University of Tehran Press

Online ISSN: 2345-475X

DESERT

Home page: https://jdesert.ut.ac.ir/

Examining the Spatial and Temporal Relationships among Aerosol Optical Depth, Soil Moisture, and Wind Speed from 2000 to 2024 (Case Study: Western Iran)

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Article Info.

Article type:
Research Article

Article history:
Received: 08 Oct. 2024
Received in revised from: 27 Nov. 2024
Accepted: 01 Dec. 2024
Published online: 27 Dec. 2024

Keywords:
Dust,
Remote Sensing,
Mann-Kendall,
Western Iran.

ABSTRACT

Dust storms create considerable environmental issues in many arid and semi-arid regions such as Iran. Hence, recognizing dust storm patterns is essential for lessening their adverse impacts. This study has utilized Aerosol Optical Depth (AOD) data from a MODIS satellite sensor, along with SW indices and Wind Speed (WS) data sourced from ERA5 reanalysis data. Subsequently, the trends of these indices were examined using the Mann-Kendall test and trend slopes from 2000 to 2024. Then, the correlation between these data was evaluated in research study period. The trend analysis results based on the Z Mann-Kendall test and Sen's slope estimator showed that the dust index AOD generally had an increasing trend in western Iran during this period. Specifically, an area of 65,143.8 km^2 exhibited an increasing trend, with 31,243.8 km^2 of this area being statistically significant. Most of this area is located in the south and southwest of the study region, which has the lowest soil water and the highest wind speeds. The correlation analysis between the dust index AOD and the two indices of soil water and wind speed showed a negative correlation between AOD and SW index in 78,543.8 km^2, of which 38,643.8 km^2 were statistically significant. The correlation between the dust index AOD and WS also showed a positive correlation in 61,343.8 km^2 of the study area, with 8,343.8 km^2 of this being statistically significant. In general, we can conclude that biophysical factors, like soil moisture, and climatic factors, such as wind speed, significantly affect dust levels. Continuous monitoring of these parameters and evaluating their impact on sensitive and fragile ecosystems can help enhance resilience to dust in these regions.

Cite this article: Eskandari Damaneh, H., Salajegheh, S., Eskandari Damaneh, H. (2024). Examining the Spatial and Temporal Relationships among Aerosol Optical Depth, Soil Moisture, and Wind Speed from 2000 to 2024 (Case Study: Western Iran). DESERT, 29 (2), DOI: 10.22059/jdesert.2024.100917

DOI: 10.22059/jdesert.2024.100917

Publisher: University of Tehran Press

1. Introduction

Dust storms have numerous detrimental effects on air quality, climate, ecological environments (Díaz *et al.*, 2017), various socio-economic sectors (Middleton & Kang, 2017; Liu *et al*., 2021), and human health (Schweitzer *et al.*, 2018). This phenomenon also leads to farm degradation, water pollution (Thiagarajan & Aeolus Lee, 2004), and reduced visibility (Furman, 2003). Additionally, dust emissions can decrease soil fertility, reducing soil organic carbon and nutrient levels in terrestrial ecosystems. (Song *et al*., 2019; Du *et al*., 2021; Chen *et al*., 2022). The deposition of dust on plant leaves may hinder photosynthesis, respiration, and transpiration (Farmer, 1993). Multiple factors simultaneously intensify dust emission, including meteorological conditions like wind speed and surface factors such as soil water, vegetation cover, surface roughness, and soil type and texture (Zhang *et al*., 2016; Foroutan *et al*., 2017; Yang *et al*., 2020). wind speed and soil water are the most critical (Lee *et al*., 2020). Direct sunlight and wind can accelerate the drying and hardening of the soil surface. Under strong and stormy winds, these areas become sources of dust production, lifting fine dust particles from the ground into the atmosphere and increasing the amount of suspended dust in the air (Gui *et al*., 2022; Zarrinabadi, 2024). Increased soil water can create significant inter-particle forces that prevent surface erosion and inhibit the initiation of saltation (Kok *et al*., 2012; Munkhtsetseg *et al*., 2016; Ju *et al*., 2018; Yang *et al*., 2020; Ghoochani *et al.*, 2023).

Studies identifying dust particles, their sources, and influencing factors have found that increased soil water raises the threshold wind speed required to initiate sand movement (Liu *et al*., 2024). In a study, decadal changes in dust activity in the Middle East were attributed to variations in wind speed caused by extensive horizontal pressure gradients and the strengthening of high-pressure systems across the Mediterranean (Mohammadpour *et al*., 2021). Evidence indicates that the number of dusty days in the western United States has increased in recent decades due to a combination of various factors, including land use changes, drought, and strong wind events (Brahney *et al*., 2013; Achakulwisut *et al*., 2017). Dust presents major global environmental issues in various arid areas, highlighting the need to forecast dust, aerosol dispersion, and transport to lessen their adverse effects (Mobarak Hassan *et al*., 2025). In light of the shortcomings of conventional dust monitoring techniques, remote sensing technology has been identified as a key asset for tracking aerosol dynamics. This technology enables accurate analysis of aerosols' spatial and temporal patterns, aiding in identifying and assessing variations in their atmospheric concentrations. Furthermore, remote sensing data can enhance air pollution models and management (Rupakheti *et al*., 2021; Savari *et al*., 2024).

The Aerosol Optical Depth (AOD) index is a quantitative measure of the absorption and scattering of sunlight by suspended particles in the atmosphere (aerosols). This index plays a crucial role in studies on air quality, climate change, and the impact of aerosols on the Earth's radiative energy balance. It is measured using remote sensing and atmospheric models (Hsu *et al*., 2012). Research has shown that the AOD in sandy areas decreases exponentially with increasing soil water for different wind speeds (Kim & Choi, 2015). This index is related to dust events and indicates that dust emission is sensitive to soil water, particularly when wind speeds exceed 5 meters per second, and soil water content ranges between 5% and 16%. The higher the wind speed, the greater the effect of soil water on dust emission. These observational findings indicate that soil water significantly impacts dust emission (Lee *et al*., 2024). Lee *et al*. (2020), using AOD data recorded by the MODIS satellite, reported a significant increasing trend in dust from 2000 to 2010. Another study using the AOD index showed that dust emissions increased annually by 15% from 2001 to 2012 in the Middle East (Yu *et al*., 2018).

Satellite AOD observations and surface dust measurements have shown that soil water and wind speed play a key role in dust activity in the northern Arabian Peninsula desert (Yu *et al*., 2018). Investigations reveal that dust sources in Iran's arid regions are expanding unprecedentedly (Eskandari-Damaneh *et al*., 2021). In this context, MODIS AOD data for the Kafter Basin in southwestern Iran (5,600 km^2) were used from 2002 to 2023. Data analysis indicated a significant increasing trend in AOD values confirmed by the Mann-Kendall test. Statistical models (with an average R^2=0.753) predicted that by 2035, the highest increase in AOD will occur in the basin's wetland areas (Afzalizadeh *et al*., 2024).

In most previous studies, the trend of changes in optical depth has been investigated using different satellites, but the interaction of multiple climatic and environmental factors has not been considered. Therefore, this study aims to investigate the trend of changes in AOD, climatic data of wind speed, and environmental data of soil moisture obtained from MODIS sensor products in Ilam and Khuzestan provinces from 2000-2024. Also, the interaction effects of these parameters on AOD in the period of MODIS were evaluated.

2. Materials and Methods

2.1. Study Area

The study area is located in southwestern Iran, covering approximately 67,000 km^2, between 46°31' to 50°39' E longitude and 29°58' to 33°4' N latitude. Due to significant elevation differences and the presence of the Persian Gulf in its southern parts, Khuzestan Province has diverse climates. The province comprises two distinct sections: the plains and the mountainous areas. The plains cover a more significant portion of the province, encompassing the southern, central, and western regions, which are influenced by desert and semi-arid climates. In the highlands, these conditions transition to semi-arid and semi-humid climates. The average annual rainfall in the southwestern part of the province is less than 150 mm. khuzestan is generally warm, with an average temperature of about 30°C in July and about 10°C in January (Eskandari-Damaneh *et al*., 2021). Ilam Province is situated between 61°60' to 68°11' E longitude and 32°02' to 36°61' N latitude in the western part of the country. The province receives an average of approximately 570 millimeters of rainfall annually, with a typical yearly temperature of 27.5°C. The province has a moderate mountainous climate. Forests cover 6,417 km^2, 32% of the province's area, and rangeland 11,467 km^2, 60% of the area.

2.2 Methodology

To analyze AOD, monthly data from the MODIS Terra satellite sensor, level 6, with a spatial resolution of 10 kilometers, were used from 2000 to 2024. Additionally, climatic data for SW in cubic meters per cubic meter and WS in m/s were obtained from ERA5 monthly reanalysis data with a spatial resolution of 10 km during these 24 years. AOD data were received from the USA Geological Survey (https://neo.sci.gsfc.nasa.gov) and soil water and wind speed indices from (https://cds.climate.copernicus.eu)

2.2.1 Mann-Kendall Non-Parametric Test

The Mann-Kendall trend test was used to examine the trend of AOD and climatic data of soil moisture and wind speed. This test was first presented by Mann (1945) and then developed by Kendall (1970). The Mann-Kendall test is used to answer the question of whether the central or median values of a time series change over time. Sen's slope estimator was used to verify the correctness and accuracy of the trend changes (Theil, 1950; Sen, 1968; Khosravi *et al*., 2017; Khosravi *et al*., 2018; Darvand *et al*., 2021; Eskandari Damaneh *et al.,* 2022).

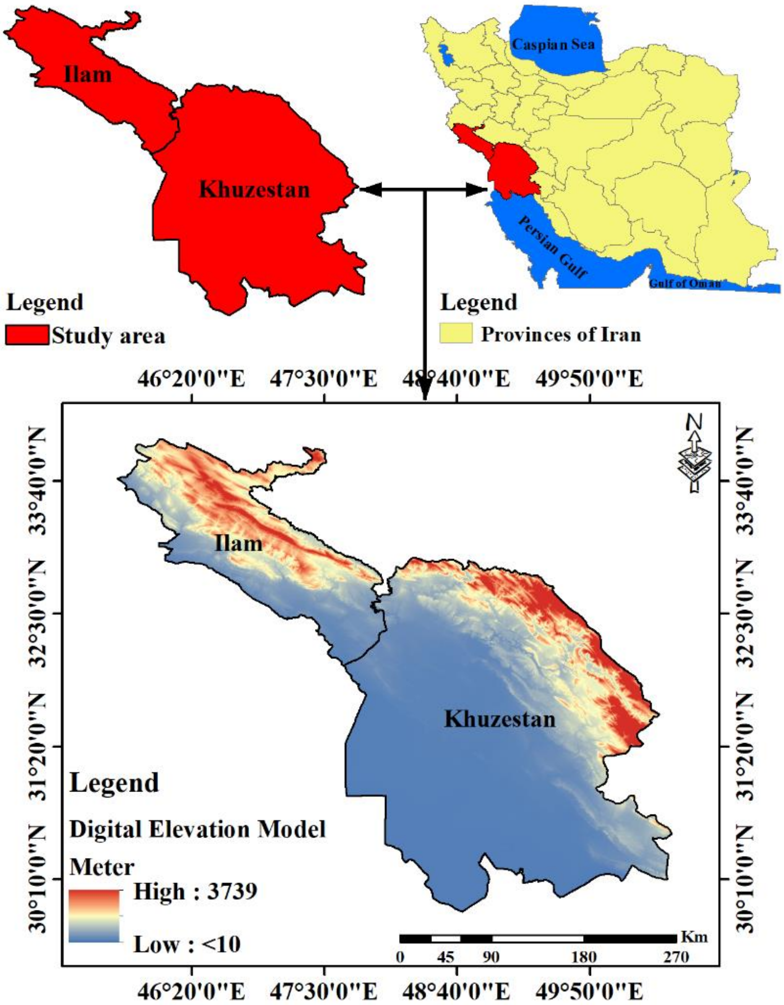

Figure 1. Location of the Khuzestan and Ilam provinces in Iran

2.2.2 Examining the Effects of Wind Speed and Soil Water on Dust

The correlation between wind speed, soil moisture, and dust was examined using Pearson's correlation coefficient. In this study, dust indices were considered independent variables, while wind speed and soil water indices were treated as dependent variables. Pearson's correlation was applied to the annual time series data for SW, AOD, and WS (Equation 1).

$$R_{x.y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_{i-}\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \times \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1$$

R_{x,y} is the simple correlation coefficient between xx and y, where x is the value of the independent index for the year i, y is the value of the dependent variables for year i, and i represents the year numbers (Kim *et al*., 2019; Li *et al*., 2019). In this study, a correlation coefficient greater than 0.5 is considered a strong positive correlation, and a correlation coefficient less than -0.5 is regarded as a strong negative correlation. Other studies have confirmed this classification (Sun *et al*., 2015).

3. Results

3.1. Spatial Variations of AOD, SW, and WS in the Period 2000-2024

The 24-year average spatial variations of WS, AOD, and SW indices are presented in Figures 3 (a to c). The 24-year average WS index (Figure 3a) showed that the highest values are in the study area's western, northwestern, southern, and southwestern parts. Conversely, the lowest values are observed in the study area's eastern, southeastern, and northeastern parts, with an average value of 2.67 m/s. The annual average spatial variations of the AOD index over this period show that the lowest dust levels (lower AOD values) are found in the study area's eastern, southeastern, northern, and northeastern parts. The average value of this index during the study period is 0.25 (Figure 3b). The 24-year variations in the soil water index in western Iran indicated that the lowest soil water levels are in the study area's western, southwestern, southern, and central parts (Figure 3c). In contrast, the highest average values are observed in the northwestern regions and sporadically in the northeastern and eastern parts, with an average value of 0.13 m^3/m^3.

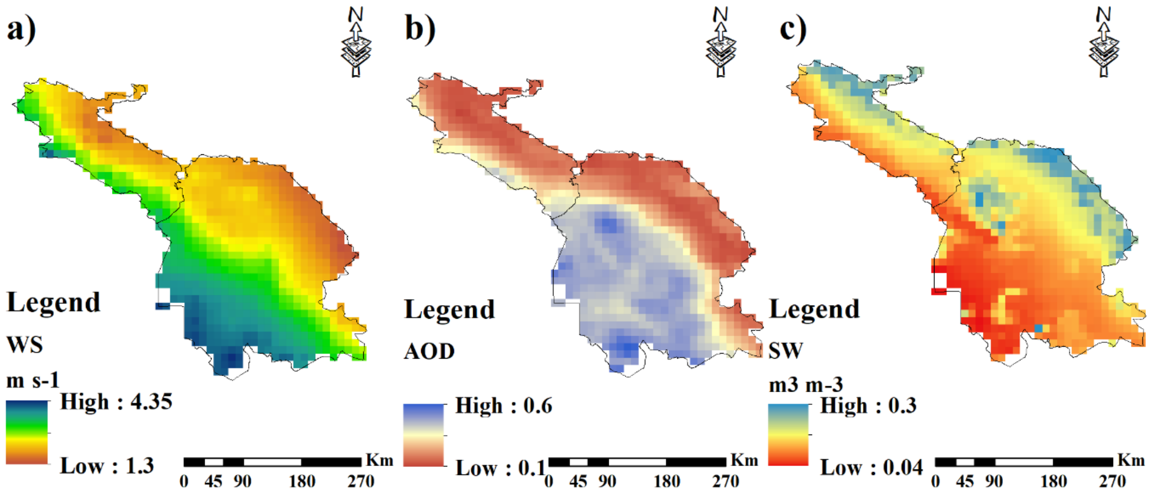

Figure 2. 24-year Average Wind Speed Index (a), Aerosol Optical Depth Index (b), and soil water Index (c) in Iran from 2000 to 2024

3.2 Trends in AOD, Soil Water, and Wind Speed Indices

The trends in wind speed, AOD, and soil water indices in western Iran from 2000 to 2024 are shown in Figures 4 (a to f) using the Mann-Kendall Z-statistic and Sen's slope estimator. According to Figure 4 (a), the wind speed trend analysis indicates that this index decreased in 55.99% of the region, with 20.37% of this decrease being statistically significant. Meanwhile, 44.01% of the region showed an increasing trend, with 9.94% of this increase being statistically significant (Figure 4, a). The Sen's slope estimator for this index also shows an increasing trend in 65.57% of the study area and a decreasing trend in 34.43% of the area (Figure 4-b). The results for the AOD index trends, shown in Figure 4 (c), indicate that this index increased in 77.6% of the region, with 37.22% of this increase being statistically significant. Conversely, 22.39% of the study area showed a decreasing trend, with 1.07% of this decrease being statistically significant. According to Sen's slope estimator, soil water increased in 77.01% of the study area and decreased in 22.99% of the region (Figure 4, d). The soil water trend analysis shows that soil water decreased in 64.97% of the region, with 3.98% being statistically significant. Furthermore, 35.20% of the region exhibited an increasing trend. The Sen's slope estimator for soil water confirms these results (Figure 4, e), indicating a decreasing trend in 69.65% of the study area and an increasing trend in 31.34% of the western region of Iran (Figure 4, f).

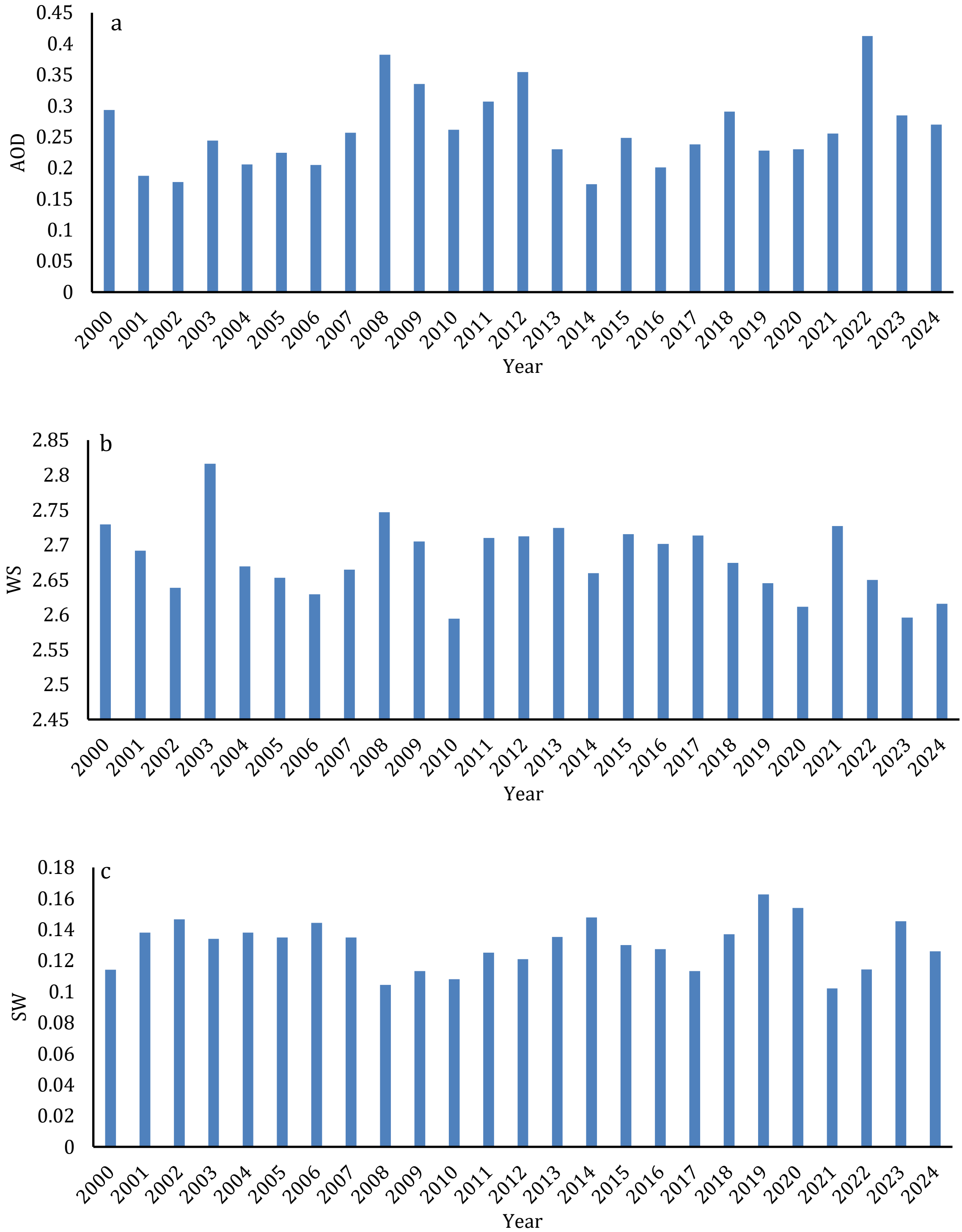

Figure 3. Trends in Annual Average Aerosol Optical Depth Index (a), Soil Water Index (b), and Average Wind Speed (c) in Western Iran from 2000 to 2024

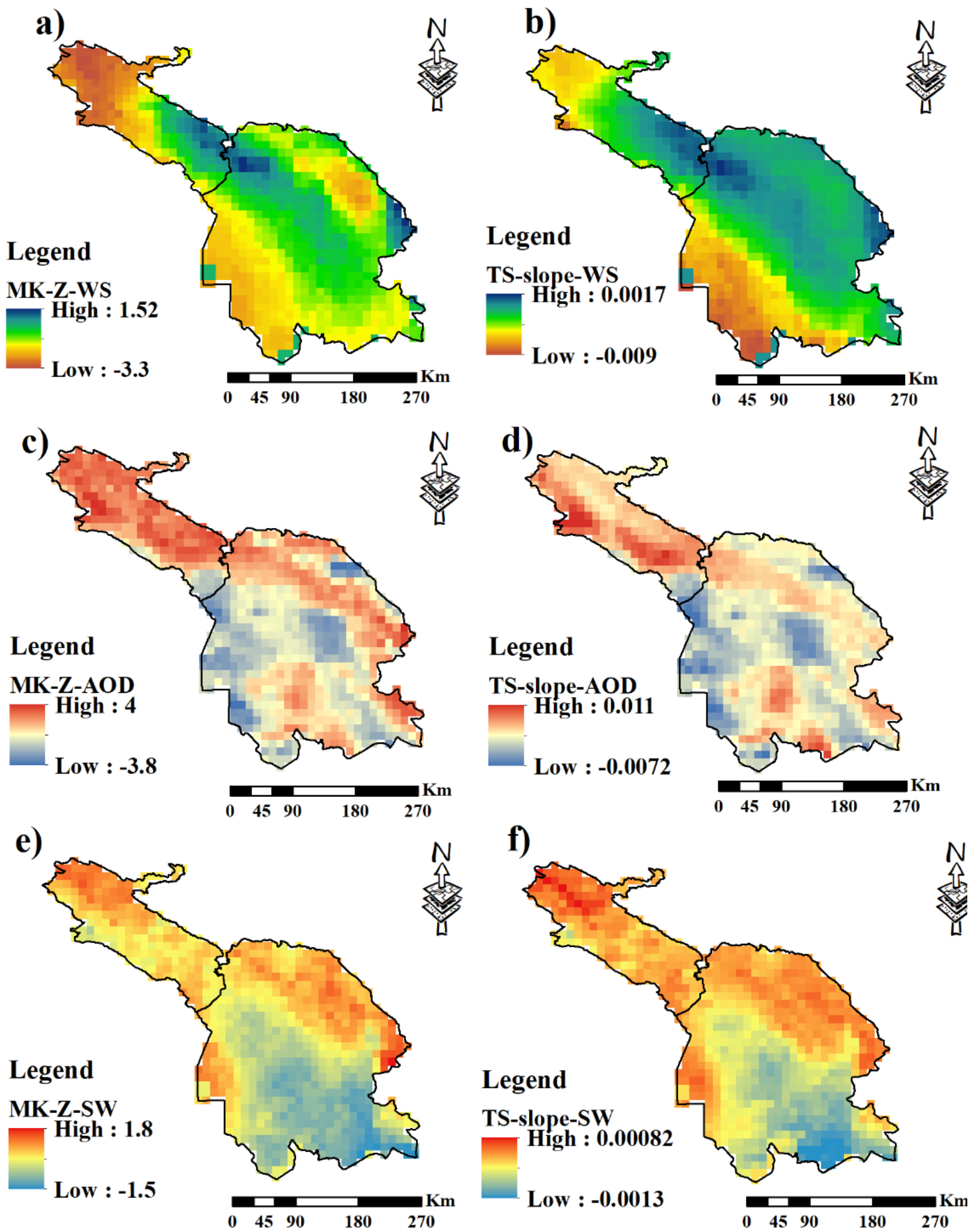

Figure 4. MaanKendall z-statistic and Sen's slope estimator Aerosol Optical Depth maps(a,b), Maan-Kendall z-statistic and Sen's slope estimator Wind Speed (c,d) and MaanKendall z-statistic and Sen's slope estimator Soil water(e,f) for Western Iran from 2000 to 2024

3.3 Correlation between AOD, Soil water, and Wind Speed Indices

Figures 6 (a and b) illustrated the relationship between the Aerosol Optical Depth (AOD) index, soil moisture, and wind speed from 2000 to 2024. In Figure 6 (a), the correlation between AOD and soil moisture reveals that 93.53% of the study area exhibited a negative correlation. Within this group, approximately 46.04% showed a strong negative correlation. Conversely, 6.43% of the area displayed a positive correlation between these indices. The correlation analysis between AOD and wind speed (WS) in Figure 6 (b) indicates a positive correlation in 73.08% of the region, with 9.94% of this positive correlation being statistically significant.

Additionally, in 26.92% of the western region of Iran, a negative correlation was observed between these two indices.

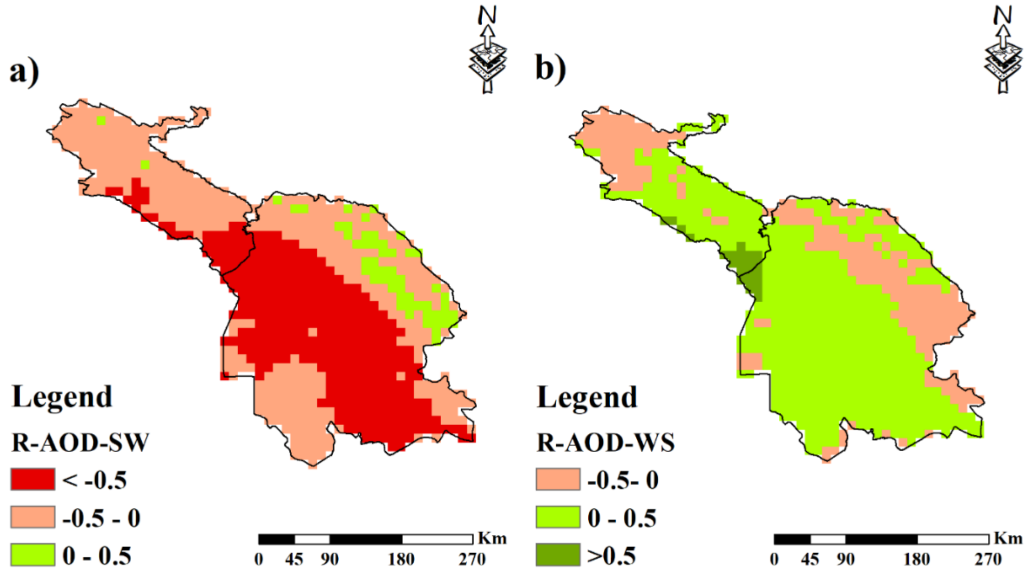

Figure 5. Correlation between AOD and Soil water (a), Correlation between AOD and Wind Speed(b) from 2000 to 2024**.**

4. Discussion

This study analyzed data from the MODIS satellite sensor concerning AOD and reconstructed model data for soil moisture and wind speed indices from 2000 to 2024. Trends and correlations in these data were assessed. The trend analysis, employing the Mann-Kendall Z-statistic and Sen's slope estimator, indicated that the AOD index has generally risen during the study period.

Over this period, an area of 65,143.8 km^2 showed an increasing trend, with 31,243.8 km^2 being statistically significant, primarily observed in the southern and southwestern parts of the study area. These results indicate the lowest soil water and highest wind speed values in these regions, with increased AOD values typically occurring under low soil water and high wind speed conditions (Kim *et al*., 2017). These findings are consistent with the research conducted by the following scholars on this topic: A study on the effects of sea surface pressure on humidity, temperature, and its impact on dust in the desert areas of Iraq and Saudi Arabia revealed that increased sea surface pressure raises relative humidity and lowers temperature, thus reducing AOD (Yousefi *et al*., 2025). The positive relationship between soil water and AOD in parts of western Pakistan, Afghanistan, and Central Asia suggests that other atmospheric parameters and mechanisms more influence AOD and dust emission in these regions, as increased soil water provides negative feedback for dust emission (Parajuli *et al*., 2019). Wind speed significantly influences AOD in Iraq and some western and southern regions of Iran, with increased wind speed leading to higher AOD levels (Fatemi & Jebali, 2022). Another study found that negative trends in precipitation and decreased soil water in dust-prone areas of Iraq and southwestern Iran significantly impact increased AOD (Yu *et al*., 2015).

The correlation analysis between AOD and soil water and wind speed indices indicated a negative correlation between AOD and SW in 78,543.8 km^2, with 38,643.8 km^2 being statistically significant. The AOD and WS correlation analysis showed a positive correlation in

61,343.8 km^2 of western Iran, with 8,343.8 km^2 statistically significant. These results are consistent with the results of the following researchers on this subject: In a study by Basharat *et al*. (2024) using Aqua-MODIS data from 2002 to 2021, the spatial variations of aerosols and their relationship with various meteorological parameters in Pakistan were examined. The results indicated a positive correlation between AOD and relative humidity, evapotranspiration, and temperature and a negative correlation between Soil water and precipitation (Basharat *et al*., 2024). Another study by Klingmüller *et al*. (2016) analyzing the correlation between AOD and soil water (SM) in Saudi Arabia, Iraq, and Iran using long-term surface soil water data from the European Space Agency (ESA-CCI) found a strong negative correlation between AOD and soil water in Iraq and surrounding areas. A study by Kim and Choi (2015) on the effects of soil water on dust outbreaks using AOD data from the MODIS satellite in East Asia showed that the average AOD exponentially decreases with increasing soil water under different wind speed conditions. Furthermore, the soil water threshold for dust outbreaks increases with higher wind speeds, and as dust outbreak criteria increase, AOD decreases (Kim & Choi, 2015). According to Park *et al*. (2014), high wind speeds are directly related to AOD values.

5. Conclusion

In conclusion, biophysical factors such as soil water and climatic factors like wind speed significantly influence dust. However, dust is affected by multiple factors, including climatic conditions and human management practices. Areas with higher dust sensitivity require specific strategies for natural resource management. These strategies should include continuously monitoring climatic changes and human activities and assessing their impacts on sensitive and fragile ecosystems to help communities preserve biodiversity and increase resilience to dust storms.

Author Contributions

All authors contributed equally to the conceptualization of the article and the writing of the original and subsequent drafts.

Data Availability Statement

“Not applicable”

Acknowledgments

The authors would like to thank all participants of the present study.

Ethical considerations

The authors avoided data fabrication and falsification.

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

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