# Temporal Trends and Meteorological Drought Characteristics of Precipitation in Zanjan Province, Iran

Nader Abbasi[1], Samar Behrouzinia[2], Farshid Taran[1]✉

[1.] Agricultural Engineering Research Institute (AERI); Agricultural Research, Education and Extension Organization (AREEO); Karaj, Iran.
[2.] Zanjan Regional Water Company, Iran.

**Corresponding Author: f.taran@areeo.ac.ir**

## Abstract

Precipitation is a key climatic variable with high spatiotemporal variability, and its changes affect water availability and agriculture, particularly in arid and semi-arid regions. This study aims to analyze precipitation trends and meteorological drought in Zanjan Province, Iran, over 22 years (2001-2023). Precipitation trends were examined at monthly and annual scales using nonparametric Mann–Kendall and Spearman tests, along with the Theil–Sen slope estimator, across eight counties. Drought was evaluated using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). The results indicated that annual trends were not significant at any station, while significant monthly trends were observed in June (Zanjan), September (Abhar), and March (Abbar). Precipitation followed a spring-concentrated pattern, with 37% of annual rainfall occurring in spring. The average annual precipitation was 283 mm, with Qeydar recording the highest (393 mm) and Abbar the lowest (254 mm). Light rainfall events (≤1 mm) were most frequent, with Qeydar having the highest number of rainy days (102) and Garmab the lowest (67). SPI analysis revealed normal conditions during approximately 60% of the study period; however, recent years (2021-2023) exhibited mild to extreme drought across most stations. SPEI analysis indicated that moderate drought dominated the one-year scale (36%), and extreme drought prevailed on the ten-year scale (46%). Severe to extreme conditions concentrated in northern, eastern, and southeastern areas. The findings indicate repeated moisture deficits in Zanjan Province during the study period. This study provides insights for agricultural planners to develop adaptive strategies for mitigating drought impacts.

**Keywords:** Climate, Mann-Kendall, SPEI, SPI, Theil-Sen Slope

## Introduction

Precipitation is one of the most important climatic components, exhibiting considerable spatiotemporal variability. Aridity, resulting from climate change through decreased precipitation and increasing temperatures, has become a major environmental concern, especially in arid and semi-arid areas (Ramezani Etedali and Koohi). However, unlike air temperature, this component is a discontinuous variable and is more variable than other climatic elements across spatial and temporal scales (New et al., 2001; Wang and Feng, 2026). Precipitation constitutes a critical component of the hydrological cycle, linking the atmosphere, ocean, and land, and its associated latent heat flux is an important source of atmospheric energy (Adler et al., 2003; Ghajarnia et al., 2015). Therefore, understanding precipitation variability is important for agricultural planning and water-resource management. In recent decades, the global climate has changed in association with increasing greenhouse-gas concentrations resulting from anthropogenic activities. These changes are reflected in the frequency, duration, and intensity of hydrometeorological extremes, particularly droughts, which indicate imbalances in the hydrological system. Drought is one of the most damaging climatic hazards, especially in semi-arid regions, because it directly affects water availability, agriculture, and ecosystem functioning (Ipek et al., 2025). Drought is also an important consequence of climate variability and change, and accurate assessment of changes in drought exposure can assist planners and policymakers in developing appropriate management strategies (Ebrahimi and Siasar, 2026). It is a complex hazard that can strongly affect water resources, agriculture, and food security (Rezvani et al., 2026). Studies have shown that many regions of the world have experienced increases in heavy and extreme precipitation, particularly at high latitudes (Hernández Ayala and Palance, 2025) and in coastal and mountainous areas (Hammas et al., 2026), whereas other regions, including tropical belts (Hernández Ayala and Palance, 2025) and southern interior regions (Hammas et al., 2026), have experienced opposite trends. At smaller spatial scales, considerable heterogeneity in precipitation distribution and trends has also been reported, reflecting interactions among climatic processes, human activities, land use, and other factors (Song et al., 2019). Because changes in precipitation patterns can contribute to floods, droughts, biodiversity loss, and reduced agricultural productivity, understanding their spatial and temporal trends is important for water-resource planning (Zaman and Jha, 2014). Given the adverse impacts of precipitation changes associated with climate change, precipitation trends are of considerable interest to climatologists (Dai, 2006; Trenberth, 2011). This issue is particularly important in Iran, a country characterized by high climatic diversity and predominantly arid to semi-arid conditions. Precipitation deficits and substantial fluctuations across temporal scales create uncertainty regarding the precipitation required for agriculture, human consumption, and groundwater recharge. Because agriculture is a fundamental component of the country's economy and depends directly on the amount and distribution of precipitation, changes in precipitation can affect agricultural production, food security, and farmers' livelihoods.

Numerous studies have investigated precipitation trends, spatiotemporal variation, and drought conditions in Iran and globally using methods such as the Mann–Kendall test, Sen's slope estimator, and regression analysis. In Iran, Nouri et al. (2021) examined the spatiotemporal trends of precipitation in the transboundary Aras River basin over the period 1983–2018 and concluded that the annual trend was increasing, except in the central parts of the basin. Seasonal precipitation trends were more pronounced, with a decreasing trend in spring and an increasing trend in fall. Falamarzi (2023) analyzed precipitation trends in Fars Province over 1990–2021 and reported a decreasing annual trend. At the seasonal scale, a decreasing trend was observed in all seasons except summer, with the reduction being less severe in the northwestern part of the province than in other areas. Kamali and Torabi Azad (2024) used monthly ERA5 data to investigate precipitation trends along Iran's southern coastal strip during 1981–2020. Their results showed an increase in spring precipitation and a decrease in winter precipitation, with increasing precipitation rates predominantly observed in the northern regions of Khuzestan Province. Sobhani and Danehkar (2025) analyzed precipitation trends in western and southwestern Iran and examined drought occurrences in the Mesopotamian Plain over 1989–2022. They reported significant decreases in seasonal and annual precipitation, accompanied by an increased frequency of drought events in the Mesopotamian Plain. Yosefi et al. (2025) investigated spatiotemporal trends in annual precipitation in the southern Zagros region during 1978–2020. Their results indicated decreasing precipitation and increasing aridity; among the 61 studied stations, 89% showed an increase in the number of dry days, and more than 90% exhibited a decreasing trend in the number of rainy days.

In other countries, Ayala and Palance (2025) combined satellite imagery and rain-gauge data to analyze global spatiotemporal precipitation patterns over the period 1998–2024. Overall, the findings revealed a dual pattern of wetting at high latitudes and drying in tropical belts. Nazeri Tahroudi (2025) analyzed spatiotemporal precipitation variations globally over the period 1891–2019 and concluded that significant increasing and decreasing trends were observed in 32% and 21% of the world's regions, respectively. In addition, 38% of global regions experienced substantial precipitation changes during 1955–1987. Overall, a shift toward more irregular precipitation patterns was reported for recent decades. Hammas et al. (2026) investigated the spatiotemporal variability of meteorological drought in northwestern Algeria over 1981–2023 and found marked differences in precipitation and drought severity between the north and south. Wetter conditions occurred in coastal and mountainous areas in the north, whereas southern interior regions were more exposed to moderate to severe drought. Haruna et al. (2026) analyzed changes in wet-day frequency, mean wet-day precipitation, and mean all-day precipitation in metropolitan France over 1950–2022. They reported complex and non-uniform trends, including widespread summer drying and increased wet-day frequency in fall. While mean wet-day precipitation showed a slight annual decrease, mean all-day precipitation generally increased, mainly because of higher wet-day frequency.

Despite the research conducted at national and global levels, a research gap exists in the simultaneous investigation of precipitation trends and meteorological drought at the provincial scale in Iran, considering the specific climatic characteristics of each province. In this context, Zanjan Province, with its cold and semi-arid climate, diverse agricultural structure, and limited water resources, represents a suitable case for such studies. Despite its considerable agricultural potential, this province has been grappling with increasingly limited surface and groundwater resources in recent years. Population growth, intensifying pressure on water resources, and the province's status under water stress conditions underscore the necessity of comprehensive climate-oriented studies in this region. The aim of the present study is to analyze precipitation trends and assess meteorological drought in Zanjan Province. For this purpose, precipitation trends at annual, seasonal, and monthly scales were analyzed using nonparametric

Mann–Kendall and Spearman tests, along with the Theil–Sen slope estimator, across eight counties of the province, including Zanjan, Mahneshan, Khodabandeh, Tarom, Khorramdarreh, Ijrud, Abhar, and Soltanieh. Furthermore, drought conditions in the province were evaluated using the SPI and SPEI indices. The findings of this analysis can provide valuable information to water-resource and agricultural planners and managers in the province to adopt necessary measures for optimal water-resource management and enhance the resilience of the agricultural sector against climatic hazards.

## Materials and Methods

### Study Area and Data

Zanjan Province, with an area exceeding 22,000 km², is located in a mountainous region in northwestern Iran, situated between 35° 35′ and 37° 15′ north latitude and 47° 11′ and 49° 25′ east longitude. The province is bordered by East Azerbaijan, Ardabil, and Gilan provinces to the north; Qazvin and Gilan provinces to the east; Hamadan and Qazvin provinces to the south; and West Azerbaijan and Kurdistan provinces to the west. The average elevation of Zanjan Province exceeds 1,500 m above sea level. Based on the De Martonne climate classification, the climate of Zanjan Province is cold and semi-arid. The province comprises eight counties, namely Zanjan, Mahneshan, Khodabandeh, Tarom, Khorramdarreh, Ijrud, Abhar, and Soltanieh. In Zanjan Province, there are 8 synoptic stations, 17 climatology stations, and 30 rain gauge stations. Fig. 1 shows the map of the counties of Zanjan Province and the location of Zanjan Province within Iran.

In this study, considering the available statistical period length based on the establishment years of the stations across the eight counties, a common 22-year period (2001-2002 to 2022-2023) was considered. However, due to instrumental failures and missing registers, data completeness varied among stations. For seven stations (Zanjan, Mahneshan, Qeydar, Garmab, Khorramdarreh, Abbar, and Soltanieh), complete daily records were available for the entire 22-year period. For Abhar station, only 16 complete years were usable. It should be noted that no gap-filling was applied; only years with complete daily records were used. Consequently, Abhar has a shorter record (16 years) than other stations (22 years). This may slightly reduce statistical power at Abhar and introduce uncertainty in spatial comparisons; therefore, its results should be interpreted with caution.

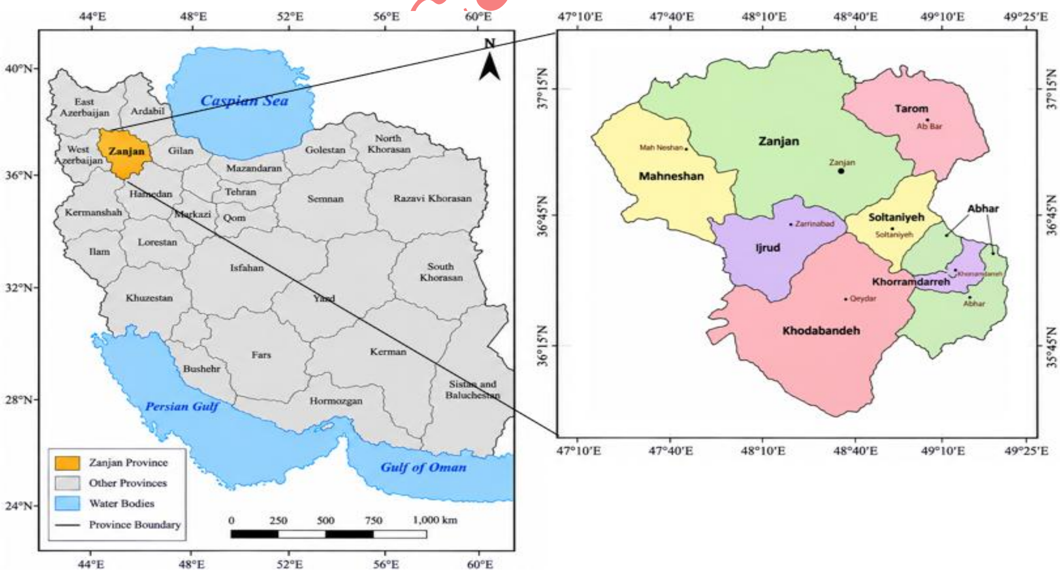



**Fig 1. Location of Zanjan Province in Iran**

### Trend Analysis of Precipitation

In this study, nonparametric statistical tests, including the Mann–Kendall test, Spearman test, and the Theil–Sen slope estimator, were employed to analyze time series and detect trends. Prior to applying the Mann–Kendall test, the autocorrelation structure of the annual and monthly precipitation series was examined. No significant autocorrelation was detected at the 5% level in the annual series, and only weak autocorrelation was observed in some monthly series. Therefore, the standard Mann–Kendall test was applied without further correction. The Mann–Kendall test was initially proposed by Mann (1945) and subsequently developed by Kendall (1975). The null hypothesis of this test implies that the data series is random and lacks a trend, while acceptance of the alternative hypothesis (rejection of the null hypothesis) indicates the presence of a trend in the data series.

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

$$sgn(x_j - x_i) = \begin{cases} +1, if\ (x_j - x_i) > 0 \\ 0, if\ (x_j - x_i) = 0 \\ -1, if\ (x_j - x_i) < 0 \end{cases} \tag{2}$$

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{3}$$

$$Z_m = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, if\ S > 0 \\ 0, if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}, if\ S < 0 \end{cases} \tag{4}$$

where n represents the number of data points, $x_i$ and $x_j$ denote the i-th and j-th data values, respectively; q is the number of tied groups (groups with equal data values comprising more than two members), $t_p$ is the number of tied data values in the p-th group, and Z is the Mann-Kendall test statistic. A value of $Z_m$<0 indicates a decreasing trend, while $Z_m$>0 suggests an increasing trend in the data series. If $|Z_m|$>2.58 and $|Z_m|$>1.96, the trend is considered significant at the 1% and 5% levels, respectively; otherwise, it is considered non-significant.

In the Spearman test, the null hypothesis assumes no monotonic trend in the time series (i.e., ranks of data are independent of chronological order), while the alternative hypothesis indicates an increasing or decreasing trend. To perform this test, the data are first arranged in ascending order and ranked from 1 to n. Subsequently, the data are considered in their historical chronological order, and the corresponding ranks for each data point are recorded. These ranks are denoted as $R(X_i)$. The D statistic for the dataset and the Spearman test statistic ($Z_s$) are then computed (Yue et al., 2012).

$$D = 1 - \frac{6\sum_{i=1}^{n}(R(X_i) - i)^2}{n(n^2 - 1)} \tag{5}$$

$$Z_s = D\sqrt{n - 2/1 - D^2} \tag{6}$$

where n is the number of data points and $R(X_i)$ is the rank of the i-th observed data value. To determine the significance of the data trend, the computed Spearman statistic is compared with the Student's t-statistic from the statistical table at a 95% confidence level with n-2 degrees of freedom. The critical value of the Spearman statistic depends on the sample size. For stations with 22 years of data (df=20), the critical value at the 95% confidence level is 2.086, while for Abhar station with 16 years of data (df=14), it is 2.145. If the computed statistic exceeds these values, the null hypothesis is rejected, and the trend is considered significant.

The Theil-Sen slope estimator is a suitable method for estimating the true slope of a trend in a time series. This method was initially proposed by Theil (1950) and subsequently developed by Sen (1968). It can be applied when the trend in the time series is linear. The Theil-Sen estimator is based on calculating a median slope for the time series and assessing the significance of the obtained slope at various confidence levels. The slope between each pair of data points is computed using Equation 7.

$$Q_i = \frac{x_t - x_s}{t - s},\ \ i = 1,2, \dots, N \tag{8}$$

where, $x_t$ and $x_s$ are the data values at times t and s, respectively, where t>s, and $N = \frac{n(n-1)}{2}$. By applying this relationship to each pair of data points, a time series of calculated slopes is obtained. The Theil-Sen slope of the trend line is then estimated by computing the median of this series of slopes. A positive value of this slope indicates an upward (increasing) trend, while a negative value indicates a downward (decreasing) trend.

**Drought Analysis**

Numerous indices have been developed in various countries for monitoring drought conditions, based on drought definitions and computational methods; however, some are more widely used due to their simplicity and applicability. In this study, two drought indices were used to assess drought conditions in Zanjan Province. The SPI was computed directly using daily precipitation records from the studied stations. The SPEI, however, was obtained from the pre-calculated drought bulletins and products of the Iran Meteorological Organization (IRIMO). In semi-arid regions of Iran, the SPEI has been widely applied for meteorological drought assessment and projection under regional climate modeling frameworks (Salehnia et al., 2026).

The SPI was developed by McKee et al. (1993) for meteorological drought monitoring. This index is calculated for various timescales and is of great importance for early warning and drought severity assessment. The SPEI, in addition to precipitation, also incorporates temperature and evapotranspiration parameters (Vicente-Serrano et al., 2010). Both indices continue to be widely used because they are simple, comparable across different climates, and suitable for analyzing the spatiotemporal dynamics of drought. In calculating the SPI, a Gamma distribution function is first fitted to the precipitation data series and then the values are transformed into a standard normal distribution (with a mean of zero and a standard deviation of one) using the inverse normal transformation. The calculation procedure for the SPEI is similar to that of the SPI, with the difference that instead of raw precipitation data, the difference between precipitation and potential evapotranspiration (PET)—representing the regional water balance—is used. To normalize this difference series, the Log-logistic distribution function is employed, ultimately transforming the SPEI values into a standard normal variable. The Gamma distribution was fitted to precipitation data over the entire study period (2001-2023), which served as the baseline reference period for SPI calculation. The SPEI values used in this study were obtained from the pre-calculated drought bulletins and products of the Iran Meteorological Organization (IRIMO). In these products, PET is calculated by IRIMO based on Penman-Monteith using temperature data from the national synoptic network. Tables 1 and 2 present the classification of wet, normal, and drought periods based on SPI and SPEI values, respectively, across seven and nine classes.

**Table 1. Classification of wet, normal, and drought periods based on the SPI**

| Classification | SPI |
|---|---|
| Extremely wet | > 2 |
| Severely wet | 1.50 to 1.99 |
| Moderately wet | 1 to 1.49 |
| Normal | −0.99 to 0.99 |
| Moderately dry | −1.49 to −1 |
| Severely dry | −1.99 to −1.50 |
| Extremely dry | < −2 |

**Table 2. Classification of wet, normal, and drought periods based on the SPEI**

| Classification | SPEI |
|---|---|
| Extremely wet | > 2 |
| Severely wet | 1.50 to 1.99 |
| Moderately wet | 1 to 1.49 |
| Mildly wet | 0.50 to 0.99 |
| Normal | −0.49 to 0.49 |
| Mildly dry | −0.99 to −0.50 |
| Moderately dry | −1.49 to −1 |
| Severely dry | −1.99 to −1.50 |
| Extremely dry | < −2 |

**Results and Discussion**

**Annual Precipitation Regime**

Annual precipitation in cities with synoptic stations, including Zanjan, Mahneshan, Qeydar (Khodabandeh), Garmab (Khodabandeh), Khorramdarreh, and Abbar (Tarom), as well as in cities with climatology stations, including Abhar, Halab (Ijrud) and Soltanieh, was evaluated according to Fig. 2. Due to extensive gaps in the recorded data at the Halab and Soltanieh stations, the estimated total precipitation at these locations is not very accurate. During the study period, the maximum annual precipitation was recorded in Qeydar with 393 mm, while the minimum annual precipitation (excluding

Soltanieh station) was observed in Abbar with 254 mm. The average annual precipitation across the analyzed stations is approximately 283 mm.

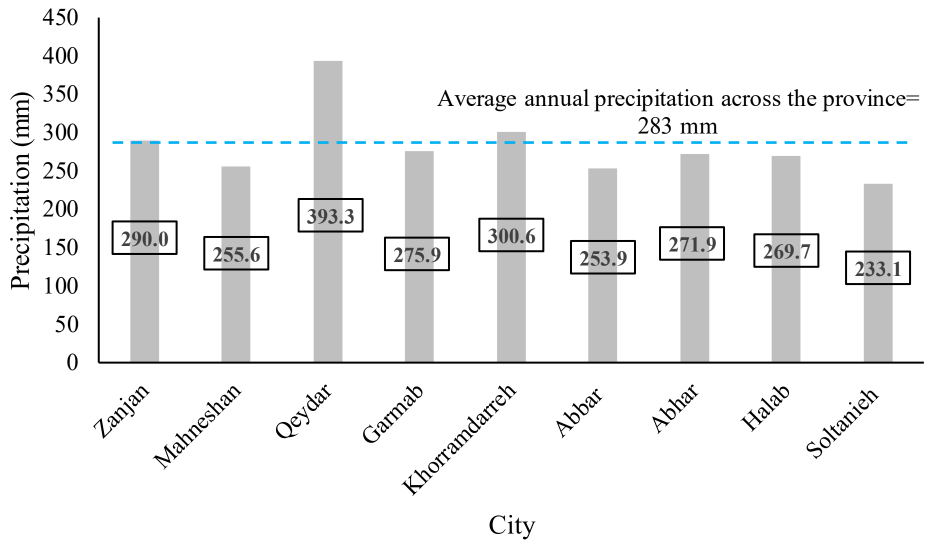



**Fig 2. Average annual precipitation across Zanjan Province**

Table 3 presents the minimum and maximum annual precipitation values, as well as the greatest decreases and increases relative to the long-term average, for various cities across the province during the 22-year study period. According to this table, Qeydar, with a maximum of 513 mm in 2019 and a minimum of 206 mm in 2008, has the highest annual precipitation among the cities, while Abbar, with a minimum of 101 mm in 2008 and a maximum of 382 mm in 2019, is the driest city. Qeydar shows the largest range between minimum and maximum annual precipitation (307 mm), whereas Abbar shows the smallest range (281 mm). The year 2008 was recorded as the driest year in four cities—Zanjan, Qeydar, Khorramdarreh, and Abbar—indicating a widespread drought across the province during that year. Additionally, the year 2019 emerged as the wettest year in five cities: Qeydar, Garmab, Khorramdarreh, Abbar, and Abhar. Regarding the greatest decrease relative to the long-term average, Qeydar experienced the most severe precipitation deficit with -187 mm, while Garmab recorded the highest increase with +173 mm above the long-term mean. Overall, Qeydar had the highest mean annual precipitation, whereas Abbar had the lowest. Fig. 3 presents the moving average, annual, and long-term precipitation graphs for these two cities as examples.

**Table 3. Annual precipitation in the cities of Zanjan Province (in mm)**

| City | Minimum precipitation (year) | Maximum precipitation (year) | Greatest decrease relative to long-term average | Greatest increase relative to long-term average |
|---|---|---|---|---|
| Zanjan | 154 (2008) | 393 (2012) | -126 | +103 |
| Mahneshan | 128 (2021) | 396 (2018) | -128 | +113 |
| Qeydar | 206 (2008) | 513 (2019) | -187 | +120 |
| Garmab | 176 (2021) | 449 (2019) | -115 | +173 |
| Khorramdarreh | 170 (2008) | 449 (2019) | -131 | +148 |
| Abbar | 101 (2008) | 382 (2019) | -153 | +128 |
| Abhar | 149 (2022) | 419 (2019) | -124 | +147 |

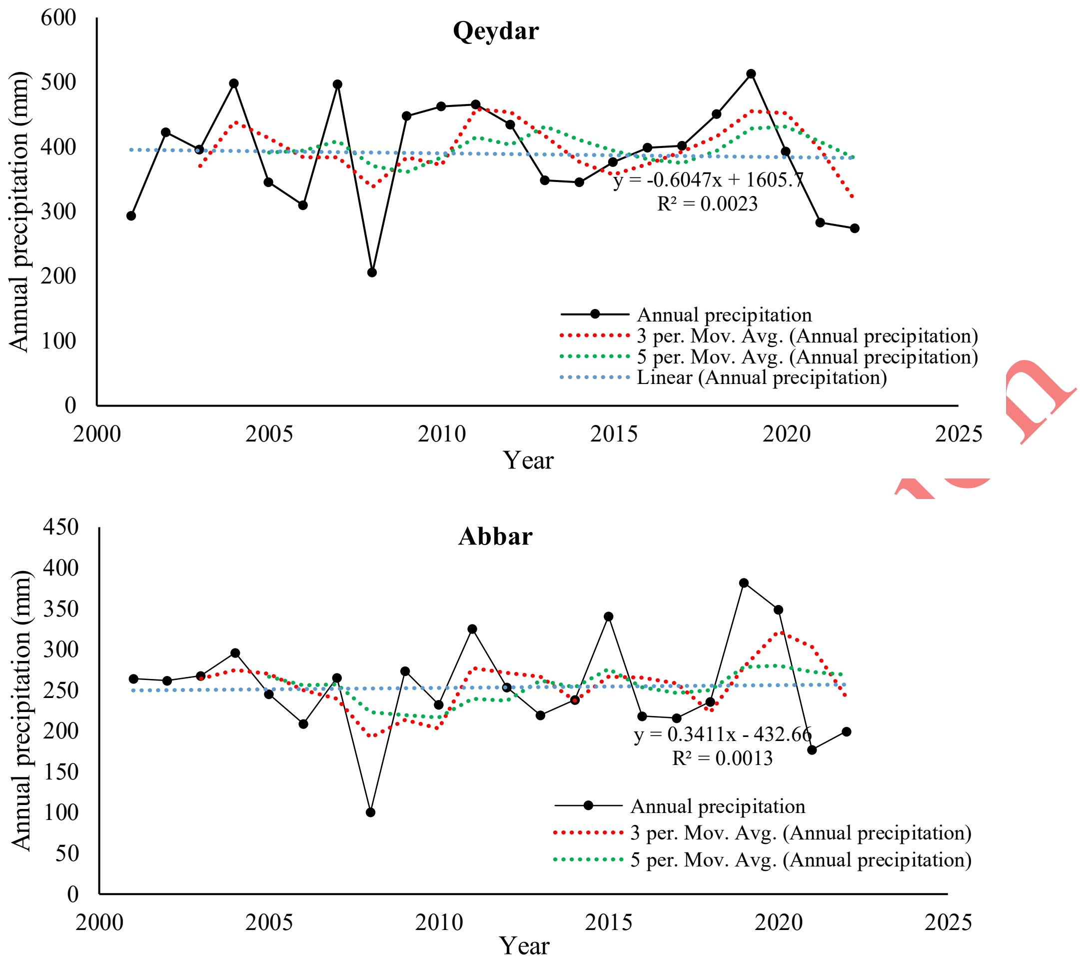



**Fig 3. Annual precipitation, 3-year and 5-year moving averages, and long-term average of precipitation**

**Seasonal Precipitation Regime**

The precipitation regime of the region follows a pattern of spring-concentrated rainfall and summer dryness. The contribution of annual precipitation during spring at the Zanjan, Mahneshan, Qeydar, Garmab, Khorramdarreh, Abbar, and Abhar stations is 38.6%, 38.7%, 33.4%, 37.3%, 35.2%, 35.4%, and 43.3%, respectively. Thus, at the studied stations, approximately 37% of the annual precipitation occurs in spring. Following spring, winter and fall account for the next largest shares of annual precipitation, with 31% and 28%, respectively. The winter contribution to annual precipitation at the aforementioned stations is 28.2%, 28.1%, 33.3%, 30.7%, 32.4%, 31.8%, and 32.7%, respectively, while the fall contribution is 26.8%, 27.8%, 29.1%, 29.3%, 29.3%, 27.9%, and 29.7%, respectively. Summer accounts for approximately 4% of the annual precipitation in the study region. The summer contribution to annual precipitation at the aforementioned stations is 6.4%, 5.5%, 4.2%, 2.7%, 3.1%, 4.8%, and 3.3%, respectively.

The rainfall regime characterized by concentrated spring precipitation followed by summer drought is evident in various regions. This pattern is influenced by climatic changes and atmospheric conditions that affect precipitation distribution and intensity. Capozzi et al. (2023) observed an increase in precipitation intensity in the Campania region, southern Italy, during spring over the period 2002-2021, particularly in mountainous areas. They stated that this increase may lead to flooding risks. Studies indicate a notable increase in summer drought occurrences around the world. For instance, in the Central U.S., a 25% decrease in precipitation during the transition from June to July has been documented, intensifying summer drought conditions since 1979 (Wang et al., 2015). While the concentrated spring precipitation can temporarily alleviate drought conditions, the subsequent summer drought poses significant challenges for water-resource management and agricultural practices. This duality highlights the need for adaptive strategies to mitigate the impacts of such climatic patterns.

This pattern is influenced by climatic changes and atmospheric conditions that affect precipitation distribution and intensity. Similar patterns have been reported globally (e.g., Wang et al., 2015; Capozzi et al., 2023). While such global comparisons provide useful context, the spring precipitation concentration in Zanjan is more directly explained by regional synoptic mechanisms. The concentrated spring precipitation can temporarily alleviate drought conditions, but the subsequent summer drought poses significant challenges for water-resource management and agricultural practices. This duality highlights the need for adaptive strategies to mitigate the impacts of such climatic patterns (Barati et al., 2016; Toulabi Nejad et al., 2018).

### Trend Analysis of Precipitation

The values of the Mann–Kendall and Spearman test statistics for determining precipitation trends in the annual time series are presented in Table 4. The results indicated that at the annual scale, precipitation fluctuations did not exhibit a significant trend in any of the cities.

**Table 4. Values of Mann-Kendall and Spearman test statistics for annual precipitation at the 95% confidence level**

| Test | Statistic | Annual precipitation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Zanjan | Mahneshan | Qeydar | Garmab | Khorramdarreh | Abbar | Abhar |
| Mann-Kendall | $Z_m$ | -1.46 | -1.41 | -0.28 | 0.39 | 0.62 | -0.51 | 0.67 |
| Spearman | $Z_s$ | -1.52 | -1.47 | -0.3 | 0.47 | 0.41 | -0.59 | 0.68 |

The results of the Mann–Kendall test (p-value) for determining the trend of monthly precipitation time series at the 95% confidence level are presented in Table 5. Months with a p-value less than 0.05 exhibit a significant trend at the 5% level. Therefore, on a monthly scale, significant trends in precipitation are observed only in three months—June, September, and March—at the Zanjan, Abhar, and Abbar stations, respectively, while no trend is evident in the remaining months.

**Table 5. The p-values of the Mann-Kendall test for monthly and annual precipitation at the 95% level**

| City | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zanjan | 0.114 | 0.310 | 0.021* | 0.183 | 0.306 | 0.073 | 0.554 | 0.535 | 0.822 | 0.284 | 0.367 | 0.102 | 0.143 |
| Mahneshan | 0.310 | 0.176 | 0.800 | 0.570 | 0.304 | 0.361 | 0.397 | 0.652 | 0.778 | 0.367 | 0.977 | 1.000 | 0.159 |
| Qeydar | 0.778 | 0.612 | 1.000 | 0.107 | 0.410 | 0.363 | 0.284 | 0.955 | 0.778 | 0.735 | 0.573 | 0.195 | 0.778 |
| Garmab | 0.778 | 0.910 | 0.323 | 0.977 | 1.000 | 0.877 | 0.366 | 0.297 | 0.612 | 1.000 | 0.955 | 0.052 | 0.693 |
| Khorramdarreh | 0.822 | 0.652 | 0.632 | 0.887 | 0.887 | 0.625 | 0.446 | 1.000 | 0.822 | 1.000 | 0.535 | 0.128 | 0.535 |
| Abbar | 0.866 | 0.866 | 0.843 | 0.589 | 0.646 | 0.611 | 0.693 | 0.499 | 0.693 | 0.822 | 0.735 | 0.021* | 0.612 |
| Abhar | 0.553 | 0.893 | 0.718 | 0.785 | 0.777 | 0.023* | 0.527 | 0.300 | 0.685 | 0.964 | 0.444 | 0.079 | 0.499 |

*Significance at the 5% level

### Number of Rainy Days

To calculate the number of rainy days, daily precipitation data from the stations in each city were used. Table 6 presents the annual average number of rainy days for different cities. Following a completely identical pattern across all cities, the highest frequency of rainy days corresponds to very light precipitation (≤1 mm), while the lowest frequency corresponds to heavy precipitation (≥10 mm). Thus, throughout the province, light rainfall events are the most frequent, whereas heavy rainfall events are rare. Fig. 4 shows the monthly distribution of the number of rainy days for the city of Qeydar, which has the highest number of rainy days compared to other cities, as an example.

**Table 6. Annual average number of rainy days for different cities of the province**

| City | Zanjan | Mahneshan | Qeydar | Garmab | Khorramdarreh | Abbar | Abhar |
|---|---|---|---|---|---|---|---|
| Mean annual rainy days | 101 | 78 | 102 | 67 | 90 | 87 | 90 |

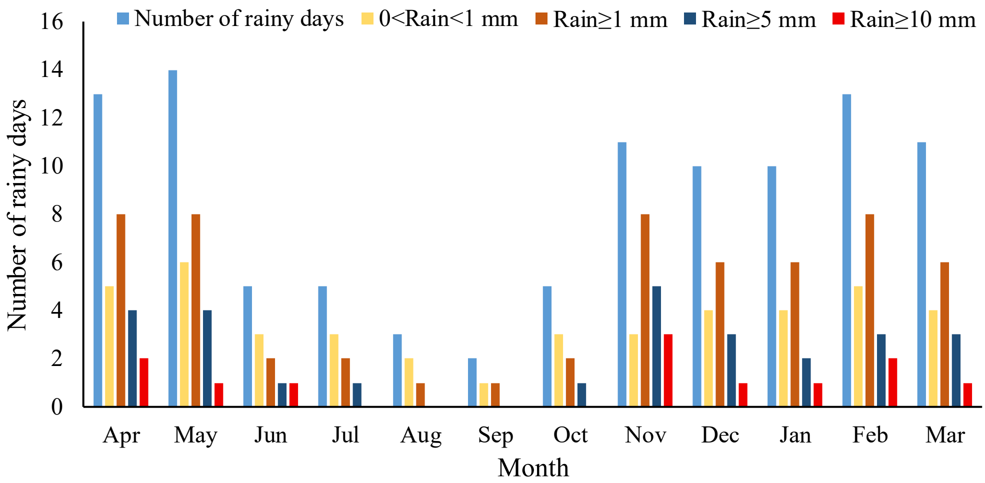


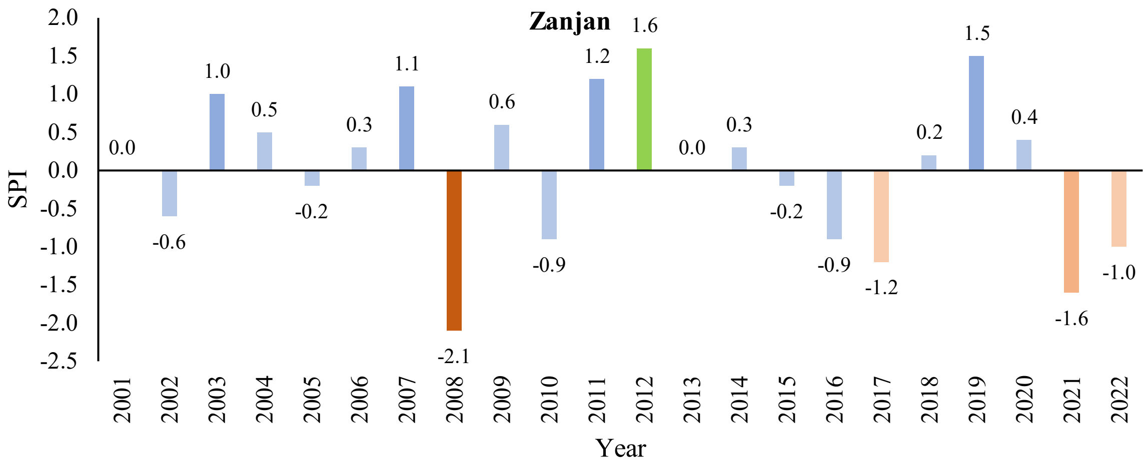

**Fig 4. Monthly distribution of the number of rainy days in Qeydar**

**Drought Analysis of Zanjan Province**

The calculation of SPI on an annual scale and its comparison with Table 1 showed that the precipitation status falls within the normal class for approximately 60% of the study period across all the stations (Table 7). In fact, the normal class, with SPI values ranging from -0.99 to 0.99, has the highest frequency among all the classes. As the study period progresses and the year 2021-2022 is reached, drought begins to emerge at the stations, such that in Zanjan, Mahneshan, and Qeydar, mild, severe, and extreme droughts prevailed in the two consecutive years of 2021-2022 and 2022-2023, respectively. Garmab and Abbar experienced normal conditions in 2022-2023, while in 2021-2022 they faced severe and mild droughts, respectively. Khorramdarreh and Abhar also encountered mild and severe drought conditions, respectively, in 2022-2023. Fig. 5 shows the SPI-based drought classification diagram for the two cities of Zanjan and Abbar as examples; the former exhibits persistent drought, while the latter recovered from mild drought in 2021-2022 to normal conditions in 2022-2023.

**Table 7. SPI-based drought classification for each station**

| Drought/Wetness class | Zanjan | Mahneshan | Qeydar | Garmab | Khorramdarreh | Abbar | Abhar |
|---|---|---|---|---|---|---|---|
| Extremely Wet | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Severely Wet | 1 | 2 | 1 | 1 | 0 | 1 | 0 |
| Moderately Wet | 4 | 3 | 2 | 2 | 2 | 2 | 2 |
| Normal | 12 | 13 | 14 | 15 | 17 | 16 | 12 |
| Moderately Dry | 2 | 3 | 3 | 1 | 1 | 1 | 0 |
| Severely Dry | 1 | 0 | 1 | 2 | 0 | 0 | 1 |
| Extremely Dry | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| Total | 21 | 22 | 22 | 22 | 22 | 22 | 16 |



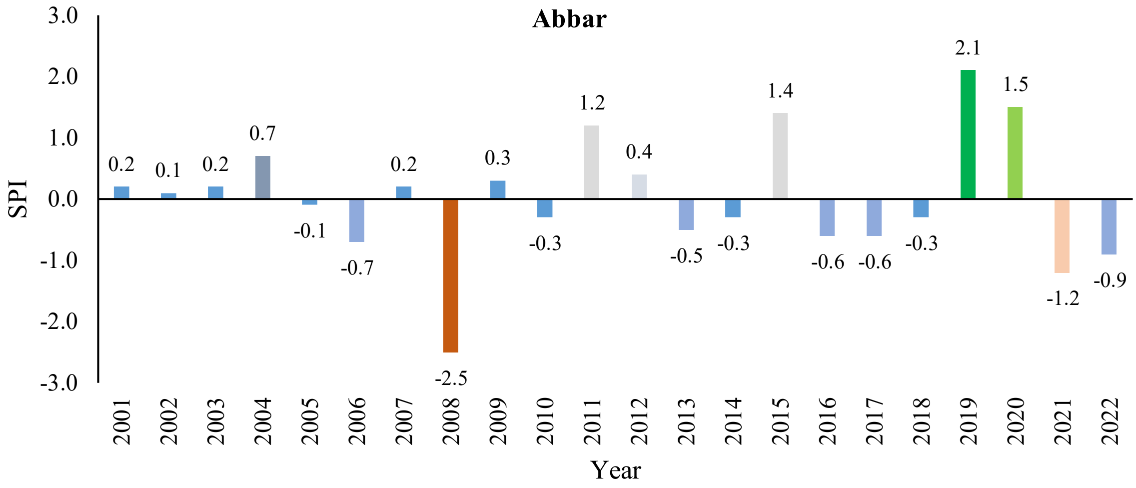




**Fig 5. SPI-based drought classification**

To assess drought in Zanjan Province based on the SPEI, the online bulletins of the Iran Meteorological Organization were used. Accordingly, the area affected by drought based on SPEI was extracted for the one-year period ending in December 2022-January 2023 and the ten years ending in December 2022-January 2023 (Table 8). The results showed that about 93% of the province's area was affected by drought during the one year. The largest portion of the province (36%) was affected by moderate drought. During the ten years, about 98% of the province's area was affected by drought, with the largest portion (46%) affected by extreme drought.

**Table 8. Percentage of area affected by SPEI-based drought in Zanjan Province (Iran Meteorological Organization, 2023)**

| Extremely wet | Severely wet | Moderately wet | Mildly wet | Normal | Mildly dry | Moderately dry | Severely dry | Extremely dry | Total drought percentage |
|---|---|---|---|---|---|---|---|---|---|
| One-year period | | | | | | | | | |
| 0.05 | 0.20 | 0.10 | 0.40 | 5.93 | 20.09 | 35.92 | 25.96 | 11.36 | 93.32 |
| Ten-year period | | | | | | | | | |
| 0 | 0 | 0 | 0 | 2.08 | 3.55 | 8.29 | 40.39 | 45.68 | 97.92 |

The meteorological drought zonings across Zanjan Province based on the SPEI for the one-year and ten-year periods are shown in Fig. 6. Based on the one-year zoning map, the drought intensity across the province is not uniform, ranging from moderate drought in the central parts to severe and extreme drought in the northern, eastern, and southeastern areas. In Tarom and Mahneshan, located in the north, northeast, and northwest of the province, extensive areas of severe to extreme drought are observed. In Zanjan and the central parts, moderate drought predominates. Soltaniyeh and Ijrud are mainly classified under moderate to severe drought. In Khodabandeh, the majority of the area is affected by moderate and severe drought. In Khorramdarreh, moderate to severe drought is dominant, and most of Abhar falls within the moderate drought class.

Based on the ten-year zoning map, severe and extreme drought prevail over a large portion of the province, indicating the persistence and accumulation of moisture deficit on a long-term scale. In Tarom and Mahneshan, extensive and relatively continuous areas of extreme drought are observed. Zanjan is mainly classified under severe and extreme drought categories. In Soltaniyeh and Ijrud, severe drought is dominant. In Khodabandeh, most of the area is under severe to extreme drought conditions. In Khorramdarreh and Abhar, severe drought prevails.

A comparison of the two maps shows that moderate drought predominates on the one-year scale, while extreme drought becomes dominant on the ten-year scale. The expansion of severe and extreme drought areas on the ten-year scale indicates that the dry conditions observed in the one-year scale are part of a more persistent and cumulative pattern of moisture deficit in Zanjan Province. This underscores the importance of paying attention to long-term drought in water-resources planning, particularly in the management and allocation of agricultural water.

The findings of this study are consistent with previous research in Iran. The lack of significant annual precipitation trends in Zanjan Province is in line with Falamarzi (2023) and Sobhani and Danehkar (2025), who reported decreasing but mostly non-significant annual trends in Fars Province and the Mesopotamian Plain, respectively. The significant monthly trends observed in June (Zanjan), September (Abhar), and March (Abbar) are consistent with Nouri et al. (2021), who found more pronounced seasonal than annual trends in the Aras River basin. The spring-concentrated precipitation pattern in Zanjan is also in agreement with Kamali and Torabi Azad (2024), who reported increased spring precipitation along Iran's southern coastal strip. Regarding drought, the dominance of moderate drought on the one-year scale and extreme drought on the ten-year scale is consistent with Hammas et al. (2026) in northwestern Algeria, where similar contrasts between short-term and long-term drought were observed. The persistent moisture deficits in Zanjan also align with Yosefi et al. (2025), who reported increasing aridity in the southern Zagros region. Differences in the magnitude and timing of trends among these studies can be attributed to differences in record length, station density, climatic zone, and the influence of large-scale atmospheric systems such as Mediterranean moisture transport.

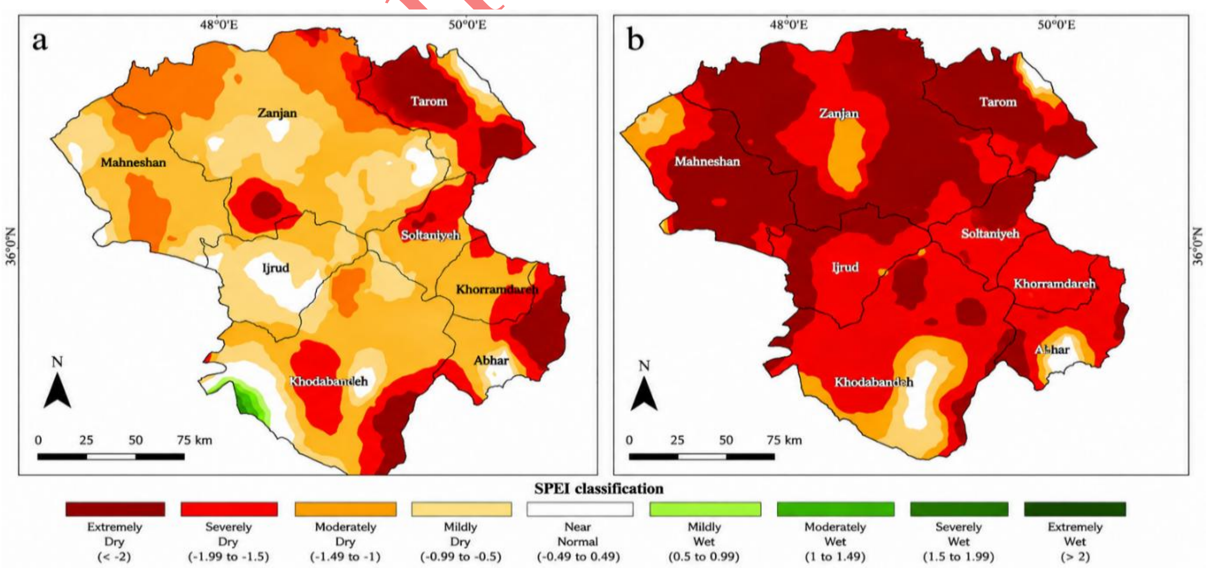



**Fig 6. Meteorological drought zoning across Zanjan Province based on SPEI for the one-year (a) and ten-year (b) periods (Iran Meteorological Organization, 2023)**

## Conclusion

This study conducted a comprehensive spatiotemporal analysis of precipitation trends and meteorological drought conditions in Zanjan Province. The findings provide critical insights into the region's hydrological behavior and climatic vulnerabilities.

1. While annual precipitation trends were not significant, notable monthly trends emerged in June (Zanjan), September (Abhar), and March (Abbar). This implies that the temporal distribution of precipitation is shifting, potentially disrupting traditional cropping calendars and water allocation schedules that rely on predictable seasonal patterns.

2. Approximately 37% of annual precipitation occurs during spring, with summer contributing only 4%. This pronounced seasonality implies high vulnerability to spring precipitation failures, as any reduction during this critical period would severely affect rainfed agriculture and spring planting, necessitating supplementary irrigation strategies.

3. The highest frequency of rainy days corresponds to precipitation ≤1 mm, while heavy events (≥10 mm) are rare. This suggests that the predominance of low-intensity rainfall events may potentially limit the contribution of precipitation to effective soil moisture and groundwater recharge, although this inference requires further investigation using groundwater and soil moisture data. These findings highlight the need for efficient rainwater harvesting and soil conservation practices.

4. Normal conditions prevailed during approximately 60% of the study period; however, 2021-2023 exhibited mild to extreme drought. This implies a recent intensification of dry conditions. This can be interpreted as a possible shift in precipitation patterns.

5. Moderate drought dominated the one-year scale (36%), while extreme drought prevailed on the ten-year scale (46%). This may suggest that evapotranspiration plays a role in moisture deficits, though further analysis is needed to confirm this. The difference between SPI and SPEI highlights the importance of considering both precipitation and temperature-driven processes in drought assessment.

6. Severe to extreme drought conditions were concentrated in northern, eastern, and southeastern areas, while central and western parts experienced moderate drought. This implies that drought impacts are spatially differentiated, requiring location-specific adaptation strategies.

7. The expansion of severe and extreme drought areas on the ten-year scale indicates that short-term dry conditions reflect a cumulative pattern of moisture deficit. This implies that water-resource planning must adopt long-term perspectives.

Finally, it should be noted that the inclusion of stations varied across analyses depending on data completeness and analytical requirements. Halab and Soltanieh were excluded from annual precipitation estimates due to extensive data gaps. Soltanieh was included in trend analysis because nonparametric trend tests are relatively robust to data gaps, whereas Halab was excluded due to insufficient records. Rainy day counts include only stations with complete daily precipitation records; Halab and Soltanieh, as climatology stations with incomplete daily data, were therefore excluded from this analysis.

In general, this research indicates recurring moisture deficits across Zanjan Province during the study period.



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