

Investigating the relationship between SPI and UNEP aridity indices with trend of the dust storm index in the central region of Iran

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ABSTRACT

The dust phenomenon has many dangers for human society and is of special importance for the residents of Iran. Different researchers have studied this phenomenon from different angles. In terms of the significance of the subject and the dangers arising from it, it is still at the top of the topics of interest of researchers all over the world. This research aims to use DSI, UNEP and SPI Indices in the evaluation and zoning of dust storms in Semnan Province. In this research, the temporal distribution of dust storms in Semnan, taking into account the weather conditions and the average wind speed of the study area during the years 2003 to 2017, was investigated in five synoptic stations. The homogeneity of climatic parameters and dust storm indices and the trends of these two variables were calculated using linear regression in the SPSS software environment, and after examining the changing trend of the UNEP index, the resulting information was zoned in the ArcGIS software environment. Correlation between drought indices, rainfall standard, and DSI shows that the DSI index has increased during the analyzed period at the same time as the severity of drought increased and its correlation with SPI during the 15 years was significant ($R^2=0.89$). These results showed that increasing the amount of drought index has a positive effect on increasing the amount of drought index, also the occurrence of dust storms has increased with the increase of the drought index.

Highlights

- DSI in Semnan rose from 2003-2017, peaking in 2011, tied to worsening drought ($R^2=0.89$ with SPI).
- UNEP index zones Semnan as arid, highly prone to desertification across all stations.
- SPI shows moderate drought in Damghan (-0.15), normal conditions elsewhere in Semnan.
- Dust storms surged west-to-east, linked to moderate dust days (MDS), per DSI zoning.
- June-July high winds and low moisture drive dust storms, per climatic data analysis.

1. Introduction

Droughts, which occur frequently as a natural disaster, can have various impacts on water resources including the supply and quality of water, as well as the availability of both surface and subsurface water. In addition, proper management of water resources may also be affected by droughts, as reported by several studies (van Loon et al., 2014; Amin et al., 2016; FAO, 2017; Scanlon et al., 2017). Four types of droughts are generally acknowledged, with the first one being meteorological drought. This type of drought is due to insufficient precipitation (Beguiría et al., 2014; Das et al., 2016; Ahmadalipour et al., 2017; Hameed

et al., 2018). The second type of drought is agricultural drought, which takes into account the deficit of moisture in the soil (Gao et al., 2014; Mishra et al., 2015; Nichol & Abbas, 2015; Vicente-Serrano et al., 2015; Yan et al., 2017; Karimi Sangchini et al., 2020). The third type of drought is hydrological drought, which refers to a deficiency of both surface and subsurface water (Barker et al., 2016; van Loon & Laaha, 2015; Zhang, 2017). The fourth type of drought is socio-economic drought, which considers the inadequacy of the water resources system caused by the other types of droughts (Huang et al., 2016; Maia et al., 2015). With the rise in global temperatures, the rate at which water moves

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around the planet is increasing causing more frequent and severe instances of extreme weather like floods and droughts (Guo et al., 2019; Han et al., 2019; Ren et al., 2019; Yu et al., 2020). Drought is often measured using drought indices. However, because the concept of drought is multifaceted and difficult to define precisely, no single measure can fully capture all aspects of drought severity and the impacts it has (Vicente-Serrano et al., 2020; Lloyd-Hughes, 2014). According to Sun et al. (2019), there has been a growing trend of droughts that vary in their intensity and duration, lasting anywhere from one month to several years (Yousefi Mobarhan et al., 2023, Yousefi Mobarhan et al., 2024). Additionally, Middleton (2017) notes that dust storms have become a significant natural hazard worldwide, particularly in regions that are arid or semi-arid. This occurrence is noticeable in regions that undergo consistent droughts, minimal precipitation and moisture, unstable and susceptible soil, insufficient flora, and powerful winds (Goudie, 2018). Conversely, if an area has appropriate vegetation and beneficial environmental and ecological circumstances, the number of these storms is infrequent. They are more likely to happen in hot and arid climates with sparse and dispersed vegetation (Xiao et al., 2008; Tan, 2016; Goudie & Middleton, 2006). Due to its location on the desertification and wind erosion belt and having over 30% of its territory being arid or semi-arid, Iran is at risk of this occurrence. The recent prolonged periods of drought have led to significant portions of Iran being affected by dust storms. These storms are more frequent and severe in the eastern and western parts of the country compared to other regions, with the southeast being recognized as one of the primary sources of dust globally (Arami et al., 2018; Fiedler et al., 2014; Miri, 2020; Miri et al., 2009; Rashki et al., 2013).

The impacts of dust storms on the environment are extensive. Apart from the source regions where millions of tons of soil particles are lost, they also affect transportation and sedimentation environments. These storms cause air pollution due to the surge in dust particle concentration, posing a threat to human health, reducing visibility leading to accidents on roads, destroying farmlands, reducing crop yields, and burying residential areas. These detrimental consequences are among the effects of this phenomenon (Middleton, 2017; Miri et al., 2007; Wang et al., 2006; Xiao et al., 2008). Overall, it can be concluded that the wide expanse of dry and semi-arid climates in Iran and neighboring countries, coupled with the inappropriate utilization of water and soil resources, have led to wind erosion and the occurrence of dust and quicksand

phenomena. These phenomena impact population centers, industrial regions, agricultural lands, and infrastructure structures annually (Yousefi Mobarhan & Khaleghi, 2024). Based on the research carried out in this area, it can be asserted that climate data has not been utilized for dust storm classification in Semnan province so far. The occurrence of dust storms and quicksand movements is viewed as a critical land degradation process and a significant obstacle in Iran, particularly in Semnan province. As climatic factors significantly contribute to this phenomenon, their consideration is crucial (Yousefi Mobarhan et al., 2021). Hence, it is crucial to investigate and comprehend these factors that contribute to the emergence and escalation of dust phenomena in order to prevent environmental crises in the future. This study aims to assess and categorize the dust phenomenon in Semnan province by analyzing the climatic data collected from synoptic stations. The primary objective is to explore the relationship between drought patterns, UNEP¹ method, SPI², and DSI³ from 2003 to 2017 in Semnan province.

2. Materials and methods

Semnan province is located between 34° 17' to 37° 51' N and 51° 58' to 57° 58' E and approximate area of 98,000 square kilometers. This region is located on the southern slopes of the Alborz Mountain range and covers more than half of its surface area with desert plains. The elevation of the province gradually decreases from the north to south, with a difference of more than 3000 meters in height. The average altitude above sea level is 1067 meters, and it can be divided into three distinct regions: mountainous, foothills, and lowland areas. The temperature in this province ranges from 12.8 to 23.7 degrees Celsius, and the average temperature is 18.3 degrees Celsius. The annual rainfall is around 136 mm. Figure 1 shows the geographical location of the study area and the position of the synoptic stations within Semnan Province.

2.1. Analysis of climatic data

To assess both the climatic aspects and the movement of sand dunes in the region, the quality control data from Semnan Meteorological Organization was utilized. To achieve this goal, five synoptic stations were carefully chosen within the study area based on both the availability of data and the research objectives. The data collected from these stations spanned the period from 2003 to 2017, and Table 1 provides detailed information on the specifications of the selected stations.

Table 1. the characteristics of the synoptic stations of Semnan Province

Rows	Station Name	Longitude	Latitude	Sea Level (M)	Average Precipitation (mm)
1	Biyarjomand	55.81	36.09	1099	122
2	Damghan	54.32	36.15	1155	107
3	Semnan	53.42	35.59	1127	136
4	Shahrud	54.39	36.38	1325	164
5	Garmsar	52.36	35.24	899	184

2.2. Determining the Dust Storm Index (DSI)

¹ United Nations Environment Programme

² Standardized Precipitation Index

³ Dust Storm Index

The DSI index was computed for a 15-year period at the synoptic stations situated in Semnan province using Eq. 1. The overall value of the DSI index was then established for Semnan province by aggregating the values obtained from each station. The annual changes in the DSI trend were analyzed through statistical and experimental means, and the gathered information was eventually categorized into zones.

$$DSI = \sum_{i=1}^n [(5 \times SDS) + MDS + (0.05 \times LDE)]_i \quad (1)$$

SDS = Stormy days with severe dust, total observations of dust codes, maximum daily code 33-35

MDS = Stormy days or average dust, total observations of dust codes, maximum daily code 30, 32, and 98

LDE = Days of storms or local dust, the sum of observations of dust codes, daily maximum code 07 and 09

The Dust Storm Index (DSI) was recorded at several stations during a specific period to determine the impact of drought on fine dust. Trend analysis was conducted by comparing the trends of these variables from 2003 to 2017, using least square linear regression against the relevant climate data (Yousefi et al. 2021).

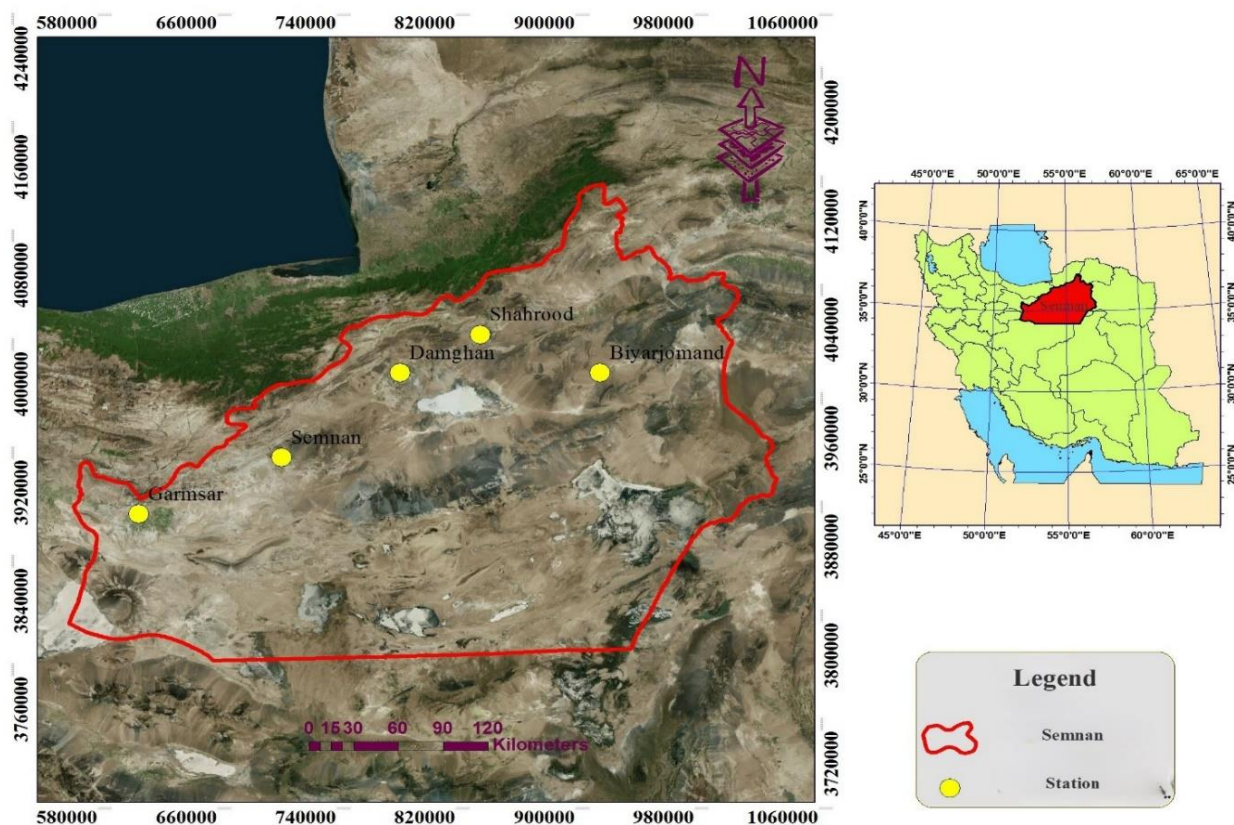


Figure 1. Geographical location of synoptic stations in the study area

2.3. Determining the Standard Rainfall Index (SPI)

To develop effective strategies for managing drought, monitoring systems play a crucial role. To quantify this phenomenon, drought indices are utilized. One such index is the Standard Precipitation Index (SPI), which measures rainfall deficits across various time scales ranging from one to 48 months (McKee et al., 1993).

The SPI is a precipitation-based drought index that assumes two hypotheses: firstly, that precipitation variability outweighs other variables like temperature and potential evaporation/transpiration, and secondly, that other variables have insignificant time trends. As one of the most commonly used indices in drought monitoring, SPI helps assess dry periods by including a time scale in its calculations. Monitoring systems for calculating SPI are vital for developing plans to manage and mitigate drought. Overall, drought indices like SPI quantify the phenomenon

of rainfall deficit across various time scales. The SPI relies solely on precipitation and operates under two assumptions: firstly, that precipitation variability is significantly greater than that of other variables like temperature, evaporation, and transpiration; and secondly, that other variables do not have significant time trends. This index is widely used in drought monitoring and assesses dry periods by including a time scale.

SPI and SPEI calculations are based on average values over the area of interest, with a value of 0 indicating near-average conditions for that particular region. However, the same value for SPEI can indicate varying degrees of water stress in different regions, depending on their respective long-term averages (Parsons et al., 2019).

The time scale for drought assessment varies based on the effects it has on hydrological and agricultural resources. The time scale can range from one month to several years.

Table 2. Classification of SPI index

Severity of drought	SPI
Acute fear	<2.00
Extreme fear	1.99 – 1.55
Moderate fear	1.49 – 1.00
Normal	0.00 – 0.99
Moderate drought	0.00 - -0.99
Extreme drought	-1.00 - -1.49
Acute drought	-1.50 - -1.99

SPI calculations are solely based on precipitation data. In this study, rainfall data from a three-month period within the desired time scale was used to calculate SPI values for each station. The calculation of SPI involves Eq. 2 and two classification values are presented in the table (Yousefi Mobarhan & Zandifar, 2023).

$$SPI = \frac{x_{ik} - \bar{x}_t}{\delta_i} \quad (2)$$

2.4. Determining the aridity index of UNEP

This study utilized the UNEP aridity index (UNEP, 1991) to evaluate the level of dryness in the air and climate. The index is recognized by the United Nations Convention to Combat Desertification (UNCCD) and is a useful scientific tool for assessing the climatic conditions of

regions and the likelihood of desertification. Several studies including Zare et al. (2016), Tavousi (2018), Tavosi et al. (2019), Abtahi and Darvish (2019), and Zandifar et al. (2020) have confirmed its effectiveness. Eq. 3, defined as the ratio between precipitation and potential evaporation and transpiration, is used to determine the prevailing climate and risk of desertification according to Table 3, which is based on the UNEP drought index (Yousefi Mobarhan et al., 2024).

$$I = \frac{P}{ETP} \quad (3)$$

I: UNEP index,
 P: average annual precipitation (mm)
 ETP: average potential evapotranspiration (mm).

Table 3. Climate zoning based on the UNEP aridity index

Climate type	Dryness index	The danger of desertification
Ultra Arid	I<0.05	Desert
Arid	0.05<I<0.2	Very Intense
Semi-Arid	0.02<I<0.5	Intense
Dry, Sub-Humid	0.5<I<0.65	Moderate
Sub-Humid	0.65<I<0.75	Low
Wet and very humid	0.75<I	NON

3. Results and analysis

3.1. Analysis

To gather comprehensive information on the condition of dusty days and dust storms in the study area, a statistical index spanning 15 years (from 2003 to 2017) was used. Graphs showing the long-term changes in precipitation, temperature, annual wind speed, evaporation, and transpiration were created using data from the synoptic

stations in the Semnan province. Figure 2 displays the annual potential, while Figure 3 represents the monthly potential. The highest amount of rainfall on both the annual and monthly scales occurred in 2007 and during April and May, respectively, in the Semnan province (as illustrated in Figure 2). The data presented in Figure 2 reveals that July and August experienced the highest average, maximum and minimum temperatures, while January had the lowest. On a seasonal level, the maximum and minimum temperature events occurred during summer and winter, respectively.

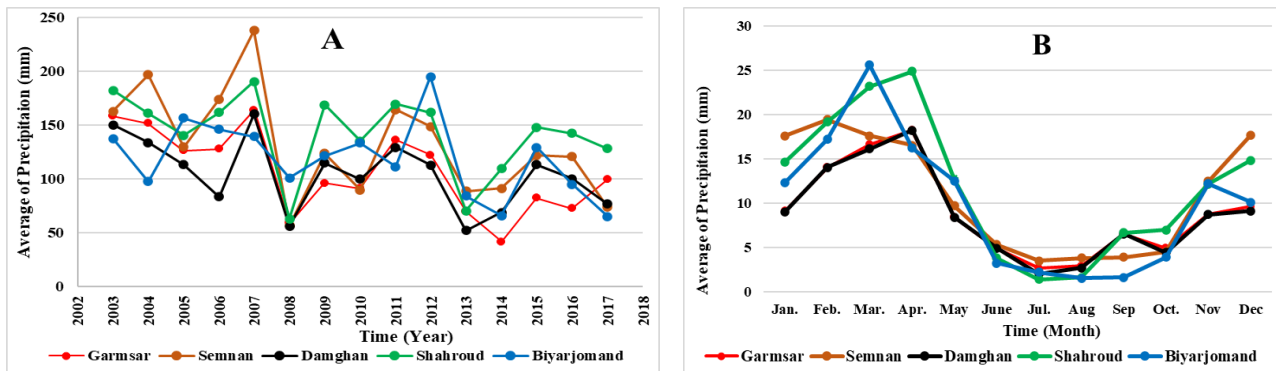


Figure 2. displays a graphical representation of the enduring alterations in yearly (A) and monthly (B) rainfall patterns observed at synoptic stations within Semnan province.

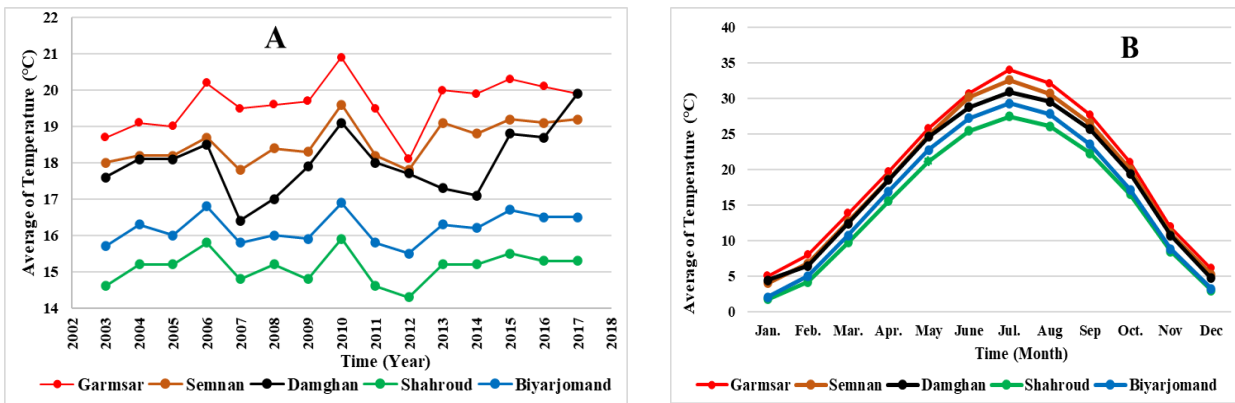


Figure 3. depicts a graphical representation showcasing the enduring alterations in yearly (A) and monthly (B) temperature patterns observed at synoptic stations within Semnan province.

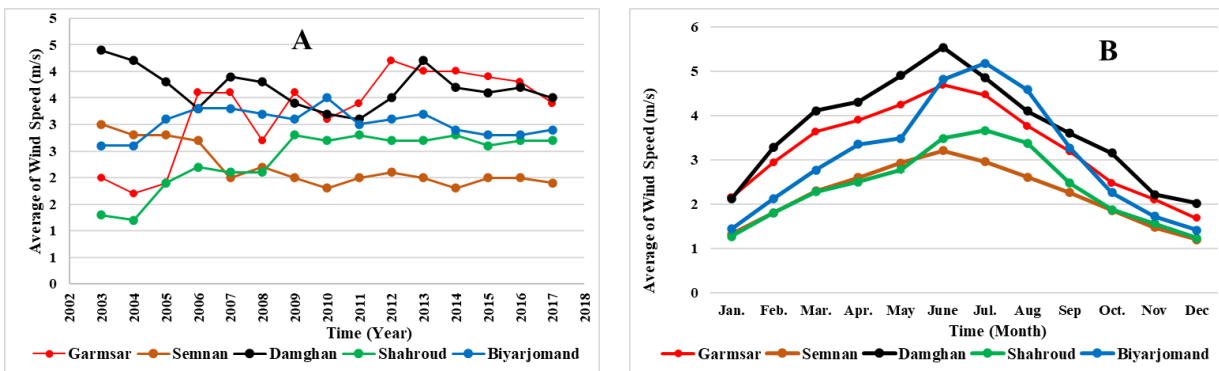


Figure 4. illustrates a graphical representation of the enduring modifications in the yearly (A) and monthly (B) wind velocity at the synoptic stations located in Semnan province.

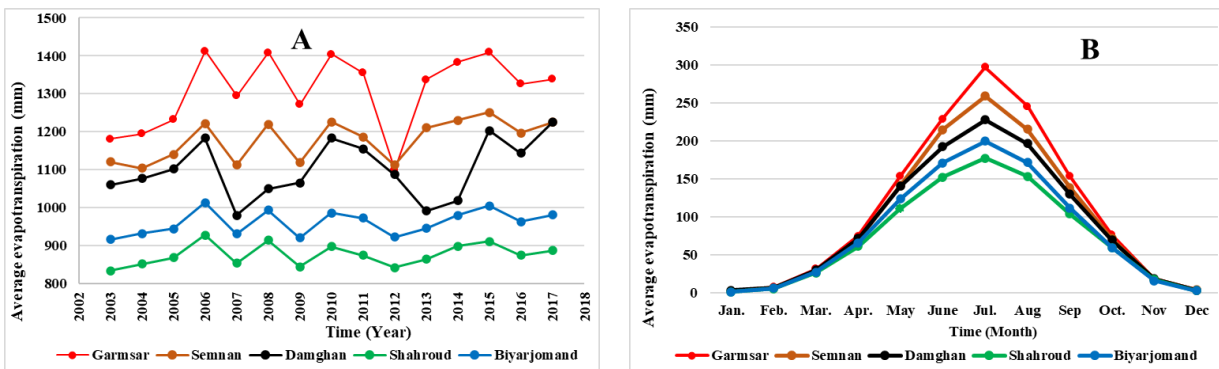


Figure 5. presents a schematic depiction of the long-term fluctuations in the yearly (A) and monthly (B) potential evapotranspiration at the synoptic stations situated in Semnan province.

Figure 3 shows that the highest surface wind speed was recorded in June and July in most of the synoptic stations of Semnan province. The analysis of potential evaporation and transpiration from 2003 to 2017 indicates that July witnessed the highest amount of these events in Semnan province, which coincides with the peak of temperature events during the same month. Other months did not observe such high levels of potential evaporation and transpiration. According Figure 4, the presence or absence of moisture is a crucial factor in the formation of dust storms alongside unstable air. If the unstable air contains adequate moisture, it leads to the occurrence of rain and thunderstorms, whereas insufficient moisture results in a dust storm. Results from the correlation analysis between monthly average temperature and the dust pollution index

indicate a positive correlation between these variables. Conversely, the relationship between the monthly average relative humidity and the dust pollution index is inverse in nature (Saavedra et al., 2012).

3.2. Status of FAO-UNEP drought index

The UNEP aridity index, which is an effective tool approved by the United Nations Convention to Combat Desertification, was utilized in this study to measure the dryness factor of the air and climate. This index has been cited in various studies as a way to assess climatic conditions and desertification risk in different areas. The first relationship, represented by a ratio of precipitation and potential evapotranspiration, is used to determine the prevailing climate and desertification risk level of a region.

Table 2 outlines the weather conditions according to the UNEP drought index (Zare et al., 2016; Tavousi, 2018; Tavosi et al., 2019; Abtahi and Darvish, 2019; Zandifar et al., 2020).

3.3. Status of SPI index

To map out the distribution of drought in the province, data from synoptic stations and changes in SPI in Semnan were analyzed, resulting in Figure 6. Out of the eight synoptic stations in Semnan, five were chosen for analysis: Biyarjomand, Damghan, Garmsar, Semnan, and Shahroud. Damghan station was found to be in the moderate drought category with an SPI index value of -0.15, while Garmsar,

Semnan, and Shahroud stations scored 0.77, 0.91, and 0.26 respectively, placing them in the normal class. The Biyarjomand station scored the highest at 1.15, indicating average precipitation levels. Table 4 summarizes these classifications. Additionally, a weak correlation between DSI and SPI indices with a correlation coefficient of 0.46 was found, suggesting an unfavorable correlation between them. Moreover, meteorological drought was found to have no impact on dust storms according to the results of the correlation analysis between SPI and DSI shown in Figure 6. The distribution of drought was determined based on the Standard Rainfall Index.

Table 4. Classification of drought based on the stations of Semnan province

Rows	Station Name	SPI	Drought class
1	Biyarjomand	1.15	Moderate fear
2	Damghan	-0.15	Moderate drought
3	Garmsar	0.77	Normal
4	Semnan	0.91	Normal
5	Shahroud	0.26	Normal

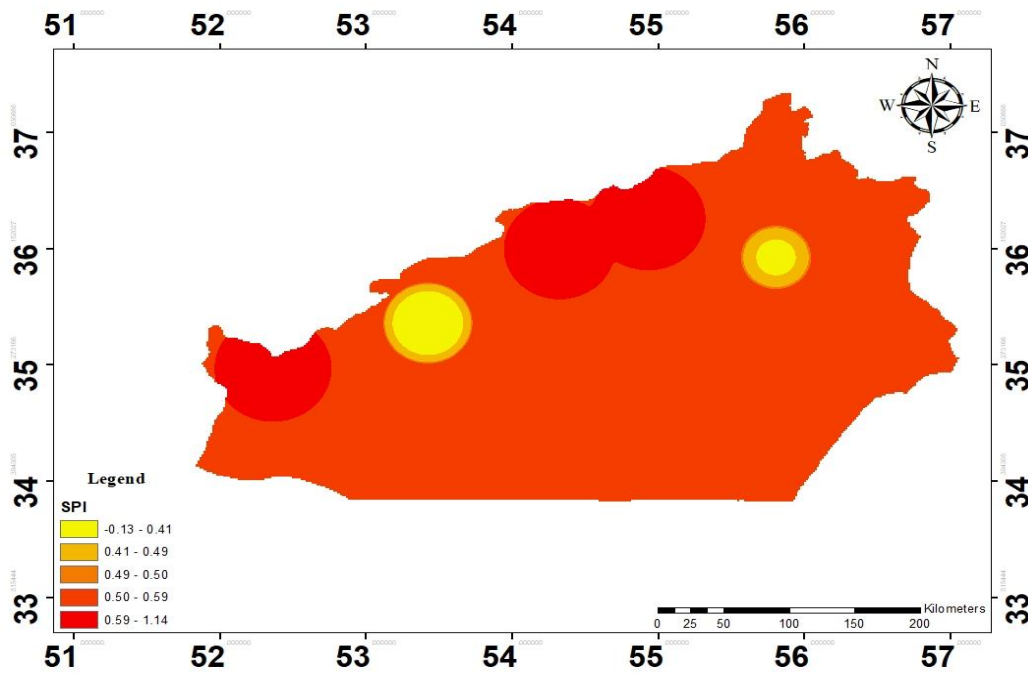


Figure 6. Drought distribution map of Semnan Province in the period of 2003-2017

3.4. Status of Dust Storm Index (DSI)

The study examined the trend of the DSI index at different stations over a period of time. The results indicated that at Garmsar, Semnan, Damghan, and Shahroud stations, there was a direct and significant correlation between the DSI index and time, meaning that as time increased, the frequency of dust during the year also increased. On the other hand, at the Biarjmand station, there was a significant inverse relationship between the two variables, indicating that as time increased, the intensity and frequency of dust decreased. Moreover, the analysis of the DSI index trend in Semnan province revealed that the

index has been increasing with time, reaching its highest value in 2011 and its lowest value in 2008 (as shown in Figure 7).

To compare spatial-temporal changes in various stations, the intensity of changes in the DSI index was calculated and then divided into zones using ArcGIS software. This resulted in a map depicting the 15-year trends in increasing and decreasing changes (Figure 8). The green points on the map indicate a decrease in dust, while the red and orange points represent an increase in dust over the mentioned period. The observed increase in dust from west to east of the province is likely due to the rise in stormy days with medium dust (MDS) frequency.

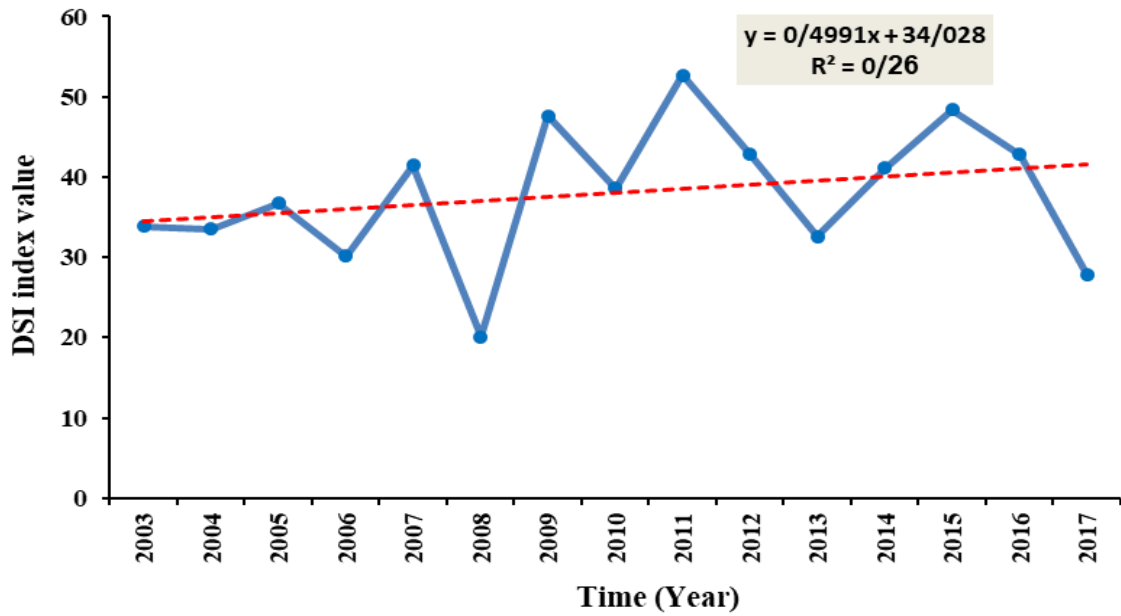


Figure 7. Trend of dust storm index (DSI) during the studied years in Semnan province

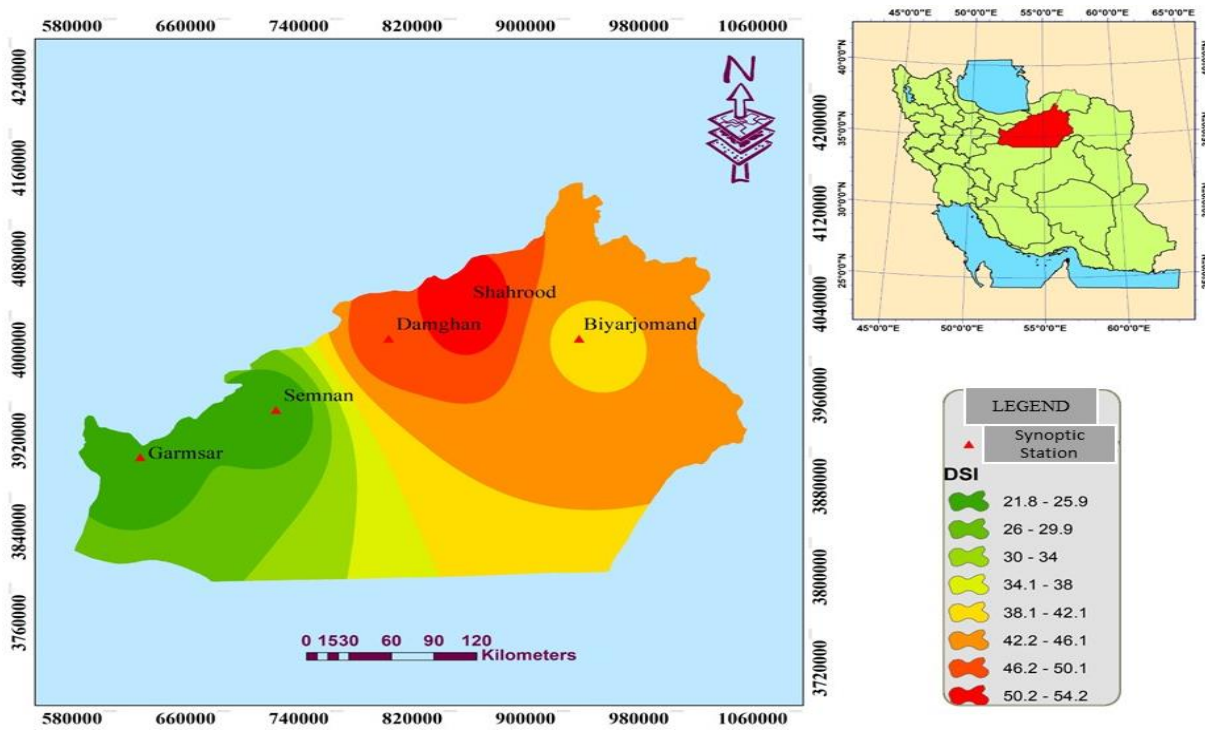


Figure 8. Regionalization of DSI index changes in different regions of the province in a 15-year statistical period (2003-2017)

Upon closer analysis of the relationship between drought indices, rainfall standards, and DSI, it was found that the severity of drought increased during the same period as the rise in DSI index, and there was a significant correlation between DSI and SPI over the 15-year period with an R^2 value of 0.89. Table five also indicates a strong correlation between drought index, DSI, and SPI in the region. In fact, during dry seasons, the DSI value decreases, while during wet seasons, the dust index value increases (as shown in Figure 9).

3.5. Reviewing the situation of the drought index (FAO-UNEP)

Table 5 displays the categorization of arid regions using the UNEP index for five stations in the area under investigation, which indicates that this region falls within the dry climate zone and is highly susceptible to desertification according to the UNEP climate index (Figure 10).

Table 5. Classification of dry areas based on the UNEP index

Rows	Station Name	Dryness index	Climate and weather	The danger of desertification
1	Garmsar	0.16	Arid	Very Intense
2	Semnan	0.12	Arid	Very Intense
3	Damghan	0.1	Arid	Very Intense
4	Shahroud	0.11	Arid	Very Intense
5	Biyarjomand	0.08	Arid	Very Intense

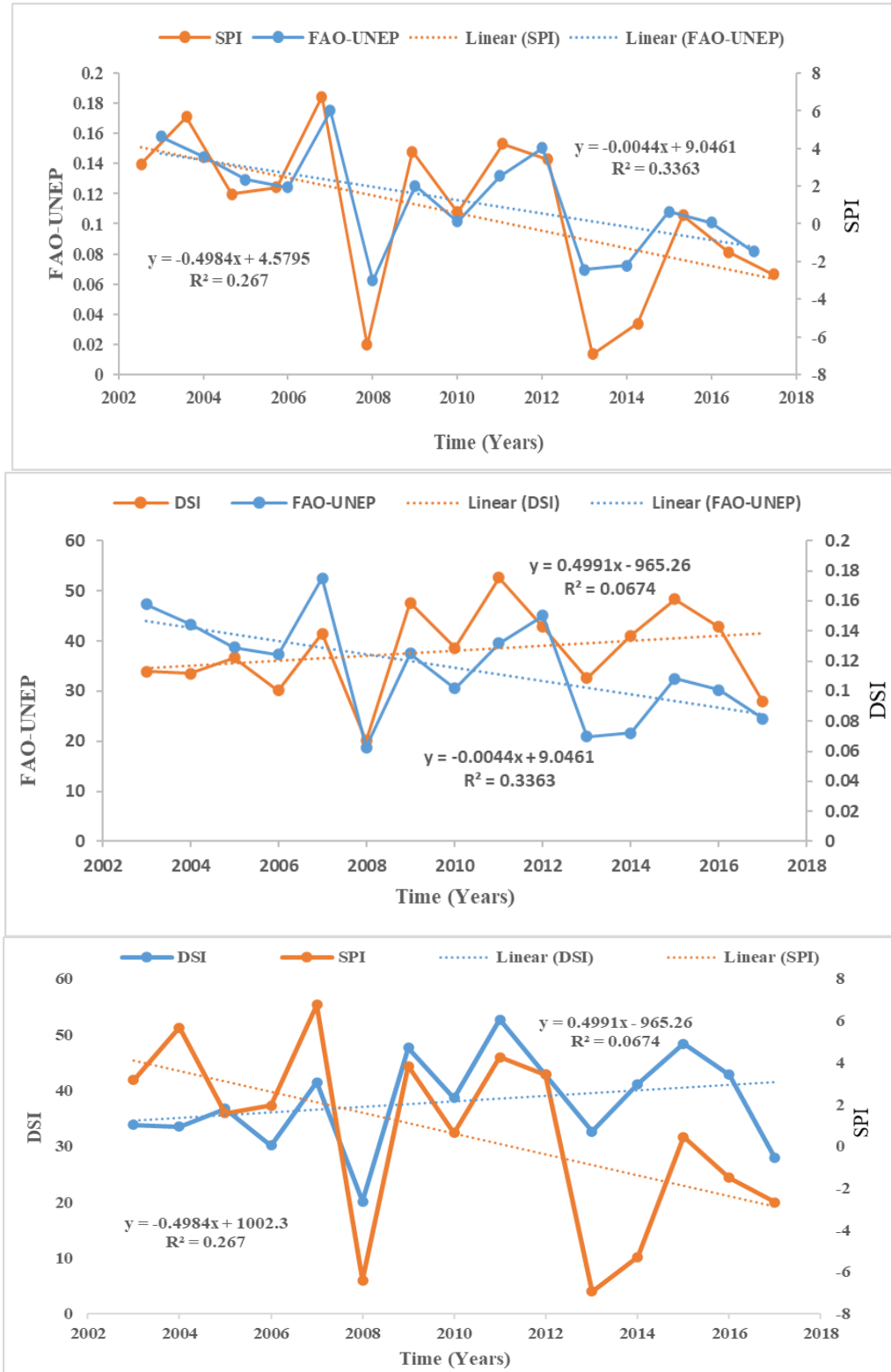


Figure 9. The degree of correlation between drought indices, SPI, DSI & FAO-UNEP

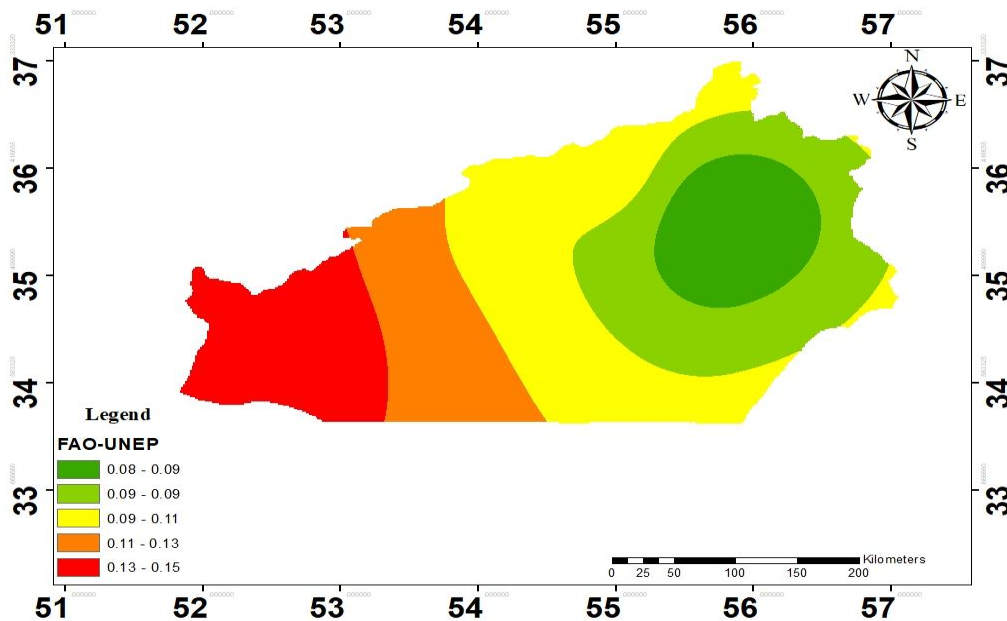


Figure 10. Drought distribution map of Semnan province with FAO-UNEP method in the period of 2003-2017

4. Conclusions

Dry area ecosystems have a highly variable climate, making them susceptible to changes in weather patterns and climate change. Dust storms have long been a source of trouble for inhabitants of dry and semi-arid areas. This study focuses on Semnan province, one of Iran's dry regions, to investigate the frequency of dust days at both yearly and monthly scales by considering local climatic conditions, such as rainfall, temperature, and wind speed. The findings indicate that over the 15-year period from 2003-2017, the average annual temperature increased significantly, leading to drought stress in the region. Moreover, the temperature rise has caused greater evaporation and transpiration and resulted in decreased moisture levels. The recent rainfall has caused an increase in surface water loss on Earth. By analyzing wind speed data on a monthly basis for each station, it was found that the months of June and July, with the highest prevailing wind speeds, have the greatest likelihood of dust storms occurring in the province. Conversely, the months of December and January had the lowest incidence of dust storms, which is consistent with findings from previous

studies by Nabavi et al. (2019). Based on the UNEP index, the severity of drought in the studied area is quite intense and at risk of severe desertification. The analysis of the trend in the dust storm index for the time period of 2003-2017 across Semnan province indicated a significant increase with changes occurring at a 95% confidence level. However, the lack of significance in changes during the last decade suggests that policy decisions related to dust management in the region have had an impact (Asghari-Podeh, 2014). The division of changes in the DSI index across various regions of the province over the 15-year statistical period indicates that dust levels have risen from the west to the east due to an increase in the frequency of moderate dust storm days (MDS). In examining the relationship between drought and the DSI index, it was found that although the DSI index increased during the studied period along with an increase in drought severity, there was no significant correlation between the two factors over the 15 years. Nevertheless, the trend in the DSI index corresponds to a dry trend pattern, which aligns with the findings of Rahi et al.'s research (2022) and Yousefi Mobarhan & Khaleghi (2024).

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