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Trends in Meteorological Drought in Iran Using the SPI Index and Mann-Kendall Test: A Comprehensive Review

Aliyeh Keshavarz

Department of Natural Resources, Isfahan University of Technology, Isfahan, Iran.

* Correspondence: a.keshavarz@na.iut.ac.ir

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Abstract

Drought is one of the most significant climatic hazards in Iran, occurring with varying intensity and frequency due to the country's wide geographical and climatic diversity. Investigating drought trends can provide valuable insights for sustainable water resource management and for reducing vulnerability in the environmental and agricultural sectors. This review systematically evaluates research on meteorological drought trends in Iran, focusing on the Standardized Precipitation Index (SPI) and the non-parametric Mann-Kendall (MK) test. Thirteen relevant articles were analyzed, and SPI data from 1951 to 2019 were reviewed. The review indicates that drought severity in Iran has generally increased over the past decades, particularly in arid and semi-arid regions. Northern Iran and the Caspian Sea region have not experienced significant changes, whereas the southern, southwestern, southeastern, eastern, and central regions have shown pronounced drought trends. The drought pattern in Iran is heterogeneous: northern regions display a slow trend with more variable and less predictable behavior, while the eastern and southern arid regions exhibit an increasing intensity and duration of drought periods. This study underscores the importance of strategic planning for climate adaptation and the improvement of water resource management.

Keywords: Meteorological drought; SPI; Mann-Kendall test; Trend analysis; Iran

1.0 Introduction

Drought is a well-known environmental disaster that has attracted the attention of agricultural scientists, geologists, hydrologists, meteorologists, ecologists, and environmentalists (Mishra & Singh, 2010). Globally, drought affects more people than any other natural disaster (Isfahani et al., 2022). Droughts occur in nearly every climate zone, including areas of high and low rainfall, and are primarily caused by a long-term decrease in precipitation over a season or year (Mistry et al., 2023). It can be viewed as a primarily climatic phenomenon characterized by an abnormal decline in precipitation (Masoudi & Afrough, 2011). Drought represents a prolonged period of water shortage that disrupts typical growth cycles, product development, and the usual interactions between humans and the environment (Mahmoudi et al., 2019). Drought is generally categorized into four main types: meteorological, agricultural, hydrological, and socio-economic. Meteorological drought is defined as a lack of precipitation over a specific area for a period of time, and precipitation is commonly used as a key metric for its analysis (Mishra & Singh, 2010).

Several review studies have addressed drought. For example, Mishra and Singh (2010) discuss drought definitions and provide an overview of its basic concepts, classifications, indicators, historical occurrences using paleoclimatic studies, and relationships with large-scale climate phenomena. Mistry et al. (2023) examine the two most widely used drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evaporation Index (SPEI), evaluating their advantages and limitations. However, factors such as global warming, climate change, increasing water demands, deforestation, soil erosion, and geographic location can influence the selection of the most appropriate method for assessing drought. Eslamian et al. (2017) provide a comprehensive overview of drought indicators, discussing their respective strengths and weaknesses to inform effective policymaking. Madani et al. (2016) introduce the concept of "water bankruptcy" and argue that drought in Iran is not only a result of climate change but also a consequence of mismanagement of water resources, overexploitation, and unsustainable agricultural practices. The authors emphasize the extensive socio-economic consequences and highlight the need for improved water productivity and management reforms.

Due to Iran's diverse geographical and climatic conditions, drought is a frequent hazard with high variability. It is one of the most significant environmental hazards in the country, exacerbated by low precipitation. Beyond its short-term effects, drought poses a threat to the sustainable development of Iran's socio-economic sectors (Noorisameleh et al., 2021). Regions characterized by arid and semi-arid climates are more severely affected by climate change. Iran is situated in a water-scarce region, and its agriculture is heavily climate-dependent, making it highly vulnerable (Zakeri et al., 2019). Historically, Iranians have had to cope with dry conditions and a range of drought-related social, economic, and environmental challenges.

The country's topography contributes to climatic diversity. Large mountain ranges, including the Alborz and Zagros, and vast water bodies, such as the Persian Gulf, Caspian Sea, and Oman Sea, influence precipitation patterns. Westerly air masses are blocked by the Zagros Mountains, resulting in above-average precipitation in western Iran, while the eastern regions remain semi-arid to hyper-arid. The Alborz Mountains condense moisture from the Caspian Sea, creating sub-humid and humid conditions along its southern coast. Southern coastal areas along the Persian Gulf and Oman Sea are also affected by airflow from these water bodies (Nouri & Homaee, 2020). Drought has historically degraded agricultural productivity and farmers' living standards. Water and rainfall shortages significantly reduce cultivated areas and food production; for instance, the 1998 drought destroyed nearly 200,000 hectares of horticultural land in Iran. Precipitation is highly variable both spatially and temporally: regions south of the Caspian Sea may receive up to 2,000 mm annually, while central and eastern areas receive less than 50 mm. Most precipitation falls during winter and autumn due to humid westerly Mediterranean winds (Raziei et al., 2009).

The Standardized Precipitation Index (SPI), introduced by McKee et al. (1993), is widely used for drought assessment due to its flexibility in characterizing droughts across multiple timescales and climates, and it has been applied by many researchers worldwide (Sharafi et al., 2022). In Iran, SPI is a commonly used tool for monitoring droughts (Noorisameleh et al., 2021). To detect monotonic trends in drought data, the Mann–Kendall (MK) trend test, a non-parametric method initially proposed by Mann (1945) and later refined by Kendall (1948), is applied. These methods provide a robust framework for analyzing temporal drought variability. The MK test is particularly suitable for investigating drought trends over time due to its non-parametric nature, which does not require assuming a specific distribution (Zhai & Feng, 2009).

Given the importance of drought studies in a predominantly arid and semi-arid country like Iran, this review aims to synthesize existing research on drought based on the SPI index and MK test, identify trends, and highlight research gaps. Understanding these trends is crucial for strategic planning and climate adaptation efforts.

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2.0 Methodology

For this review, articles related to drought trends were systematically examined using the Standardized Precipitation Index (SPI) and the Mann–Kendall test. Papers published between 2011 and 2022 were considered. The Google Scholar database was searched using keywords such as "drought," "SPI," "Mann-Kendall," "trend analysis," and "Iran." A total of 13 peer-reviewed articles were selected based on their relevance to the objectives of this study. Selected articles were required to analyze drought trends using SPI and/or the Mann–Kendall test and to provide sufficient information regarding the time frame, region, and methodology. Extracted data included the study area, time period, SPI calculation method, and trend analysis results, which were compiled to provide an overview of drought trends in Iran.

2.1 Study Area

Iran has an area of approximately 1.648 million km² and a population of around 85 million. It is located in southwestern Asia, between latitudes 25.05°–39.78°N and longitudes 44.08°–63.30°E, and is bounded by Turkey, Iraq, Oman, the Persian Gulf, Afghanistan, Pakistan, Turkmenistan, Azerbaijan, Armenia, and the Caspian Sea (Figure 1). The mean altitude of the country is 2,787.5 m. The mean annual precipitation and potential evapotranspiration are 361.55 mm/year and 1,806.41 mm/year, respectively, and the mean annual temperature is 17.85 °C. Most of Iran experiences hyper-arid (HyA), arid (Ar), and semi-arid (SeA) climate conditions (Ghasemi et al., 2022). Drought is one of the most common disasters in Iran, causing significant loss of life, serious economic, environmental, and social impacts, and substantially hindering the development process (Sayari et al., 2013).

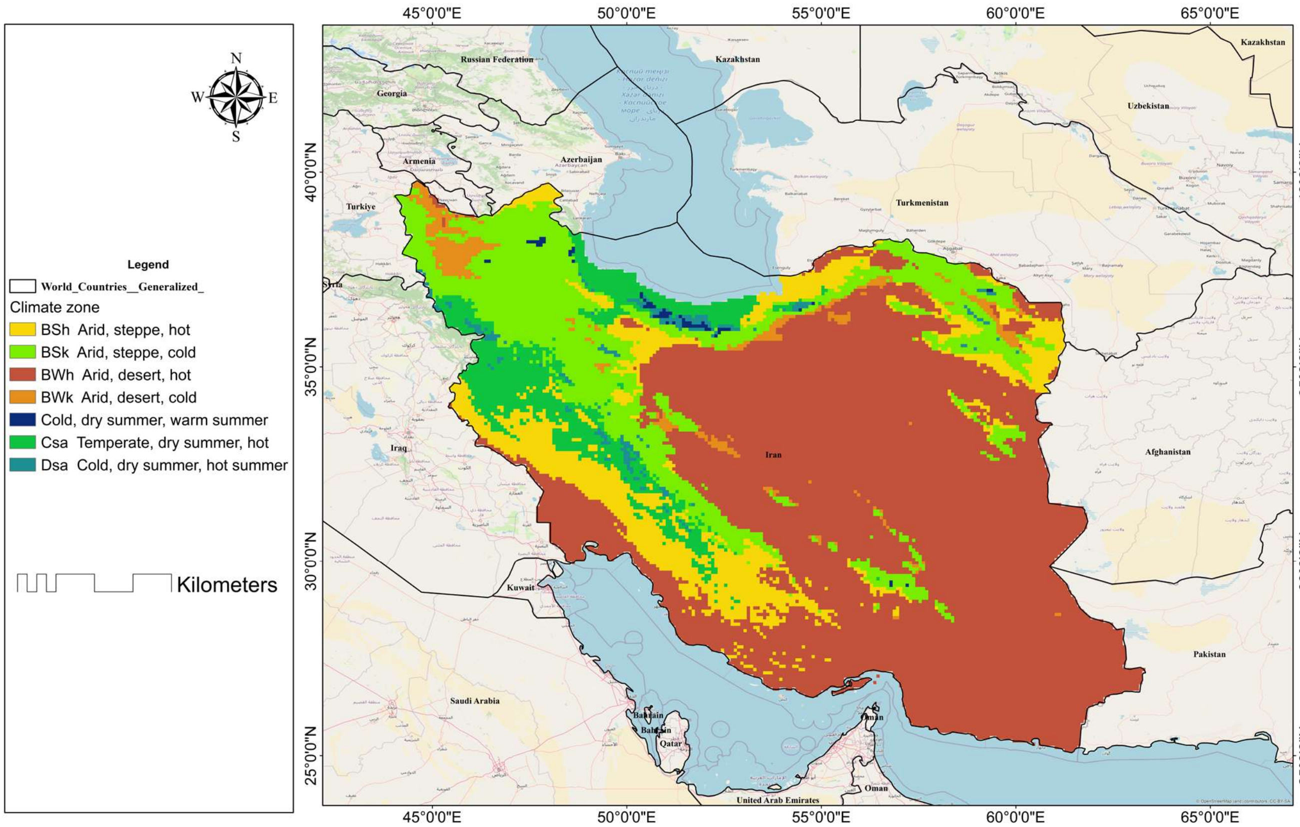

Figure 1: Geographical location and topographical map of Iran

2.2 Standardized Precipitation Index (SPI)

The drought index is an important tool for monitoring and assessing drought because it simplifies the complex interrelationships among various climate and climate-related parameters. Indices facilitate communication of climate anomalies to diverse user groups and allow scientists to quantitatively assess these anomalies in terms of intensity, duration, frequency, and spatial extent (Tabari et al., 2012). The Standardized Precipitation Index (SPI) offers several advantages over other indices due to its simplicity and flexibility (Rousta et al., 2020). A key benefit of SPI is that its interpretation is spatially invariant, and it can be calculated over a wide range of timescales, from 1, 2, 3,…, 48,… up to 72 months. Short timescales of SPI (e.g., 3 or 6 months) are typically used for agricultural applications, whereas longer timescales are applied in water resource management and hydrological studies. To provide a comprehensive view of a drought event, multiple SPIs across several timescales (e.g., 1, 3, 6, 9, 12, and 24 months) should be considered simultaneously (Moghbeli et al., 2020).

What constitutes a "drought" in a tropical region might be considered "heavy rainfall" in a desert area. The SPI allows regions to be compared against their historical rainfall records, producing a normalized value that describes current precipitation conditions. This normalization enables rainfall comparisons across different locations (Javanmard et al., 2017). The SPI is a valuable tool for early drought detection and has been recommended by the World Meteorological Organization as a measure of meteorological droughts (Golian et al., 2015). Previous studies highlight that SPI is simple yet effective for drought monitoring: it requires relatively limited input data and is highly sensitive to precipitation fluctuations, making it a reliable indicator of changes in drought severity. For example, Mahmoudi et al. (2019) compared seven precipitation-based drought indices in Iran using meteorological data from 41 stations between 1985 and 2013, finding that SPI was the most suitable index for drought studies in the country.

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2.3 Mann–Kendall test

This method is commonly and extensively applied in the trend analysis of hydrological and climatological series. Among its advantages is its suitability for time series that do not follow a specific statistical distribution. Another benefit is its minimal sensitivity to extreme values observed in some time series. In this context, the null hypothesis assumes randomness and the absence of trends in the data series; rejecting the null hypothesis indicates the presence of trends in the data (Salahi et al., 2016). Studying drought trends is particularly important because it is directly related to the availability of food and water resources, which can become scarce during drought events (Zakeri et al., 2019). Investigating drought trends contributes to a better understanding of drought conditions and facilitates more effective management of their adverse impacts (Ghasemi et al., 2022).

The Mann–Kendall (MK) test has demonstrated good performance in trend detection in hydrology and has been widely applied in drought studies (Golian et al., 2015). For analyzing precipitation time series, as well as drought intensity and duration, the non-parametric MK test was employed. According to Zhai and Feng (2009), this test offers several advantages: (1) the data do not need to conform to a particular distribution, allowing for extreme values; (2) missing values are permissible; (3) rankings rather than numerical values are used, which enables the inclusion of 'trace' or 'below detection limit' data by assigning them a value smaller than the lowest measured value; and (4) it is not necessary to specify whether the trend in a time series is linear.

2.4 Limitations of SPI and Mann–Kendall Approaches

The Standardized Precipitation Index (SPI), despite its wide applicability and advantages, has several limitations. Mishra and Singh (2010) reported two major limitations in using SPI for drought monitoring: the length of rainfall records and the default assumption of a gamma probability distribution function for rainfall data. According to Nadi and Shiukhy Soqanloo (2023), previous research indicates that, because SPI values are based on fitting a probability distribution function to rainfall data, the choice of distribution affects the calculated SPI values. In dry climates, the large number of rain-free months may result in short-term SPI values that are not normally distributed and exhibit strong bias. High skewness and inadequate fit of the gamma distribution to rainfall data can cause SPI values to inaccurately reflect drought conditions, producing significant errors. Using the gamma distribution to fit annual precipitation data may also displace drought classifications. Additionally, Shahabfar and Eitzinger (2013) noted that SPI calculation requires complete time series data. A record length of at least 30 years is recommended because drought index classes are calibrated to that period and allow intercomparison across sites with different climates.

Despite the widespread use of the Mann–Kendall (MK) test for analyzing climatic and hydrological data trends, this method also has limitations. By default, the MK test assumes that data are independent and identically distributed. However, environmental data often exhibit autocorrelation, which can obscure real trends (Blain, 2014). Seasonality or spatial variability can violate the assumption of homogeneity of distribution. Furthermore, incomplete or sparse data due to missing values or irregular sampling can reduce the accuracy of results. Although the MK test is non-parametric and does not require normally distributed data, autocorrelation and seasonality can still affect the validity of its results. Therefore, it is essential to account for these limitations and, where necessary, apply corrective methods to ensure valid trend detection (Collaud Coen et al., 2020).

3.0 Review of Studies

3.1 National Studies

Several national-level studies have examined drought trends in Iran using the SPI and Mann–Kendall tests (Table 1). The results consistently indicate increasing drought severity, particularly in arid and semi-arid regions, while some humid regions (e.g., the Caspian Sea rim) show no significant trends. Notable drought events, such as those from 1998 to 2001, coincided with La Niña phases, highlighting the influence of large-scale climate variability.

Table 1. Summary of national-level drought studies in Iran

Study	Period and data	Method	Key findings
(Bari Abarghouei et al., 2011)	1975–2005, 42 synoptic stations	SPI (3–24 months), MK test	Increasing drought in SE, W, SW; no significant trend in Caspian & NE regions
(Golian et al., 2015)	1980–2013	SPI (6 months), MK test	Significant drying in N, NW, Central Iran; no significant trend in E, severe drought 1998–2001 (~80% of the country).
(Bazrafshan, 2017)	1951–2014	SPI (12 months), MK test	Temperature ↑, precipitation ↓; drought severity ↑ in most stations.
(Zakeri et al., 2019)	-	SPI, MK test	Positive SPI trend in N & NW; negative in W & Central Iran.
(Nouri & Homaee, 2020)	1966–2012	SPI (3–24 months), MK test	Dry conditions ↑; most severe droughts 1998–2012; spring short-term droughts ↑.
(Noorisameleh et al., 2021)	1989–2018, 44 stations	SPI(1 months), MK test	Winter drought intensity slightly ↑; spring & autumn droughts ↑ in NW, Caspian, Central plateau.
(Bazrafshan et al., 2019)	1996–2014	SPI (3–48 months), MK test	Drought ↓ in cold/dry climates; ↑ in hot/dry climates.
(Khanmohammadi et al., 2022)	1960–2014	SPI(1-3 months), MK test	SPI trend downward in most stations.
(Sharafi & Ghaleni, 2022)	1969–2019, 43 stations	SPI (12 months), MK test	Increasing drought in winter & summer across most climates.
(Sharafi et al., 2022)	1969–2019, 43 stations	SPI (1–48 months), MK test	Short-term SPI trend not significant; long-term (SPI-48) trend significantly negative; drought severity ↑ over decades.

Abbreviations of geographic directions: N = North; NE = Northeast; E = East; SE = Southeast; S = South; SW = Southwest; W = West; NW = Northwest

3.2 Regional Studies

Studies focused on regional drought patterns in Iran have largely confirmed intensifying drought conditions (Table 2). Across southern and arid regions of Iran, research reports increasing drought severity and decreasing precipitation, with spatially variable but consistently negative SPI trends. These investigations reveal that the severity, duration, and frequency of droughts vary significantly across different climatic zones. The regional analyses also underscore the role of topography, local climate variations, and human activities such as water resource management and land use changes in shaping these patterns. Collectively, these studies highlight the need for location-specific adaptation strategies to mitigate the socio-economic and environmental impacts of drought across Iran.

Table 2. Summary of regional-level drought studies in Iran

Study	Study Area	Period	Method	Key findings
(Dashtpagerdi et al., 2015)	25 stations in arid &semi-arid regions	1975–2005	SPI (3–24 months), MK test	~50% stations showed significant drought intensity trends; severity increased in most stations.
(Zarei, 2019)	16 stations, southern Iran	1980–2014	SPI (3 months), MK test	Negative SPI trend on winter/annual scales; drought intensified, arid areas expanded.
(Zarei & Eslamian, 2017)	Southern Iran	1985–2013	SPI (12 months), MK test	Precipitation declined in spring/winter; no significant trend in SPI-12.

4.0 Discussion and Conclusions

The combined use of the Standardized Precipitation Index (SPI) and the Mann–Kendall (MK) test provides a robust framework for monitoring and analyzing drought trends. While the SPI measures the severity and frequency of droughts, the MK test evaluates the direction and significance of their temporal trends. The findings of this study indicate that drought severity in Iran has generally increased over past decades, particularly in arid and semi-arid regions. National and regional studies support this trend. Northern Iran and areas near the Caspian Sea have not experienced significant changes, whereas the southern, southwestern, southeastern, eastern, and central regions have been most affected. Overall, the drought trend in Iran is heterogeneous: northern regions show a slow trend, while eastern and southern arid regions exhibit increasing intensity and duration of droughts. Zakeri et al. (2019) argued that the primary driver of the observed negative drought trends in western and central Iran is the obstruction of western low-pressure systems by the Alborz and Zagros mountain ranges.

The study also demonstrates that the severity and frequency of droughts in Iran are significantly linked to large-scale climate phenomena. According to Golian et al. (2015), the most severe drought occurred between 1998 and 2001, affecting approximately 80% of Iran. This period coincided with a prolonged La Niña phase in the Pacific Ocean, which played a key role in climate variability. Similarly, Nouri and Homaee (2020) found that the most severe and prolonged droughts occurred between 1998 and 2012, and their overlap with frequent La Niña events amplified both drought intensity and persistence. These findings highlight the importance of examining interactions between local climate factors and large-scale atmospheric phenomena in drought management.

Globally, severe droughts in recent years have affected large areas across Europe, Africa, Asia, Australia, South America, Central America, and North America (Mishra & Singh, 2010). Rising demand for scarce water resources has increased pressure on food production and security. Overexploitation of groundwater further exacerbates these challenges. Thus, integrated water resource management programs, supported by adaptive strategies, are essential to mitigate the impacts of water scarcity. Comprehensive analyses of drought characteristics are also needed to identify the most effective statistical parameters for monitoring observed trends (Dashtpagerdi et al., 2015).

In Iran, the intensification of drought events is particularly pronounced in arid and semi-arid regions, posing serious challenges to water resource management. Arid zones are prone to rapid geomorphological changes even under modest environmental shifts (Tabari et al., 2012). Iran's arid and semi-arid regions, covering over 90% of the country, already face severe water limitations (Dashtpagerdi et al., 2015). Further research is needed to predict SPI trends at different temporal scales and across diverse climatic zones. Policymakers and water managers must integrate these findings into planning, especially in water-dependent sectors like agriculture, to mitigate negative impacts (Zarei, 2019).

Even non-significant negative trends in SPI may serve as early warnings of potential future declines. Water management strategies should account for shifting rainfall patterns and the spatial variability of drought frequency. Changes in precipitation have significant consequences for agriculture and ecosystem restoration, particularly in southeastern Iran, where declining rainfall may accelerate desertification and increase sandstorm frequency. Therefore, rainfall variability and drought distribution must be considered in agricultural planning and drought risk reduction (Bari Abarghouei et al., 2011).

Also, due to decreasing annual precipitation combined with increasing potential evapotranspiration, Iran has experienced severe drought conditions in recent decades (Bazrafshan, 2017). In semi-desert, desert, and coastal desert climates, the use of the Standardized Precipitation Index (SPI) for drought monitoring is insufficient. Because temperature acts as a moisture-limiting factor, the Standardized Precipitation Evapotranspiration Index (SPEI) should be used for more effective and accurate drought monitoring (Sharafi & Ghaleni, 2022).

Potential Evapotranspiration (PET) is therefore a critical factor that must be considered in drought calculations, particularly in arid areas. The SPI, which relies solely on precipitation, is unsuitable for warm regions such as southwestern Iran, where high temperatures exacerbate drought conditions. Consequently, indices that incorporate both precipitation and PET, such as SPEI, are recommended in these regions (Lotfirad et al., 2022). The southern regions of Iran are particularly vulnerable to drought, highlighting the importance of appropriate water management during warm months, including the preservation and harvesting of precipitation in periods of higher rainfall (Bayatavrkeshi et al., 2023).

It is recommended that drought assessments be systematically conducted after evaluating the applicability of different drought indices under specific climatic conditions and localizing them. Variations in drought frequency and intensity have significant economic, social, and political consequences. Effective water resource management across diverse climatic zones and seasons is therefore essential, particularly to safeguard food security, which is closely linked to climate variability and water availability (Sharafi & Ghaleni, 2022).

Studies in Iran demonstrate the successful application of these tools across different regions. However, to further improve analyses, it is advantageous to incorporate indices such as SPEI, climate projections, machine learning approaches, or multi-parameter assessment techniques in future investigations. Overall, recent increases in the frequency and severity of drought have had significant negative impacts on Iran's agricultural sector, emphasizing the urgent need to develop and implement adaptation strategies to mitigate the destructive effects of drought.

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