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Forecasting the impact of climatic factors on sand dune mobility in the Salt Lake Basin using sensitivity analysis

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ABSTRACT

Due to its location in in the arid and semi-arid region of central Iran, The Salt Lake basin is constantly affected by erosive winds leading to the transportation and deposition of sediments. The annual transfer of fine sand causes significant damage to residential areas, transportation routes, and agricultural land. Over a 20-year period, the level of sand dune activity was investigated in the Salt Lake basin using the data of 15 synoptic stations. The climatic factors including hourly wind speed, dust storm phenomenon codes, rainfall, temperature, evaporation, and transpiration were analyzed to determine the Lancaster index. The results of this index indicated that sand dune activity is dormant sand dunes in 67% of stations, 27% active only in sand dune canopy areas, and 7% active. The stabilization of sand dunes resulted from management measures such as arboriculture, afforestation, grazing management, rangeland exclusion, and mulch. Also, the highest and lowest frequency of days with dust is Arak station with 5460 days and Abali station with 148 days respectively. Based on the aridity index, the region is considered semi-arid to arid. It is at high risk for desertification. According to the sensitivity analysis test, it was determined that a 30% increase in erosive winds would result in a corresponding 30% increase in sand dune activity and movement. Conversely, a 30% rise in rainfall would lead to a 43% decline in sand dune activity. Finally, the mobility of sand dunes is more sensitive to changes in rainfall than wind speed.

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1. Introduction

Soil erosion refers to the process of soil degradation by wind and water. This process consists of three stages: detachment, transportation, and deposition. Wind erosion effects on soil in a similar manner to water erosion (Shehata & Al-Rehaili, 2013; Al-Soud & Al-Shakar Chi, 2020). But in arid and semi-arid regions due to high temperature and lack of rainfall, as well as strong wind movement and circulation, wind erosion is far more severe than water erosion.

More severe than water erosion (Shehata & Al-Rehaili, 2013). The activity of sand dunes is one of the most important and dynamic geomorphologic phenomena sensitive to wind erosion in these regions , which depends on several factors such as wind regime, (Lancaster, 1985; Anderson *et al*., 1988; Gillette *et al*., 2001; Zou *et al*., 2001; Liu *et al*., 2005) grain size, surface moisture,(Jackson, 1998; Wiggs *et al*., 2004), surface crusting (Leys & Eldridge, 1991) surface scaling, topography, (Iversen & Rasmussen, 1994; Hesp *et al*., 2005 vegetation (Buckley, 1987; Kuriyama *et al*., 2005), precipitation, temperature, and evapotranspiration.

The shape and size of sand dunes depend on the direction and intensity of the wind, as well as the characteristics of the sediment. Sand dunes can vary in length and height, and they are also mobile, capable of changing their location. (Tsoar, 2001). Sand dune movement is a significant factor in desertification, and it can have long-lasting negative effects on soil productivity and the region's ecology (Belsky & Amundson, 1986; Lam *et al*., 2011). Additionally, it plays a crucial role in spreading dust into the atmosphere, which is a significant contributor to global dust sources (Harrison *et al*., 2001) Also, they are a geomorphology and sedimental environment that responds to changes and climate variation across temporal and spatial scales (Lancaster, 2013).

Finally, the mobility of sand dunes can cause the destruction of land, infrastructure, industry, settlements, water and soil resources, flora and fauna, and increase local risk assessment (Amin *et al*., 2019; Ding *et al*., 2020).

In recent years, several researchers have analyzed the effects of climate change on the dynamics of sand dunes. They investigated the potential impact of two climatic indices, precipitation and evapotranspiration, on sand dune movement in Australia (Ash *et al*., 1983). Then, they added the climatic factor of the percentage of winds exceeding the threshold speed (Wasson *et al*., 1983). Also, the aridity index (the ratio of potential evapotranspiration to rainfall) and the percentage of winds exceeding the threshold were introduced to investigate the movement of sand dunes in the southeast of the Kalahari Desert (Lancaster, 1988). The effects of climate change on the movement and stability of coastal sand dunes in the state of Ceará in northeastern Brazil have shown that wind plays an important role in determining the movement and stability of the sand dunes. During periods of high winds, sand dunes accumulate, and they become stabilized when wind speeds are low. If sand dunes are stabilized by vegetation cover, they cannot be activated even with an increase in wind speed (Tsoar *et al*., 2009). The climatic factors affecting dune mobility near Grand Falls on the Navajo Nation, southwestern United States, have shown that wind is the dominant factor controlling the movement of sand dunes during the current long-term drought (Bogle *et al*., 2015). The impact of erosive wind and sand drift on the coastal region of Urmia Lake using the Lancaster sand mobility index has quantified that the sand dunes are inactive. However, it has been observed that due to low vegetation coverage, human activities such as cattle grazing and trampling, coupled with the salinity caused by the drying of the lake, have contributed to increase of sand mobility (Nazari *et al*., 2018). The monitoring of DSI and Lancaster indices for the study of dust and sandstorms at the Mehrabad synoptic station in Tehran have shown that the temperature and evaporation values are high, while precipitation and humidity values are low relatively. There is a strong positive correlation between the dust storm index (DSI) and the sand dune mobility index (Sharifi *et al*., 2021).

A study was conducted to monitor and forecast the impact of climatic factors on the movement of sand dunes in Semnan province. The results of the Lancaster index showed that the Damghan station has fully active sand dunes. It also revealed that the movement of sand dunes is more sensitive to changes caused by increased rainfall than changes in wind speed. If the average wind speed decreases by 30% in the future or the amount of rainfall increases by 30%, the status of the dune will change from fully active to active (Yousefi *et al*., 2021).

A study conducted to identify the effects of climatic factors on the sand dunes mobility in the Sirjan desert using the Lancaster index revealed that sand dunes are only active in sand dune canopy areas. Also, the sensitivity analysis indicated that a 30% increase in the frequency of erosive winds and potential evapotranspiration will lead to a 69% increase in sand dune activity (Hanifehpour *et al*., 2022). According to the Lancaster Index, the sand dunes mobility is very high in the Dayer region of Bushehr province. Moreover, considering the aridity index, this area is at risk of severe desertification (Rahi *et al*., 2022).

Due to the fact that the important and populous cities of Iran located in the Salt Lake basin, they are often affected by dust storms and the sand dunes activity. Therefore, the purpose of this research is to study the climatic factors affecting the movement of sand dunes and dust during a statistical period of 20 years and to predict the effects of climate change on the mobility of sand dunes in the future using the Lancaster index.

2. Materials and methods

2.1. Study area

The study basin with an area of 9274939 ha is surrounded by the Alborz Mountain range from the north, the Zagros Mountain range from the west, the Karkas mountain from the south, and the desert plain from the east. This area is located between 48° 07 '35" to 52° 19' 30" eastern longitude and 26° 31' 25" to 32° 57'15"northern latitude (Figure1). The average annual rainfall of the region is 299 mm, the average annual temperature is 14.7 C°, and annual evapotranspiration 1208 mm. The highest and lowest altitudes of the area are 4323 meters in the north of Fasham and 657 meters in the northeast of Qom, respectively.

2.2. Methodologies

2.2.1. Data collected of climatic factors

Climatic data from the synoptic stations of the Salt Lake basin were received from the Iran Meteorological Organization. 15 synoptic stations with a statistical period of 20 years were randomly selected (Table 1). In the next step, we analyzed data of rainfall, temperature, evapotranspiration, wind speed and direction, and dust storm codes (07-08-09-30-35).

2.2.2. Sand transport potential

The movement of sand and dust was analyzed using the wind speed and direction, prevailing winds, and the percentage of winds exceeding the erosive threshold in 8 directions (N-NE-E-SE-S-SW-W-NW). The data was calculated monthly and annually using the WR-Plot View 7 software.

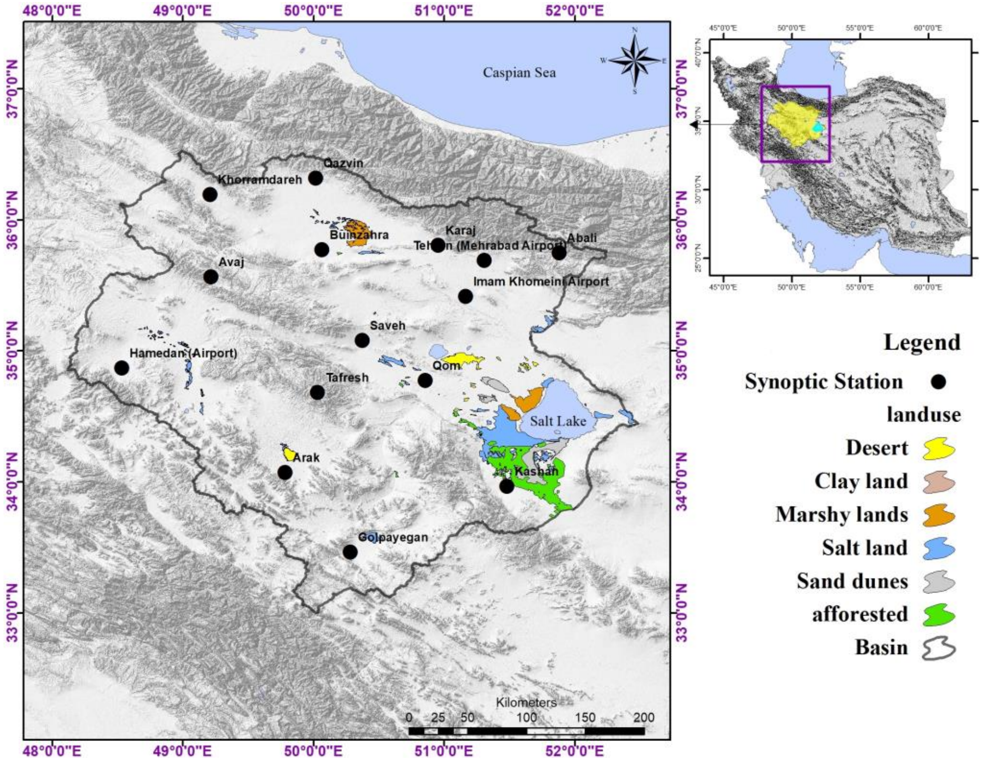


Fig. 1. The location of the Salt Lake basin in central Iran

Table 1. The location of selected synoptic stations in the study area

Stations	Latitude	Longitude	Elevation
Abali	35° 45' 00" N	51° 53' 00" E	2465
Arak	34° 4' 190" N	49° 47' 00" E	1703
Avaj	35° 34' 00" N	49° 13' 00" E	2035
Buinzahra	35° 46' 25" N	50° 04' 02" E	1282
Golpayegan	33° 28' 00" N	50° 17' 00" E	1870
Hamedan (Airport)	34° 52' 10" N	48° 32' 05" E	1741
Imam Khomeini Airport	35° 25' 00" N	51° 10' 00" E	990
Karaj	35° 48' 25" N	50° 57' 14" E	1293
Kashan	33° 58' 10" N	51° 28' 51" E	955
Khorramdareh	36° 11' 45" N	49° 12' 39" E	1575
Qazvin	36° 19' 09" N	50° 01' 12" E	1279
Qom	34° 46' 29" N	50° 51' 19" E	879
Saveh	35° 04' 48" N	50° 22' 28" E	1112
Tafresh	34° 41' 04" N	50° 02' 00" E	1980
Tehran (Mehrabad Airport)	35° 41' 35" N	51° 18' 33" E	1191

2.2.3. Estimation of Lancaster Index and UNEP Aridity Index

The Lancaster model, known as the sand dune mobility index (Eq. 1), is based on two major factors.

$$M = W/(P/PE) = (W \times PE)/P \quad (1)$$

Where M is the mobility of sand dunes,

W is the percentage of winds exceeding the erosion threshold velocity (m/s),

P is average annual rainfall (mm/year)

PE is annual potential evapotranspiration (mm/year). In this research, it was calculated using the Torrent-White method and based on the average monthly temperature.

If M is < 50, dunes are dormant sand dunes, between 50-100active only in sand dune canopy areas, between 100-200active and 200> fully active.

Also, the risk of desertification has been determined for all stations using Aridity index (P/PE: effective rainfall, Table 2).

Table 2. Drought category according to drought index (FAO, 1977)

UNEP AI	Drought Category
0.05 <R	Hyper arid
0.2<R <0.05	Arid
0.5< R <0.2	Semi-arid
0.65< R <0.5	Dry sub-Humid
0.75< R <0.65	Humid
R <0.75	Pre humid

2.2.4. Prediction of the effect of climate elements changes on the sand mobility

After calculating the amount of activity of wind sediments, using the method of sensitivity analysis, the increase or decrease of each variable has been determined. On the other hands by increasing or decreasing some climate elements such as rain, wind, and evaporation that significantly affect the mobility of sand dunes, we can predict their mobility in the future. Sensitivity analysis is a method that by systematically changing the inputs of a statistical model, it is possible to predict the effects of these changes on the model's output (Rahi *et al*., 2022).

3. Results

3.1. Investigating the trend of climatic factors

The results revealed a decreasing trend in annual rainfall across all stations. The station of Kashan had the lowest annual rainfall (126.2. mm), while the station in Abali had the highest amount (554 mm). The analysis of monthly rainfall at all stations indicated a decreasing trend from June to September (Figure 2).

It has been observed that the annual temperature trend has increased in all stations. Additionally, all stations have experienced a rise in temperature from June to October. The highest and lowest temperature increase have recorded in Kashan and Abali stations at 7.19°C and 4.9°C, respectively (Figure 3).

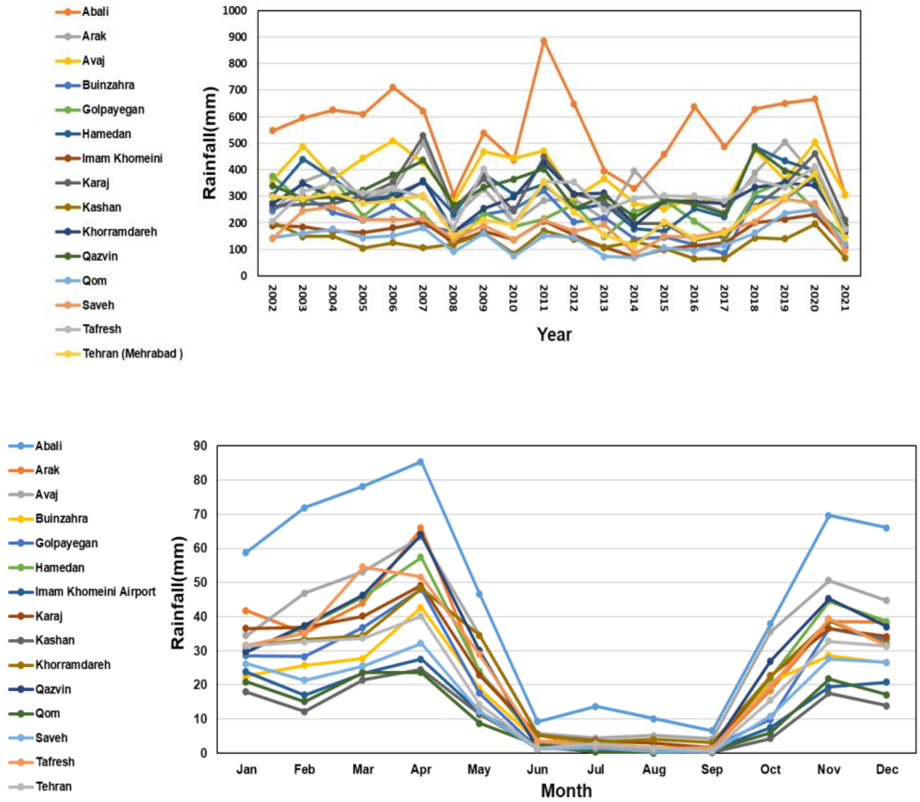


Fig. 2. The long-term changes in annual (a) and monthly (b) rainfall at synoptic stations

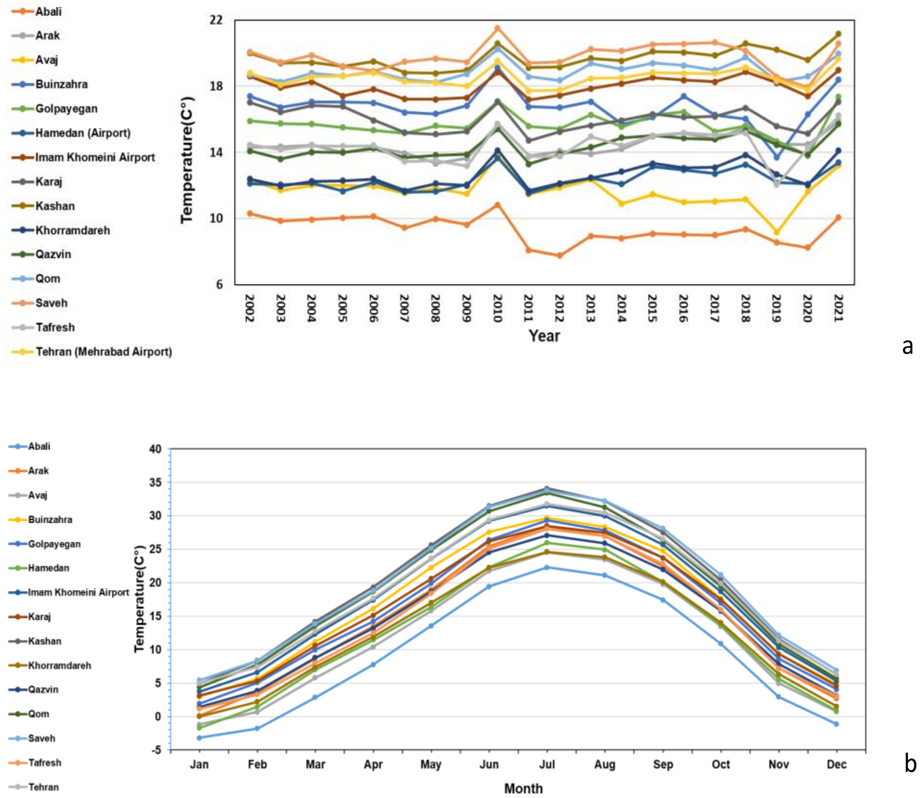
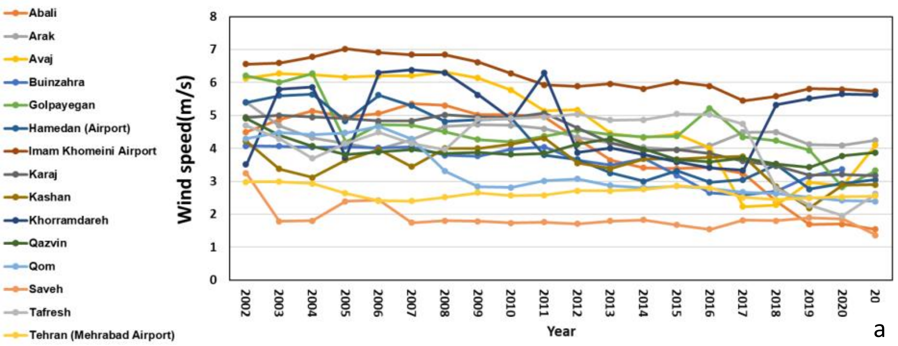


Fig. 3. The long-term changes in annual (a) and monthly (b) temperature at synoptic stations

Figure 4 shows that the annual wind speed trend is increasing at all stations. Specifically, the Khorramdareh synoptic station has experienced significant changes in wind speed, while the Imam Khomeini station has had smaller changes. Additionally, most stations have recorded the highest wind speeds from March to July. The Imam Khomeini station has had a peak wind speed of 7.3 m/s in July.



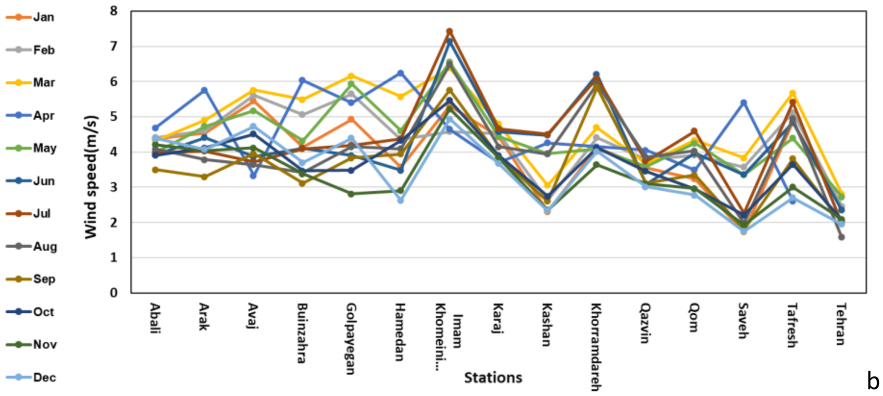


Fig. 4. The long-term changes in annual (a) and monthly (b) wind speed at synoptic stations

Fig 5 shows that the potential evapotranspiration in the synoptic stations has a direct correlation with temperature. Furthermore, the maximum evapotranspiration was observed in July at the Kashan station, amounting to 1301.9 mm in 2021.

Figure 6 shows the maps of Iso rainfall (mm), Isothermal (°C), and Iso evapotranspiration (mm) of 20-years period.

The maps indicate that in the eastern part of the region, there is a decrease in rainfall and an increase in temperature, evapotranspiration, while in the western part of the region, there is an increase in rainfall and a decrease in temperature, evapotranspiration.

3.2. Wind speed

The percentage of erosive winds recorded at the synoptic stations \indicates that Imam Khomeini Airport has the highest percentage of erosive winds at 28.8 m/s. While, the Qazvin station has the lowest rate at 0.3 m/s (Table 3).

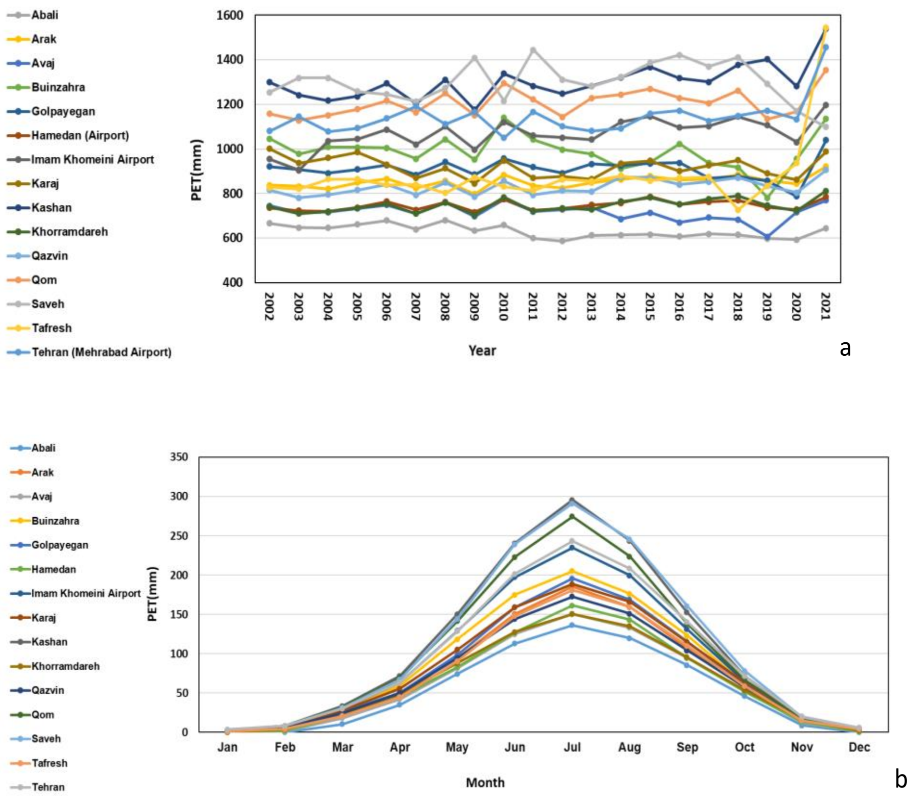


Fig. 5. The long-term changes in annual (a) and monthly (b) potential evapotranspiration at synoptic stations

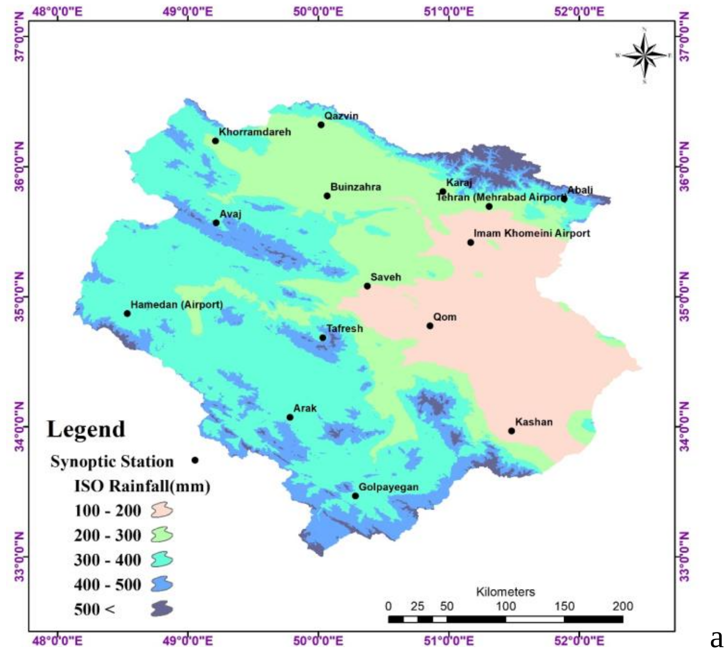
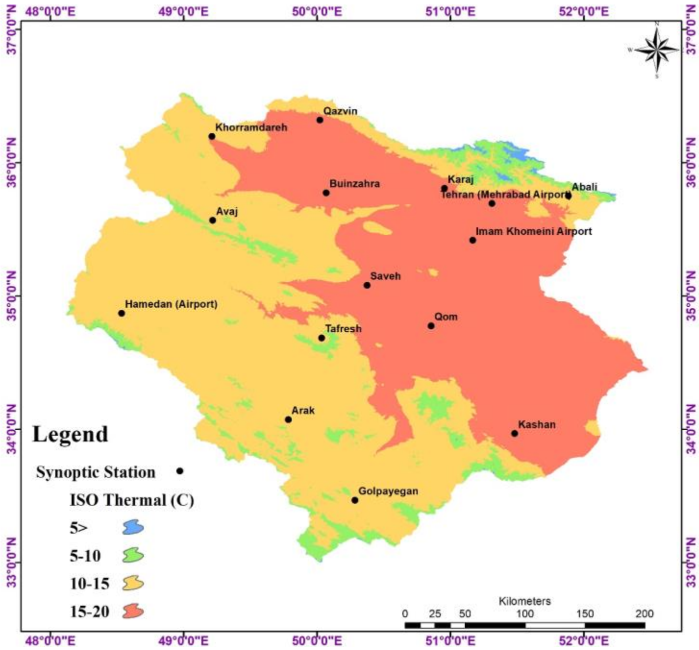
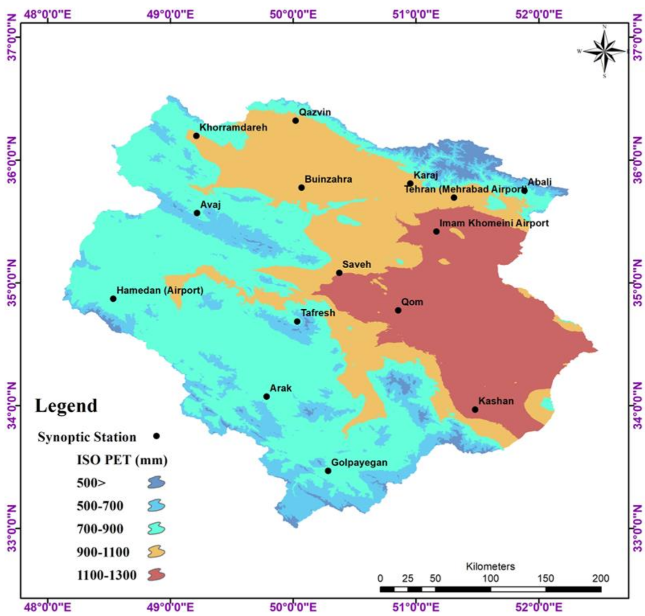


Fig. 6. ISO rainfall (mm)-a, ISO Thermal (°C)-b, ISO PET (mm)-c



b



c

Fig. 6. Continued

3.3. Frequency of dust days

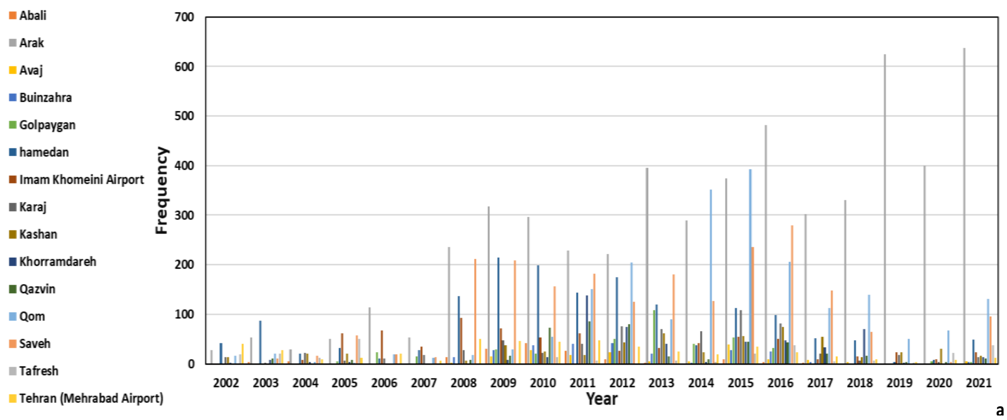
The Long-term changes in the frequency of dust days during the statistical period using local and extra-local station codes shows that the highest frequency of dust days was recorded in Arak station in 2021(Figure 7 a). Also, the highest and lowest frequency of dust was recorded in Arak station (5460 days) and Abali station (148 days), respectively (Figure 7b).

3.4. The analyze of the results of Lancaster index and Aridity index

Table 4 shows the results of the movement of sand dunes and dust in the synoptic stations using the Lancaster indices, aridity index, and the risk of desertification based on climatic factors.

Table 3. The percentage of erosive winds in the synoptic stations of the Salt Lake basin

Stations	Non Erosive Wind (%)	Erosive Wind (%)	Calm (%)
Abali	50.8	12.3	36.8
Arak	36.9	8.5	54.6
Avaj	68.1	20.6	11.3
Buinzahra	74.7	10.7	14.6
Golpayegan	46.7	26.1	27.3
Hamedan (Airport)	43.6	10.4	46.0
Imam Khomeini Airport	65.3	28.8	5.9
Karaj	55.4	12.9	31.8
Kashan	27.5	5.3	67.2
Khorramdareh	45.7	16.1	38.2
Qazvin	29.6	0.3	70.1
Qom	71.1	12.1	16.8
Saveh	86.8	2.1	11.1
Tafresh	52.9	18.3	28.8
Tehran (Mehrabad Airport)	77.6	0.8	21.6



Tehran (Mehrabad)	Tafresh	Saveh	Qom	Qazvin	Khorramdareh	Kashan	Karaj	Imam Khomeini	hamedan	Golpaygan	Buinzahra	Avaj	Arak	Abali	Station
490	267	2138	2072	450	506	542	673	740	1615	388	242	165	5460	148	Sum

b

Fig. 7. The long-term variation of dust days' frequency at synoptic stations

The results showed that the sand dunes are active at Imam Khomeini airport station. While in Qom, Tafarsh, Kashan and Golpayegan stations, sand dunes are active in the canopy areas, and other stations have inactive sand dunes. Also, the drought index showed that the Salt Lake basin is located in the arid to semi-arid area and the risk of desertification in this basin is severe to very severe. Figure 8 shows the zonation map of the Lancaster index of the Salt Lake basin.

3.5. Predicting the impact of climate factors changes on sand dune movement (sensitivity analysis)

Figure 9 shows the results of predicting the impact of potential changes in erosive wind speed and rainfall on the movement of the sand dunes for the Qom synoptic station.

The results indicated a positive correlation between sand mobility index and wind changes and a negative correlation with rainfall changes. In other words, if the speed of erosive winds increased and rainfall decreased, the amount of sand mobility increased. With a 30% increase in the erosive winds, the sand dunes mobility index increased by about 30%, and with a 30% decrease in the erosive winds, this index decreased by about 30%. However, if the average rainfall increases by 30%, the Lancaster index decreases by 23%. On the contrary, if the average rainfall decreased by 30%, an increase of 43% had been shown at this index

Table 4. Results of Lancaster indices, drought index, and desertification risk

10	Effective rainfall	Lancaster Index-M	Sand dunes activity	Aridity Index	Desertification
Abali	0.9	14.1	dormant sand dunes	pre humid	---
Arak	0.4	22.9	dormant sand dunes	semi-arid	high
Avaj	0.5	38.6	dormant sand dunes	dry sub humid	moderate
Buinzahra	0.2	47.1	dormant sand dunes	semi-arid	high
Golpayegan	0.3	96.9	active only in sand dune canopy areas	semi-arid	high
Hamedan (Airport)	0.4	25.3	dormant sand dunes	semi-arid	high
Imam Khomeini Airport	0.1	195.2	active	arid	Very high
Karaj	0.3	40.4	dormant sand dunes	semi-arid	high
Kashan	0.1	54.8	active only in sand dune canopy areas	arid	Very high
Khorramdareh	0.4	41.3	dormant sand dunes	semi-arid	high
Qazvin	0.4	0.9	dormant sand dunes	semi-arid	high
Qom	0.1	104.2	active only in sand dune canopy areas	arid	Very high
Saveh	0.1	14.7	dormant sand dunes	arid	Very high
Tafresh	0.3	53.5	active only in sand dune canopy areas	semi-arid	high
Tehran (Mehrabad Airport)	0.2	4.0	dormant sand dunes	semi-arid	high

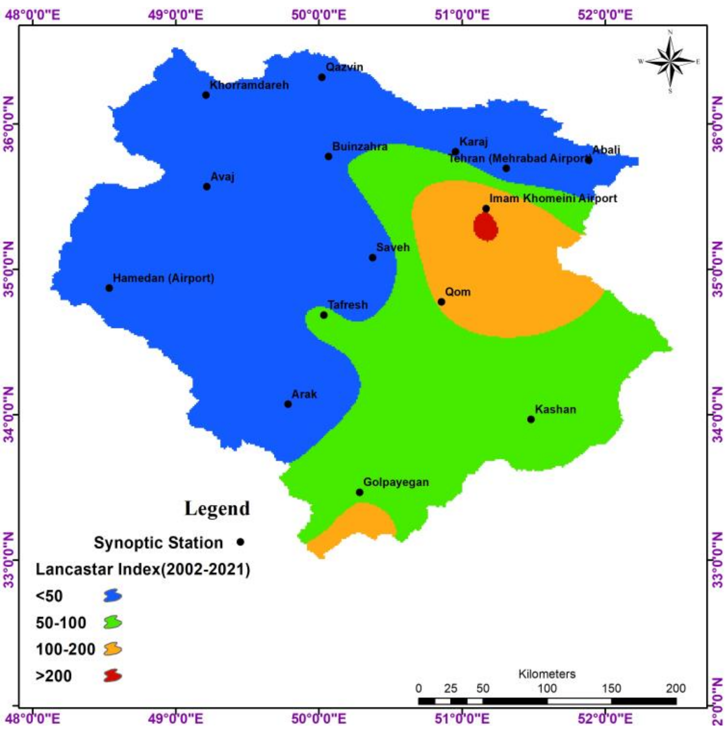


Fig. 8. The Lancaster index at the Salt Lake basin

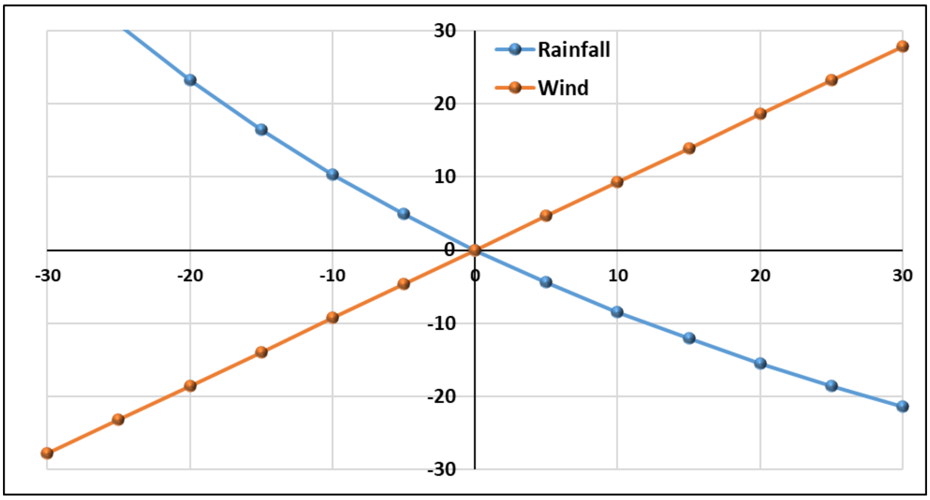


Fig. 9. Predicting the movement of sand dunes in the Salt Lake basin based on sensitivity analysis test

4. Discussion

In arid and semi-arid regions of Iran, the activity of sand dunes and dust has always caused many problems for the people. Therefore, identifying active sand dunes and stabilizing them is necessary to reduce the damages caused by them. This research tries to analyze the past and current mobility of sand dunes and dust in the Salt Lake basin stations and predict their future movement. This study has examined the climatic factors of rainfall, temperature, wind speed, and the frequency of dust days' during 20 years (2002-2021) in annual and monthly scales. This research showed that there was a decrease in the frequency of dust days between 2000 and 2007 followed by an increasing trend from 2007 to 2021. The increase of dust in the basin generally had a local origin. The most important reasons for this were changes in land use, over-harvesting of groundwater, industrial activities, reduced rainfall, increase in temperature and wind speed, and evapotranspiration. The same results have been observed by Hazbavi *et al*. (2024) and Yasien & Al-Zubaidi (2023). Due to rising temperatures, increased evapotranspiration, and erosive winds, the region experiences arid and semi-arid climatic conditions, putting 60% of the area at risk of severe desertification. As a result, with the increase in temperature, evapotranspiration, erosive winds have become intense and the transfer of sand and dust particles increased, providing a suitable bed for the movement of sand dunes.

The results of the Lancaster index classification showed that the level of activity of sand dunes is mostly inactive and only active at Imam Khomeini Airport station. The same results have been observed by Nazari *et al*., 2018. The main reasons for the inactivity of sand dunes in the region are as follows: some selected stations such as Abali and Avaj are located in high-altitude areas and are not affected by this phenomenon. In other stations of the basin, management measures have been taken to stabilize and reduce dust and sand dune activity. However, given the activity of sand dunes in the basin, these measures have not been sufficient and require new management and planning. Finally, the sensitivity analysis of sand movement revealed that rainfall changes are greater than wind speed changes. This have been consistent with the results of Yousefi *et al*. (2020), Zandifar *et al*. (2021), Naeimi *et al*. (2021) and Hanifpour *et al*. (2022).

5. Conclusion

Sand dunes are one of the most important landforms in arid and semi-arid regions. Monitoring and predicting their activity, as well as analyzing dust events in the past, present, and future using climatic factors that affect them are important for reducing the desertification process in these areas. Hence, it is necessary to study on sand dune movement to minimize the environmental impact

The research results indicate that from 2002 to 2021, the Salt Lake basin has experienced an increase in temperatures, evapotranspiration, erosive winds, and decreasing rainfall.

According to the Lancaster index, sand dunes in the basin are generally inactive and stabilized. The important reasons for this include management activities such as arboriculture, afforestation, grazing management, rangeland exclusion, and mulching.

However, the rise in fine dust in the area results from an increase in agricultural and industrial activities, changes in land use, dwindling streams, and excessive groundwater extraction. These factors have led to land degradation and heightened the risk of desertification in the basin.

The Lancaster index is an important method in the world to analyze the condition of sand dunes, which uses three climatic factors of rainfall, erosive winds, and evapotranspiration.

In the end, assessing the movement of sand dunes involves analyzing satellite images and conducting field measurements, which will be further studied to confirm the accuracy of this approach. The results of this research can be utilized for predicting the future condition of sand dunes and determining appropriate management measures to control and reduce potential damage to other land uses in the region.

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