Meteorological application of wind speed and direction linked to remote sensing images for the modelling of sand drift potential and dune morphology

Samira Zamani1 | Majid Mahmoodabadi1 | Najme Yazdanpanah2 | Mohammad Hady Farpoor1

1Department of Soil Science, Agriculture Faculty, Shahid Bahonar University of Kerman, Kerman, Iran
2Department of Water Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran

Correspondence
Majid Mahmoodabadi, Department of Soil Science, Agriculture Faculty, Shahid Bahonar University of Kerman, Kerman, Iran.
Email: mahmoodabadi@uk.ac.ir

Abstract
Wind velocity and its direction are important erosive factors affecting sand drift potential and dune morphology in arid and semi-arid environments. The study assesses sand drift potential using wind meteorological data acquired from eight synoptic stations of Kerman province in southeastern Iran for a statistical period of 2006–2010. Three diagrams including wind rose, storm rose and sand rose were plotted for the selected stations using WR Plot View 8 and Sand Rose Graph 3.0. The analyses were performed at seasonal and mean annual time scales. The unidirectional index and wind energy classification were compared with sand dune morphology obtained from satellite images. The seasonal analysis indicated intermediate directional variability and high energy winds, with the most erosive winds occurring in winter. The total sand flux in all directions and discharge sand flow in the resultant drift direction ranged from 53.4 to 319.1 and from 13.8 to 247.6 t m⁻¹ year⁻¹, respectively. The transverse dune was the main type of sand dune detected in the region with an intermediate directional variability, implying positive sand supplies. Dune morphology coincided reasonably well with the resultant drift direction. An appropriate match was found between the wind data analyses and the morphology of dunes observed in the satellite images.

KEYWORDS
meteorological data, morphology, sand dune, wind erosion, wind speed

1 INTRODUCTION

Wind erosion is one of the most serious problems in arid and semi-arid environments (Lackoova et al., 2013; Zhang et al., 2018; Sirjani et al., 2019). Because wind erosion is influenced by the climatic conditions (Skidmore, 1986), it mainly occurs in arid regions with dry soils containing a low moisture content and lack of vegetation cover for most of the year (Ekhtesasi and Sepehr, 2009; Mahmoodabadi, 2011; Broomandi et al., 2017; Hereher, 2018). Rainfall deficiency and the difference in temperature between mountain and plain areas are major climatic factors affecting wind speed and, consequently, the wind erosion rate (Ekhtesasi and Sepehr, 2009). Under
these conditions, sand dunes are formed as they are highly susceptible to wind erosion activity in a region (Broomandi et al., 2017).

Aeolian transport is an essential issue in wind erosion studies because it is an important geomorphological process that threatens the arid ecosystems severely (Dong et al., 2012). In addition, aeolian transport causes several problems, such as damaging crops, desertification, degrading soil resources by removing fine fertile particles and leaving coarse particles from the soil surface (Goossens, 2004; Ekhtesasi and Sepehr, 2009; Dong et al., 2012; Wang et al., 2016; Kheirabadi et al., 2018).

In general, aeolian transport is a result of wind and soil surface interactions and, therefore, depends strongly on wind characteristics and soil surface properties (Bagnold, 1941; Dong et al., 2012; Deng, 2016; Rezaei Arshad et al., 2019; Shahabbagejad et al., 2019a, 2019b). Therefore, it is necessary to prepare and analyse the anemometric data of wind characteristics to quantify the relationship between aeolian processes and the local and regional wind regimes based on the monitoring of erosive dust storms (Mesbahzadeh and Ahmadi, 2012; Zhang et al., 2014).

Wind power is responsible for many of the characteristics of arid zone geomorphology (Yang et al., 2014; Zhang et al., 2014). In other words, wind energy influences the formation and mobility of sand dunes, since it affects the magnitude of sand deposits (Al-Awadhi et al., 2005; Mesbahzadeh and Ahmadi, 2012; Zhang et al., 2015). This is directly related to the major characteristics of wind such as wind speed and the prevailing wind direction (Presley and Tatarko, 2009; Zhang et al., 2012b; Rezaei Arshad et al., 2019). Wind speed is a key factor in determining the potential sand transport, and wind velocity data can be used efficiently in the risk assessments of blowing sand (Zhang et al., 2014; Liu et al., 2015; Kheirabadi et al., 2018). Moreover, the prevailing wind direction depends on the local topography and season (Jewell and Nicoll, 2011; Zhang et al., 2012a). The analysis of wind speed and direction data results in a better understanding of the prevalent wind regime at different temporal and spatial scales (Wal and McManus, 1993) and in an appropriate recognition of different types of sand dunes (Jewell and Nicoll, 2011; Hereher, 2014).

The potential sand transport means the potential aeolian transport into the dune based on wind speed and wind direction (Deng, 2016). The study of wind regime in relation to aeolian erosion, sediment transport and depositional processes is fundamental for the modelling of drift potential (DP) as well as sand dune morphology, activity and mobility. Basically, the method suggested by Fryberger (1979) is a useful approach for evaluating sand DP by wind (Wal and McManus, 1993; Al-Awadhi et al., 2005; Mesbahzadeh and Ahmadi, 2012; Zhang et al., 2015). One of the most important concepts in aeolian transport is threshold wind velocity, which is the minimum wind speed required to move sand particles from the soil surface (Yang et al., 2014). However, it is difficult to determine in wide-scale field studies, so many studies that have been performed on DP assumed that the threshold wind velocity can be considered to remain constant for the whole study area (Nazari Samani et al., 2013). Wind frequency above the threshold as the erosive wind is directly related to the calculated DP (Zhang et al., 2014). In addition to wind characteristics, soil erodibility is important for modelling soil erosion and sand DP. Soil erodibility is directly related to soil properties, which have a spatially continuous and soil scrape related variability (Avalos et al., 2018; Kheirabadi et al., 2018). Soil erodibility expresses the intrinsic susceptibility of a soil to erosion and is high when the soil is not protected by surface cover, roughness, crusting and/or high moisture content (Mahmoodabadi and Ahmadian, 2013). In arid regions, many factors such as rock fragment cover, aggregate size, clay percentage, moisture content and soil organic carbon significantly affect the erodibility of soils by wind (Mahmoodabadi, 2011; Sirjani et al., 2019).

Most parts of Iran are located in arid and semi-arid regions (Broomandi et al., 2017). Therefore, large areas of the country are vulnerable to desertification, since deserts cover approximately 20% of the country's area. Kerman as the largest province is subjected to this destructive phenomenon. Sand dunes occupy a vast expanse of desert areas and are considered a threat for urban regions and agricultural lands (Jamali et al., 2018). The cyclonic circulations with regional winds are responsible for the transmission of dust particles over this region (Nazari Samani et al., 2013). The assessment of sand transport and aeolian dune morphology is necessary for recognizing problems associated with sand encroachment in desert regions (Al-Awadhi et al., 2005). Therefore, the present paper (1) analyses the anemometric wind data taken from the main synoptic stations of Kerman province at the seasonal and annual time scales; (2) investigates sand DP, the unidirectional index (UDI) and wind energy classification by analysing wind rose, storm rose and sand rose for the period 2006–2010; and (3) identifies the major types of sand dunes using remote sensing satellite images and compares them with the results of wind analysis. The findings will improve one’s understanding of sediment transport processes and sand dune formation in arid regions based on wind characteristics analysis.
2 | MATERIALS AND METHODS

2.1 | Study area

Kerman province was selected as the study area. With a total area of 180,424 km², it is the largest province in Iran, located in the southeast of the country (between 25°55' and 32°N, and 53°26' and 59°29'E). The climate of the region varies from arid to semiarid, with hot summers and cold winters (Atapour and Aftabi, 2002). The formation of soils has been influenced by physical weathering because of the arid and semi-arid conditions. In other words, the soils are weakly developed in this area and contain low organic matter. Residual soils have been developed over limestone, conglomerate outcrops and alluvial sediments (Beckett, 1958). According to the American system of soil classification, most of the soils are aridisols, inceptisols and entisols (Nadimi, 2010). The main sources of aeolian sediments in the province include construction activities, barren lands, non-residential roads, sand dunes, playa surfaces and alluvial fans (Hassanzadeh, 2006). In the present study, eight

| TABLE 1 | General characteristics of the synoptic stations of Kerman province for the statistical period of 2006–2010 |
|---------|---------------------------------------------------------------|
| Station | Longitude | Latitude | Altitude (masl) | Temperature (°C) | Precipitation (mm) |
| Bam     | 58 21     | 29 06    | 1,067           | 24.3             | 33.5               |
| Jiroft  | 57 48     | 35 28    | 601             | 25.1             | 101.5              |
| Kerman  | 56 58     | 30 15    | 1,754           | 17.3             | 93.8               |
| Lalezar | 56 50     | 29 31    | 2,775           | 12.1             | 191.5              |
| Rafsanjan | 55 24   | 30 25    | 1,581           | 18.2             | 75.6               |
| Shahrbabak | 55 08 | 30 06    | 1,834           | 16.1             | 81.7               |
| Sirjan  | 55 41     | 29 28    | 1,739           | 18.1             | 99.5               |
| Zarand | 56 34     | 30 48    | 1,670           | 20.1             | 75.4               |

FIGURE 1 | Geographical location of the synoptic stations containing the digital elevation model (DEM) on the province map.
synoptic stations of the province were selected by which wind data analyses were performed. The location, mean annual temperature and precipitation of the selected stations are presented in Table 1. In addition, the geographical location of the synoptic stations containing the digital elevation model (DEM) on the province map is shown in Figure 1. The selection of these stations was made based on more accurate and detailed statistics. In general, the stations are at a wide range of altitudes, ranging from 601 masl at Jiroft station to 2,775 masl at Lalezar station (Figure 1). The mean annual precipitation ranges from 33.5 mm at Bam station to 191.5 mm at Lalezar station. The mean annual temperature ranges from 12.1°C at Lalezar station to 25.1°C at to Jiroft station.

2.2 Wind data analysis

There are many equations for estimating sediment transport potential. Among them, the Fryberger (1979) method has been widely used (Al-Awadhi et al., 2005; Mesbahzadeh and Ahmadi, 2012). The method is based on a formula proposed by Lettau and Lettau (1978). Accordingly the sand drift may be expressed as:

\[ DP = V^2(V - V_t)t, \]  

where DP is the amount of sand drift potential for each direction expressed in vector units (VU); V and \( V_t \) are, respectively, the average wind velocity and the threshold velocity of wind to move sand (12 kn ~ 6.2 m s\(^{-1}\)) both at 10 m height for each direction and for the time period t; and t is the percentage of occurrence of wind in each direction. Fryberger (1979) found that the threshold velocity for sand movement was 12 kn under dry conditions. The combination of \( V^2(V - V_t) \) is termed as “weighting factor”, in which strong winds are given high weightings and weaker winds lower weightings. The value of \( V^2(V - V_t) \) is divided by 100 to lower the magnitude of the weighting factors and to simplify the plotting of sand roses. Fryberger (1979) has been used in the analysis of wind data and estimating the sand DP of different arid regions (Al-Awadhi et al., 2005; Mesbahzadeh and Ahmadi, 2012; Nazari Samani et al., 2016).

The anemometer database of the selected synoptic stations of the province was used for a statistical period of five years from 2006 to 2010. The standard wind data, that is, wind speeds and directions with a frequency of 3 hr data at a height of 10 m, were collected from Kerman Meteorological Organization. To analyse the collected wind data, WRPlot View 8.0.2 software (Wind Rose Plots for Meteorological Data, 1998–2018 Lakes Environmental Software) was used. By using this software, wind statistical calculations and drawing of wind rose and storm rose were performed. In addition, because of the complexity in the calculations and the analyses of the sand transportation potential, Sand Rose Graph software was used (Nazari Samani et al., 2013). It is a computer program that can read wind velocity and direction data from meteorological stations. In fact, Sand Rose Graph software is an accessible program that estimates sand DP by winds, resultant drift potential (RDP) and unidirectional index (UDI) and for plotting sand roses, which will be described below. Before the analysis, the available data were converted to Lake Format before being used by the software (Mesbahzadeh and Ahmadi, 2012). Moreover, in order to investigate the erosive winds, all the wind velocities below the threshold wind velocity of 6.5 m s\(^{-1}\) were eliminated, as suggested by Fryberger (1979), and the remaining data were incorporated to plot the storm rose and sand rose.

A wind rose is the simplest statistical representation of anemometry by which wind directions and the mean velocity in different directions can be shown using a circular graph (Nazari Samani et al., 2013). The frequency of calm winds (wind velocity of < 1 kn, 0.5 m s\(^{-1}\)) is usually written in the central circle of the wind rose (Rajabi et al., 2006). However, the wind rose is not a practical criterion for stormy and dusty wind analysis, since wind threshold velocity is not considered (Nazari Samani et al., 2013). Therefore, another diagram, namely a storm rose, is used in which only the erosive winds faster than the threshold velocity are included (Nazari Samani et al., 2013). In fact, a wind rose determines the windiness of a region, whereas a storm rose is more suitable for analysing wind erosion based on threshold erosion velocity (Ahmadi et al., 2013). Furthermore, a sand rose is a vector diagram of wind energy representing sand drift (Nazari Samani et al., 2013). A sand rose is a diagram that shows not only the direction of wind transportation but also the wind erosion potential (Rajabi et al., 2006). Unlike a wind rose and a storm rose, in a sand rose the sand DP is calculated through wind frequency and velocity in different directions by a vector algebra procedure (Nazari Samani et al., 2013). In other words, a sand rose includes a group of arms corresponding to the DPs from all directions (DP\(_t\)) and an arrow that reflects the net RDP and resultant drift direction (RDD) (Fryberger, 1979; Hereher, 2018).

2.3 Sand transport calculations

In the present study, a wind rose and a storm rose were drawn for eight wind directions at seasonal and annual time scales (Rajabi et al., 2006). To draw a storm rose, the
threshold velocity of 6.5 m s$^{-1}$ was considered, as suggested by Fryberger (1979) and similar to previous studies (e.g., Al-Awadhi et al., 2005; Nazari Samani et al., 2013). This means that only wind velocities of $\geq 6.5$ m s$^{-1}$ were included in the wind data analysis, as soil erosion by wind occurs mainly during high wind speed events (Sirjani et al., 2019).

Overall, a total sand drift potential (DP$_t$) was calculated for each station at seasonal and mean annual time scales as a summation of DPs (per VU) for all eight directions:

$$\text{DP}_t = \sum_{i=1}^{8} \text{DP}_i. \quad (2)$$

Based on Fryberger’s (1979) suggestion for the comparison of wind energy, the DP$_t$ values were categorized into three classes: (1) DP$_t < 200$ VU = low energy; (2) 200 < DP$_t < 400$ VU = intermediate energy; and (3) DP$_t > 400$ VU = high energy. In addition, the RDP and RDD were calculated by considering DPs for each orientation class (Fryberger, 1979; Pearce and Walker, 2005):

$$\text{RDP} = \sqrt{(C^2) + (D^2)} \quad (3)$$

$$\text{RDD} = \arctan\left( \frac{C}{D} \right) \quad (4)$$

$$C = \sum_{i=1}^{8} (\text{DP}_i) \sin(\theta_i) \quad (5)$$

$$D = \sum_{i=1}^{8} (\text{DP}_i) \cos(\theta_i) \quad (6)$$

where $\theta$ is the midpoint of the orientation classes. Moreover, the UDI as a well-known index was used to interpret the forms of sand dunes in sandy deserts (Fryberger, 1979; Zhang et al., 2015):

$$\text{UDI} = \frac{\text{RDP}}{\text{DP}_t}. \quad (7)$$

The UDI ratio explains the effect of cross-winds in a region with a standardized indication of the directional variability of the wind (Al-Awadhi et al., 2005). Values $< 0.3$ indicate high directional variability; 0.3–0.8 indicate intermediate directional variability; and $> 0.8$ indicate low directional variability.

In addition, the total sand flux in all directions (TSF) and the discharge sand flow in the resultant drift direction (DSF) were calculated automatically by Sand Rose Graph 3.0, on the basis of the equation proposed by Lettau and Lettau (1978):

$$q = \left( \frac{C\rho}{g} \right) V^2(V - V_t), \quad (8)$$

where $q$ is sand flow discharge (t m$^{-1}$ year$^{-1}$); $C$ is a constant; $\rho$ is the density of air (kg m$^{-3}$); and $g$ is the gravitational acceleration (m s$^{-2}$).

### 2.4 Sand dunes morphology

In the present study, the dominant types and forms of sand dunes were identified in the region using remote sensing satellite image analysis. For this purpose, images of each region were acquired from the United States Geological Survey (USGS) Earth Explorer gateway (http://

---

| Station     | Calm winds (%) | Mean wind velocity (m s$^{-1}$) | Classes of erosive wind speed (m s$^{-1}$) |
|-------------|----------------|---------------------------------|------------------------------------------|
|             |                |                                 | 6.7–7.7 | 7.7–9.8 | 9.8–11.8 | 11.8–13.9 | $\geq$13.9 |
| Bam         | 4.4            | 4.5                             | 6.35    | 9.58    | 5.91    | 2.40     | 1.26      |
| Jiroft      | 26.6           | 2.2                             | 1.42    | 1.70    | 1.42    | 0.49     | 0.76      |
| Kerman      | 8.7            | 2.7                             | 6.73    | 7.55    | 2.84    | 0.93     | 1.15      |
| Lalezar     | 1.0            | 4.1                             | 1.04    | 7.61    | 4.70    | 0.82     | 0.98      |
| Rafsanjan   | 12.0           | 4.1                             | 5.58    | 10.78   | 11.39   | 4.10     | 3.17      |
| Shahrbabak  | 10.5           | 3.2                             | 6.19    | 9.46    | 5.47    | 1.53     | 0.93      |
| Sirjan      | 26.0           | 2.5                             | 10.13   | 10.89   | 5.48    | 1.75     | 0.44      |
| Zarand      | 11.5           | 3.6                             | 10.89   | 5.58    | 5.80    | 1.58     | 1.31      |
earthexplorer.usgs.gov/). For each region, the type of sand dunes was determined based on Breed and Grow (1979). Accordingly, different types of dunes, including longitudinal, transverse and star dunes, were recognized depending on the alignment of the dune slip faces with respect to the direction of the prevailing winds. Finally, the UDI and wind energy classification acquired from the RDD and RDP analysis were compared with the sand dunes’ morphology obtained from satellite image analysis.

3 | RESULTS AND DISCUSSION

The frequency of calm winds (wind speeds ≤ 0.5 m·s⁻¹) and the average wind speeds in addition to different erosive wind classes for the selected stations of Kerman province during the statistical period of 2006–2010 are presented in Table 2. The frequency of calm winds ranged from 1.0% at Lalezar to 26.6% at Jiroft, while the mean wind velocity varied from 2.2 m·s⁻¹ at Jiroft station.
to 4.5 m s$^{-1}$ at Bam station. The result also indicated that two stations of Sirjan and Zarand with 10.13% and 10.89%, respectively, showed the highest frequencies in a wind speed class of 6.7–7.7 m s$^{-1}$. For a wind speed class of 7.7–9.8 m s$^{-1}$, Sirjan and Rafsanjan stations with 10.89% and 10.78% experienced the highest frequencies. In the rest of the classes, that is, 9.8–11.8, 11.8–13.9 and ≥13.9 m s$^{-1}$, Rafsanjan with 11.39%, 4.10% and 3.17%, respectively, showed the highest frequencies. This means that the most erosive wind speed classes were allocated to Rafsanjan station. On the other hand, except Zarand at 6.7–7.7 m s$^{-1}$ and Rafsanjan at 9.8–11.8 m s$^{-1}$ wind classes, the other stations experienced the highest frequencies in the 7.7–9.8 m s$^{-1}$ class. In fact, despite the higher and the lower wind speed classes, the intermediate wind speed class (i.e. 7.7–9.8 m s$^{-1}$) was dominant in the stations, which is supported by Saremi Naeini (2016). This is of importance since the erosive energy of wind is significantly effective in the control of wind erosion rate (Presley and Tatarko 2009), sediment transport as well as the morphology of sand dunes (Saremi Naeini, 2016).

Figure 2 maps the annual wind roses for the selected stations categorized at eight wind directions and six speed classes. The wind rose analysis indicated that the prevailing wind direction for Bam, Kerman and Rafsanjan stations is north, for Sirjan and Shahrbabak is southwest, and for Jiroft, Zarand and Lalezar is south, northwest and west, respectively. Regarding the prevailing wind directions, it is recognized that the whole province can be partitioned into two: (1) the western part of the province with the prevailing western and southwestern wind directions; and (2) the eastern part of the province in which north winds predominate. The province contains large mountainous areas in the centre affecting near-surface wind speed.

Figure 3 shows the frequency of erosive winds for different seasons at different erosive wind classes for the stations. The least erosive winds occurred during the autumn for all stations, except Lalezar. Also, the most erosive winds occurred at Rafsanjan station, whereas Jiroft experienced the least erosive wind speeds. A plausible reason is that Jiroft station is located relatively on a
lower altitude with humid air conditions as compared with the other stations (Table 1). Moreover, the most frequencies of winds were observed at speed classes of 7.7–9.8 m·s⁻¹ for all the stations except Zarand.

The frequency of erosive winds for different seasons and wind directions during the statistical period of 2006–2010 is shown in Figure 4. The most erosive winds at Bam are in summer with a northerly direction, at Zarand in summer with a northeasterly direction, at Jiroft, Shahrbabak, Lalezar and Sirjan stations in winter with a southwesterly direction, and at Rafsanjan and Kerman stations in winter with a westerly direction. The results of Figures 3 and 4 also indicate that the highest speeds (≥ 13.9 m·s⁻¹) have occurred in winter in most stations. Basically, wind erosion and sand transport are influenced by wind erosivity and soil erodibility (Zamani and Mahmoodabadi, 2013). Therefore, only the occurrence of an erosive wind during a season cannot be an acceptable reason for high or low wind erosion rates. In other words, further information on soil characteristics such as soil surface erodibility and threshold wind velocity is required for the better estimation of wind erosion rates and sand transport potentials in a region. Although the most erosive winds (≥ 13.9 m·s⁻¹) were identified during winter, the higher precipitation and less evaporation (Table 1) and probably the greater threshold velocity during this season

**FIGURE 4** Seasonal changes in the directions of erosive winds for the selected stations of Kerman province during the statistical period of 2006–2010
make the estimations more difficult. In fact, atmospheric humidity is an important factor weakening the potential for sand drift during winter (Achberger et al., 2006; Bernhardson et al., 2019). Bärring et al. (2003) found that strong winds in combination with no precipitation are the most favourable conditions for sand transport. However, the strongest or most common winds during a season are not necessarily those responsible for large sand drifts (Bernhardson et al., 2019). Zhang et al. (2015) found that DP increased with increasing wind velocity and temperature; however, there was little or no significant relationship with precipitation and relative humidity.

The map of annual storm roses for the selected stations on Kerman is shown in Figure 5. The results indicate that the western and southwestern winds had the most roles in wind erosion and sediment transport in the province. At Bam, Zarand and Jiroft stations, the most prevailing winds are northern, northeastern and southern, respectively. In previous studies, the southern parts of Iran were found to be mainly influenced by western
and southwestern winds (Lorestani et al., 2012; Ekhtesasi and Dadfar, 2014). In addition, due to low precipitation (Table 1) and probably the low soil moisture content of the soils, they are likely susceptible to wind erosion (Yamani et al., 2011; Zamani and Mahmoodabadi, 2013). The analysis of storm roses is essential to determine the origin of sediments in a region in order to combat wind erosion. Moreover, the direct energy of the wind is mainly used in the detachment of particles finer than 2 mm (Yamani, 2001). In arid and semi-arid regions, changes in the direction, speed and frequency of erosive winds are important factors affecting wind erosivity and, consequently, the morphology of sand dunes and wind-erosion features (Lorestani et al., 2012).

The DPt and UDI for different seasons are presented in Figure 6. The DPt maximums were found at Bam, Jiroft and Zarand stations in summer, and at Kerman, Rafsanjan, Shahrbabak, Sirjan and Lalezar stations in winter (Figure 6a). Among the studied stations, Rafsanjan with 911 VU showed the highest DPt, which was observed in winter. According to Figure 6b, Rafsanjan in winter, Kerman in winter and autumn, Jiroft in autumn, and Bam in summer with UDI > 0.8 experienced low directional variability winds. The other stations in all seasons showed intermediate variability winds. Using the UDI index, it is possible to characterize the morphology of sand dunes and other wind-erosion features. The UDIs close to 1 indicate the winds have low directional variability, whereas those close to zero imply multidirectional winds (Ekhtesasi and Dadfar, 2014).

The map of the annual sand rose during the statistical period of 2006–2010 is shown in Figure 7. Analysis of the sand roses at the studied stations indicates that the RDD of sediments at Kerman, Jiroft, Sirjan, Rafsanjan and Shahrbabak stations is from west to east, at Lalezar is from southwest to northeast, at Bam is from north to south, and at Zarand is from northwest to southeast. It is also indicated from the result that, in most cases, the prevailing wind directions of the sand roses are in line with the directions of the storm roses, indicating the acceptable results of the storm roses. However, using the wind rose analysis alone, it is not possible to achieve the most effective winds involved in wind erosion in the predominant direction. Similarly, Ekhtesasi and Sepehr (2009) found that a wind rose alone cannot show sand dune direction, because all prevalent winds are not
necessarily erosive. This is because wind speeds less than the threshold velocity were eliminated in the analysis of the storm rose and the sand rose (Parsamehr and Khosravani, 2017).

Table 3 shows the summary characteristics of sediment transport quantities and wind regime indices in relation to sand dune morphology in the region derived from Sand Rose Graph 3 and remote sensing analyses. The maximum TSF was observed at Rafsanjan station, with an estimate of 319.1 t·m⁻¹·year⁻¹; the lowest was at Jiroft station, with 53.4 t·m⁻¹·year⁻¹. The DSFs at these two stations were 247.6 and 13.8 t·m⁻¹·year⁻¹, respectively. In other words, the discharge sand flow in the RDD had a 25.8% and a 77.6% contribution to the TSF of these two stations, respectively. A similar result was obtained by Ahmadi and Mesbahzadeh (2011) in a previous study at Kerman station during the period 1985–2005; they found that the predicted TSF for this station was 89.93 m³·m⁻¹·year⁻¹, which is close to the present study's estimation of 87.0 t·m⁻¹·year⁻¹ (Table 3). Also, the result of Parsamehr and Khosravani (2017), when using the anemometric data of six stations in Isfahan province during a 20 year period, showed that the highest TSF in all directions was 79.19 t·m⁻¹·year⁻¹,
of which 20.03 t·m\(^{-1}\)·year\(^{-1}\) was transported in the RDD. However, the transport rate of sediment depends on wind erosivity and soil erodibility (Wang, 2001; Kheirabadi et al., 2018). Even a small error in wind speed can be amplified to produce a large relative error in the wind's erosivity and DP estimation (Van Donk et al., 2005; Shen et al., 2019).

The result also indicates that the mean annual values for DP\(_t\) varied from 366.9 VU at Lalezar station to 1,637 VU at Rafsanjan station, while the RDPs for these stations ranged from 125.3 to 1,290.4 VU, respectively (Table 3). It is also found that the UDI as the ratio of RDP to DP\(_t\) ranged from 0.23 (Zarand) to 0.79 (Rafsanjan), indicating a wide range of directional variability for winds in the province. According to Fryberger (1979), except for Lalezar station with intermediate wind energy, the other stations experienced a high wind energy. A plausible reason for the lower wind energy at Lalezar is its higher elevation and mountainous conditions, resulting in lower wind speeds at the near surface. In addition, the ranges of UDI indicated that Zarand had high, Jiroft had intermediate to high, and the other stations had intermediate directional variability. Ekhtesasi et al. (2011) showed that in most parts of this region, the variability of winds is intermediate. The result of the present study reveals that dune morphology coincides reasonably well with the direction of the prevailing wind direction (RDD) obtained from wind analysis (Jewell and Nicoll, 2011; Sparavigna, 2013). Different values for DP\(_t\) and RDP have been reported in previous studies. Nazari Samani et al. (2013) in Tehran province reported DP\(_t\) and RDP values of 245.7 and 222.0 VU, respectively. Tavakkolifard et al. (2013), in five stations around Kashan Erg, found that DP\(_t\) varied from 202 to 2,153 VU. Poormand et al. (2015), in the desert of Kuwait, the average annual DP\(_t\) was predicted to be 354 VU by Al-Awadhi et al. (2005). Louassa et al. (2018) in the western Algerian Hautes Plaines reported DP\(_t\) values from 96 to 496. Zhang et al. (2015), in China's Badain Jaran Desert, obtained different DP\(_t\) values from 73.8 to 733.4.

Figure 8 provides the fine-resolution images used successfully to identify the dominant type of sand dunes in each region. The selected sand dunes are the typical features at the nearest distance to the stations. It was observed from the satellite images that the main types of sand dunes detected in the region are barchans and transverse dunes, although no evident sand dune was detected around Jiroft.

### Table 3

Summary characteristics of sediment transport quantities and wind regime indices in relation to sand dune morphology in the region derived from sand rose graph 3 and the remote sensing analyses

| Station | TSF (t·m\(^{-1}\)·year\(^{-1}\)) | DSF (t·m\(^{-1}\)·year\(^{-1}\)) | DSF/TSF (%) | Wind energy | RDD | RDP (VU) | UDI (VU) | Wind direction |
|---------|-------------------------------|-----------------------------|--------------|-------------|-----|---------|----------|----------------|
| Bam     | 92.4                          | 57.9                       | 0.99         | High        | Transverse | 367.9   | 0.59     | High Intermediate Transverse |
| Jiroft  | 53.4                          | 25.8                       | 0.30         | High        | Intermediate-high | 427.9   | 0.61     | High Intermediate-high |
| Kerman | 87.0                          | 41.1                       | 0.66         | High        | Intermediate | 256.8   | 0.61     | High Intermediate |
| Lalezar | 129.0                         | 76.1                       | 0.66         | Intermediate | Intermediate | 366.9   | 0.66     | Intermediate |
| Rafsanjan | 319.1                    | 163.7                      | 0.51         | High        | Barchan     | 1,637.1  | 0.79     | High Intermediate |
| Sirjan | 90.5                          | 30.8                       | 0.46         | High        | Intermediate | 538.7   | 0.46     | High Intermediate |
| Zand    | 74.2                          | 18.2                       | 0.25         | High        | Transverse  | 546.3   | 0.23     | High Transverse |

Abbreviations: DP\(_t\): total drift potential; DSF: discharge sand flow in the resultant drift direction; RDD: resultant drift direction; RDP: resultant drift potential; TSF: total sand flux in all directions; UDI, unidirectional index.
and Lalezar stations. As Jiroft station is located in an area with humid air conditions and Lalezar has the highest precipitation among the stations (Table 1), the threshold wind velocity in these two regions is probably higher than at the other regions. On the basis of sand dune morphology, it is possible to determine the sand supply in the region (Hereher, 2014). According to Wasson and Hyde (1983) and Hereher (2018), transverse dunes indicate a significant sand supply (a positive sand budget), barchans are accompanied by a low supply, and longitudinal dunes reveal a negative sand budget. As transverse dunes predominate in the region, it means there are positive sand supplies with unlimited sources in the region. Moreover, compound dunes in some regions indicate a more sand supply than...
simple dunes (Hereher, 2014). On the other hand, transverse dunes were found mainly in the region with an intermediate directional variability. These types of dunes are formed perpendicular to the prevailing winds (Hereher, 2018). Also, barchans are formed in the direction of the predominant wind. An appropriate match was found between wind data analyses and the morphology of dunes observed in remote sensing images. This is an important finding because the predominant directions of sand transport in the study area can be applied to combat wind erosion and reduce the damage of sandstorms by soil stabilization in the origins and surroundings. However, local wind speeds and sand transport pathways may deviate significantly from the regional winds because of forcing effects and topographical steering and sheltering (Bigarella et al., 2006; Levin et al., 2014).

4 | CONCLUSIONS

The findings of the present study indicate the high potential of erosive winds in the production of aeolian sediments contributing to the formation of sand dunes. Sand drift potential (DP) and its direction varied at the seasonal time scale. Generally, in the western part of the province, the prevailing winds are from the west and southwest, while in the eastern parts, the winds blow mainly from the north. This finding is important for determining the origin of wind erosion sediments, as well as the morphology of wind-erosion features. The main types of sand dunes detected in the region are transverse sand dunes with an intermediate directional variability, indicating positive sand supplies with unlimited sources. The results showed that dune morphology coincided reasonably well with the direction of the prevailing wind direction obtained from the wind analysis. An appropriate match was found between wind data analyses and the morphology of dunes observed in remote sensing images. It was inferred that although the wind erosivity analysis gives valuable information on the status of wind erosion and the sediment transport regime, for a more realistic analysis of erosion it is necessary that information on the threshold velocity and soil erodibility is considered and used.

Ahmadi, H. and Mesbahzadeh, T. (2011) modelling of sand drift potential estimating using momentum method and Fryberger velocity classes method (case study: Jask and Kerman). Journal of Water and Soil, 25(1), 11–18.
Ahmadi, H., Saremi Naeini, M.A. and Yadegari, M. (2013) Use of anemometric results and threshold velocities for determination of proper regions where sand storms are generated (case study: around the synoptic station of Yazd). Desert, 17(3), 225–231.
Al-Awadhi, J.M., Al-Helal, A. and Al-Enezi, A. (2005) Sand drift potential in the desert of Kuwait. Journal of Arid Environments, 63, 425–438.
Atapour, H. and Aftabi, A. (2002) Geomorphological, geochemical and geo-environmental aspects of karstification in the urban areas of Kerman city, southeastern, Iran. Environmental Geology, 42, 783–792.
Avalos, F.A.P., Silva, M.L.N., Batista, P.V.G., Pontes, L.M. and Oliveira, M.S. (2018) Digital soil erodibility mapping by soilscape trending and kriging. Land Degradation and Development, 29, 3021–3028.
Bagnold, R.A. (1941) The Physics of Blown Sand and Desert Dunes.- New York, NY: William Morrow.
Bärring, L., Jönsson, P., Mattsson, J.O. and Åhman, R. (2003) Wind erosion on arable land in Scania, Sweden and the relation to the wind climate—a review. CATENA, 52, 173–190.
Beckett, P.H.T. (1958) The soils of Kerman, South Persia. European Journal of Soil Science, 9, 21–37.
Bernhardson, M., Alexanderson, H., Björck, S. and Adolphi, F. (2019) Sand drift events and surface winds in south-central Sweden: from the deglaciation to the present. Quaternary Science Reviews, 209, 13–22.
Bigarella, J.J., Klein, A.D.F., Menezes, J.T. and Vintem, G. (2006) Southern Brazilian coastal dunes movement and structures. Journal of Coastal Research, 39, 1–15.
Breed, C.S. and Grow, T. (1979) Morphology and distribution of dunes in sand seas observed by remote sensing. In: McKee, E.D. (Ed.) A Study of Global Sand Seas. U.S. Geological Survey Professional Paper 1052. Washington, DC: U.S. Government Printing Office, pp. 253–302.
Broomandi, P., Dabir, B., Bonakdarpour, B. and Rashidi, Y. (2017) Identification of dust storm origin in south west of Iran. Journal of Environmental Health Science and Engineering, 15, 1–14.
Deng Y. (2016) Moisture-including modelling of annual aeolian sand supply to coastal dunes. M.Sc. Thesis, Faculty of Geosciences, Utrecht: Utrecht University.
Dong, Z., Lv, P., Zhang, Z., Qian, G. and Luo, W. (2012) Aeolian transport in the field: a comparison of the effects of different surface treatments. Journal of Geophysical Research, 117, D09210. https://doi.org/10.1029/2012JD017538.
Ekhtesasi, M.R. and Dadfar, S. (2014) Investigation on relationship between coastal hurricanes and sand dunes morphology in south of Iran. Physical Geography Research Quarterly, 45(4), 61–72.
Ekhtesasi, M.R., Dadfar, S., Kamrani, F. and Shah, B.R. (2011) Identification of storm areas of desert plains by the combination of wind rose, storm rose and sand rose graph results (case study: Bafgh plain). Iranian Journal of Watershed Management Science and Engineering, 5(16), 39–44.
Ekhtesasi, M.R. and Sepehr, A. (2009) Investigation of wind erosion process for estimation, prevention, and control of DSS in Yazd-
Ardakan plain. *Environmental Monitoring and Assessment*, 159 (1–4), 267–280.

Fryberger, S.G. (1979) *Dune forms and wind regime*. In: McKee, E. D. (Ed.) *A Study of Global Sand Seas*. Professional Paper 1052. Washington, DC: United State Geological Survey, US Government Printing Office, pp. 137–169.

Goossens, D. (2004) Wind erosion and tillage as a dust production mechanism on north European farmland. In: Goossens, D. and Riksen, M. (Eds.) *Wind Erosion and Dust Dynamics: Observations, Simulations Modelling*. Wageningen: ESW Publications, Department of Environmental Sciences, Erosion and Soil and Water Conservation Group, Wageningen University, pp. 15–40.

Hassanzadeh R. (2006) *An investigation on urban geological conditions and hazards of Kerman city, using GIS techniques*. M.Sc. Thesis. Shahid Bahonar University of Kerman, p. 212.

Hereher, M.E. (2018) Geomorphology and drift potential of major geomorphically effective winds. *Geography Nile Valley and Delta* using climatic and satellite data. *Applied Geography*, 55, 39–47.

Hereher, M.E. (2018) Geomorphology and drift potential of major aeolian sand deposits in Egypt. *Geomorphology*, 304, 113–120.

Jamali, A.A., Zarekia, S. and Randhir TO. (2018) Risk assessment of sand dune disaster in relation to geomorphic properties and vulnerability in the Saduq-Yazd Erg. *Applied Ecology and Environmental Research*, 16, 579–590.

Jewell, P.W. and Nicoll, K. (2011) Wind regimes and aeolian transport in the Great Basin, U.S.A. *Geomorphology*, 129, 1–13.

Kheirabadi, H., Mahmoodabadi, M., Jalali, V.R. and Naghavi, H. (2018) Sediment flux, wind erosion and net erosion influenced by soil bed length, wind velocity and aggregate size distribution. *Geoderma*, 323, 22–30.

Lackoova, L., Halaszoa, K., Kliment, M. and Urban, T. (2013) Wind erosion intensity determination using soil particle catcher devices. *Journal of Central European Agriculture*, 14, 1347–1355.

Lettau, K. and Lettau, H.H. (1978) Experimental and micrometeorological field studies of dune migration. In: Lettau, H. and Lettau, K. (Eds.) *Exploring the World’s Driest Climate*. University of Wisconsin-Madison, Institute for Environmental Studies, Report 10: 110–147.

Levin, N., Neil, D. and Syktus, J. (2014) Spatial variability of dune form on Moreton Island, Australia, and its correspondence with wind regime derived from observing stations and reanalyses. * Aeolian Research*, 15, 289–300.

Liu, L., Yang, Y., Shi, P., Zhang, G. and Qu, Z. (2015) The role of maximumwind speed in sand-transporting events. *Geomorphology*, 238, 177–186.

Lorestanii, G., Sharihvari, A. and Maghsoudi, M. (2012) The effect of diameter distribution and frequency of sand particles on the deformation of the main components of Barkhan (case study: Borkhan Maranjab). *Geography and Development Iranian Journal*, 9(25), 179–196.

Louassa, S., Merzouk, M. and Merzouk, N.K. (2018) Sand drift potential in western Algerian Hautes Plaines. *Aeolian Research*, 34, 27–34.

Mahmoodabadi, M. (2011) Sediment yield estimation using a semi-quantitative model and GIS-remote sensing data. *International Agrophysics*, 25(3), 241–247.

Mahmoodabadi, M. and Ahmadbeigi, B. (2013) Dry and water-stable aggregates in different cultivation systems of arid region soils. *Arabian Journal of Geosciences*, 6, 2997–3002.

Mesbahi-zadeh, T. and Ahmad, H. (2012) Investigation of sand drift potential (case study: Yazd-Ardakan plain). *Journal of Agricultural Science and Technology*, 14, 919–928.

Nadimi M. (2010) *Soil genesis and classification in Mahan-Joopar area, Kerman province*. M.Sc. Thesis, Department of Soil Sciences, Shahid Bahonar University of Kerman.

Nazari Samani, A.A., Dadfar, S. and Shahbazi, A. (2013) A study on dust storms using wind rose, storm rose and sand rose (case study: Tehran province). *Desert*, 8(1), 9–18.

Nazari Samani, A.A., Khoosravi, H., Mesbahi-zadeh, T. and Rahdari, M.R. (2016) Investigate of wind regime and sand drift potential in order to identify of sand dunes forms. *Journal of Watershed Management Research*, 111, 19–33.

Parsa-mehr, A. and Khoosravani, Z. (2017) Analysis of erosive winds and depositions drift potential in desert regions of Esfahan province. *Iranian Journal of Range and Desert Research*, 23(4), 832–842.

Pearce, K.J. and Walker, L.J. (2005) Frequency and magnitude biases in the Fryberger model with the implications for characterizing geomorphically effective winds. *Geomorphology*, 68, 39–55.

Poormand, S., Gholamalizade-Ahangar, A. and Dehvari, A. (2015) Sand drift potential by wind in Shileh plain of Sistan. *Journal of Water and Soil*, 29(1), 139–150.

Plessey D. and Tatarko, J. (2009) *Principles of wind erosion and its control*. Kansas State University. Available at: http://www.weru.ksu.edu [Accessed 12th March 2019].

Rajabi, M.R., Rohani, F., Ektetessai, M.R. and Ghazanfarpoor, N. (2006) *Dynamic analysis of wind faces using spatial sand rose model in Zabol and Zahak region, Iran*. *Desert*, 11, 45–51.

Rezaei Arshad, R., Mahmoodabadi, M., Farpoor, M.H. and Fekri, M. (2019) Experimental investigation of rain-induced splash and wash processes under wind-driven rain. *Geoderma*, 337, 1164–1174.

Saremi Naeini, M.A. (2016) Estimation of the frequency of speed and direction of the erosive winds and dust storms in Yazd province, by using wind rose, storm rose and sand rose. *Desert Management*, 8, 96–106.

Shahabinejad, N., Mahmoodabadi, M., Jalalian, A. and Chavoshi, E. (2019a). In situ field measurement of wind erosion and threshold velocity in relation to soil properties in arid and semiarid environments. *Environmental Earth Sciences*, 78(16), 501. https://doi.org/10.1007/s12665-019-8508-5.

Shahabinejad, N., Mahmoodabadi, M., Jalalian, A. and Chavoshi, E. (2019b). The fractionation of soil aggregates associated with primary particles influencing wind erosion rates in arid to semiarid environments. *Geoderma*, 356, 113936. https://doi.org/10.1016/j.geoderma.2019.113936.

Shen, Y., Zhang, C., Huang, X., Wang, X. and Cen, S. (2019) The effect of wind speed averaging time on sand transport estimates. *CATENA*, 175, 286–293.

Siriani, E., Sameni, A., Moosavi, A.A., Mahmoodabadi, M. and Laurent, B. (2019) Portable wind tunnel experiments to study soil erosion by wind and its link to soil properties in the Fars province, Iran. *Geoderma*, 333, 69–80.

Skidmore, E.L. (1986) Wind erosion climatic erosivity. *Climatic Change*, 9, 195–208.

Sparavigna, A.C. (2013) A case study of moving sand dunes: the barchans of the Kharga Oasis. *International Journal Of Science, 2*, 95–97.
Tavakkolifard, A., Ghasemieh, H., Nazari Samani, A.A. and Mashhadi, N. (2013) Determining the risk of sand transportation to residential areas around Kashan Erg using anemometry data analysis. Desert, 18, 163–172.

Van Donk, S.J., Wagner, L.E., Skidmore, E.L. and Tatarko, J. (2005) Comparison of the Weibull model with measured wind speed distributions for stochastic wind generation. Transactions of ASAE, 48(2), 503–510.

Wal, A. and McManus, J. (1993) Wind regime and sand transport on a coastal beach-dune complex, Tentsmuir, eastern Scotland. Geological Society, London, Special Publications, 72, 159–171.

Wang, X. (2001) Relations between morphology, air flow, sand flux and particle size on transverse dunes, Taklimakan sand sea, China. Geomorphology, 42, 183–195.

Wang, X., Lang, L., Yan, P., Wang, G., Li, H., Ma, W. and Hua, T. (2016) Aeolian processes and their effect on sandy desertification of the Qinghai-Tibet Plateau: a wind tunnel experiment. Soil & Tillage Research, 158, 67–75.

Wasson, R.J. and Hyde, R. (1983) Factors determining desert dune type. Nature, 304, 337–339.

Yamani, M. (2001) Relationship between the diameter of the sand particles and the frequency of wind speeds in the area of the Rig of Kashan. Geography Res., 38, 115–132.

Yamani, M., Zahab Nazoori, S. and Goorabi, A. (2011) Morphometric study and causes of Kerman rig deployment through the analysis of wind characteristics and sand grain. Journal of Arid Regions Geographic Studies, 1(4), 17–33.

Yang, Y., Qu, Z., Shi, P., Liu, L., Zhang, G., Tang, Y., Hu, X., Lv, Y., Xiong, Y., Wang, J., Shena, L., Lv, L. and Sun, S. (2014) Wind regime and sand transport in the corridor between the Badain Jaran and Tengger deserts, central Alxa Plateau, China. Aeolian Research, 12, 143–156.

Zamani, S. and Mahmoodabadi, M. (2013) Effect of particle-size distribution on wind erosion rate and soil erodibility. Archives of Agronomy and Soil Science, 59(12), 1743–1753.

Zhang, K., Qu, J. and An, Z. (2012a) Characteristics of wind-blown sand and near-surface wind regime in the Tengger Desert, China. Aeolian Research, 6, 83–88.

Zhang, X., Zhao, W., Wang, L., Liu, Y., Feng, Q., Fang, X. and Liu, Y. (2018) Distribution of shrubland and grassland soil erodibility on the Loess Plateau. International Journal of Environmental Research and Public Health, 15(1193). https://doi.org/10.3390/ijerph15061193.

Zhang, Z., Dong, Z. and Li, C. (2015) Wind regime and sand transport in China’s Badain Jaran Desert. Aeolian Research, 17, 1–13.

Zhang, Z., Dong, Z. and Zhao, A. (2014) The effect of the time interval used to calculate mean wind velocity on the calculated drift potential, relative drift potential, and resultant drift direction for sands from three deserts in northern China. Theoretical and Applied Climatology, 123, 151–160. https://doi.org/10.1007/s00704-014-1345-2.

Zhang, Z., Wieland, R., Reiche, M., Funk, R., Hoffmann, C., Li, Y. and Sommer, M. (2012b) Identifying sensitive areas to wind erosion in the Xilingele grassland by computational fluid dynamics modelling. Ecological Informatics, 8, 37–48.

How to cite this article: Zamani S, Mahmoodabadi M, Yazdanpanah N, Farpoor MH. Meteorological application of wind speed and direction linked to remote sensing images for the modelling of sand drift potential and dune morphology. Meteorol Appl. 2020;27:e1851. https://doi.org/10.1002/met.1851