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Regionalization, temporal-spatial characteristics, and trend of changes in precipitation and drought in Iran

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Abstract
This study regionalizes Iran's precipitation and analyzes the temporal-spatial behavior of precipitation and drought in Iran. It used two sets of precipitation data. The first data set is the monthly precipitation data of 63 synoptic stations and the second data set is the Gridded precipitation data of three databases: Global Precipitation Climatology Center (GPCC), Climatic Research Unit (CRU) of the University of East Anglia (UEA) of England and University of Delaware (UDel) of the United States. As the results showed, the GPCC Gridded precipitation data set with a very high correlation ($R^2 = 0.97$) with Iranian station data was recognized as the most suitable Gridded precipitation data set for Iran. Cluster analysis on this precipitation dataset showed Iran can fall under seven different precipitation regions. Various characteristics of droughts, such as intensity, duration, and frequency of each precipitation region, were extracted and analyzed through four standardized precipitation indices (SPI), percentage of normal precipitation (PNPI), precipitation variability (RVI), and deciles (DI). The results disclosed that the three precipitation regions of Southwest (SW), Central Iran (CI), and Northwest-Northeast (NW-NE), among the seven precipitation regions of Iran, are the most vulnerable precipitation regions to drought.

Keywords: Precipitation, drought, Thiessen polygon method, cluster analysis, trend, Sen’s slope estimator, Iran

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1 Introduction

Iran, predominantly characterized by arid and semi-arid climates, faces significant vulnerability to drought, a recurring and damaging natural hazard with profound implications for the nation's water resources, agricultural productivity, and socio-economic stability (Savari et al., 2024: Zarepour Moshizi et al., 2023; Madani et al., 2016) . The country's high spatio-temporal variability in precipitation, coupled with increasing water demands, exacerbates the impacts of meteorological droughts – defined by precipitation deficits – often triggering subsequent agricultural and hydrological droughts (Kazemi Garajeh et al., 2024; Noorisameleh et al., 2021: Tabari et al., 2011). Understanding the patterns, characteristics, and trends of precipitation and associated droughts across different regions of Iran is therefore crucial for developing effective water management strategies and drought mitigation plans.

Quantifying meteorological drought, driven primarily by precipitation deficits, relies on various indices developed over decades (e.g., Palmer 1965; Gibbs and Maher 1967; Willeke et al. 1994; McKee et al. 1993, 1995; Byun and Wilhite 1999; Vicente-Serrano et al. 2010). These indices translate complex precipitation data into standardized values representing drought severity, duration, and frequency, which are essential for monitoring and early warning systems (Vicente-Serrano et al., 2022; Quiring, 2009). However, different indices may capture different facets of drought or perform differently depending on the climatic context and timescale of interest (Mahmoudi et al., 2019a; Mahmoudi et al., 2019b; Tefera et al., 2019; Homdee et al., 2016). Therefore, utilizing multiple indices can provide a more robust and comprehensive assessment of drought conditions, particularly in regions with diverse climates like Iran (Sharafi et al., 2025). This study employs a selection of precipitation-based indices (detailed in the Methodology section) to characterize drought across different Iranian regions.

Comparative studies of several indicators allow researchers to compare the indicators with each other and specify their accuracy, relevance, and integrity about a specific goal besides choosing the best indicator for monitoring droughts in the region under study (Mahmoudi et al. 2019b). Some of the most important studies are Ng et al. (2023), Burka et al. (2023), Patra (2020), Dikichi (2020), Mahmoudi et al., (2019b), Jain et al. (2015), Dogan et al. (2012), Morid et al. (2006) and Wu et al. (2001). Mahmoudi et al. (2019b) compared seven precipitation-based drought indices in a comparative study for different climates of Iran to choose the best index for monitoring droughts in Iran, and concluded that effective drought indices (EDI) and standardized Precipitation Index (SPI) performed better than other indices. Tsakris et al. (2007) also concluded after a systematic study on various indicators for identifying and evaluating the severity of meteorological droughts that none of the drought monitoring indicators has the global capability of the standardized precipitation index (SPI).Trend analysis of drought characteristics has also been a focus, revealing complex spatial and temporal patterns across the country. Studies have reported varying trends in drought severity, duration, and frequency depending on the region, season, timescale, and chosen index (e.g., Lornezhad et al. 2023; Isfahani et al. 2022; Bahrami et al. 2019; Modarres et al. 2016; Golian et al. 2015). For instance, some analyses indicated significant drying trends in specific areas like the west and southwest (Bari Abarghouei et al. 2011), while others showed differing seasonal trends (Nouri and Homaee, 2020; Mahmoudi et al., 2019a). However, many trend analyses were conducted either at the station level, aggregated nationally, or based on pre-defined administrative or broad climatic zones that may not perfectly capture the nuanced spatial patterns of precipitation variability itself.

Extensive research has addressed various facets of drought in Iran, including atmospheric drivers (e.g., Mahmoudi et al. 2022; Ghassabi et al. 2022; Rezaei 2021; Omidvar et al. 2016), frequency and intensity analysis (e.g., Kheyruri et al. 2023; Mahmoudi et al. 2022a; Dinpashoh et al. 2022; Adib and Marashi 2019: Raziei et al. 2013), prediction modeling (e.g., Mahmoudi and Rigi 2023; Shakeri et al. 2023; Aghelpour et al. 2021; Khosravi et al. 2017), socio-economic and environmental impacts (e.g., Akbari et al. 2022; Hesam et al. 2021; Farboodi et al. 2018; Lashkari and Bannayan 2013; Sharifikia 2013), and adaptation strategies (Shiravand and Bayat 2023; Yaghoubi and Bannayan 2022; Khalili et al. 2021; Heydari Alamdarloo et al. 2020; Fatehi Marj and Hosseini Hossein Abadi 2020). Comparative studies have also evaluated the performance of different drought indices within Iran's diverse climatic zones, often highlighting the suitability of indices like the Standardized Precipitation Index (SPI) while also suggesting that no single index is universally optimal across all regions and timescales (Rahnama et al., 2024; Morid et al., 2006). Furthermore, the critical need for reliable precipitation data has led to evaluations of various gridded datasets against station observations for hydrological and climatological studies in Iran (e.g., Najafi et al., 2025).

Despite the extensive body of research, a gap remains in providing an integrated assessment that combines a robust evaluation of gridded precipitation data, data-driven precipitation regionalization, and a subsequent comprehensive multi-index analysis of drought climatology and trends specifically tailored to these derived precipitation regimes in Iran. Addressing this gap is crucial for improving regional drought monitoring, impact assessment, and adaptation planning. Therefore, this study aims to: (1) identify the most suitable gridded precipitation dataset for Iran through validation against station data; (2) delineate homogenous precipitation regions across Iran using cluster analysis based on the selected dataset; (3) analyze the spatio-temporal characteristics of precipitation and drought (severity, duration, frequency) within each identified region using multiple drought indices (including RVI, DI, PNPI, and SPI); and (4) investigate long-term trends in precipitation and drought characteristics within these regions. Ultimately, this work seeks to provide a detailed and regionally nuanced understanding of precipitation and drought climatology in Iran, highlighting areas most vulnerable to drought hazards.

2 Data and Methods

2.1 Study area

This study focuses on Iran, a country spanning approximately 1.65 million km² in Southwest Asia. Its diverse topography is characterized by major mountain ranges, notably the Zagros (west and south) and Alborz (north), which encircle a vast central plateau containing extensive deserts like Dasht-e

Kavir and Dasht-e Lut . This geographical structure significantly shapes Iran's climatic patterns and water resource distribution, as the mountains act as crucial barriers or receptors for atmospheric moisture and are primary sources of snowmelt-derived water, while also creating rain shadow effects influencing the arid interior (Deldarzehi et al., 2024).

Climatologically, Iran is dominated by arid and semi-arid conditions, covering an estimated 85-90% of its territory. The average annual precipitation is low, around 230-250 mm (well below the global average), and exhibits high spatiotemporal variability, ranging from less than 50 mm in central deserts to over 1800 mm along the Caspian coast. Furthermore, rainfall is strongly seasonal, concentrated mainly in winter and spring, resulting in long, dry summers. The temperature regime is marked by extreme heat in summer, particularly in the interior, contributing to high potential evapotranspiration rates, and cold winters, especially in mountainous and northwestern regions (World Bank Group, 2021; Mesgaran et al., 2016).

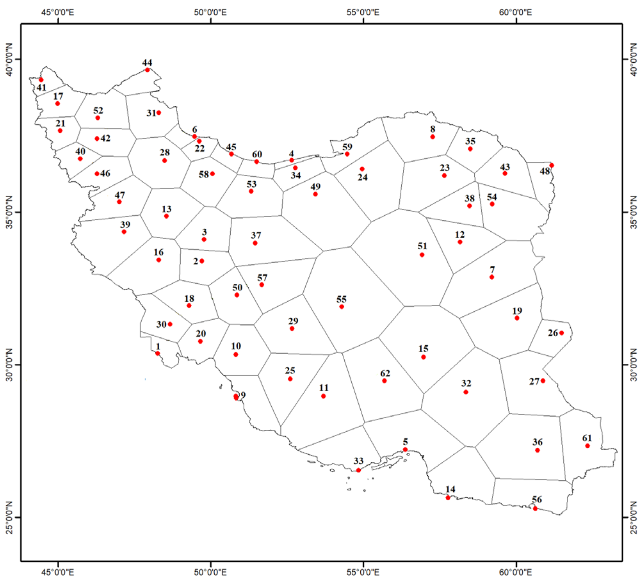
This combination of factors – the prevalence of arid/semi-arid lands, low, highly variable, and seasonal precipitation, high potential evapotranspiration, and reliance on mountain water resources – makes Iran exceptionally susceptible to frequent and severe meteorological, agricultural, and hydrological droughts (Hamarash et al., 2022). The country has a documented history of widespread droughts with significant socio-economic and environmental consequences (Bostani et al., 2024). Consequently, Iran is selected as a critical and relevant study area for investigating drought characteristics, trends, and impacts. A better understanding of drought phenomena in this vulnerable region is vital for sustainable water resource management and developing effective climate change adaptation strategies.

Figure 1. Geographical location and topography map of Iran in Southwest Asia (imgflip 2020).

2.2 Data

This research used two sets of precipitation data. The first dataset comprised monthly precipitation records from 63 synoptic meteorological stations across Iran, obtained from the Iranian Meteorological Organization (IRIMO) for the 30 years from 1987 to 2016. This period aligns with the standard WMO climatological normal period. Stations were selected based on the length and completeness of their records (minimum 30 years) and their spatial distribution, aiming to represent the diverse climatic conditions across the country. The dataset exhibited high reliability with minimal missing values; these gaps were filled using standard correlation and regression techniques based on neighboring station data (Asakereh, 2022). Crucially, the homogeneity of each station's time series was rigorously assessed using four established statistical tests: the Standard Normal Homogeneity Test, the Buishand range test, the Pettitt test, and the Von Neumann ratio test, following the methodology outlined by Wijngaard et al. (2003). All time series were homogeneous at the 95% confidence level. Figure 2 shows the geographical distribution of the 63 studied stations within the political borders of Iran. The Thiessen polygon method was also chosen to calculate regional weighted precipitation (RWP) for Iran (Thiessen 1911). Figure 2 shows an area of the whole of Iran that has been assigned to each station using this method.

The second dataset consisted of gridded monthly precipitation products, selected to evaluate their suitability for climatological analysis over Iran, a region characterized by complex topography where station network density can vary. Three widely recognized global datasets were chosen, each with a spatial resolution of 0.5° x 0.5° and covering the same 1987-2016 period: (1) the Global Precipitation Climatology Centre (GPCC) (Schneider et al. 2022), known for its high reliance on gauge data; (2) the Climatic Research Unit (CRU) (Harris et al. 2020), also gauge-based but employing a



Station name	Code	Station name	Code	Station name	Code
Abadan	1	Rasht	22	Mashhad	43
Aligudarz	2	Sabzevar	23	Parsabad	44
Arak	3	Shahrud	24	Ramsar	45
Babolsar	4	Shiraz	25	Saqez	46
Bandarabbas	5	Zabol	26	Sanandaj	47
Bandar Anzali	6	Zahedan	27	Sarakhs	48
Birjand	7	Zanjan	28	Semnan	49
Bojnurd	8	Abadeh	29	Shahrekord	50
Bushehr	9	Ahvaz	30	Tabas	51
Dogonbadan	10	Ardabil	31	Tabriz	52
Fasa	11	Bam	32	Tehran	53
Ferdows	12	B. Lengeh	33	T. Heydariyeh	54
Hamedan	13	Gharakhil	34	Yazd	55
Jask	14	Quchan	35	Chabahar	56
Kerman	15	Iranshahr	36	Esfahan	57
Khorramabad	16	Kashan	37	Qazvin	58
Khoy	17	Kashmar	38	Gorgan	59
M. Soleyman	18	Kermanshah	39	Nowshahr	60
Nehbandan	19	Mahabad	40	Saravan	61
Omidiyeh	20	Maku	41	Sirjan	62
Orumiyeh	21	Maragheh	42		

Figure 2. Distribution and geographic location of the stations under study and their region through the Thiessen polygon method.

different interpolation method; and (3) the University of Delaware (UDel) (Willmott and Matsuura 2001), which utilizes gauge data combined with topographic information for interpolation. Comparing these datasets, known for their extensive use in global and regional climate studies, allows for an assessment of their performance against local station observations in the Iranian context.

2.3 Methodology

Following data preparation, the first methodological step was to evaluate the performance of the three gridded precipitation datasets (GPCC, CRU, UDel) against the quality-controlled station observations to identify the most suitable dataset for subsequent climatological and drought analyses across Iran. This evaluation was conducted by comparing the monthly time series of each of the 63 stations with the time series of the corresponding nearest grid point (0.5° x 0.5° resolution) from each gridded dataset over the 1987-2016 period. Several statistical metrics were calculated to assess the agreement: The Pearson correlation coefficient (r) and non-linear regressions (exponential, logarithmic, polynomial, and power) (Bates and Watt 2007), to measure linear and non-linear association. The dataset exhibiting the highest correlation was selected for the main analysis.

Given Iran's vast geographical extent and highly diverse topography, leading to significant regional variations in precipitation patterns, a country-wide analysis alone is insufficient to capture the nuances of its precipitation climatology and drought characteristics. Therefore, a crucial step in this study was to delineate homogeneous precipitation zones across the country using cluster analysis. This regionalization allows for a more detailed and meaningful assessment of precipitation and drought within areas exhibiting similar climatological behaviour. The clustering was performed on the most suitable gridded precipitation dataset (0.5° x 0.5° resolution, 1987-2016). The input data for the clustering algorithm consisted of the mean monthly precipitation values for each grid point located within Iran's political borders. An agglomerative hierarchical clustering approach was employed. The similarity (or distance) between the precipitation of different grid points was measured using the Squared Euclidean distance. This metric was chosen as it accentuates larger differences between observations, potentially leading to more distinct clusters. For merging clusters, Ward's linkage method was utilized. Ward's method aims to minimize the increase in the within-cluster variance at each merging step; often resulting in compact, well-separated clusters that are frequently adopted in hydroclimatic regionalization studies due to their tendency toward spatial coherence (Brian et al. 2011; Mahmoudi and Alijani 2014).

A critical aspect of cluster analysis is determining the optimal number of clusters (k). In this study, the final number of clusters (k=7) was selected through visual inspection of the dendrogram produced by Ward's method to identify potential natural groupings. Furthermore, the resulting spatial patterns for different k values were examined for spatial coherence and climatological interpretability, ensuring that the final 7 zones represented geographically meaningful and distinct precipitation within Iran. Based on this, k=7 was deemed the most appropriate number of clusters. Subsequently, a precipitation zoning map was generated by assigning each precipitation grid cell within Iran to its corresponding cluster, effectively partitioning the country into seven distinct precipitation zones (presented in the Results section).

To provide a comprehensive characterization of drought conditions and their variations within each identified zone, four distinct meteorological drought indices were calculated The use of multiple indices, each with different sensitivities and calculation methods, allows for a more robust assessment of drought occurrence, severity, and temporal patterns across Iran's diverse precipitation regimes. These indices include the Rainfall Variability Index (RVI), Deciles Index (DI), Percentage of Normal Precipitation Index (PNPI), and the Standardized Precipitation Index (SPI), which are detailed below.

Rainfall Variability Index (RVI)

The Rainfall Variability Index (RVI), calculated based on annual precipitation totals for each zone, provides a straightforward measure of the normalized departure of annual precipitation from its long-term mean relative to the typical inter-annual variability. It offers a quick assessment of the magnitude of annual wet and dry anomalies. Following Gocic and Trajkovic (2013), RVI for a given year i within a specific zone is calculated as:

$$\mathrm{RVI} = \left(\frac{p_i - \mu}{\sigma}\right) \quad (3)$$

Where p_i is the annual precipitation for ith year, μ is the long term (1987-2016) average annual precipitation, and σ is the standard deviation of the annual precipitation over the same period. The severity of dry (drought) and wet conditions based on RVI values was classified according to the categories presented in Table 1 (Adnan et al. 2016).

Table 1. Classification of droughts and wet years based on Rainfall variability index (RVI).

Class name	Numerical value of index
extreme dry	$p < \mu - 2 \times \sigma$
dry	$\mu - 2 \times \sigma < p < \mu - \sigma$
normal	$\mu - \sigma < p < \mu + \sigma$
wet	$P > \mu + \sigma$

Deciles index (DI)

The Deciles Index (DI) was employed as a non-parametric method for assessing precipitation deficits and surpluses, relying solely on the historical ranking of precipitation amounts (Gibbs and Maher, 1967). Its primary advantage lies in its simplicity and distribution-free nature, requiring no assumptions about the underlying statistical distribution of precipitation. To calculate DI for a specific zone, the annual precipitation totals for the entire period (1987-2016) were first arranged in ascending order. This ranked distribution was then divided into ten equal parts (deciles). Precipitation values falling in the first decile (lowest 10%) indicate severe drought conditions, while those in the tenth decile (highest 10%) represent extremely wet conditions. While calculable for various timescales (Mahmoudi et al., 2019b), in this study, DI was computed based on annual precipitation totals. The classification of drought and wet period severity based on decile ranges is provided in Table 2 (Gibbs and Maher, 1967).

Table 2. Classification of the severity of droughts based on the index of deciles

Classes	Deciles
Intense wet	10
Severe wet	9
Moderate wet	8
Mild wet	7
Normal	6 and 5
Mild drought	4
Moderate drought	3
Severe drought	2
Intense drought	1

Percentage of Normal Precipitation Index (PNPI)

The Percentage of Normal Precipitation Index (PNPI) offers a direct and easily interpretable measure of precipitation conditions relative to the long-term average. It is calculated simply as the ratio of precipitation in a given period to the normal (average) precipitation for that same period, expressed as a percentage (Willeke et al., 1994). While relatively simple, it provides a valuable baseline assessment, particularly for communicating conditions relative to what is expected historically. In this study, PNPI was calculated using annual precipitation totals for each zone:

$$PNPI = \frac{P_i}{\overline{P}} \times 100 \tag{4}$$

Where P_i is the annual precipitation for year i in a given zone, and $\overline{P}$ is the long-term average annual precipitation (1987-2016) for that zone. Table 3 presents the standard classification scheme used to categorize drought and wet conditions based on PNPI values.

Table 3. Drought severity classification based on the percentage of normal precipitation index (PNPI)

Classes	PNPI Limits
Extremely drought	< 40
Severely drought	40 - 55
Moderately drought	55 - 70
Light drought	70 – 80
Normal	80 -120
Light wet	120 - 130
Moderately wet	130 - 145
Severely wet	145 - 160
Extremely wet	> 160

Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) (McKee et al., 1993, 1995) was selected as a principal drought indicator due to its robustness and versatility. Its key strengths include standardization, which allows for meaningful comparisons of drought severity across different climate zones regardless of their baseline precipitation amounts, and its ability to quantify precipitation deficits or surpluses over various timescales. SPI calculation involves fitting a probability distribution (typically the Gamma distribution) to the time series of precipitation accumulated over a chosen period (k months) for each location (here, each precipitation zone) and then transforming the cumulative probability into a standard normal variable with zero mean and unit variance (Guttman, 1999; Paulo and Pereira, 2008). Positive SPI values indicate wetter-than-average conditions, while negative values indicate drier-than-average conditions.

In this study, to capture drought impacts across different temporal scales, SPI was calculated for timescale 12-month (SPI-12) accumulation periods using the monthly precipitation time series (1987-2016) averaged for each of the seven precipitation zones.

A drought event is typically defined as a period during which SPI is continuously negative and reaches a value of -1.0 or less.

The event ends when SPI becomes positive. ey drought characteristics derived from the SPI time series include duration (length of the event), intensity (minimum SPI value during the event), and magnitude (cumulative SPI deficit during the event). The classification of drought and wet spell severity based on SPI values, as proposed by McKee et al. (1993), is shown in Table 4.

Table 4. Classification of drought based on the Standardized Precipitation Index (SPI)

Classes	SPI limits
Extreme wet	SPI ≤ 2
severe wet	1.99 ≤ SPI ≤ 1.5
Moderate wet	1.49 ≤ SPI ≤ 1
Mild wet	0.99 ≤ SPI ≤ 0.50-
Normal	0.49 ≤ SPI ≤ -.049
Mild drought	-0.50 ≤ SPI ≤ -0.99
Moderate drought	-1 ≤ SPI ≤ -1.49
Severe drought	-1.5 ≤ SPI ≤ -1.99
Extreme drought	-2 ≤ SPI

Finally, Sen's slope estimator non-parametric test was used to analyze the trend of long-term changes in the amount of precipitation and severity of droughts in Iran. Thiel first presented this method in 1950 and then Sen expanded it in 1968. This method, like many other non-parametric methods such as Mann-Kendall, relies on analyzing the difference between the observations of a time series. This method is usable when the trend in the time series is linear (Alijani et al. 2012). Figure 3 shows the flowchart of the research steps.

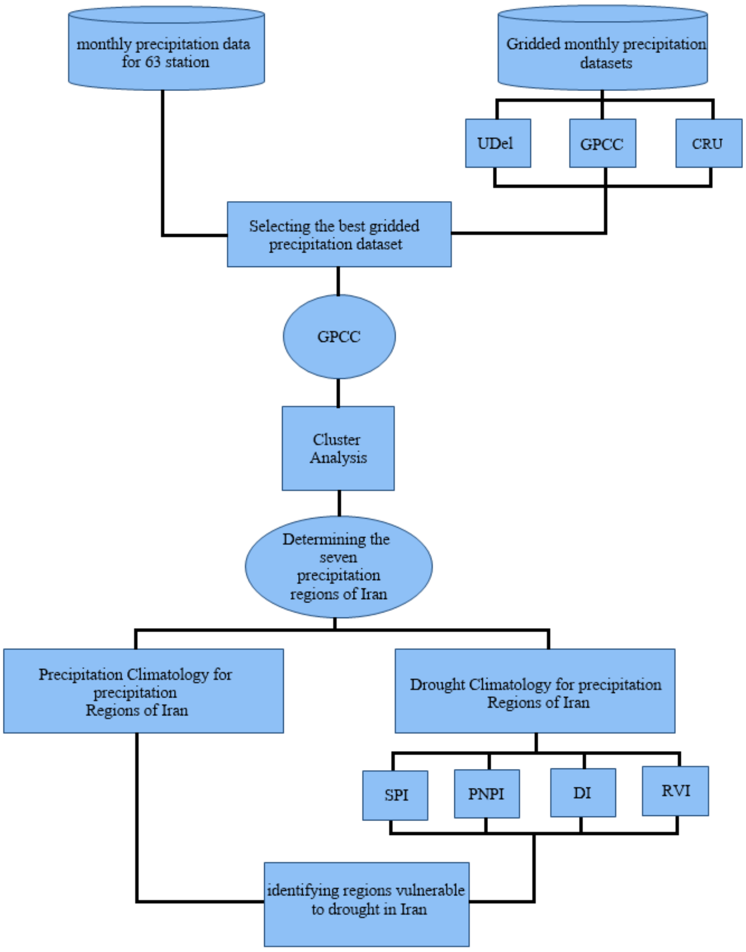


Figure 3. Flowchart of research steps.

4 Results and Discussion

The initial step in evaluating the gridded precipitation datasets involved assessing the consistency in temporal patterns between the Global Precipitation Climatology Center (GPCC) dataset and two other widely used datasets, the Climatic Research Unit (CRU) and the University of Delaware (UDel), along with their ensemble mean, across Iran for the period 1987-2016. This analysis, utilizing correlation metrics, aimed to understand the degree of agreement in year-to-year variability between GPCC and the alternative datasets. The selection of GPCC as the reference dataset was underpinned by numerous studies highlighting its relatively higher accuracy and reliability for precipitation analysis in Iran compared to other gridded products (Saemian et al., 2021; Bárdossy et al., 2021; Hosseini-Moghari et al., 2018; Ahmadi et al., 2020; Darand and Zand Karimi, 2016; Miri et al., 2016; Darand et al., 2015; Masoodian et al., 2014). This comparative step helps ascertain if alternative datasets could potentially serve as proxies should GPCC become unavailable, while acknowledging that this initial correlation primarily reflects pattern similarity rather than absolute value congruence.

The correlation analysis between the annual precipitation series of GPCC and the other datasets yielded varied results (Figure 3). Using linear regression, GPCC showed a strong positive correlation with the Ensemble mean (Average of three precipitation gridded datasets GPCC, CRU, and Udel) ($R^2 = 0.92$, p-value = 0.01, Eq. [$y = 0.4984x + 37.582$ for Fig 3c]), and a weak, albeit statistically significant, correlation with the UDel dataset ($R^2 = 0.56$, p-value = 0.01, Eq. [$y = 0.0658x + 7.6084$. for Fig 3a]). Recognizing that relationships might be non-linear, particularly for data with inherent fluctuations (Carter & Robertson, 1998), polynomial regressions were also explored. Notably, for the GPCC-CRU comparison, a second-order polynomial regression provided a significantly better fit ($R^2 = 0.74$, p-value = 0.01, Eq. [$y = -0.001x^2 + 1.2434x - 3.7758$. for Fig 3b]), indicating a non-linear aspect to the agreement in their temporal patterns (Figure 3b). These results quantify the degree of temporal synchrony, confirming that while the Ensemble mean and CRU data exhibit considerable pattern harmony with GPCC, the UDel dataset shows less agreement in its annual variability over Iran during the study period.

To further evaluate the GPCC dataset, specifically against ground observations, we compared its 0.5° x 0.5° gridded annual precipitation data with Area-Weighted Rainfall (AWR) derived from 62 meteorological stations across Iran for the same period (1987-2016). The AWR was calculated using the Thiessen Polygon method (Thiessen, 1911), a standard technique to estimate areal precipitation from point measurements (Rhynsburger, 1973; Fiedler, 2003). The temporal comparison (Figure 4a) revealed two key features: first, a consistent offset, with GPCC estimates generally higher than the station-based AWR throughout the study period; second, despite this difference in magnitude, the inter-annual variability and overall temporal trends of the two datasets show remarkable similarity. This indicates that while there might be a systematic bias in the absolute values reported by GPCC compared to this specific network of stations, GPCC effectively captures the year-to-year fluctuations in precipitation across Iran. Furthermore, the spatial correlation analysis between the long-term mean annual precipitation from GPCC grid points and the corresponding station AWR values demonstrated a very strong positive linear relationship (R^2 = 0.97, p-value= 0.01, Figure 4b).

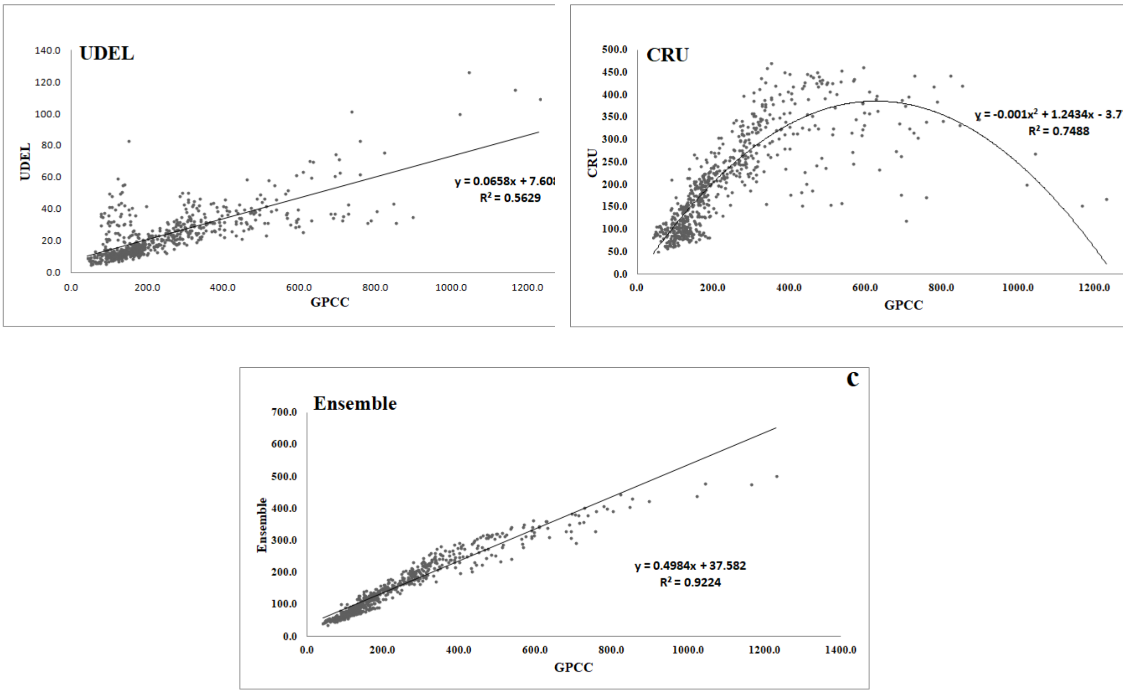


Figure 3. Correlation between GPCC precipitation dataset with three precipitation datasets CRU, UDel and the Ensemble mean of two precipitation datasets CRU and UDel on an annual scale (1987-2016) for the range of political borders of Iran.

The observed discrepancy in absolute values (GPCC < AWR, Fig 4a) likely stems from several factors, including the denser effective network underlying GPCC (incorporating more stations globally, potentially including some not used in our AWR calculation), differences in interpolation methods, quality control procedures (Schneider et al., 2014), and potential under-catch issues in station measurements, especially in complex terrain. However, for the primary objectives of this study – precipitation regionalization based on temporal patterns and drought analysis using standardized indices (like SPI, PNPI) – the accurate representation of relative spatial patterns and temporal variability is often more critical than absolute precipitation amounts. The high temporal similarity (Fig 4a trends) and the exceptionally strong spatial correlation (Fig 4b, R^2=0.97) strongly suggest that GPCC reliably captures these crucial aspects of Iran's precipitation climatology. Therefore, despite the observed offset in magnitude, the GPCC dataset was deemed the most suitable gridded dataset available for achieving consistent spatial coverage and conducting the subsequent analyses of regional patterns and standardized drought characteristics across Iran, acknowledging the potential bias in absolute totals but relying on its strength in representing variability and spatial distribution.

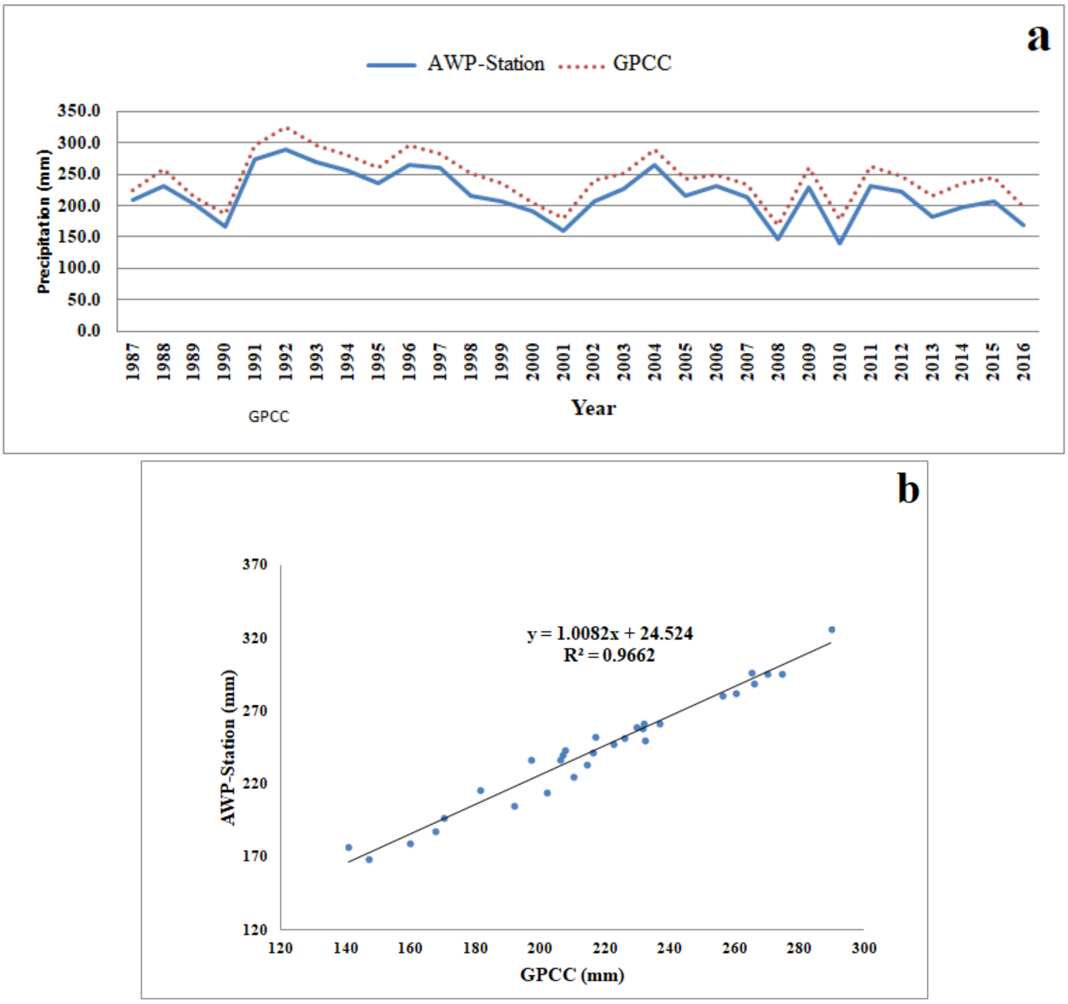


Figure 4. Temporal-spatial analysis of GPCC precipitation data set and region weighted precipitation (AWR) of 62 meteorological stations in Iran in the period of 1987-2016.

Performing cluster analysis on the monthly precipitation values of GPCC gridded points verified Iran can be divided into 7 separate clusters based on the behavior of its monthly precipitation time series. Indeed, each cluster in this division represents a group of grid points that show the highest similarity in the behavior of their annual precipitation time series. A dendrogram (Figure 5a) presents the results. This dendrogram clearly marks 7 selected clusters by different colors. The gotten clusters, in the next step, were converted into a zoning map as a zoning map of Iran's precipitation (Figure 5b). The seven rain regions of Iran can have these names: Central Iran Precipitation Region (CI), Caspian Coast Precipitation Region (CC), Southeast Precipitation Region (SE), West Precipitation Region (W), High Zagros Precipitation Region (HZ), southwest precipitation zone (SW) and northwest-northeast precipitation zone (NW-NE).

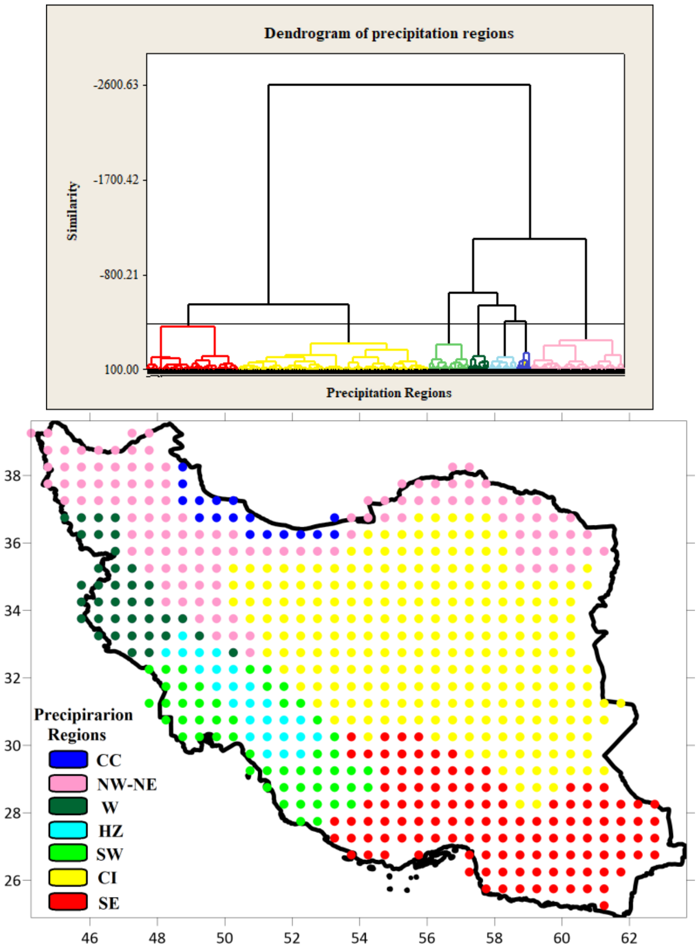


Figure 5. (a) Dendrogram of cluster analysis on annual precipitation values of GPCC gridded points and (b) zoning of Iran, based on annual precipitation values of GPCC gridded points.

4.1 Precipitation Climatology for Precipitation Regions of Iran

The seven precipitation regions of Iran can determine the precipitation regime of these regions. Precipitation regime means the proportion of received precipitation in each month or season from the total annual precipitation (Masoudian, 2005). Southwest precipitation region (SW), high Zagros precipitation region (HZ), and southeast precipitation region (SE) have a winter regime by receiving 63, 58.4 and 55.4% of the total annual precipitation in winter, respectively (Fig. 6). But the two precipitation regions of Central Iran (CI) and West (W) have a winter-spring precipitation regime. Around 87.6 percent of the precipitation region of Central Iran (CI) and about 79.7 percent of the annual precipitation in the western precipitation region (W) falls in these two seasons (Figure 6). The North-West-Northeast (NW-NE) precipitation region has the spring-winter precipitation regime (72.4%) and the Caspian Coast (CC) precipitation region has the autumn-winter precipitation regime (62.8%) (Fig. 6).

The most precipitation regions of Iran are the Caspian Coast (CC), High Zagros (HZ), West (W), and North-West-North-East (NW-NE) respectively, the most precipitation months of which are October (104.2 mm), January (141.4), January (77.3) and March (49.8) (Table 5). Its least precipitation regions belong to Central Iran (CI), South East (SE), and South West (SW) respectively, whose most precipitation months are March (27.6 mm), January (35 mm), and January (73.4 mm) (Table 5). The Caspian Coast precipitation region (CC), among the precipitation regions under study, is the only precipitation region that receives over 30 mm of precipitation in all months of the year. The Southeast (SE) precipitation region and the Northwest-

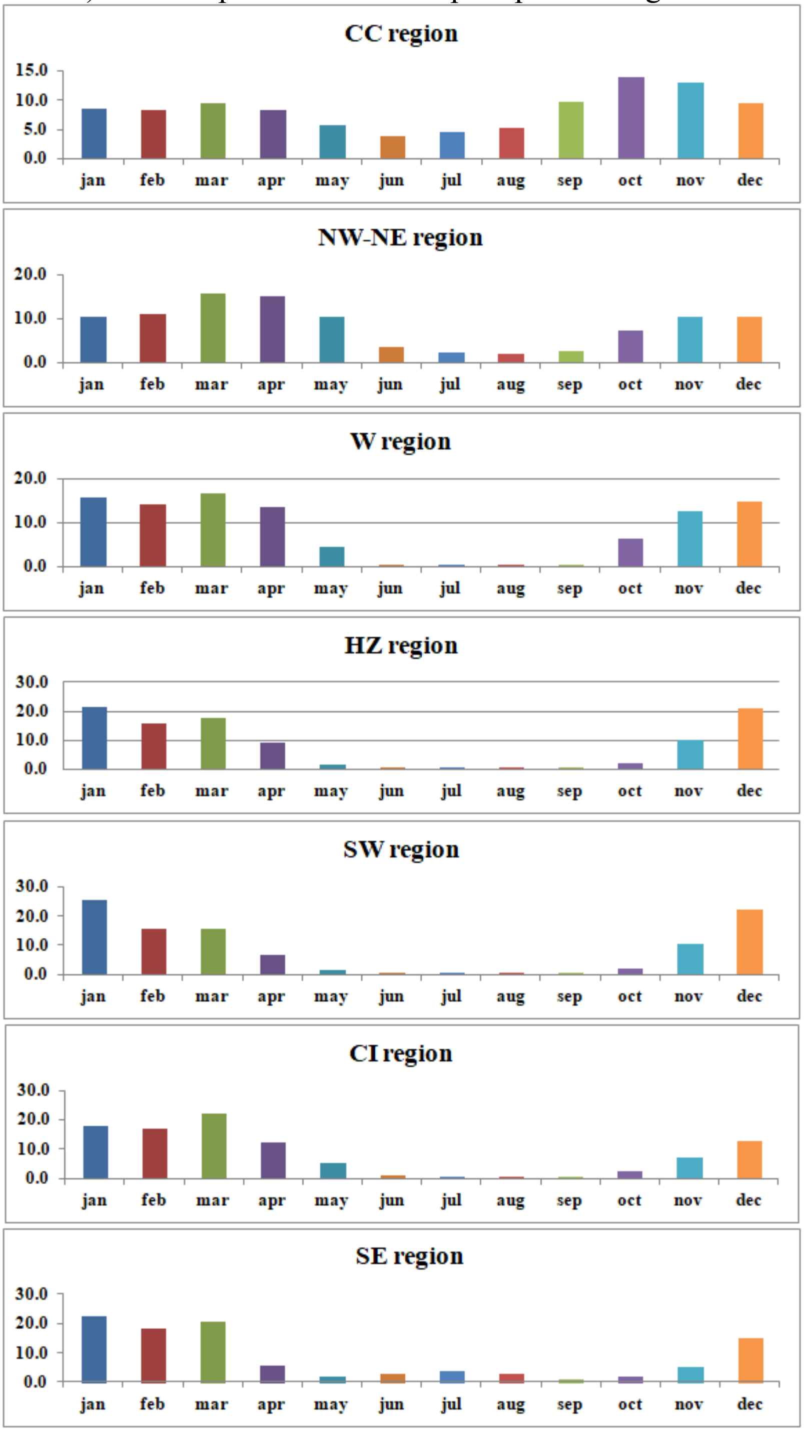


Figure 6. Ratio of received precipitation each month from the total annual precipitation for the seven precipitation regions of Iran using GPCC data for the statistical period of 1987-2016.

Table 5. Long-term average monthly precipitation (1987-2016) of seven precipitation regions of Iran, based on GPCC data set.

Regions	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
SE	35	28.7	32	8.5	2.6	4.4	5.6	4.4	1.7	2.8	7.9	23.1	**156.7**
SW	73.4	44.7	44.7	19.7	3.8	0.4	0.8	1	0.7	6.1	30.2	64.5	**290**
CI	22.4	21.4	27.6	15.6	6.7	1.5	0.9	0.6	0.8	3.1	8.7	16.1	**125.4**
HZ	141.4	105.7	115.3	60.3	11.4	0.7	1	1.2	1.3	14.7	68.3	138	**659.3**
W	77.3	68.6	82	66.3	22.2	2.5	1.9	1	1.7	30.7	61.5	72.4	**488.1**
NW-NE	32.2	34.2	49.8	47.6	32.3	10.6	7.4	5.6	7.8	22.5	33	32.2	**315.2**
CC	63.7	63.1	71.9	62.6	43.8	29	35.1	3.9	73.8	104.2	97.2	72.1	**755.5**

Northeast (NW-NE) precipitation region also receive little precipitation in the summer. This occurrence in these two precipitation regions has different reasons. The summer rains of the southeast rain region (SE) come down under the influence of monsoon systems, and the summer rains of the northwest-northeast rain region (NW-NE) occur under the influence of convective conditions. Other precipitation regions of Iran receive brief rains in the summer.

Table 6 has given descriptive statistics of the annual precipitation of seven precipitation regions of Iran, including minimum, maximum, and average precipitation, coefficient of variation, and coefficient of skewness. As you can see in Table 6, the maximum annual precipitation belongs to the Caspian coast precipitation region (CC) with 1069.4 mm, and the minimum precipitation pertains to the Southeast precipitation region (SE) with 56.1 mm. The coefficient of variation of annual precipitation in the seven precipitation regions of Iran bears out a wide range of variations. Hence, the southeast precipitation region (SE) has the highest coefficient of variation (34.96) and the northwest-northeast precipitation region (NW-NE) has the lowest values of the coefficient of variation (14.47) (Table 6). The coefficient of variation is an index that takes into account the changes in the variable under study, which are the annual precipitation values of the stations compared to their long-term average in percentage. Precipitation regions whose coefficient of variation values are higher than other precipitation regions are those regions whose annual precipitation values possess large changes from year to year compared to the long-term average, and this can show an uncertain attitude to the rains as a main source of water supply in these regions. However, the regions with lower coefficient of variation evidence different conditions compared to other regions. The annual precipitation changes from year to year in these regions are very low and the reliability of precipitation as a principal source of water supply is very high (Balouchi et al. 2022).

The skewness coefficient values for the precipitation regions under study also reveal that the three precipitation regions of Zagros High (ZH), Northwest-Northeast (NW-NE), and Southwest (SW) are negative. The rest of the precipitation regions, including the Southeast (SE), West (W), Caspian coasts (CC), and Central Iran (CI) have positive skewness (Table 6). If the number of the data above the average is more than the data below the average, or on the contrary if the number of data below the average is more than data above the average, then the data is skewed and if they are equal, the data are symmetric. The first case is left-skewed, the second case is right-skewed and the third case is symmetrical distribution (Balouchi et al. 2022). Indeed, skewness shows the deviation of the data to one edge of the symmetrical distribution. Whenever the skewness coefficient of a precipitation region is between 0.1 and -0.1, it upholds the symmetry of the data curve of that precipitation region. But when the skewness coefficient for the average annual precipitation of a precipitation region is over 0.5 or less than 0.5, their data curve will have a high skewness. Thus, precipitation regions with a positive skewness coefficient have a high potential for the occurrence of droughts. The highly irregular temporal and spatial distribution of precipitation in different years, being far from moisture sources, the establishment of high pressure in the subtropical atmosphere of Iran in the semi-hot part of the year, and its highly seasonal precipitation regime can be the most important reasons for this skewness in these regions in Iran.

Table 6. Descriptive statistics of seven precipitation regions of Iran.

Regions	Minimum Precipitation	Average precipitation	Maximum precipitation	Coefficient of variation of precipitation	Precipitation skewness
SE	56.1	156.7	281.1	34.96	**0.86**
SW	130.7	290.3	457	25.90	**0.11**
CI	81.3	125.5	188.4	22.38	**0.23**
HZ	372.5	659.4	880.1	17.42	**0.43**
W	327.5	488.2	770.1	20.19	**0.77**
NW-NE	209.5	315.2	390.3	14.47	**0.37**
CC	511.7	755.5	1069.4	15.01	**0.63**

The Percentage of Normal Precipitation Index (PNPI) was calculated on an annual scale for all seven precipitation regions of Iran and was prepared for their time series. Plotting the time series Diagram of the Percentage of Normal Precipitation Index (PNPI) for the seven precipitation regions of Iran revealed some similarities between the behavior of the time series of this index among the seven precipitation regions of Iran. The behavior of the time series of percent of normal precipitation index (PNPI) for the four precipitation regions of Southwest (SW), Central Iran (CI), High Zagros (HZ) and Northwest-Northeast (NW-NE) are almost similar to each other (Fig. 7). However, these similarities do not rest for the three precipitation regions of Southeast (SE), West (W), and Caspian coast (CC) (Figure 7). Precipitation regions of Southwest (SW), Southeast (SE) and Central Iran (CI) have the highest frequency of drought with 7 drought events, and the precipitation region of the Caspian coast (CC) has the lowest frequency of drought occurrence with 2 drought events (Figure 7).

Time series analysis of annual rainfall variability index (ARVI) and distribution percentage of very dry, dry, normal and wet years were calculated for Iran, respectively (Figures 8 and 9). As you can see in Figure 8, the behavior of the time series for the annual rainfall variability index (ARVI) differs from each other for each precipitation region. 1990, 2008 and 2010 were the driest years in Iran according to this index. The highest frequency of very dry and dry years

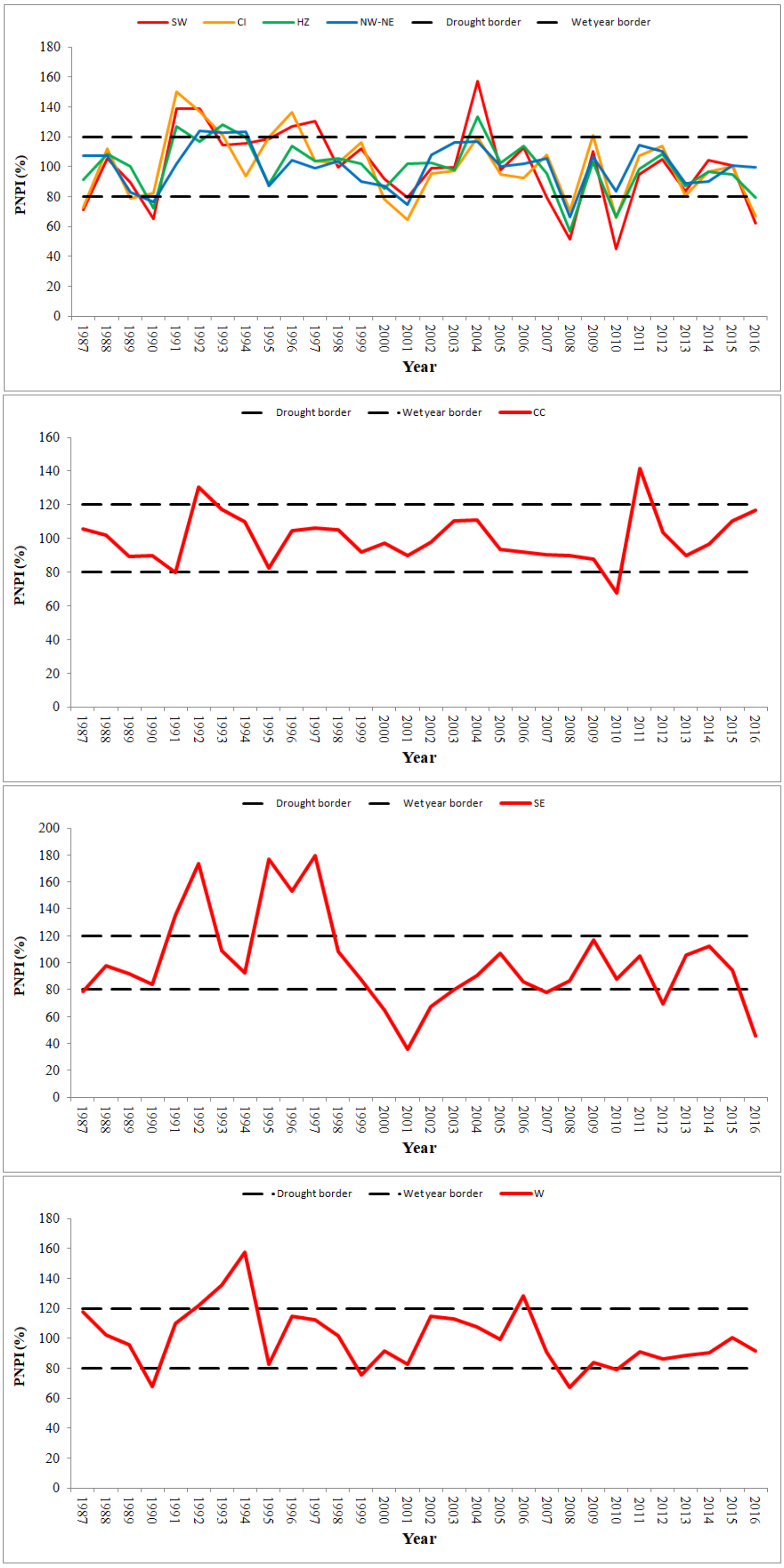


Figure 7. Time series diagram of The Percentage of Normal Precipitation Index (PNPI)for the seven precipitation regions of Iran.

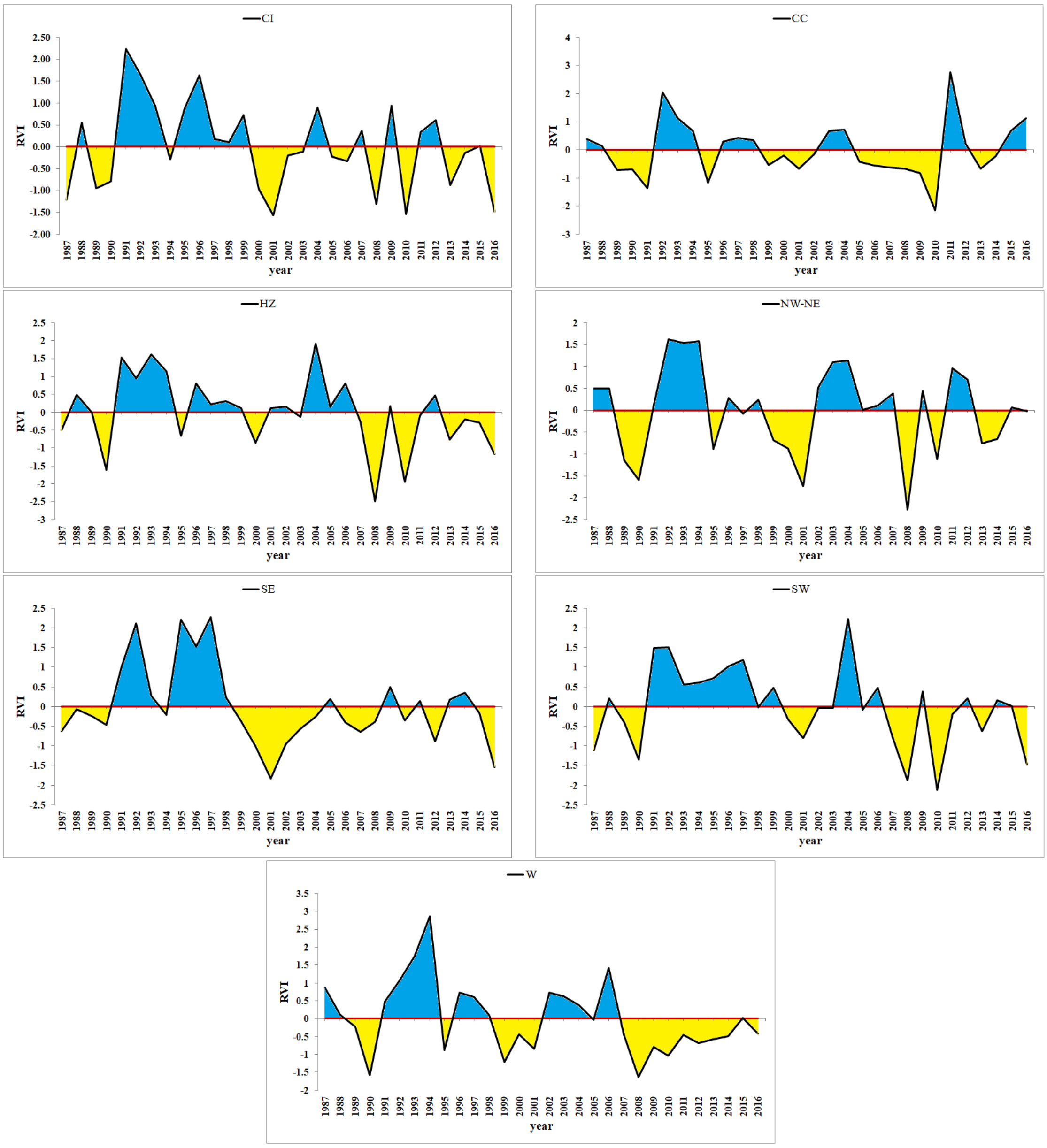


Figure 8. Time series diagram of changes in the annual rainfall variability index (ARVI) for the seven precipitation regions of Iran during the period of 1987-2016.

belonged to the southwest (SW), north-west-northeast (NW-NE) and central Iran (CI) precipitation regions (Figure 9).

The slope value of the long-term change trend in annual precipitation was tested through the Sen's slope estimator, and their significance at the probability level of α=0.05 through the Mann-Kendall test. Table 7 gives the results. As Table 7 visualizes, the slope of the long-term change trend in annual precipitation is decreasing in all seven precipitation regions under study in Iran. However, only the slope of the change trend in the three precipitation regions of Southwest (SW), High Zagros (HZ) and West (W) was significant at the α=0.05 probability level.

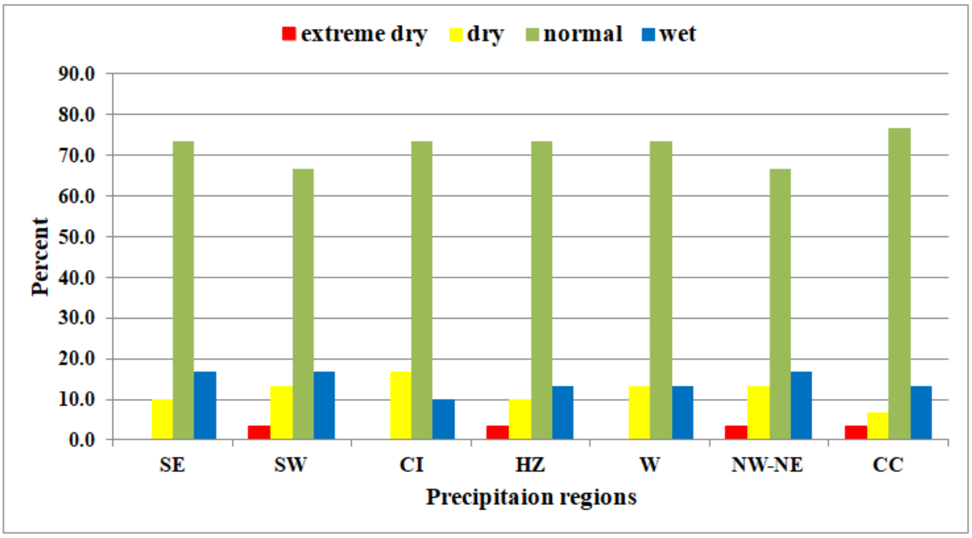


Figure 9. Frequency of occurrence of very dry, dry, normal and wet years for the seven precipitation regions of Iran.

Table 7. Results of the analysis of the changes in the annual precipitation values of the seven precipitation regions of Iran.

precipitation regions	CC	NW-NE	W	HZ	CI	SW	SE
trend slope	-0.18	-0.68	-3.89*	-4.07*	-0.95	-0.65*	**-0.82**

4.2 Drought Climatology for precipitation Regions of Iran

The deciles index (DI) for the seven precipitation regions under study is calculated first on an annual scale to analyze Iran's droughts and is shown its results in Figure 10. The first, second, third, and fourth deciles show very severe, severe, moderate, and weak droughts, respectively. As analyses reveal, all the seven precipitation regions of Iran, during the years 1990 and 2008, have experienced different classes of severity of droughts. Putting it otherwise, the most widespread droughts in Iran have occurred in these two years (Figure 10). 2001, 2010 and 2013 have witnessed extensive droughts among the seven studied precipitation regions (Figure 10). The longest drought period belongs to the West Precipitation Zone (W), which lasted 8 years (2007-2014). Five-year periods of droughts have taken place in the southeast (SE) and Caspian coasts (CC) between 1999-2003 and 2006-2010, respectively.

We divided the 30 years under study (1987-2016) into three ten-year sub-periods (1987-1996), (2006-1997) and (2007-2016) and observed the changes in the frequency of severe and very severe droughts during these three sub-periods (Figure 11). As is visible in Figure 11, the frequency of severe and very severe droughts from the first decade (1987-1996) towards the third decade (2007-2016) has increased in the four precipitation regions of Southeast (SE), Southwest (SW), Central Iran (CI) and High Zagros (HZ). Therefore, these four precipitation regions are probably among the most vulnerable precipitation regions of Iran to drought. This trend is reversed in the two precipitation regions of North-

West-North-East (NW-NE) and Caspian Coast (CC), and the frequency of severe and very severe droughts has decreased. Thus, four severe and very severe droughts were recorded in the first decade (1987-1996) in the Caspian Coast (CC) precipitation region, while this frequency in the second decade (1997-2006) was zero and reached 2 occurrences in the third decade (2007-2016) (Figure 11). The western precipitation region was the only region where changes in this trend did not take place, and severe and very severe drought occurred every 2 decades (Figure 11).

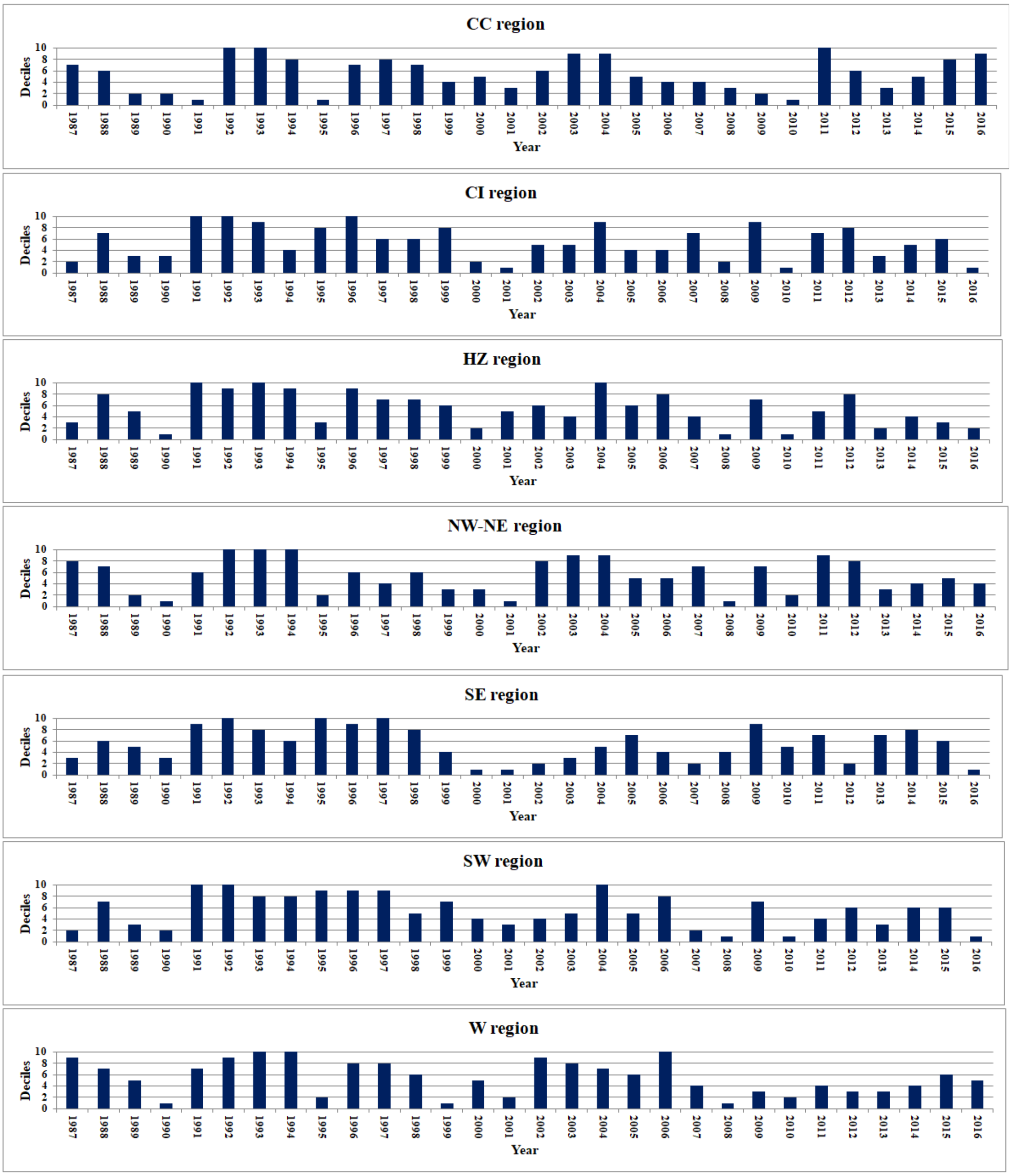


Figure 10. Diagram of time series of The deciles index (DI) for the seven precipitation regions of Iran for the

statistical period of 1987-2016.

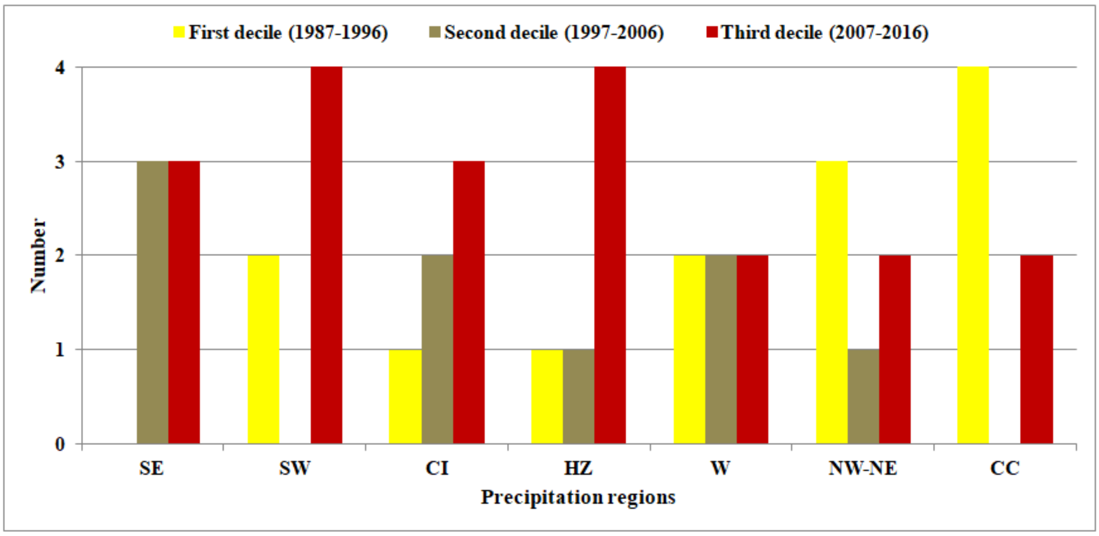


Figure 11. Total number of severe and very severe droughts based on decade division for the seven precipitation regions of Iran.

The second drought index the research used to analyze droughts in the seven precipitation regions of Iran is the Standardized Precipitation Index (SPI). This index is calculable in different time scales. The time scales of 3, 6, and 9 months of this index are much more efficient for studying the effect of drought on the agricultural sector (Paulo and Pereira 2008), and the time scales of 12 and 24 months are so for examining the effects of droughts on water resources management (Raziei 2009). Therefore, the standardized precipitation index (SPI) was calculated on an annual scale (1987-2016) for the seven precipitation regions of Iran, and Figure 12 shows its results as seven diagrams. The highest number of occurrences of droughts during the period under study appertained to the precipitation region of the Caspian coast (CC) (12 occurrences) and the precipitation region of the northwest-northeast (NW-NE) (10 occurrences). High Zagros Precipitation Zone (HZ) also had the lowest number of drought occurrences, with 7 occurrences. The most severe and widespread droughts took place in 2001, 2008, and 2010, respectively, and almost all seven precipitation regions under study underwent different classes of drought. The lowest value of the standardized precipitation index (SPI) pertained to the high Zagros precipitation region (HZ) with a value of -2.84, which was recorded in 2008 (Table 8). Table 8 gives the characteristics of droughts on an annual scale for the seven precipitation regions under study.

The highest frequency of weak droughts has been outlined in the precipitation region of the Caspian Sea coast (CC), while the frequency of moderate droughts for five of the seven precipitation regions of Iran was equal to 6.7% in the entire period under study. However, the highest percentage of severe droughts has been observable in the precipitation region of Central Iran (CI). Precipitation regions of Southwest (SW) and High Zagros (HZ) also possessed the highest frequency of very severe droughts (Figure 13). However, the frequency of extremely severe droughts is much lower compared to other classes of droughts; Moreira et al. (2008) have discussed this earlier. A general summary revealed that the precipitation regions of

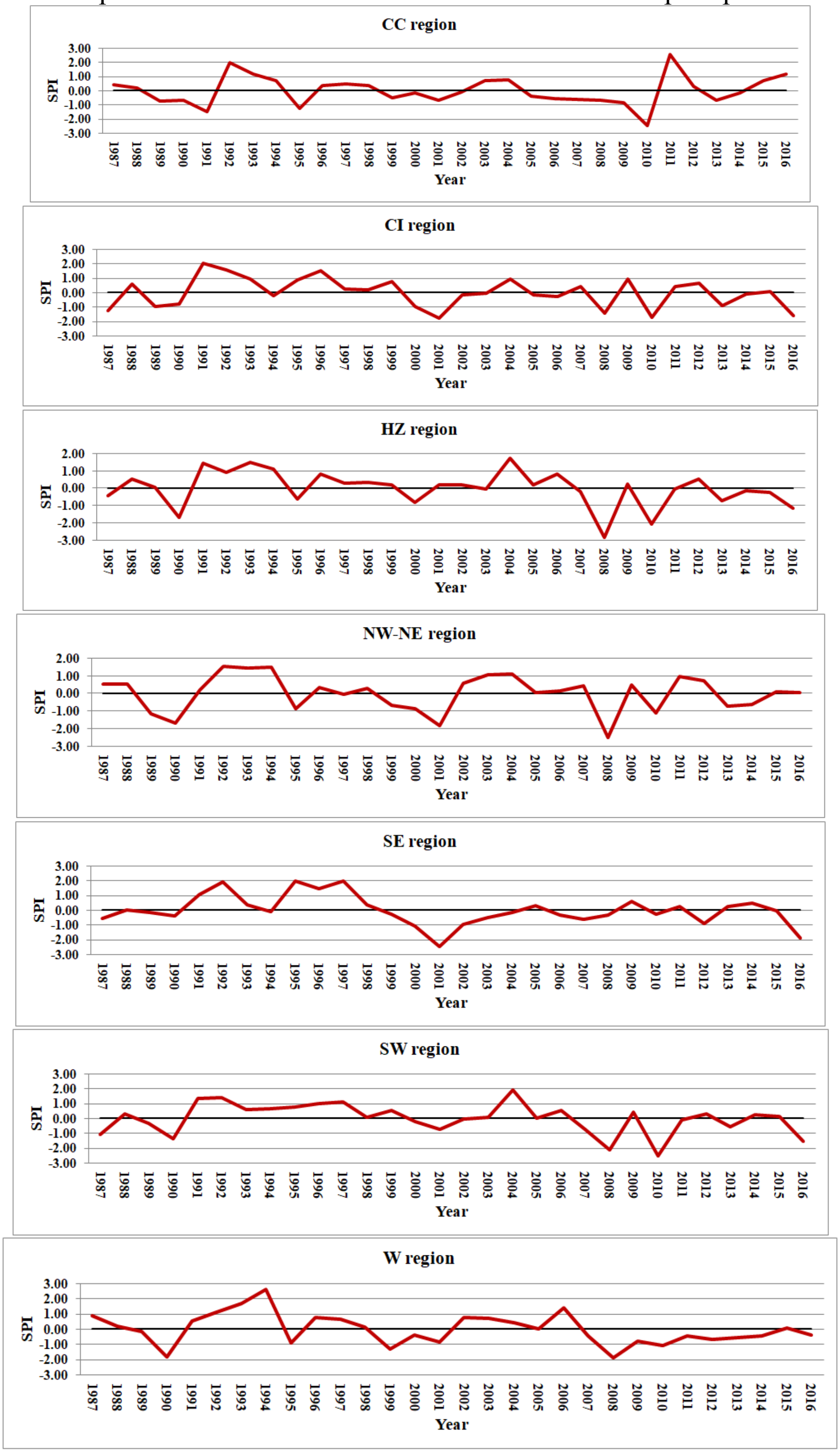


Figure 12. Diagram of time series of Standardized Precipitation Index (SPI) for seven precipitation regions of Iran for the statistical period of 1987-2016.

Table 8. Characteristics of annual droughts in the seven precipitation regions of Iran, based on the Standardized Precipitation Index (SPI).

precipitation regions	The most severe drought		Number of droughts observed during the study period				
	SPI value	year	Mild	Moderate	Severe	Extreme	Total
SE	-2.46	2001	5	1	1	1	8
SW	-2.52	2010	3	2	1	2	8
CI	-1.75	2001	4	2	3	0	9
HZ	-2.84	2008	3	1	1	2	7
W	-1.86	2008	5	2	2	0	9
NW-NE	-2.51	2008	5	2	2	1	10
CC	-2.46	2010	9	2	0	1	12

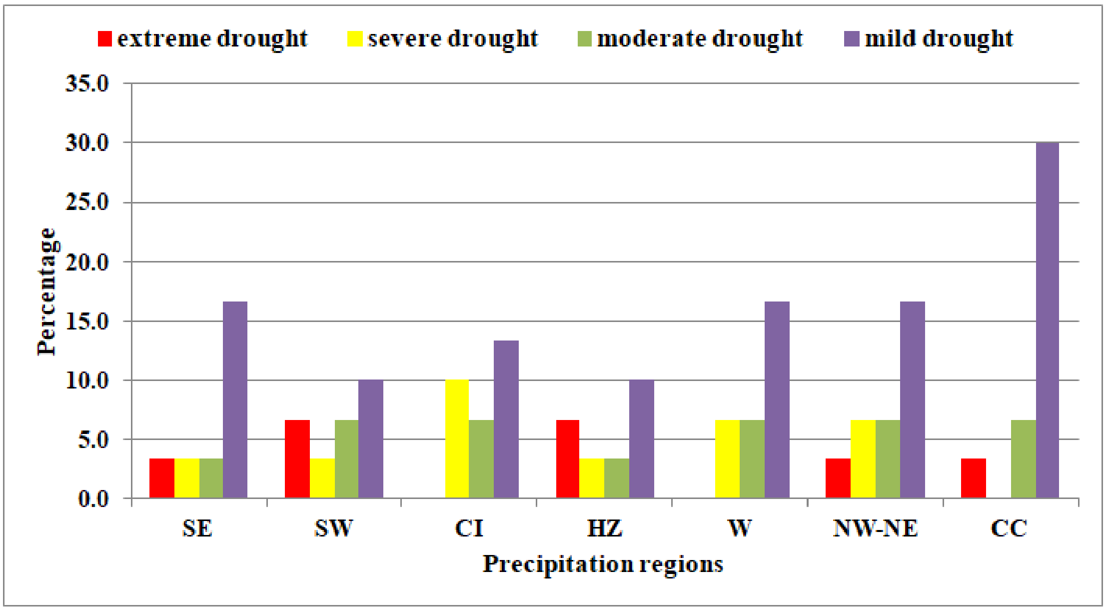


Figure 13. Frequency percentage of occurrence of different classes of annual droughts in the seven precipitation regions of Iran, based on the Standardized Precipitation Index (SPI) for the period of 1987-2016.

the Caspian coast (CC) and North-West-North-East (NW-NE) have the highest frequency of droughts with 40 and 33.3%, respectively, and the high Zagros region (HZ) with 23.3 percent owned the lowest percentage of droughts (Figure 13).

The annual values of three indices, standardized precipitation index (SPI), precipitation variability index (RVI) and percent of normal precipitation index (PNPI), were plotted on diagrams and their correlation coefficient was calculated in order to evaluate their ability in monitoring droughts in the seven precipitation regions of Iran. Figure 14 reveals the example of the time series diagram of the annual values of the three indices in this study for the Southeast (SE) precipitation region. This diagram (Figure 14) clarifies that the behavior of the time series of these three indicators in monitoring the droughts of the Southeast (SE) precipitation region and other precipitation regions of Iran are almost similar to each other. The annual values of the two rainfall variability indices (RVI) and the percent of normal precipitation index (PNPI) in monitoring droughts in the precipitation regions of Iran are completely consistent with each other, and this consistency is also observable in the numerical value of the correlation coefficient. The value of the correlation coefficient between these two indicators for all the precipitation regions of Iran was approximately 0.99. Albeit, this coordination decreases a bit for the Standardized Precipitation Index (SPI). The standardized precipitation index (SPI), compared to the other two indices, shows droughts a bit more severe and precipitation years a bit milder. The correlation coefficient of the annual values of this index with two indices of precipitation variability (RVI) and the percent of normal precipitation index (PNPI) was about 0.97. Therefore, these three indicators have a direct relationship with each other and all three have the same performance in monitoring droughts in the precipitation regions of Iran.

The trend of long-term changes in standardized precipitation index (SPI) values on an annual scale was analyzed through the Sen and Mann-Kendall slope estimator methods. The results showed that the slope of the standardized precipitation index (SPI) values during the 30-year period under study (1987-2016) was a decreasing trend for all seven precipitation regions of Iran (Table 9). This decreasing trend upholds the intensification of droughts for all seven precipitation regions of Iran. But it is noteworthy that the slope of these changes is not the same for the seven precipitation regions under study. Rather, the slope of the change trend is high for some regions, such as the precipitation region of the West (W) and low for some other regions, such as the precipitation region of the Caspian coast (CC) (Table 9). The significance of the slope of the change trend was also tested through the Mann-Kendall method. As the results showed, the slope of change trend in the three precipitation regions of Southwest (SW), High Zagros (HZ) and West (W) was significant at the α=0.05 probability level (Table 9). The results of the trend analysis of this section are completely consistent with those of the annual precipitation trend analysis. Putting it otherwise, a decrease of precipitation in different precipitation regions of Iran has aggravated droughts in Iran.

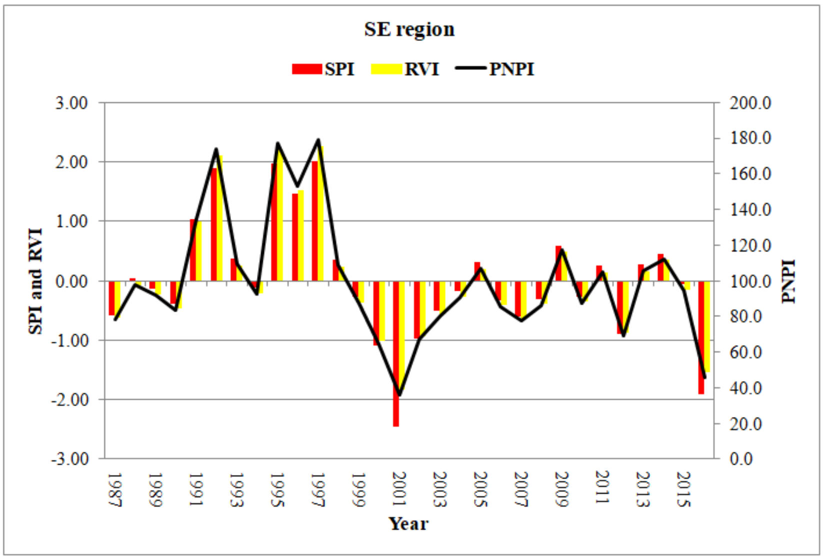


Figure 14. Comparison of the annual values of the standardized precipitation indices (SPI), the precipitation variability index (RVI) and the percent of normal precipitation index (PNPI) during monitoring droughts in the seven precipitation regions of Iran (1987-2016).

Table 9. Results of the trend analysis of the changes in the values of the Standardized Precipitation Index (SPI) on an annual scale for the seven precipitation regions of Iran.

precipitation regions	CC	NW-NE	W	HZ	CI	SW	SE
trend slope	-0.002	-0.014	-0.043*	-0.033*	-0.035	-0.035*	**-0.016**

5 Discussions

This study aimed to construct a comprehensive, regionally nuanced climatology of precipitation and drought across Iran. Our approach integrated the validation of high-quality gridded data (GPCC), an objective data-driven regionalization, and a multi-index, multi-scalar analysis of drought characteristics and trends. The findings not only delineate Iran's hydroclimatic heterogeneity but also reveal critical patterns of drought vulnerability with significant implications for water resource management.

A foundational step was to establish a reliable precipitation dataset for a country marked by complex topography and uneven station distribution. Our validation confirmed the GPCC dataset's superior capacity to capture spatial precipitation patterns (R^2 = 0.97) compared to other products, justifying its use for regionalization and standardized drought analysis. This aligns with a consensus in regional hydroclimatic research favoring GPCC for its robust gauge-based foundation (e.g., Saemian et al., 2021; Hosseini-Moghari et al., 2018). While we noted a consistent magnitude difference relative to our station network—a common issue stemming from varied interpolation algorithms and station densities (Schneider et al., 2014)—the strong agreement in inter-annual variability ensures the fidelity of relative dynamics, which is paramount for calculating standardized indices like SPI and for identifying coherent climatic zones.

Moving beyond administrative boundaries, our cluster analysis objectively partitioned Iran into seven distinct precipitation zones, providing a robust framework rooted in meteorological reality. The geographical configuration of these zones is a direct testament to the dominant control of Iran's macro-scale orography and its location at the crossroads of major atmospheric circulation patterns. The Caspian Coast (CC) zone, for instance, stands as a stark anomaly of high precipitation, unequivocally shaped by moisture advection from the Caspian Sea and the powerful orographic lift of the Alborz Mountains. In sharp contrast, the vast Central Iran (CI) zone embodies the classic rain shadow effect, where the towering Zagros and Alborz ranges act as barriers to moisture-bearing westerly systems, condemning the interior plateau to the arid and hyper-arid conditions of the Dasht-e Kavir and Dasht-e Lut deserts. Similarly, the High Zagros (HZ) and West (W) zones capture the precipitation gradient across the Zagros massif, which intercepts westerly systems and is the primary water tower for western Iran (Alijani, 2008). The other zones (SE, SW, NW-NE) represent unique transition areas, influenced by different moisture sources and atmospheric dynamics, such as occasional intrusions from the Arabian Sea in the southeast (Mahoutchi et al., 2023) or a complex interplay of westerly systems in the northwest and northeast. This data-driven regionalization provides the essential spatial context that national-level analyses often obscure, allowing for a more meaningful assessment of drought vulnerability.

Indeed, our multi-index drought assessment revealed profound spatial heterogeneity in vulnerability. The Central Iran (CI), Southwest (SW), and the geographically distinct but climatologically linked Northwest-Northeast (NW-NE) zones consistently emerged as hotspots of frequent and intense drought. The vulnerability of the CI zone is a direct consequence of its inherent aridity and high variability, where even moderate negative precipitation deviations trigger severe drought conditions. More revealing is the high vulnerability of the SW zone; despite its moderate mean precipitation, it suffers from significant drought, likely due to a combination of high inter-annual variability, greater sensitivity to shifts in winter storm tracks south of the main Zagros ridge, and potentially higher evaporative demand not captured by precipitation-only indices (Bari Abarghouei et al., 2011). The consistency of these findings across multiple indices (SPI, PNPI, DI), each with different theoretical underpinnings, strengthens the conclusion that these zones are Iran's most drought-prone regions. This multi-index approach is crucial, as it provides a more holistic and robust picture of drought risk than any single index could alone (Mahmoudi et al., 2019b).

Furthermore, our trend analysis signals a potential intensification of these vulnerabilities. The significant negative trends in SPI observed over the 1987-2016 period, particularly within the already vulnerable CI, SW, and NW-NE zones, suggest an escalating risk of water stress. These drying trends are consistent with broader regional observations across the Middle East, which are often linked to large-scale atmospheric shifts and are in line with climate model projections for the region under continued global warming (Nouri and Homaee, 2020). The lack of a significant trend in the Caspian Coast (CC) zone, for example, highlights its distinct climatic drivers, reinforcing the necessity of a regionalized approach to trend analysis.

While this study provides a robust, spatially detailed climatology, certain limitations must be acknowledged to guide future work. The 0.5° resolution of the GPCC data, though the best available for this analysis, may not fully resolve orographic precipitation in highly complex terrains like the Zagros and Alborz. Future research should leverage higher-resolution datasets and incorporate temperature-driven evaporative demand through indices like SPEI to provide a more complete assessment of agricultural drought. Moreover, the 30-year study period, while standard, warrants longer-term analysis to better disentangle multi-decadal natural variability from anthropogenic trends. The findings, however, carry immediate and significant implications. The identification of specific drought-vulnerable zones provides a scientific basis for prioritizing investments in water management infrastructure, developing targeted agricultural adaptation strategies, and designing region-specific early warning systems. The observed trends are a clear call to action, emphasizing the urgency of integrating climate change projections into national and regional policy to build resilience in Iran's most vulnerable regions.

5 Conclusions

This study successfully constructed a robust climatological framework for understanding regional drought patterns across Iran. By integrating validated gridded data with objective regionalization, we moved beyond administrative boundaries to identify seven hydroclimatically coherent zones, providing an essential foundation for localized risk assessment.

The primary scientific contribution of this work is its integrated methodology, which provides a replicable, data-driven template for national-scale drought analysis in regions with complex topography. The key takeaway is the stark spatial heterogeneity in drought vulnerability, with the Central, Southwest, and Northwest-Northeast zones identified as priority areas for intervention. Our findings confirm that a one-size-fits-all approach to drought management in Iran is inadequate. The significant drying trends observed in critical water-producing regions underscore the urgent need for proactive, evidence-based policy.

While our analysis provides a comprehensive meteorological overview, it is bounded by its focus on precipitation deficits and the resolution of the dataset. Future research should build directly on this work by: 1) incorporating temperature effects through indices like SPEI to assess the impact of warming on drought intensity; 2) utilizing high-resolution climate model outputs to project future changes within our identified vulnerable zones; and 3) investigating the teleconnections between large-scale climate oscillations and drought characteristics within each specific region to improve predictive capabilities. These steps are critical for translating this diagnostic climatology into actionable, forward-looking strategies for enhancing Iran's water security and climate resilience.

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