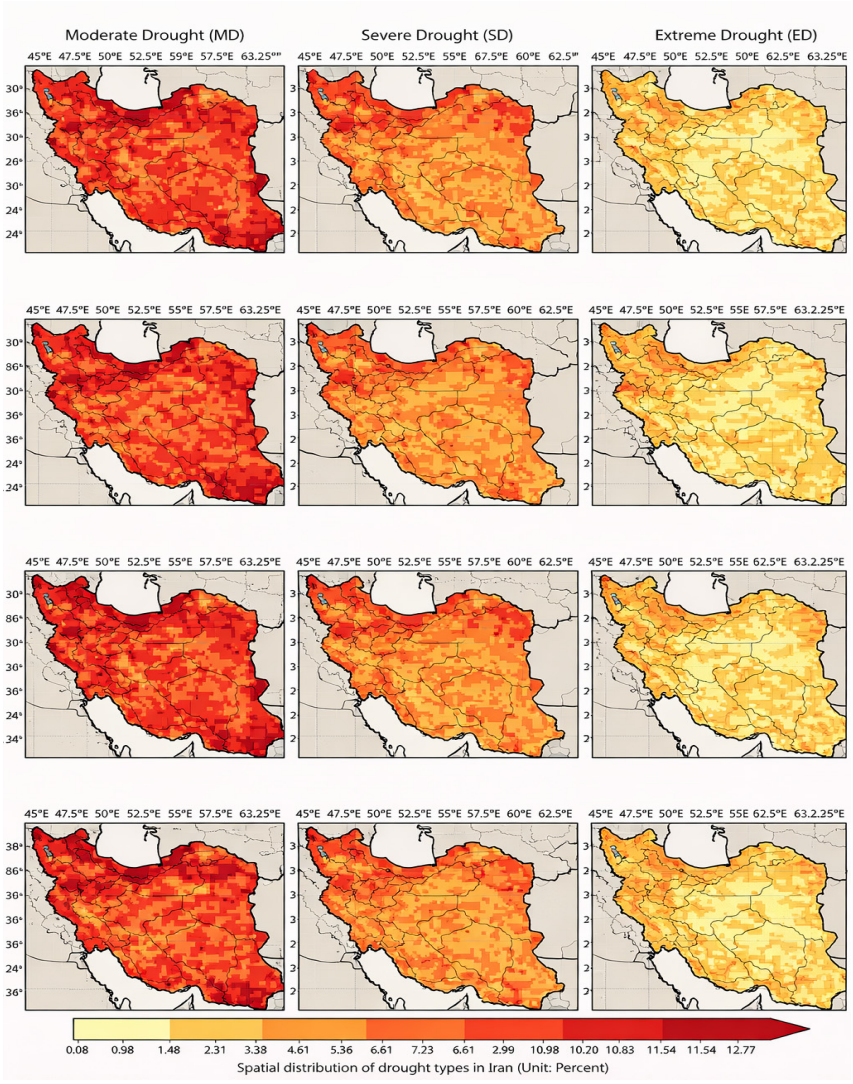


Fig. 3. Spatial Distribution of Drought Types Across Iran

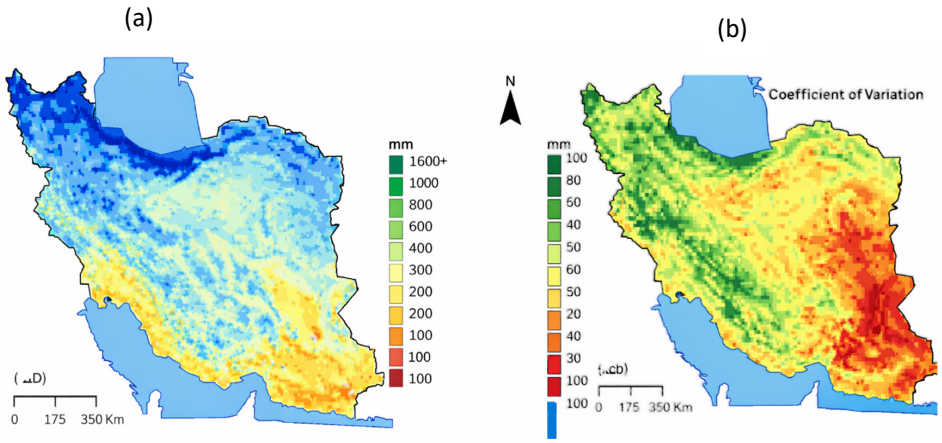


Fig. 4. Spatial distribution of (a) mean annual precipitation and (b) interannual precipitation variability (coefficient of variation) across Iran for the recent period 2014–2024. This period was additionally considered only to illustrate recent hydroclimatic spatial variability and was not included in SPI/SPEI computation, copula fitting, or return-period estimation. The maps illustrate regional contrasts in average precipitation totals and interannual variability, highlighting fundamental hydroclimatic disparities between humid and arid zones.

(b) Interannual Precipitation Variability (Coefficient of Variation)

The coefficient of variation (CV) reveals substantial spatial disparities in precipitation reliability across Iran. Elevated CV values are concentrated across arid and semi-arid zones, particularly in southeastern and eastern Iran, indicating high year-to-year precipitation uncertainty relative to the climatological mean. Conversely, humid zones such as the Caspian littoral and sectors of the northern Zagros exhibit low CV values, indicative of stable annual precipitation regimes. High interannual variability in dry regions exacerbates agricultural risk, complicates reservoir operations, and elevates underwriting risk in crop insurance, highlighting the necessity of integrating variability metrics into regional adaptation planning.

COMPARISON WITH PREVIOUS STUDIES

The dominance of the Clayton copula in arid and hyper-arid basins aligns with prior dependence modeling studies in Iran and comparable dryland settings. Empirical investigations have repeatedly documented strong lower-tail dependence between precipitation deficits and elevated atmospheric water demand in water-limited environments, which increases the likelihood of concurrent extreme droughts (Kheyri et al., 2021).

The superior performance of the Student-t copula in semi-arid zones is consistent with findings indicating moderate symmetric tail dependence in transitional climatic zones, where both severe dry spells and pluvial extremes exhibit coupled behavior. Conversely, the poor fit of the Gaussian copula across all zones confirms its inability to model tail dependence, an established deficiency in multivariate hydroclimatic modeling (Genest & Favre, 2007; Salvadori & De Michele, 2004).

Overall, regional variation in optimal copula structures reflects Iran's underlying hydroclimatic diversity and reinforces the consensus that tail-dependent copulas are necessary for accurate compound drought risk assessment.

Drought Risk and Return Periods

Estimated univariate return periods for extreme drought events ($\mathrm{SPI} < -2.00$ or $\mathrm{SPEI} < -2.00$) are as follows:

- Arid Central Plateau: ~15–25 years (95% CI: 12–28 years)
- Semi-Arid Northwest: ~30–40 years (95% CI: 26–45 years)
- Caspian Coast: >50 years (95% CI: 45–60 years)

Bivariate probability calculations demonstrate that concurrent severe droughts across arid basins have an estimated joint recurrence interval of approximately 20 years ($95\%\ \mathrm{CI}: 16–25\ \mathrm{years}$), highlighting the risk of multi-station synchronous drought events.

Comparison with Historical Droughts in Iran

"Historical drought records indicate major regional drought episodes over the Central Plateau, including those reported during 1972–1973, 1999–2001, and 2018–2019. While events occurring before the analyzed period are used only as historical references, drought episodes within the 1981–2020 dataset provide a more direct basis for comparison with the estimated return periods.". In the Northwest and Caspian regions, severe droughts occurred with lower frequency, consistent with their longer estimated return periods.

Implications for Future Climate Change

Projected shifts in precipitation distribution and

Table 4. Estimated return periods of extreme drought events (SPI/SPEI < -2) across major climatic zones of Iran, including 95% confidence intervals derived from copula-based joint probability modeling.

Region	SPI/SPEI < -2	Return Period (yrs)	95% Confidence Interval (yrs)
Arid Plateau	0.07	14–20	12–28
Semi-Arid NW	0.04	25–35	26–45
Caspian Coast	0.02	50+	45–60

thermal regimes under future climate pathways suggest an intensification in both the frequency and duration of severe droughts, particularly across arid and semi-arid zones. Consequently, return periods estimated from historical baselines are projected to contract, indicating elevated compound risk in upcoming decades. Incorporating non-stationary projections into risk modeling is essential for water resource planning, agricultural adaptation, and parametric insurance calibration.

Implications for Agricultural Insurance

The joint probability of SPI and SPEI extremes provides a quantitative framework for designing index-based agricultural insurance. Calibrated using Clayton copula parameters, an index trigger can be constructed to disburse payouts when $\text{SPEI-6} \leq -1.50$ and $\text{SPI-12} \leq -1.50$ occur concurrently, mitigating financial losses in vulnerable crop-producing provinces.

For example, in Yazd and Kerman provinces, historical agronomic data indicate that severe compound droughts reduce rainfed wheat yields by 20%–35% on average. Calibrating insurance triggers to these joint thresholds ensures timely indemnification that covers a substantial fraction of anticipated farm revenue losses.

Economic Analysis

Assuming a baseline rainfed wheat yield of $2.5\ \text{tons/ha}$ and a reference market price of $\text{USD}250\ \text{per ton}$, a 30% yield deficit translates to an average loss of $\text{USD}187.50\ \text{per hectare}$. An index-based insurance contract calibrated via copula models can provide coverage aligned with this expected loss, offering a cost-effective mechanism for risk transfer. By dampening farm income volatility, such parametric instruments bolster financial resilience and sustain agricultural investments under changing climatic conditions.

DISCUSSION

The findings of this study underscore the value of coupling multiscale drought indices (SPI and SPEI) with copula modeling to establish an empirical framework for drought risk assessment in Iran. The following subsections interpret these results in the context of regional vulnerability, statistical dependence, insurance design, climate adaptation, methodological constraints, and future research directions.

Comparison with Previous Drought Studies

The dependence structures and compound drought risk patterns identified in this study corroborate and extend previous hydroclimatic assessments in Iran. Earlier investigations focused primarily on univariate drought indices, trend detection, and the spatial distribution of precipitation-based indicators (Farajzadeh & Ahmadian, 2014), emphasizing the baseline vulnerability of arid zones such as the Central Plateau and eastern Iran.

The marked lower-tail dependence between SPI and SPEI observed in arid basins agrees with empirical evidence indicating that extreme droughts in water-limited regions are exacerbated by the simultaneous occurrence of rainfall deficits and elevated atmospheric water demand (Hosseini et al., 2021). Comparable asymmetric dependence structures have been documented in copula-based drought studies across climatically similar drylands in Turkey and Pakistan, confirming the wider regional applicability of these results.

Conversely, the weaker dependence identified along the humid Caspian coastal zone reflects more stable precipitation regimes and lower sensitivity to temperature-driven evaporative anomalies. By explicitly modeling joint SPI–SPEI behavior via copula theory, this study moves beyond linear correlation approaches, delivering a probabilistic characterization of compound drought risk suited for hydroclimatic planning and parametric insurance design.

Regional Risk Variation

The results reveal significant spatial heterogeneity in drought risk across Iran's climatic zones. Arid and semi-arid environments, including the Central Plateau and Eastern Desert, experience more frequent and acute droughts than the humid northern coastal provinces. Historical records indicate that annual precipitation deficits during extreme drought years range between 15% and 30% across these arid zones, with SPI-12 and SPEI-6 values frequently dropping below -1.50. In provinces such as Yazd and Kerman, wheat yields have historically declined by $20\%–35\%$ during such episodes.

In the semi-arid northwest, drought recurrence is lower, though interannual variability remains high.

Return period analyses indicate that extreme droughts recur approximately every $14–20$ years in the Central Plateau, $25–35$ years in the northwest, and exceed 50 years along the Caspian littoral.

Policy Implications

These spatial disparities highlight the need for tailored regional drought mitigation policies. In arid and semi-arid provinces, strategic priority should focus on introducing drought-tolerant crop cultivars, modernizing pressurized irrigation infrastructure, and deploying parametric crop insurance. Conversely, in humid northern basins, policy should prioritize watershed conservation, soil moisture management, and early-warning hydroclimatic monitoring. Integrating spatially differentiated interventions into national resilience frameworks will optimize public capital allocation, safeguard crop production, and reduce systemic vulnerability to compound extremes.

Tail Dependence and Statistical Implications

The prominent lower-tail dependence between SPI and SPEI across arid basins indicates an elevated probability of concurrent meteorological and agricultural droughts. Such compound occurrences amplify agronomic damage, particularly in rainfed farming systems. Formulating this interaction via copulas—especially the Clayton family—provides insurers and water authorities with a probabilistic tool for evaluating compound events rather than assessing isolated univariate risks.

Conversely, Student-t copulas provide a superior fit across semi-arid zones characterized by symmetric tail co-dependence. These findings demonstrate that multivariate models must be selected based on local hydroclimatic conditions. Regionally differentiated model calibration ensures statistical rigor and operational utility in risk management.

Implications for Insurance and Financial Risk Management

A central contribution of this study is its operational applicability to parametric agricultural insurance design. By explicitly modeling the joint distributions of precipitation deficits and atmospheric evaporative demand via SPI and SPEI, the copula framework enables probabilistic quantification of compound risk. Compared to traditional single-index schemes, joint probability modeling establishes an objective basis for trigger calibration and loss probability estimation, thereby reducing basis risk and improving contract transparency.

To illustrate this application, consider an index contract structured for arid farming zones such as Yazd and Kerman. Agronomic records confirm that severe droughts in these provinces result in rainfed wheat losses of $20\%–35\%$. “Applying our empirical results, a dual trigger requiring both SPI and SPEI values below -2 corresponds to a copula-derived joint occurrence probability of approximately 7%, representing an annual recurrence interval of roughly 14 years. This probability reflects the simultaneous occurrence of extreme drought conditions in both indices rather than the individual exceedance probability of either SPI or SPEI. In underwriting terms, this value defines the expected annual payout frequency for the proposed parametric insurance framework.”

Such probabilistic parameters provide an actuarial foundation for estimating Expected Annual Losses and pricing risk premiums without requiring localized loss adjustment or historical claims adjustments. More broadly, the framework bridges hydroclimatic modeling and insurance underwriting, offering a scalable, data-driven methodology for managing drought risks across arid agricultural systems.

Economic Analysis

Assuming a baseline wheat yield of 2.5 tons/ha and a market valuation of $\text{USD}250$ per ton，a 30% yield contraction results in an estimated loss of $\text{USD}187.50$ per hectare. Parametric insurance structured around copula triggers can provide coverage matching this loss exposure, stabilizing farm revenues against climatic variability. Furthermore, copula-based spatial dependence modeling aids reinsurance structuring by quantifying inter-regional correlation, enabling efficient capital allocation and actuarial diversification.

Nonetheless, operational deployment in Iran requires addressing several institutional hurdles, including meteorological station network density, digital payout infrastructure, and farmer participation. Addressing these constraints will necessitate coordinated initiatives among government ministries, domestic insurers, and international technical bodies.

Climate Change and Long-Term Implications

The findings underscore the role of temperature-driven evaporative demand in escalating drought hazard, highlighting the utility of SPEI in monitoring water stress under progressive climate warming. Even during years with near-average precipitation, elevated temperatures can accelerate evapotranspiration, triggering “invisible droughts” that univariate precipitation indices fail to identify.

For example, across the Central Plateau (e.g., Yazd), a projected $+2^{\circ}\text{C}$ increase in mean surface temperature—holding precipitation constant—depresses the SPEI-6 index by approximately 0.5 units, shifting baseline conditions from moderate to severe

drought. Such shifts could induce additional wheat yield contractions of $15\%–20\%$ relative to historical drought baselines, escalating regional food security risks.

Furthermore, climate warming introduces statistical non-stationarity into hydroclimatic time series, weakening historical precipitation–temperature relationships. Integrating downscaled CMIP6 or CORDEX climate projections into copula models will enable forward-looking simulations of coupled warming and drying trends. These projections can inform proactive adaptation strategies, including irrigation scheduling, crop portfolio optimization, and parametric insurance recalibration.

Methodological Limitations and Future Prospects

Despite its analytical contributions, this study is subject to several methodological limitations. The primary constraint is the limited spatial density of high-resolution soil moisture and flux measurements, which affects the precision of empirical PET and SPEI estimations. Additionally, the copula framework assumes statistical stationarity across the 1981–2020 baseline, an assumption that may be compromised by ongoing climate change. Spatial data sparsity across desert interiors also introduces interpolation uncertainties.

Future research could integrate copula dependence modeling with supervised machine learning algorithms (e.g., Random Forests, Gradient Boosting Machines, or neural networks) to better capture non-linear and non-stationary hydroclimatic interactions. Merging these statistical models with satellite-derived products (e.g., MODIS NDVI or SMAP soil moisture) would enhance spatial and temporal granularity. Finally, linking copula-derived drought probabilities with dynamic crop growth models and macroeconomic loss functions would improve the translation of hydroclimatic hazards into actionable financial metrics.

In summary, copula-based modeling provides a rigorous, interdisciplinary framework for compound drought risk evaluation. By linking atmospheric science, risk modeling, and financial adaptation, it supports a strategic shift from reactive disaster relief toward proactive climate risk management across Iran's agricultural sector.

CONCLUSION

This study provides a quantitative assessment of drought risk across Iran by coupling copula dependence modeling with multiscale drought indices (SPI and SPEI). This approach improves the analytical precision of drought hazard modeling while linking climatological findings with operational strategies for agricultural management and risk transfer.

The empirical findings confirm that bivariate copulas—particularly the Clayton and Student-t families—accurately capture non-linear tail dependence between precipitation deficits and atmospheric evaporative demand. Capturing this joint behavior is critical for understanding the co-occurrence of severe drought anomalies and designing targeted risk mitigation instruments. The strong lower-tail dependence observed across arid and semi-arid regions demonstrates that meteorological and agricultural droughts frequently occur concurrently, compounding economic and agronomic damages.

Spatially, the analysis highlights significant hydroclimatic heterogeneity across Iran. The Arid Central Plateau and Eastern Desert experience frequent, severe droughts with estimated bivariate return periods of $14–20$ years, whereas the humid Caspian littoral exhibits greater stability, with return intervals exceeding 50 years. These disparities highlight the necessity of implementing regionally tailored drought management frameworks rather than uniform national policies.

Beyond its climatological contributions, this study provides an actuarial framework for parametric agricultural insurance design. By quantifying the joint probability of extreme drought events, copula models establish an objective baseline for trigger calibration and premium calculation. Parametric instruments reduce administrative overhead, eliminate loss adjustment delays, and enhance contract transparency through objective index triggers. For underwriters and reinsurers, this framework enables probabilistic risk pricing, capital reserve optimization, and spatial risk diversification.

At the policy level, integrating joint drought probabilities into irrigation planning, agricultural development, and rural credit programs can strengthen community resilience. Furthermore, the methodology facilitates transboundary risk sharing and technical collaboration across climatically linked neighboring states, including Pakistan, Türkiye, and Afghanistan.

Future investigations should address the limitations identified herein by incorporating high-resolution satellite observations, dynamic crop simulation tools, and downscaled CMIP6 climate projections to account for statistical non-stationarity. Coupling copula dependence structures with machine learning algorithms could also enable real-time forecasting and dynamic premium adjustments.

Institutionally, establishing a national drought risk observatory and a dedicated parametric insurance data platform would foster collaboration among meteorological agencies, insurance providers, and academic institutions. Ultimately, this research bridges climate modeling and financial resilience, providing an empirical foundation for proactive, adaptive drought risk management in Iran and similarly vulnerable dryland regions.

GLOSSARY OF TECHNICAL TERMS

Term	Definition
Copula	A multivariate cumulative distribution function with uniform marginal distributions on $[0,1]$, used to link univariate marginals into a joint distribution and model dependence structures between variables (e.g., SPI and SPEI).
Standardized Precipitation Index (SPI)	A standardized meteorological drought index based on long-term precipitation series fitted to a parametric distribution (e.g., gamma), quantifying precipitation anomalies across accumulation timescales (1, 3, 6, 12, and 24 months).
Standardized Precipitation Evapotranspiration Index (SPEI)	A multiscalar drought index based on the climatic water balance (P − PET), incorporating both precipitation and temperature-driven potential evapotranspiration.
Potential Evapotranspiration (PET)	The theoretical rate of evapotranspiration from a standardized vegetative surface with adequate moisture, computed here using the FAO-56 Penman–Monteith formulation.
Return Period (T)	The expected average recurrence interval between occurrences of a hydroclimatic event exceeding or breaching a defined intensity threshold.
Tail Dependence (λ_L, λ_U)	A copula-derived asymptotic metric measuring the conditional probability of concurrent extreme events occurring in the lower or upper tails of joint distributions.
Parametric (Index-Based) Insurance	An insurance mechanism where financial disbursements are automatically triggered when a pre-agreed environmental parameter (e.g., SPI ≤ -1.50) is reached, eliminating on-site loss adjustment.
Joint Probability	The statistical probability of two or more random variables simultaneously satisfying defined threshold conditions (e.g., $P(\text{SPI} \leq -1.50 \cap \text{SPEI} \leq -1.50)$), quantified via copula functions.
Arid/Semi-Arid Regions	Hydroclimatic regimes characterized by low annual precipitation, high evaporative demand, and elevated coefficient of variation, representing the highest baseline drought vulnerability.
Marginal Distribution	The univariate probability distribution of an individual random variable within a multivariate framework, estimated prior to copula coupling.
Hydroclimatic Risk	The expected likelihood and magnitude of adverse socioeconomic or environmental impacts arising from extreme climate-water interactions.
Non-Stationarity	The property of a hydroclimatic time series wherein statistical properties (such as mean, variance, and dependence structure) vary over time due to natural variability or anthropogenic climate change.
Lower-Tail Dependence (λL)	The asymptotic measure quantifying the likelihood that both drought indices concurrently reach extreme negative anomalies (severe compound drought).
Maximum Likelihood Estimation (MLE)	An estimation method that determines distribution and copula parameters by maximizing the likelihood function of observed sample data.

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CONFLICT OF INTEREST

The author(s) declares that there is no conflict of interest regarding the publication of the registered research. Furthermore, ethical considerations including plagiarism, informed consent, misconduct, fabrication and/or falsification of data, duplicate publication, and also Journal Policy on Artificial Intelligence Use have been fully observed by the authors.

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