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Aeolian Geomorphology of Ergs and Dunefields in Iran

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ABSTRACT

Iran's geographical location causes the majority of the country to be semi-arid, arid, or hyper-arid. The existence of ergs and dunefields in the central and eastern parts of Iran has caused residential areas and all kinds of land use to be affected by sand movement and dust risk. Despite this, there is no comprehensive research on ergs and dunefields in Iran. The aim of this study is to identify, classify, and monitor Iran's ergs and sand dunes, as well as their wind characteristics. We used 66 synoptic stations throughout the country, satellite images from the Ergs region (Landsat 8 and Google Earth), geological and topographical maps at scales of 1:100000, 1:250000, and 1:50000, a digital elevation model with 12.5 meter resolution, and data from field work to achieve our objectives. In addition, using different software, classification of sand dunes, wind erosion potential, and descriptive and analytic maps were prepared. According to the findings, the total area of ergs and dunefields in Iran covered approximately 2.9 percent of the country. Sand dunes come in a variety of shapes and sizes, due to climate and geomorphological diversity in different parts of Iran. Also sand dunes in the south-east of Iran have migrated at a rate of more than 18 meters per year over the last 16 years. The results of the correlation between sand dunes movement and wind characteristics show a close direct correlation, so that sand dunes have the most displacement in areas with high wind velocity and Total Drift Potential (DPt), but have low displacement in other areas due to sand dunes stabilization with vegetation and topographic obstacle.

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1. Introduction

Large areas of the world's continents are covered by semi-arid, arid, and hyper-arid regions (Parsons and Abrahams, 2009). Semi-arid, arid, and hyper-arid regions cover 17.7, 12.1, and 7.5 percent of the world's land area, respectively (Table 1). According to the United Nations environmental program for arid lands, arid land is defined as any land with an annual precipitation of less than 0.65 evapotranspiration (UNDP, 1997). Arid lands have a variety of land forms, including ergs and dunefields that cover large areas. Desert landforms are widely distributed in countries located in the world's desert belt between the two hemispheres. Iran is located in the world's desert belt, with desert areas covering two-thirds of the country (Khosroshahi *et al*, 2018). Iran's arid and hyper-arid areas cover 472562 (29.12%) and 573884 (35.2%) square kilometers, accounting for approximately 63.5 percent of the country's total area (Khalili, 1992).

Table 1. Distribution of the desert area in the world, Asia and Iran
(Base on UNEP, 1997 and Khalili, 1992)

Region	Semi humid arid	Semi-arid	Arid	Hyper-arid	Total
World	9.9	17.7	12.1	7.5	47.2
Asia	8.3	16.3	14.7	6.5	45.8
Iran	4.9	19.9	29.0	35.2	89.1

There is no information about how these ergs and dune fields formed in Iran. Some believe that the formation of these ergs, or at least a portion of these ergs, is related to paleoenvironmental conditions. (Thomas *et al*, 1997., Mehrshahi, 2012). According to OSL dating, the Yazd region sand ramp age dates back between 31 and 25 thousand years ago (Thomas *et al*, 1997). In comparison to other parts of the world, ergs and dunefields were very large around 18000 years ago, according to a map (Sarnthein, 1978., Pye & Tsoar, 2009., Thomas, 2011). Also Aeolian sand accumulation began around 19 and 9 ka in different parts of northern China (Fan *et al*, 2013).

All different kinds of arid landforms can be found in Iran, including different surfaces of playas, desert rivers, alluvial fans, erosional surfaces like Yardangs and deflation hollows, and desert pavements, as well as accumulation landforms like sand seas and dunefields, including nebkhas, linear dunes, star dunes, barchan and barchanoid, transverse dunes, sand sheet, and other sand dunes (Maghsoudi, 2021). There are many ergs (rigs) in Iran's desert region that are unique in some way, such as the world's highest sand dune (Mahmoudi, 2002). In Persian, rig is used instead of erg, sand sea, draa, or dunefield, and there is no distinctive terminology for a collection of sand dunes of varying size and shape in specific areas. The area and number of these ergs (rigs) grow from west to east and north to south across the country. In fact, the shape and size of these ergs are frequently influenced by topographic and climatic factors (Breckle *et al*, 2008., Maghsoudi et al, 2018., Al-Dousari *et al*, 2020). The presence of ergs in desert areas increases the risk of dust and sand storms, as well as the movement of sand dunes (Baas, 2007). In fact, sand movement by wind causes sand migration in three types of suspension, saltation, and creep at various levels, which is a potential risk in desert areas (Tang *et al*, 2021). The amount of sand moved by the wind depends on a variety of factors, including topography, vegetation (Hesp *et al*, 2005., Kuriyama *et al*., 2005), grain size, and moisture. As a result, some areas have a high potential for sand and sand dunes movement, as well as dust storms. Sand dunes movement has long been studied and monitored in different regions of the world using various methodologies (Hamdan *et al*, 2016., Maghsoudi *et al*, 2017). All of these studies reveal the active dynamic of sand dunes and sand sheets, which may endanger the various land uses in rural and urban areas (Gharibreza & Motamed, 2005., Negaresh & Latifi, 2008., Maghsoudi *et al*, 2020). Despite these studies and the abundance of ergs in different parts of the country, there has yet to be comprehensive studies of ergs and dunefields in Iran. In fact, these landforms are components of Iran's geographical spaces, and understanding their characteristics aids in understanding their morphological complexities and active dynamics. Because many cities, villages, and various land uses are located near ergs and dunefields, studding these features is critical to managing settlement around them. On the other hand, the potential use of ergs for the development of their surrounding regions, environmental planning, land use planning, geotourism, and environmental conservation is only possible by studying and identifying the ergs and dunefields. Mahmoudi (2002) estimated the area of Iran's ergs and dunefields. According to these studies, the area of Iranian ergs is approximately 36,000 square kilometers of the country (Mahmoudi, 2002). He investigates the geomorphological characteristics and elevation of 20 large ergs in Iran. Furthermore, Abbasi (2012) estimates the area of Iranian sand dunes and sand features (ergs and dunefields) to be around 46,355 square kilometers. Of course, case studies have been conducted in various parts of Iran, such as Ekhtesasi *et al* (2006) in the Yazd- Ardakan plain, Maghsoudi in Kalleh Erg (Maghsoudi *et al*, 2017), Mashhadi in Kharturan erg (Mashhadi *et al*, 2006), Foroutan and Zimbelman in Yallan sand sea (Lut desert erg) (Foroutan & Zimbelman, 2016), Birgani in Band-e Rig or Rig Boland-e Kashan (Birgani, 2017), and a number of other Persian-language articles.

Table 2. Area and percentage of major Ergs in Iran (Mahmoudi, 2002., Abbasi, 2012)

The name of sand sea (erg)	(Abbasi, 2012)		(Mahmoudi, 2002)	
	Area (km2)	%	Area (km2)	%
Rig-e Yallan (Lut) sand sea	11,529	24	10763	30.8
Rig-e Jazmorian sand sea	5588	12	4026	11.5
Rig-e Jen sand sea	4512	9.6	2730	7.8
Rig-e Khuzestan sand sea	2614	5.6	1570	4.5
Rig-e Shotoran sand sea	2612	5.5	2477	7.1
Rig-e Zir kuhe Qaen sand sea	2208	4.7	1722	4.9
Rig-e Kharturan sand sea	2081	4.4	1690	4.8
Rig Boland sand sea	2013	4.3	1762	5
Rig-e Sarakhs sand sea	813	1.8	Not mentioned	
Rig-e Boshruyeh sand sea	623	1.3	715	2
Sistan ergs and dunefields	641	1.4	323	0.9
Costal ergs and dunefields (Persian and Oman Gulf)	1039	2.2	Only Oman Gulf 951	2.7
Other ergs dunefields	10,082	22	6220	17.8
Total	46,355	100	34948	100

In terms of sand dunes classification, little work has been done in Iran, and a comprehensive classification of sand dunes in Iran has yet to be achieved. In some cases, a classification map of sand dunes has been prepared for ergs such as Kharturan erg (Amirahmadi & Farzinkia, 2015) and Jen erg (Fatahi *et al*, 2018), but the studies have not been comprehensive. In this study for the first time, a comprehensive classification map of sand dunes from all ergs of Iran was prepared, and all ergs were also divided into 9 regions based on some criteria. There have been many studies on the classification of sand dunes. Pye & Tsoar (2009) classified sand dunes into three groups based on origin and variability of wind direction. Sand dunes were also classified as crescent, transverse, linear, or longitudinal by Mainguet (1984) based on the shape and role of wind in their formation. McKee (1979) categorizes sand dunes into five major types based on their shape and number of slip faces: crescent, linear, transverse, star dune, and parabolic. Goldberg and Macphail (2006) classified sand dunes based on their wind regime, number of slip faces, and morphology. Livingston (2013) compared the Namib sand sea classification maps of Grow (1979), Besler (1980), Breed & Lancaster (1985) and Lancaster (1989) while studying the geomorphology of the Namib sand sea. The most important aspect of the Namib sand sea classification is that almost the entire map details do not match, indicating a different visual interpretation and different types of classifications used by the researchers when creating the map. The importance of studying sand dunes has resulted in an increase in this type of research in recent years all over the world. Some researchers have pinpointed the exact location and classification of sand dunes (Lancaster *et al*, 2010). The movement of sand dunes has been studied in some research based on wind characteristics and topographic conditions in the region (Zhang *et al*, 2015., Hamdan *et al*, 2016., Hereher *et al*, 2018., Zhang *et al*, 2019., Zou *et al*, 2020). Also, remote sensing has been used in some studies to monitor sand dune changes (Othman *et al*, 2019., Dashti *et al*, 2021., Qi *et al*, 2021). In this study, in addition to identifying and classifying sand dunes using remote sensing methods, the movement of the sand dunes was monitored, and the correlation between sand dune movement and wind characteristics was analyzed using information obtained from wind characteristics of the study area. Concerning the aforementioned, the objectives of this research are to identify the precise location of ergs and dunefields in Iran, to classify sand dunes and to monitor sand dunes movement in ergs and dunefields, and finally, to investigate the relationship between wind characteristics and sand dunes.

2. Study Area

The study area for this research is all of Iran's ergs and dunefields. Temperature, precipitation, and overall climate diversity in Iran are highly variable due to geographic location and topographic conditions. As a result, the average annual temperature in the northern and western parts of the country is less than 15 degrees Celsius, while it is more than 30 degrees Celsius in the south eastern and southern parts. There is a significant difference in rainfall, so that in some parts of Iran's northern regions, the total annual rainfall exceeds 1500 mm, whereas in many parts of Iran's eastern and southern regions, the total annual rainfall is less than 100 mm, so that even in the western part of the Lut desert, it reaches about 28 mm (Iran meteorological organization, 2020). In terms of the aforementioned, the majority of Iran is located in arid and hyper-arid regions (Fig. 1). As a result of this situation, wind erosion has become the dominant erosion factor in a large portion of the country, resulting in the formation of sand dunes and other wind erosion landforms. The ergs and dunefields studied in this research are mostly found in the country's central, eastern, and south-eastern regions. The Khuzestan erg, on the other hand, is found in the Khuzestan plain in southwestern Iran. As previously stated, the size and number of ergs and dunefields in Iran have grown in size and number from north to south and west to east. The location of studied ergs and dunefields has been strongly influenced by the direction of mountainous regions, drainage networks, the location of playas and depressions, alluvial fans, and plains. The Zagros mountain ranges, which run northwest to southeast, and the Alborz mountain ranges, which run west to east, have intensified aridity in the country's central and southern regions, creating favorable conditions for the development of sand dunes.

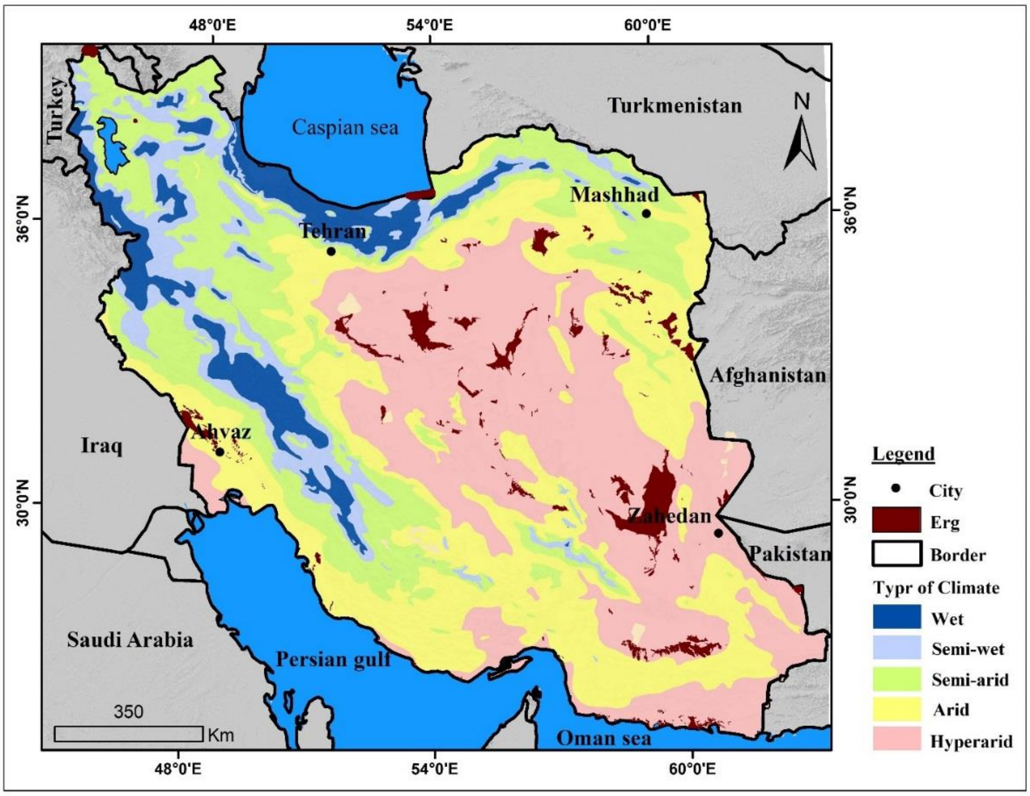

Fig 1. Climate classification and location of ergs and dunefields in Iran (Iran Meteorological Organization, 2020)

3. Materials and methods

In this study, data from 66 synoptic stations of Iran's meteorological station, satellite images (Landsat 8 [1]and Google Earth) of ergs and dunefields areas, geological and topographic maps at scales of 1:100000, 1:250000, 1:50000, and a digital elevation model with a 12.5-meter resolution have been used to achieve the objectives. Field studies also allow us to learn more about ergs and dunefields while also validating the results. Furthermore, various softwares were used for data analysis, sand dunes classification, drawing wind and sand rose diagrams, and creating various maps and outputs.

This study took several steps, which are as follows: The first step (determining the exact boundaries of the ergs and dunefields): in order to draw the sand dunes' (ergs and dunefields) boundary, information about the location of the sand dunes was obtained using library and field studies, and then the exact boundary of the sand dunes was digitized manually using Google Earth images. The second step (sand dunes classification): in this study, a modified classification of sand dunes was used, which was based on characteristics of Iranian sand dunes and a literature review (Breed & Grow, 1979., McKee, 1979., Fryberger & Goudie, 1981., Mainguet, 1984., Pye & Tsoar, 2009., Lancaster, 1995 and 2010., Goldberg & Macphail, 2006., Livingstone, 2013). The diversity of sand dunes forms is due to the geographical location of ergs and dunefields in different parts of the country (from the south of the Alborz Mountain to the south, southeast, and Khuzestan plain). As a result, three approaches to classifying Iran's sand dunes have been considered:

1 https://earthexplorer.usgs.gov

- Using the classification that other researchers have used;
- Using different classification for each erg or group of ergs; and
- Using a modified classification to include almost all types of sand dunes and ergs

Regarding the aforementioned sand dunes, they are classified as linear, crescentic, star, and parabolic based on their shape, with sub-types identified for some of them due to density and complexity. Some types of sand dunes, on the other hand, are still influenced by vegetation and topographic barriers, and as a result, nebkha and topographic types were added to the classification. The complexity of sand dunes caused by wind direction and the combination of barchan, seif, transverse, star, and other sand dunes was so great in some cases that we couldn't give them any other name. Of course, these sand dunes could be given a name, but it was far from comprehensive name, and no other name seemed appropriate for this type of sand dunes except complex. Sand sheet was the name given to areas that were covered in sand but did not take on a specific shape. Only ripples and mega ripples can be seen in these areas, which are divided into three groups: thick, medium, and low thickness (Fig. 2). In general, the criteria for drawing boundaries and classifying sand dunes in this study were based on the study's scale and available data. Of course, in a large polygon with a dominant type of sand dunes, there may be small patches of other types of sand dunes. Because of their small size, the small patches' boundaries have not separated (deleted) in these cases. In fact, when naming the polygons, special attention was paid to which types of sand dunes were dominant, and the types of sand dunes were determined and named as a result of the polygons' generalization.

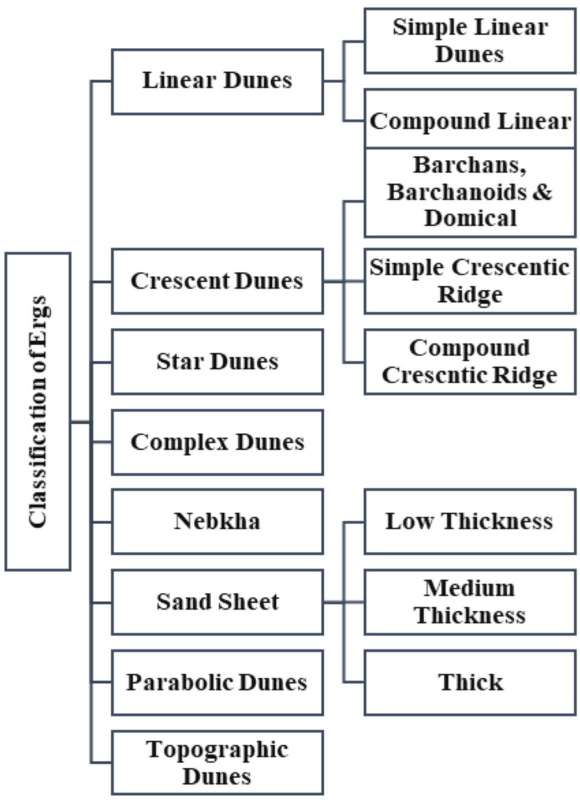

Fig. 2. Sand dune classification based on a review of the literature and the location of sand dunes in Iran

The third step was to monitor the movement of sand dunes. Many researchers have used satellite images to monitor the movement of sand dunes (Kwarteng *et al*, 2000., Liu *et al*, 2008., Fadhil, 2013., Sparavigna, 2013., Elhag *et al*, 2019., Aydda *et al*, 2020., Mohammadpoor & Eshghizadeh, 2021). Sampling was used in this study to monitor sand dunes movement using satellite images. When compared to other methods, this method has a high level of accuracy. In this method, some points (for example, 203 sample points in the ergs of the southern slopes of Alborz range and Dasht-e Kavir) were used as sample points in each erg, and the amount of change in the sand dunes was calculated from 2005 to 2020 using Google Earth and Landsat satellite images. The number of sample points was determined by the ergs' shape. Indeed, in ergs with a high diversity of sand dunes (such as the western portion of Jazmorian), more sample points were used, while in ergs with a low diversity of sand dunes, fewer sample points were used (such as the eastern part of Jazmorian). The type and shape of sand dunes play an important role in the rate of movement and movement of sand dunes, which is why this kind of sampling has been used. Considering areas with a diversity of sand dunes have a different rate of displacement, more sample points should be used in these areas to improve accuracy. Also, because the difference in displacement between different parts of a sand dune is less, the number of sample points can be used less in these areas. Finally, after using the IDW (Inverse distance weighting) interpolation method to estimate the amount of sand movement in each point, a map of the amount of movement of each erg was created. In fact, Due to the location and distribution of the stations, this method was used. Therefore this method has also been used because the degree of correlation and similarity in the IDW model is based on distance (Bhargava *et al*, 2017., Borges *et al*, 2018).

The fourth step (wind analysis): 66 synoptic stations were used in this study to analyze the characteristics of wind in the region, and wind data was used to calculate wind velocity, direction, and frequency. The average annual wind speed (meters per second) was calculated first, followed by the monthly and seasonal wind velocity in stations. Wind velocity and direction maps were created with Geographical Information System (GIS) environment using the IDW interpolation method. For each station, the sand drift potential (DP factor) was calculated (Hamdan *et al*, 2016., Sadeghi Ravesh, 2018., Abbasi *et al*, 2019). In fact, DP is calculated for all stations using Fryberger and Dean's (1979) method. In the equation below (Equation 1):

$$\text{Equation 1 :}DP=V^2\,(V-V_t)t$$

DP is the sand drift potential in a vector unit (UV), V is the wind velocity at 10 meters above the land surface, Vt is the wind velocity threshold, and t is the time when the wind blows faster than the threshold velocity. The DP, in fact, depicts the total amount of wind energy used for sand transportation in a station. Table 3 can be derived from Fryberger and Dean's (1979):

Table 3. Classification of wind energy in desert environments (based on Fryberger & Dean's, 1979)

DP	Erosion energy
Less than 200	Low energy
200-400	Intermediate energy
400 or greater	High energy

To calculate DP, the mean wind velocity (meters per second) and a monthly and seasonal DP index were calculated first, and then the DP map of the study area was drawn using the IDW interpolation method. An isoline map for wind direction has also been prepared based on the information obtained in the study area.

The fifth step is to evaluate the degree of correlation between wind characteristics and the rate of sand dunes displacement: The correlation between the rate of sand dunes movement and wind characteristics was evaluated in this step by analyzing the correlation between sand dunes displacements, wind velocity, and DP over various time periods. As a result, the pixel method was used to calculate the correlation between the wind velocity map, the DP index, and the sand dunes displacement in ergs.

4. Results and Discussion

4.1. Identification of ergs in Iran

For the identification of ergs in Iran, the relative position of ergs was first recognized using librarian study and field observation, and then the exact position was drawn using satellite images. According to the findings, the total area of ergs and dunefields is 47811 square kilometers, or about 2.9 percent of Iran's land area. These sand dunes are known by various names due to the distribution of ergs in different parts of Iran. Because of the high diversity of ergs and the lack of a comprehensive classification, ergs are divided into nine groups in this study based on their location and previous studies: Khouzestan Ergs, Southern coast ergs, Sistan ergs, Jazmorian ergs, Lut ergs (Yallan sand sea and ergs around it) Markazi ergs, Great Kavir (Dasht-e Kavir) and southern Alborz ergs, eastern ergs and northern ergs (Fig. 3). The Yallan sand sea (in the Lut desert world heritage) is Iran's largest erg, covering approximately 14629 square kilometers and 30.6 percent of the country's total erg area. The Great Kavir (Dasht-e Kavir) and southern Alborz ergs, as well as the eastern ergs, are the largest ergs after the Yallan sand sea, with 13081 (27.4 percent of the total area of ergs) and 5737 square kilometers (12 percent of the total area of ergs, respectively (Table 4).

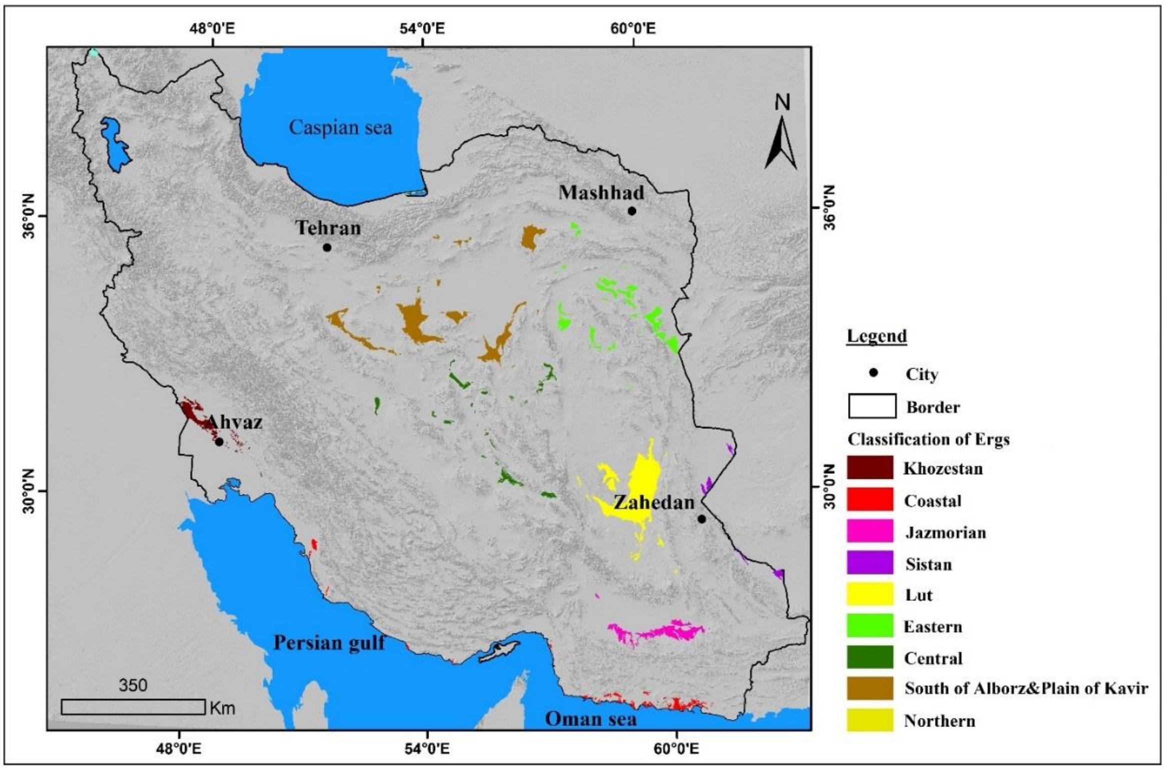

Fig. 3. A location-based classification map of ergs in Iran.

Table 4. Area and percentage of ergs in Iran based on geographic location.

Sand Dunes	Area	Percent
Khouzestan erg	2629	5/5
Coastal erg	2751	5/8
Jazmorian erg	4261	8/9
Sistan erg	1068	2/3
Yallan (Lut)sand sea	14629	30/6
Eastern erg	3221	6/7
Central erg	13081	27/4
South of Alborz and Great Kavir (Dasht- e Kavir)	5737	12
Northern erg	434	0/9
Total	47811	100

4.2. Sand dunes are categorized in ergs

Different factors such as wind velocity and direction, topography conditions, hydroclimatic conditions, and vegetation form diverse sand dunes and sand sheets in ergs and dunefields (Sloss *et al*, 2012., Yang el al, 2019., Zhu *et al*, 2021). Because Iran's geomorphology and hydroclimatic conditions are so diverse, each of the aforementioned factors can have a different impact on sand dunes' distribution, shape, and movement. As a result, ergs in Iran have a wide range of sand dunes types and can be classified into several types. Sand dunes in ergs were identified and classified into different types in this study using Google Earth images (Fig. 4). According to the classification concerning the research method, linear, transverse, and complex sand dunes cover a large portion of the country's ergs. There are usually no topographic obstacles in areas where linear sand dunes exist. Also the prevailing wind direction varies throughout the year in areas with complex sand dunes (Hugenholtz *et al*, 2012., Yang *et al*, 2012). In some areas where barchan and transverse sand dunes exist, the direction of the arms and slip faces of these sand dunes changes throughout the year as wind directions change. Furthermore, the development of nebkhas can be seen in many ergs of Iran, particularly those with more precipitation or access to surface or ground fresh water resources. However, because they are frequently accompanied by other sand dunes, the name nebkha has been omitted, unless in locations where nebkha is the only sand dunes present. In fact, different types of sand dunes can be found in various ergs, including coastal ergs. Furthermore, all small and large sand dunes in the Iranian ergs were shown on maps because sand dunes in the Iranian ergs were drawn with high accuracy in this study (Figs. 4, 5 and 6).

The area and percentage of sand dunes in each class in Iran are shown in table 5. According to the findings, transverse sand dunes have covered a significant proportion of Iran's ergs. The simple and composite transverse dunes, as well as barchans, cover 9599.2, 4560.1, and 1316.6 km^2, respectively. Low-, medium-, and thick-thickness sand sheets cover 7932.1, 7209.6, and 3773.9 km^2 (16.2 percent, 14.7 percent, and 7.7 percent, respectively) of the total area of ergs in Iran. In addition, Simple and composite linear sand dunes cover 1319.1 and 5603.7 km^2 (2.7 percent and 11.4 percent, respectively), star dunes 800.6 km^2 (1.6 percent), complex sand dunes 6739.7 km2 (13.7 percent), nebkha 71.4 km2 (0.15 percent), parabolic sand dunes 60.5 km2 (0.12 percent), and topographic sand dunes 101.1 km2 (0.2 percent) of Iran's total erg.

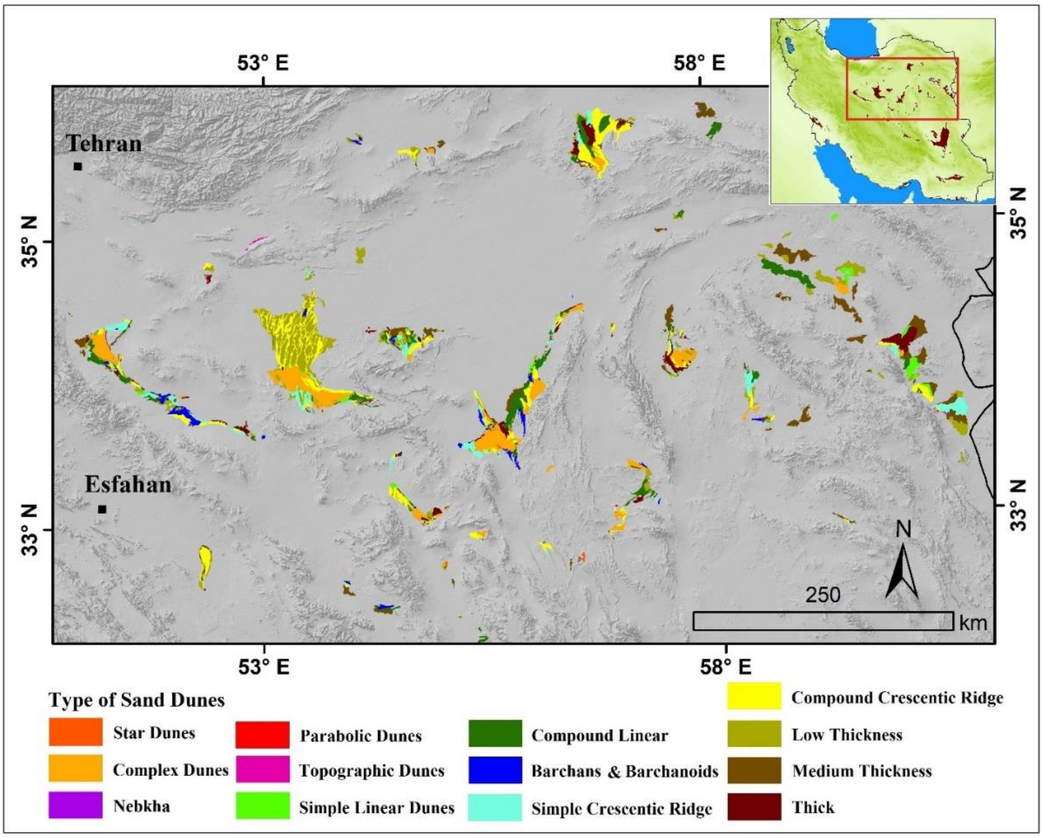

Fig. 4. Map of sand dunes classification in Iran's ergs and dunefields (Great Kavir and south of Alborz, eastern and central ergs)

4.3. Monitoring of sand dune displacement

Various factors affect sand dunes throughout the year, and they are usually associated with a significant displacement changes. The rate of sand dunes movement is influenced by topographic conditions, sand dunes shape, wind direction and velocity and vegetation coverFieldwork monitoring, satellite images (Aydda & Algouti, 2014., Brownett & Mills, 2017., Aydda *et al*, 2020), and radar image data (Havivi *et al*, 2017., Blasco *et al*, 2020) have all been used to assess the amount of sand dunes movement. As stated previously in this study, satellite images were used to detect sand dunes displacement using sampling methods (2005 to 2020). In fact, for sand movement monitoring, 795 sample points were selected.

The sand dunes of the study area from 2005 to 2020 were associated with significant movement, with a displacement rate of between 2 and 97 meters over a 15-year period, according to the results of monitoring the movement of sand dunes using 795 sampled points (Fig. 7). Also, sand dunes have moved at the fastest rate in the marginal parts of Yallan sand sea, Sistan ergs, and some parts of the Great Kavir and south of Alborz range ergs (Fig. 8). In fact, These regions have the highest rate of sand dunes displacement due to a lack of topographic obstacles, low vegetation cover, high wind velocity and DP, and consistent wind direction throughout the year. Also, some parts of coastal ergs, Khouzestan ergs, Jazmorian ergs, and eastern ergs had the lowest sand dunes movement, with the main causes being sand dunes stabilization by humans, the presence of topographic obstacles, low wind velocity, and DP.

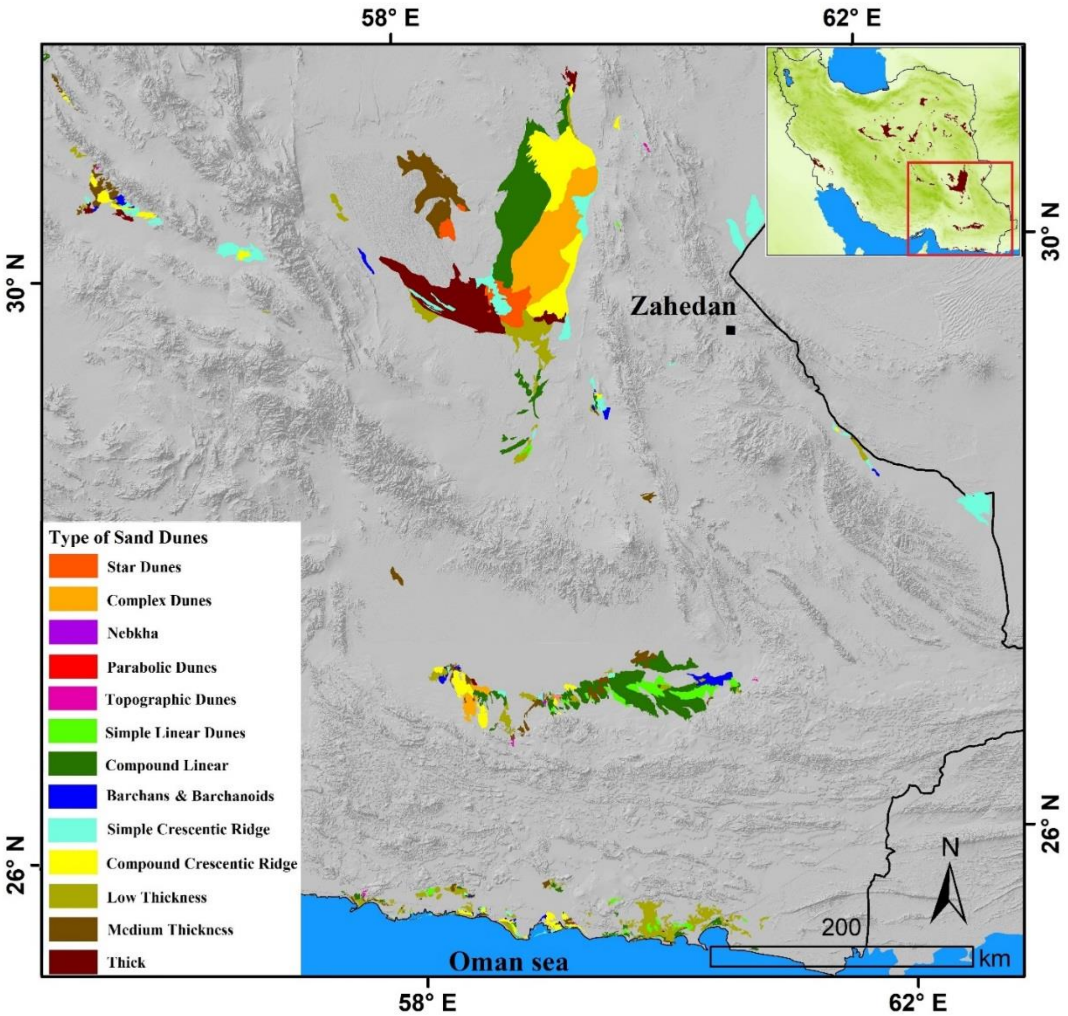

Fig. 5. Map of sand dunes classification in Iran's ergs and dunefields (Lut, Sistan, Jazmorian and coastal ergs)

It should be noted that the amount of movement may have been greater in some places, but the results obtained from monitoring the movement of sand dunes were based solely on sampling points because only sampling points were used in the prepared maps. When these findings are compared to other Iranian erg research, such as monitoring of central ergs (Barzegari Dahaj, 2017), the consistency of the two studies is clear. However, according to other research (Maghsoudi *et al*, 2017), sand dunes in the western part of the Yallan sand sea are migrating at a rate of about 12.5 meters per year. This amount was higher than the amount estimated in the current study. The main reason is that only a few barchans were considered to have the most movement by Maghsoudi *et al*. (2017), but it should be noted that the amount of movement in different types of barchans and sand dunes varies. Different shapes of sand dunes were used in this study to calculate the amount of displacement, so the amount of difference could be justified. Fig. 9 depicts sand dune displacement along the south coast, Yallan sand sea and Sistan ergs. According to measurements, the sand dune on the south coast has a displacement of 49 meters, 97 meters on the Yallan sand sea, and 61 meters on the Sistan ergs (Fig. 9).

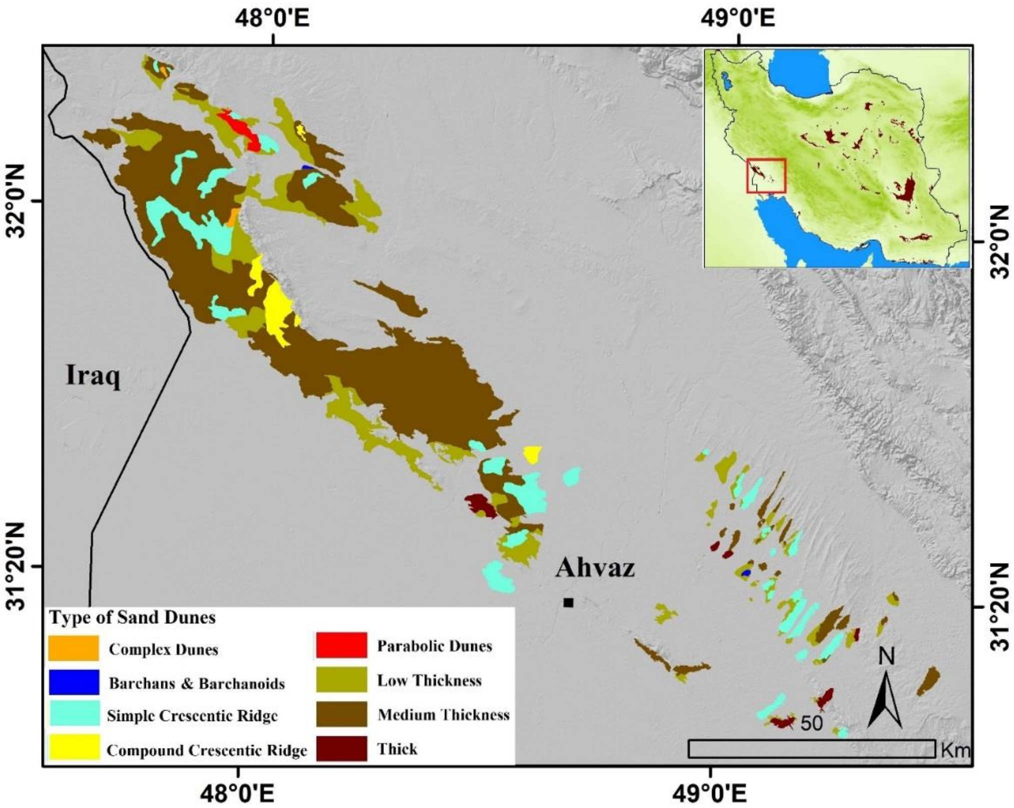

Fig. 6. Map of sand dunes classification in Iran's ergs and dunefields (Khuzestan ergs)

Table 5. The area and percentage of different types of sand dunes in Iran's ergs.

Sand Dunes	Area	percent
Star Dunes	800.6	1.6
Complex Dunes	6739.7	13.7
Nebkha	71.4	0.15
Parabolic Dunes	60.5	0.12
Topographic Dunes	101.1	0.2
Simple Linear Dunes	1319.1	2.7
Compound Linear	5603.7	11.4
Barchans	1316.7	2.7
Simple Crescentic Ridge	4560.1	9.3
Compound Crescentic Ridge	9599.2	19.6
Low Thickness	7932.1	16.2
Medium Thickness	7209.6	14.7
Thick	3773.9	7.7
Total	47811	100

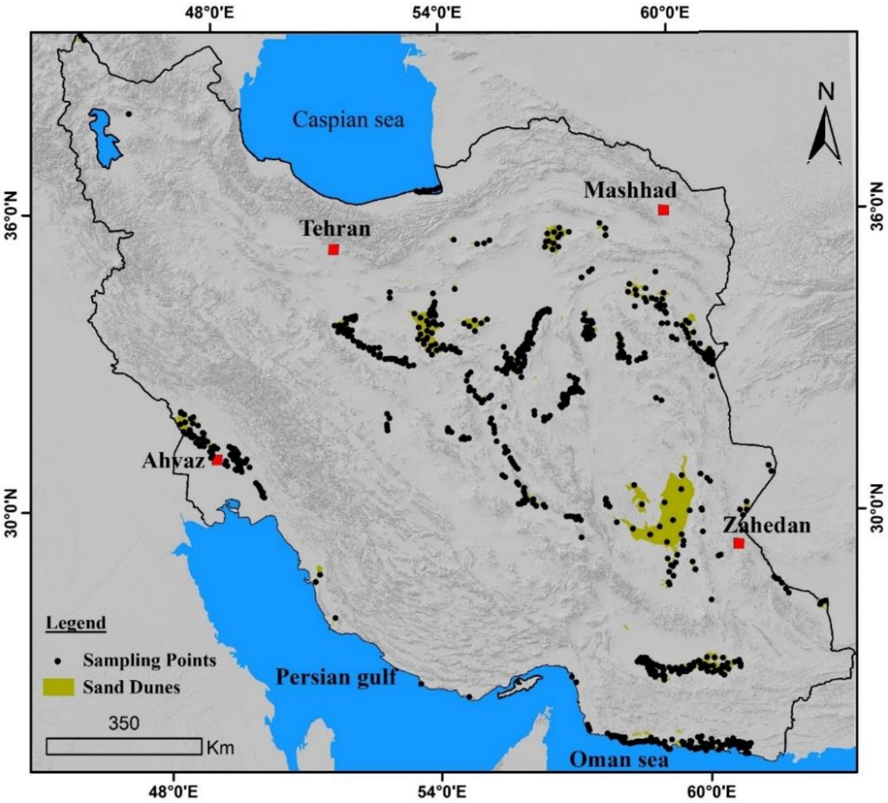

Fig. 7. Location of sampling points in various ergs across Iran

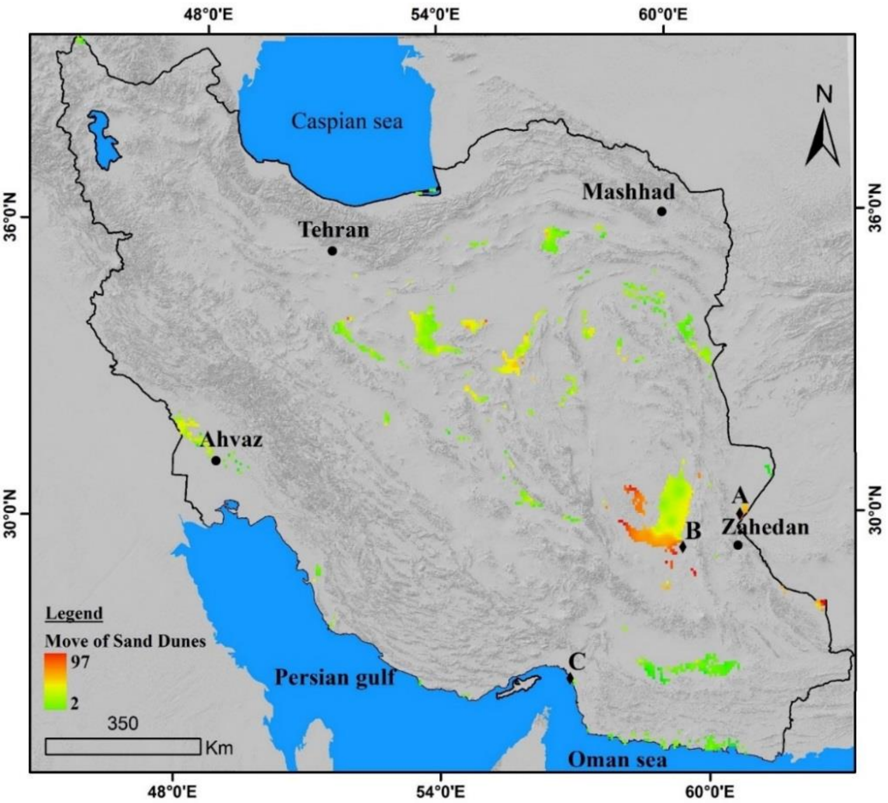

Fig. 8. Map of displaced sand dunes in different ergs across Iran from 2005 to 2020

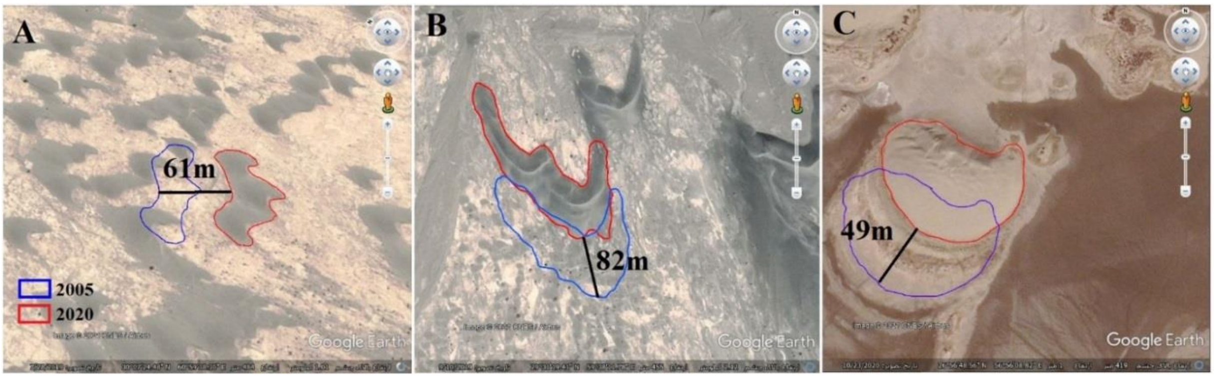

Fig. 9. Examples of displacement of sand dunes in the study area during the 2005 to 2020 (A. Sistan erg B. Yallan sand sea C. Coastal erg)

4.4. Wind analysis in the region

In order to assess the dynamic of ergs in Iran, wind velocity and DP were calculated using data from 51 stations adjacent to the ergs, and seasonal and annual wind direction maps were created using data from 66 meteorological stations.

4.4.1. Wind velocity

To assess wind velocity in the regions, the mean wind velocity was calculated using available data for a period of time, and table 6 was prepared based on the calculations. An annual and seasonal wind velocity map for the study area was also created using the IDW method and the mean annual and seasonal wind velocity (Fig. 10). According to the findings, Zabol station has the highest mean wind velocity at 13.4 m/s and Kashan station has the lowest at 1.7 m/s. In terms of mean seasonal wind velocity, Zabol station has the highest with 21.6 m/s in summer and Kashan station has the lowest with 2.1 m/s in spring. In terms of mean monthly wind velocity, Zabol station has the highest with 24.6 m/s in July and Kashan station has the lowest with 2.4 m/s in April, similar to annual and seasonal wind velocity. The standard deviation of mean wind velocity for all stations was also calculated in this study. According to the findings, the Zabol station has the highest standard deviation of 6.39, while the Kashan station has the lowest standard deviation of 0.46. This section's results indicate that because the highest mean wind velocity was related to Zabol and Zahak stations, the highest mean wind velocity belongs to the eastern and Sistan ergs. Furthermore, these stations have the highest standard deviation, it can be assumed that the average wind velocity in these areas varies throughout the year. In fact, the presence of the 120-day Sistan wind (from June to October) and, in recent years, the 170-day, is the main reason for the high average wind speed in this area (Mofidi *et al*, 2014). As a result, the stations in the Sistan areas have the highest standard deviation value. Due to topographic conditions, some parts of the central ergs, in addition to the eastern and Sistan ergs, have high mean wind velocity. In other regions, such as Khouzestan, mean wind velocity is lower due to the presence of sub-tropical high pressure and a lack of difference pressure.

4.4.2. Wind direction

The movement of sand dunes and their various shapes are influenced by wind direction and changes in wind direction patterns. The rate of sand dunes movement is usually high and the diversity of sand dune forms is low in regions with unidirectional wind throughout the year (Fryberger & Dean, 1979., Alghamdi & Al-Kahtani, 2005., Du *et al*, 2012., Han, 2017). In fact, Iran's topography (mountains, plains, and depressions) causes different wind directions due to its geographic location and trend. The annual wind velocity isoline of Iran is represented in figure 11. The dominant wind pattern in winter in the east of the country is from the north and north-west, while the dominant wind pattern in the west and north-west is from the west and south-west, according to the map (Fig. 11). The dominant wind pattern in the country's south east, such as Zabol, is from the northwest in the spring, from the east in Kerman's east, and from the north and northwest in Khuzestan. Summer winds in the south east and south west of the country are predominantly from the west and north. In the summer, the dominant wind is from the north and north-east in the north-east regions. In the autumn, the wind pattern in the south-east of the country is more north west. The predominant wind is from the north and east in the north-east, and from the west in the west of the country. In fact, the annual dominant wind patterns in different parts of the country are extremely diverse, according to the findings.

Table 6. Mean annual wind velocity, and maximum seasonal and monthly wind velocity in studied stations

Station	Annually (Mean)	Monthly (max)	Seasonal (max)	Monthly (SD)	Station	Annually (Mean)	Monthly (max)	Seasonal (max)	Monthly (SD)
Ilam	5.2	6.4-Jun	5.9-Spr	0.92	Aghda	8	10.4-Mar	9-Win	1.24
Mehran	5.7	8.5-Apr	7.2-Spr	1.4	Meibod	7.8	9.6-Dec	8.9-Win	1.25
Dezfol	2.4	3.3-May	3-Spr	0.53	Yazd	5.8	7.2-Jul	6.5-Spr	0.91
Shoshtar	5.7	7.6-Apr	7.2-Spr	1.02	Mehriz	6.9	7.9-Apr	7.5-Spr	1.05
Masjedsoleyman	4.2	5.7-May	5.5-Spr	1. 12	Shahrbabk	4.8	7.2-Aug	6.4-Sum	1.36
Izeh	4.5	6.4-Aug	5.9-Sum	1.09	Rafsanjan	9.8	11.3-May	10.8-Spr	0.96
Ramhormoz	3.4	5.2-May	3.5-Spr	0.81	Zarand	4	6.7-Mar	5.4-Win	1.24
Hendijan	8.2	10.4-Jan	10-Win	1.02	Sirjan	5	6.4-Aug	5.9-Sum	0.85
Khark	8.4	10-Dec	9-Win	1.18	Shahdad	6.6	11.6-Aug	8.7-Sum	2.29
Lamerd	4	6.4-May	5.4-Spr	1.29	Kerman	5.6	7.3-Jul	6.4-Spr	1.33
Shiraz	6.2	6.3-May	7.2-Spr	1.09	Lalehzar	9	14-Feb	12.2-Sum	2.05
Esfahan	3.2	5.1-Apr	4.1-Spr	1.15	Kahnoj	5.6	8.8-Jul	8.1-Sum	2.2
Ardestan	7.5	9.4-Aug	9-Sum	1.85	Jiroft	2.8	4.4-Aug	3.9-Sum	1.12
Kashan	1.7	2.4-Apr	2.1-Spr	0.46	Bam	3.5	5.2-Aug	4.2-Sum	0.76
Kahak	10.1	12.8-Aug	11.2-Spr	2.05	Dehsalam	4. 9	5.4-Jul	5.3-Win	0.67
Salafchegan	8.8	11.5-Apr	9.8-Spr	2.05	Nehbandan	5.1	7.3-Jul	6.6-Sum	1.3
Semnan	5.6	7.1-Jul	6.6-Sum	0.97	Zabol	13.4	24.6-Jul	21.6-Sum	6.39
Shahroud	3.6	6.1-Jul	4.7-Sum	1.22	Zahak	10.2	19.7-Jul	16.5-Sum	4.91
Sabzevar	5.4	7.6-Jul	6.5-Spr	1.49	Nosratabad	4.6	5.9-Jun	5.5-Spr	0.7
Mashhad	5.5	7.1-Jul	6.5-Spr	1.1	Zahedan	6.8	8.6-Feb	8.1-Win	1.23
Torbatejam	8.1	12.8-Jul	11.6-Sum	2.75	Khash	7.3	8.5-Feb	7.9-Spr	1.12
Kashmar	2.8	3.5-Jun	3.1-Spr	0.48	Saravan	6.6	7.6-Jun	7.6-Spr	0.69
Khoor birjand	9.2	14.1-Jul	12.4-Sum	2. 65	Iranshahr	6.7	7.8-Jul	7.5-Sum	0.83
Tabas	3.6	4.8-Jul	4.1-Sum	0.71	Jask	7.9	10.3-Aug	9.9-Sum	1.52
Khoor Biabanak	3.6	4.3-Jul	4.1-Spr	0.69	Kenarak	6.7	8.8-Jul	8.3-Sum	1.94
Robat Poshtbadam	5.9	7.5-Jul	6.9-Sum	1.08					

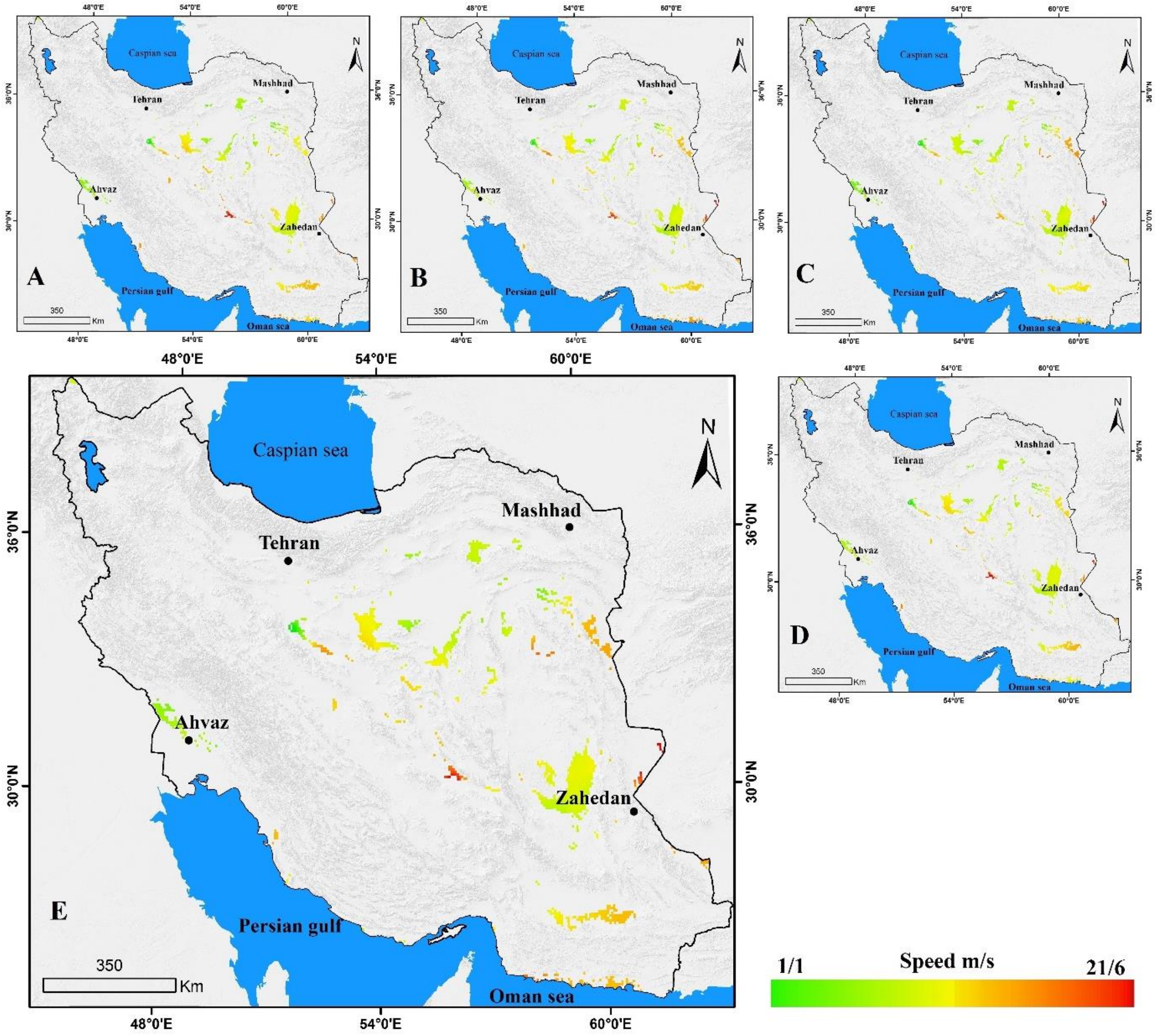

Fig. 10. Iran's annual and seasonal wind velocity interpolation maps in ergs A. winter, B. spring, C. summer, D. autumn, E. annual

In Zabol station, the predominant wind direction is northwest. It comes from the south-west in Ilam (west of the country), the south-east in Mashhad (north east of the country), and the north in Torbat-e Jam (east of the country). Overall, the results of wind direction analysis show that during the study period, dominant wind directions in some regions, such as Sistan ergs and the southern part of the Yallan sand sea, change less throughout the year, and as a result, the sand dunes movement in this region have high velocity and little shape variety. Furthermore, due to high changes in dominant wind direction, sand dunes movement and diversity are low in some regions, such as Khuzestan and parts of central Erg.

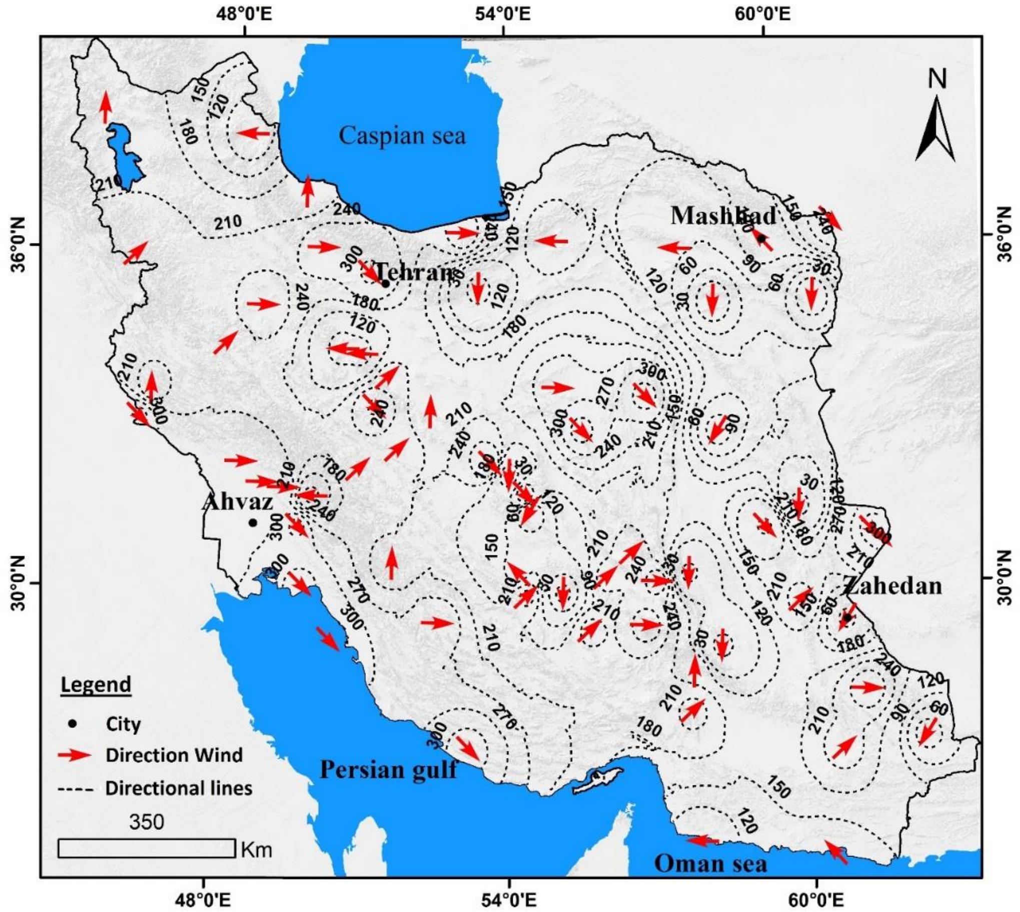

Fig. 11. Annual and seasonal wind direction of Iran

4.4.3. Calculate DP value

Total drift potential, or DP, is an important factor in recognizing the form and movement of sand dunes which is used to determine sand transportation potential (Fryberger & Dean, 1979). When DP exceeds 400, the region faces a high potential of wind erosion and sand dunes movement, as previously stated (Abbasi *et al*, 2019). To calculate DP in stations near Iran's ergs, researchers first calculated the mean annual, seasonal, and monthly DP in each station (Table 7), and then used the IDW interpolation method to create mean annual and seasonal DP maps (Fig. 12). According to the results, Zabol station has the highest DP (2122) and Ramhormoz station has the lowest DP (45). Zabol station has the highest mean seasonal and monthly DP with 2850, followed by Zahak station with 2339 and 2079. Furthermore, the results of standard deviation and IDW interpolation methods show that DP around ergs is highly variable throughout the year, with the highest DP occurring in the northern part of the Yallan sand sea and eastern ergs during the spring and summer. It's worth noting that DP has a high value all year in some ergs, such as Sistan ergs. In fact, DP in Sistan ergs has the highest potential sand transportation potential in the country. As a result, according to Abbasi *et al* (2019), it is the most active erg in Iran. Also, according to this index, because Khuzestan ergs have a low DP throughout the year, the potential for sand transportation and sand dunes movement is limited.

Table 7. The monthly and seasonal DP values of the studied stations

Station	Annually (Mean)	Monthly (max)	Seasonal (max)	Monthly (SD)	Station	Annually (Mean)	Monthly (max)	Seasonal (max)	Monthly (SD)
Ilam	262	457-Mar	399-Win	136.9	Aghda	369	1529-Mar	951-Win	424.2
Mehran	963	2173-Aug	1547-Sum	587.4	Meibod	434	1627-Feb	748-Win	435.6
Dezfol	86	308-Feb	230-Win	101.8	Yazd	72	205-Feb	132-Win	71.2
Shoshtar	517	1110-Mar	866-Win	349.8	Mehriz	70	236-Mar	128-Win	62.9
Masjedsoleyman	161	269-Apr	221-Win	81.4	Shahrbabk	219	530-Mar	367-Win	125.2
Izeh	170	442-Jul	227-Aut	136.1	Rafsanjan	620	1911-Mar	1421-Win	557.3
Ramhormoz	45	74-Mar	66-Win	29.1	Zarand	321	1001-May	573-Spr	263.3
Hendijan	336	621-May	596-Spr	198.6	Sirjan	324	700-Mar	461-Win	176.3
Khark	378	770-Nuv	565-Aut	225	Shahdad	894	2007-Agu	1261-Win	564.5
Lamerd	183	416-May	280-Spr	107.6	Kerman	346	693-Feb	539-Win	202.8
Shiraz	167	330-May	248-Spr	88.8	Lalehzar	1341	1522-Feb	1344-Win	533.6
Esfahan	470	1776-Feb	888-Win	506	Kahnoj	255	444-Jun	333-Sum	142.2
Ardestan	460	1329-Mar	785-Win	332.9	Jiroft	285	558-Jun	573-Spr	190.8
Kashan	140	555-Apr	272-Spr	151.9	Bam	214	499-Sep	488-Sum	145.4
Kahak	638	1315-Feb	933-Sum	474.1	Dehsalam	426	633-Jan	601-Win	200.8
Salafchegan	936	1964-Apr	1067-Win	658.7	Nehbandan	487	2111-Jul	2021-Sum	778
Semnan	203	369-Mar	310-Spr	138	Zabol	2122	2850-Jul	2850-Sum	946.1
Shahroud	211	582-Mar	348-Win	150	Zahak	1541	2339-Agu	2079-Sum	756.3
Sabzevar	100	206-Jun	158-Spr	64.1	Nosratabad	327	1211-May	1094-Spr	365.5
Mashhad	69	136-Jun	100-Spr	42.8	Zahedan	348	1001-May	706-Win	272.5
Torbatejam	373	592-Aug	484-Sum	172.8	Khash	233	397-Feb	342-Win	122.4
Kashmar	50	244-Mar	92-Atu	72.6	Saravan	179	329-Feb	236-Win	84.4
Khoor birjand	864	1587-Jul	1328-Sum	444.9	Iranshahr	150	278-Jul	234-Sum	86.5
Tabas	81	164-May	134-Spr	48.3	Jask	205	370-Mar	340-Win	121.8
Khoor Biabanak	93	364-May	179-Spr	92.3	Kenarak	323	398-Jan	595-Atu	105.2
Robat Poshtbadam	52	139-Mar	91-Win	31.8					

4.5. Correlation between wind characteristics and sand dunes displacement

The correlation between sand dunes displacement and wind characteristics of the study area was calculated annually, seasonally, and monthly in this study to evaluate the relationship between them (Table 8). According to the findings, the annual correlation between sand dunes displacement and wind velocity is 0.598. August has the highest monthly correlation value of 0.702, while spring has the highest seasonality value of 0.674. According to the correlation results, there is a significant relationship between sand dunes movement and wind velocity in the region. In fact the wind had the highest velocity in areas where sand dune displacement was high. The correlation between sand dunes movement and annual DP is 0.633, with the highest seasonal correlation (0.702) and monthly correlation (0.697) occurring in the summer. In relation to the aforementioned, there is a strong link between sand transportation potential and sand dunes displacement in the study area. In addition, there is a 0.679 correlation between annual wind velocity and annual DP index. In terms of seasonal correlation, summer has the highest correlation of 0.721, while July has the highest monthly correlation of 0.757. Wind speed and DP coefficient have a significant and strong relationship in Iran's ergs, according to the above mentioned.

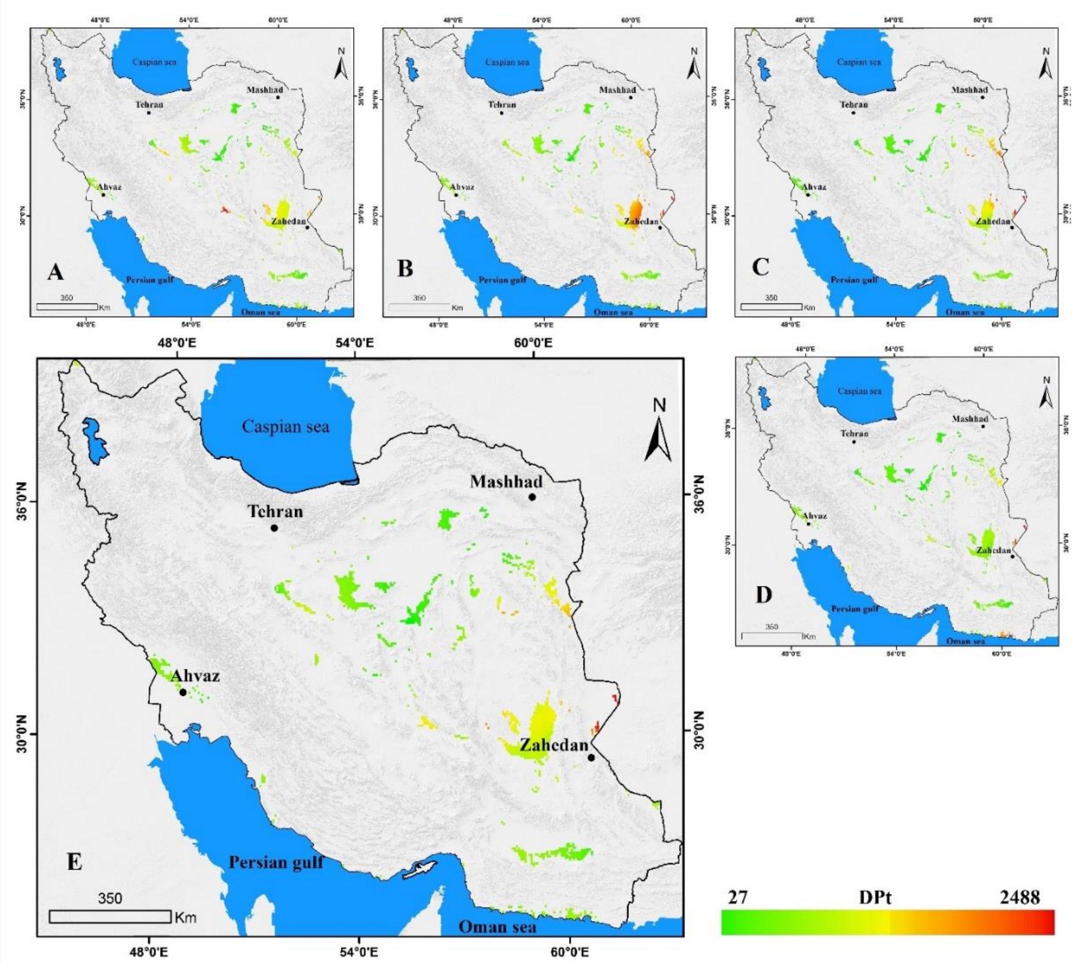

Fig. 12. Interpolation maps of annual, seasonal, and monthly DP: A. winter, B. spring, C. summer, D. autumn, and E. annual

Table 8. Correlation between wind characteristics and sand dunes displacement rate

Period	Correlation between sand dune movement and wind velocity	Correlation between sand dune movement and DP	Correlation between wind velocity and DP
January	0.513	0.533	0.621
February	0.548	0.524	0.619
April	0.498	0.491	0.578
March	0.502	0.509	0.608
May	0.619	0.683	0.698
June	0.678	0.631	0.721
July	0.592	0.697	0.757
August	0.702	0.549	0.636
September	0.513	0.552	0.639
October	0.498	0.358	0.579
November	0.547	0.458	0.603
December	0.334	0.371	0.521
Winter	0.524	0.579	0.639
Spring	0.674	0.669	0.704
Summer	0.604	0.702	0.721
Autumn	0.514	0.624	0.621
Yearly	0.598	0.633	0.679

5. Conclusion

According to the study's findings, Iran has 47811 km^2 of ergs and dunefields, which account for approximately 2.9 percent of the country's total area. Due to topographic and climatic conditions, the central and southeastern parts of Iran have the highest density of ergs, according to a study of sand dunes distribution in Iran. Iran's ergs are also diverse in terms of topographic diversity and wind direction differences. Compound transverse dunes, with 19.6% of the total area, are the most common type of sand dunes. Because a large portion of Iran's sand dunes are in the form of migration dunes, these sand dunes move a lot throughout the year, so their displacement over a 15-year period was between 2 and 97 meters. In fact, the Yallan sand sea has the highest displacement rate. Monitoring the displacement of sand dunes in various study areas has revealed that regions with high wind velocity and high DP, sparse or no vegetation, no topographic obstacles, and vast flat surfaces (such as the Yallan sand sea) have the highest rate of displacement. According to the results of the correlation between wind characteristics and sand dunes displacement, sand dunes have displaced much more in regions with high velocity and high DP, but the rate of sand dunes displacement was low in some regions, despite high wind velocity and DP (some parts of central and eastern ergs). The stabilization of sand dunes by vegetation cover, as well as topographical obstacles, are the main reasons. Human intervention, such as sand dunes stabilization, can play an important role in sand dunes movement control, as mentioned above.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

This study did not involve any human participants, animals, or personally identifiable data. All remote sensing data and spatial information used in this research were obtained from publicly available sources or licensed databases. The data were used in accordance with their respective usage policies and licenses. Therefore, no ethical approval was required.

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Conflict of interest

The authors declare no conflict of interest.

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