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ORIGINAL PAPER

Determination of sand dune characteristics through geomorphometry and wind data analysis in central Iran (Kashan Erg)

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Abstract The combination of wind measurements and remotely sensed geomorphometry indices provides a valuable resource in the study of desert landforms, because arduous desert environments are difficult to access. In this research, we couple wind data and geomorphometry to separate and classify different sand dunes in Kashan Erg in central Iran. Additionally, the effect of sand-fixing projects on sand dune morphology was assessed using geomorphometry indices (roughness, curvature, surface area, dune spacing and dune height). Results showed that a Digital Elevation Model of the National Cartographic Center of Iran (NCC DEM) with 10-m resolution and accuracy of 54% could discriminate geomorphometry parameters better than the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data with 30-m resolution and Shuttle Radar Topography Mission (SRTM) data with 90-m resolution and 45.2 and 1.6% accuracy, respectively. Low classification of SRTM DEM was associated with too many non-value points found in the DEM. Accuracy assessment of comparison ground control points revealed that ASTER DEM (RMSE = 4.25) has higher accuracy than SRTM and NCC DEMs in this region. Study of curvature showed that transverse and linear sand dunes were formed in concave topography rather than convex. Reduced slopes in fixed sand dunes were established due to wind erosion control projects. Measurements of dune height and spacing show that there is significant correlation in compound dunes (R^2 = 0.546), linear dunes (R^2 = 0.228) and fixed dunes (R^2 = 0.129). In general, the height of dunes in Kashan Erg increases from the margin of the field to the center of the field with a maximum height of 120 m in star dunes. Analysis of wind data showed that sand drift potential is in low-medium class in Kashan Erg. Linear sand dunes in Kashan Erg show that they are following a global trend in forming of these. Finally, established of geomorphometry method in dune classification will help researchers to identify priority of land management and performance assessment of sand dunes fixing projects in arid arduous environment.

Keywords Geomorphometry · Dune classification · Sand drift potential · Discriminant analysis · Kashan Erg · Iran

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Introduction

Dune type and size varies greatly across the globe (e.g. Cooke and Warren 1973; Fryberger 1979; Goudie 2002; Shao 2008; Thomas 2011). Our understanding of dune morphology is largely based on relationships between dune morphology and wind regimes (e.g. Bagnold 1941; Fryberger 1979; Pye and Tsoar 2008).

Geomorphometry is the science of quantitative land-surface analysis (Pike et al. 2009) and has been applied to regions around the world (Pike 2000). Geomorphometry combines earth science and computer science with mathematics and engineering (Pike 2000; Florinsky 2002; Pike et al. 2009). Land-surface analysis is known variously as terrain modelling (Pike 2000; Minár and Evans 2008), terrain analysis (Pike 2000; Wilson and Gallant 2000; Florinsky 2002) or the science of topography (Mark and

Smith 2004). Digital Elevation Model (DEM) data is the most common input to geomorphometry, ever since the U.S. Geological Survey (USGS) first began distribution of 3-arc-second DEMs in 1974 (Allder et al. 1982; O'Callaghan and Mark 1984; Usery 2010).

In morphological classification, dunes are classified by their shape and the numbers of slip faces, and thus include barchan, crescentic, transverse, linear, reversing and star dunes (Breed and Grow 1979; McKee 1979; Livingstone and Warren 1996; Thomas 2011; Summerfield 2014). The prevalent method of classifying sand dunes requires field study by a specialist group to visit the sand sea and numeration of slip faces, which is subjected to uncertainty analysis. There have been many recent studies about arid and desert regions in the Middle East at regional and local scales (e.g. Al-Awadhi et al. 2000; Jafari et al. 2004; Al-Dousari and pye 2005; Al-Dousari et al. 2009; Rashki et al. 2012, 2015; Al-Enezi et al. 2014; Azarnivand et al. 2015; Kaskaoutis et al. 2015). However, better

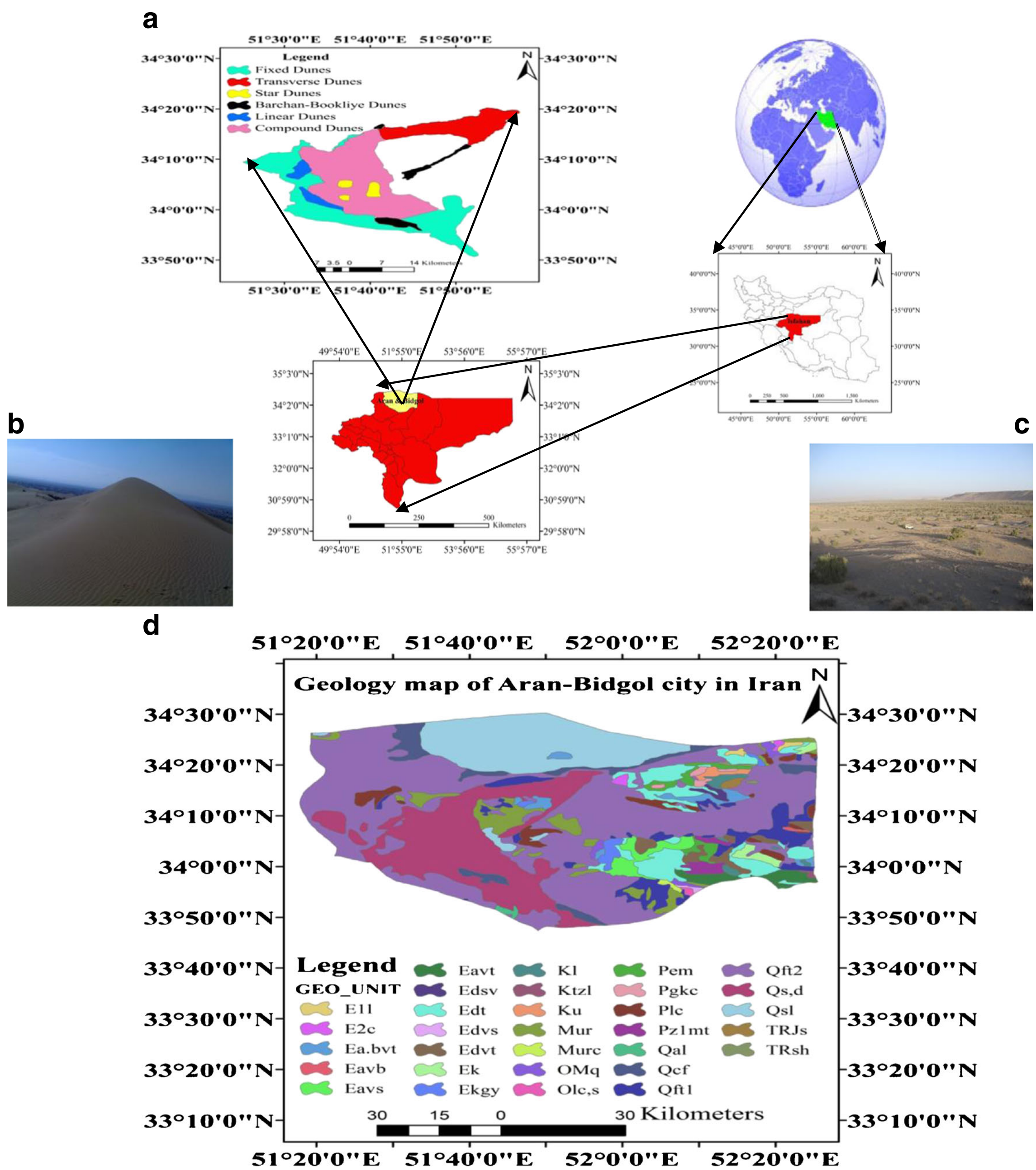

Fig. 1 **a** Location of case study area in Iran and zoning of sand dune types in Kashan Erg, **b** star dunes in Kashan Erg, **c** fixed dunes in Kashan Erg and **d** geology map of Aran-Bidgol city in Iran (Geological Survey and Mineral Exploration of Iran)

Table 1 Meteorological data of stations close to the case study area

Meteorology station	Geographical coordinates	Wind speed (knots)	Rainfall (mm)	Temperature (°C)	Humidity (%)
Ardestan	33° 23′N 52° 23′E	5	127	19	30
Jangalbani Badrood	33° 42′N 52° 02′E	7.4	125	19.1	36
Garmsar	35° 14′N 52° 21′E	4.8	121.1	18.1	40
Kashan	33° 59′N 51° 27′E	1.6	136	19.1	40
Qom	34° 42′N 50° 51′E	4.9	148	18.2	41

understanding of dune formation and the study of their movement with quantitative classification could give valuable insight into Aeolian geomorphology. Different studies combined remote sensing (RS) and geographical information systems (GIS) to assess arid environments (Ehsani et al. 2010; Effat et al. 2011; Al-Masrahy and Mountney 2013; Parajuli et al. 2014; Hereher 2014, Telfer et al. 2015; Babaeian et al. 2015; Day and Kocurek 2015; Karkon Varnosfaderani et al. 2016). In order to establish a performance assessment of sand dune fixing projects in arid environment, quick and reliable information on dunes activity is needed, which is a controversial issue. Thus with the development of geomorphometry science, quantitative indices can be used to identify sand dune patterns and activity; also, there is few research that they had briefly described as other subjects of sand dune geomorphometry (Fisher et al., 2007; Bonnici and Eisner, 2007; Bubenzer and bolten, 2008; Ogor et al., 2015).

Previous research showed that areas of active wind erosion in Iran cover C. 24 Mha, of which 12.8 Mha are from deflation, 6.8 Mha from transportation and 4.4 Mha from deposition (Ahmadi 2004), although Mahmoodi (1991) showed that depositional regions are C. 3.6 million Mha. Seasonal and local winds play a major role in the transport and accumulation of sand in all deserts of Iran with the exception of the shores of the Oman Sea (Mahmoodi 1991). The most important sand seas are formed by the influence of ground relief in Iran. For example, Kashan Erg is formed on a strip of Miocene marl (Ahmadi 2008). Some of them were expanded

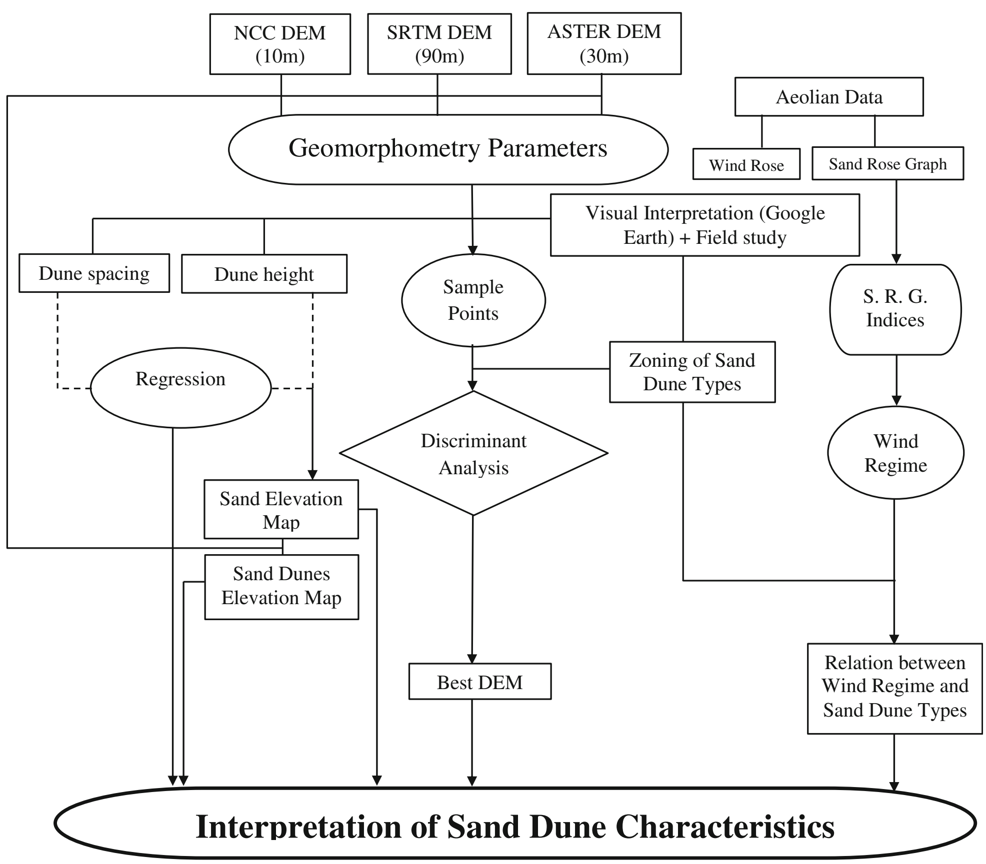

Fig. 2 Schematic diagram of methodology in this study

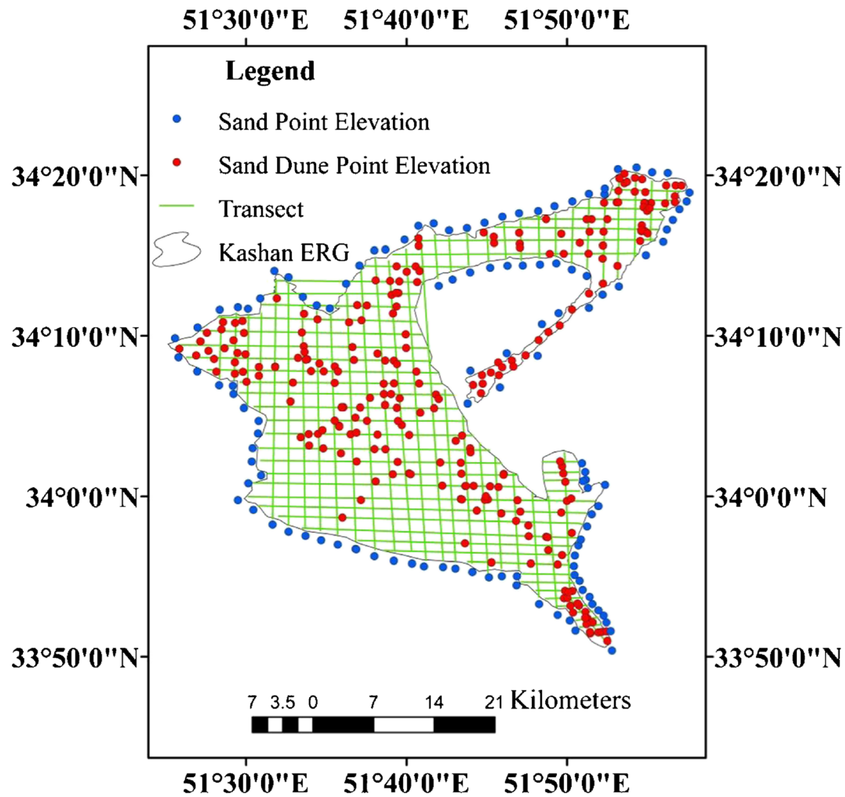

Fig. 3 Horizontal and vertical transects (*green lines*), record points for sand dunes elevation (*red point*) and record points for starting of sand deposition (*blue points*)

downwind of terrain relief (hills) and were included in Lut Erg (Foroutan and Zimbelman 2016), Jenn Erg, Hulwan Erg, and Jazmurian Erg (Harrison 1943). Different aspects of desert areas in Iran have been studied including wind erosion (Ekhtesasi and Sepehr 2009; Rahdari et al. 2013; Rashki et al. 2014; Zehtabian et al. 2014, Rayegani et al. 2016), desert management (Hashemimanesh and Matinfar 2012), wind data (Mesbahzadeh and Ahmadi 2012; Rahdari et al. 2014c), climate regime (Kousari et al. 2011) and barchan morphology (Moosavi et al. 2014). Although more than 60% of Iran is located in arid and semi-arid regions, little attention has been given to its many sand seas (Modarres and Silva 2007; Nazari Samani et al. 2016). Conversely, many works have studied arid and desert environments in the nearby Middle East (e.g. Tielbörger and Kadmon 1997; Tielborger 1997; Al-Abdulqader et al. 2008; Al-Dousari et al. 2008; Zaady et al. 2009; Hereher 2010; Hadeel et al. 2010; Ahmed and Al-Dousari 2013; Al-Awadhi and Al-Dousari 2013; Alshemmari et al. 2013; Ehsani and Foroutan 2014; Ahmady-Birgani et al. 2015; Hereher 2016). Many kinds of dunes can be found in small areas within the ergs of Iran, which is advantageous for field morphometric studies.

The main aim of this research is to test the capability of coupling gemorphometric indices with wind data to separate different dune types and assess gemorphometric characteristics in dunes. Findings enable fast dune classification and assist in identifying priority land management projects.

Materials and methods

Study area

The study area, Rig Bolad Kashan or Band Rig (Ahmadi 2008), is located south of Kashan Lake in Aran-Bidgol city. The study area is crescent-shaped and convex toward the west Kashan Erg which extends from 51° 27′–51° 56′ longitude and 33° 52′–34° 20′ latitude (Fig. 1a) with an estimated area of about 969.9 km^2 (Rahdari 2014a). This area is located in the playa unit and some geological units, such as Q_c, Qf_2, Qm, Qsd and Qs (Fig. 1d). Table 1 shows averages of wind speed, annual rainfall, annual temperature and relative humidity for the long-term period, from the Iran Meteorological Organization's information. The origin of sand in this area is derived from local minerals. Previous studies showed that Kashan Erg sands are dominantly quartz with lime content at ~17–24% (Rahdari et al. 2014b).

Zoning of sand dune types

In this research, we used the sand dune classification method introduced by Summerfield (2014). All common classifications in sand dune types have some resemblance with each other. Kashan Erg in central Iran is near residential and urban

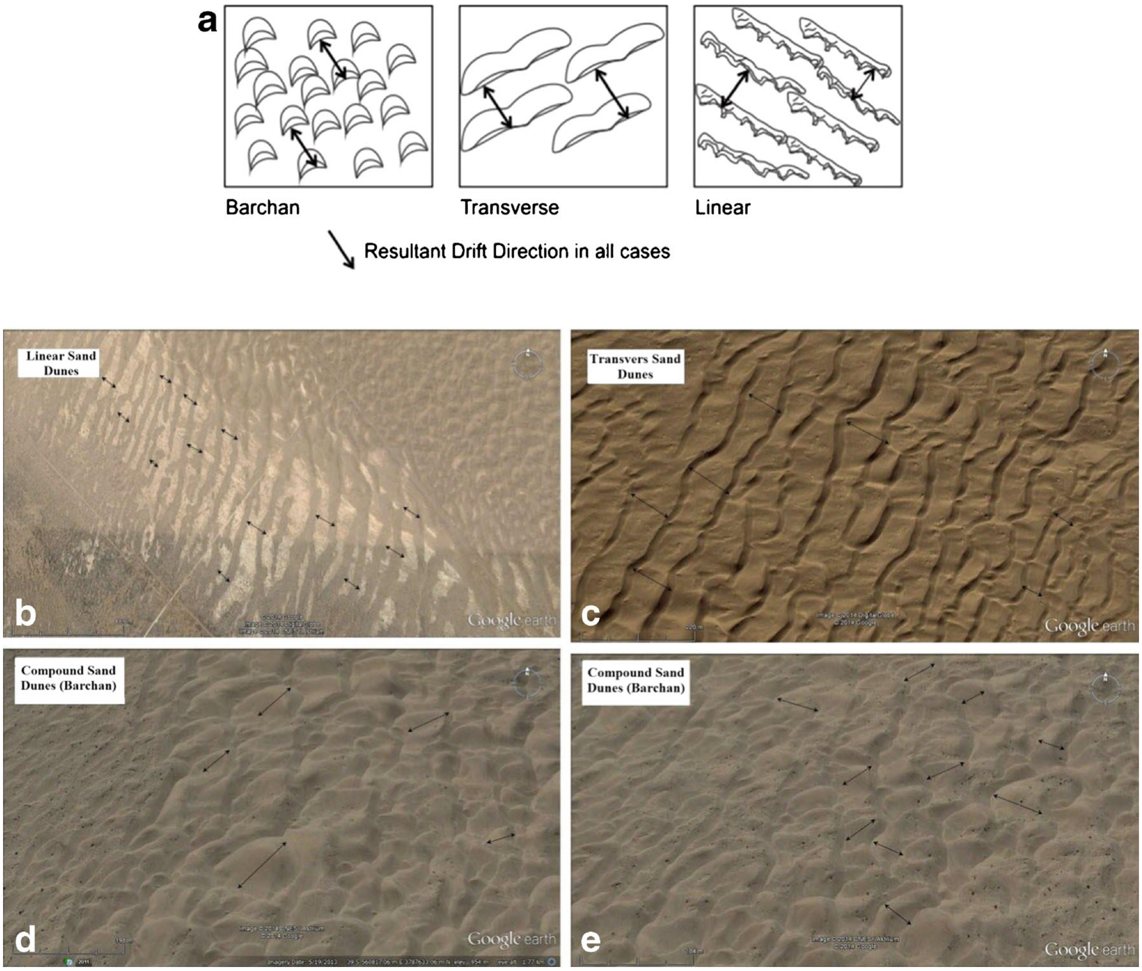

Fig. 4 **a** Schematic illustration of how bed-form spacing has been determined for different sand dune types with Google Earth Pro software. In Kashan Erg, the authors tried to calculate sand dunes spacing in **b** linear dune, **c** transverse sand dunes, and **d**, **e** compound dunes made from many barchans

areas, so use of fixed dune types is important for comparing them with other types of sand fields.

Actually, none of the common sand dune classifications considers the fixed dunes as a separate type, but in some cases, the anchored and phytogenic dune terms were used. Because Aran-Bidgol, Kashan and the surrounding countryside are all suffering from the sand field migrations, over the past decades, sand-fixing projects were established to stop sand dune encroachment. Therefore, one of the aims of this research was to introduce a quick, digital method for assessing the fixation operation of sand dunes morphometry by geomorphometry analysis.

Geomorphometry parameters

In this research, we applied various analysis and software. The processes of study and research details are shown in Fig. 2:

Surface area

Surface area is a fundamental measure of landscape topographic roughness (Jenness 2000). The surface area ratio of any particular region on the landscape can be calculated by dividing the surface area of that region by the planimetric area in different landscape (Jenness 2004; Brasington et al. 2012; Nield et al. 2013). Researches show that there are a variety of methods in the concept for measuring terrain irregularity (Hobson 1972; Beasom et al. 1983; Jenness 2000). Lopez and Berry (2002) mention that an estimate of surface area also could be derived from slope and aspect within a cell. In this study, we used DEM surface tools from ArcGIS (Jenness 2013); the following formula was used for calculating the surface area:

$$\text{Surface Area} = \frac{C^2}{\cos\left(S\left(\frac{\pi}{180}\right)\right)}$$

where C is cell size and S is slope in degrees.

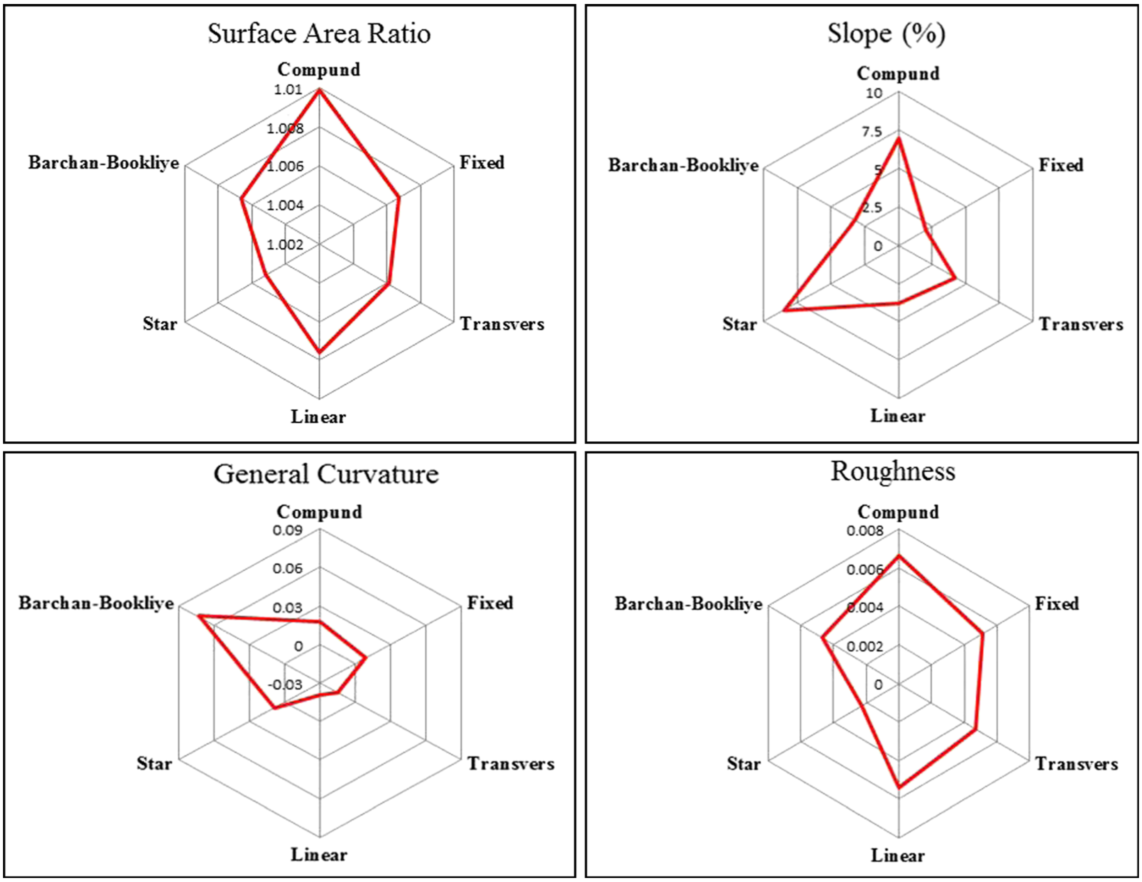

Fig. 5 Geomorphometry parameter changes in different sand dune types

Curvature

Landscape curvature is amazingly difficult to describe. There are numerous equations and definitions in the literature but these often conflict with each other. Two broad approaches (Evans approach and Zevenbergen and Thorne approach) are commonly used to calculate curvature from the raster DEM. The ArcGIS Spatial Analyst follows Zevenbergen and Thorne approach, but in this research, we used Evans approach by applying DEM surface tools in ArcGIS. Jenness (2013) says that in general, curvature units are in Radian/LU, where LU = linear unit (usually meters or feet).

Roughness

Surface roughness is a key factor in describing the earth's surface (Olaya 2009), and is used in earth and space science to identify the earth's unevenness (Hobson 1972). Surface roughness indicates material properties and processes performed on the earth's surface, as well as the elapsed time of its formation. In literature ruggedness (Beasom et al. 1983), rugosity (Jenness 2004), microrelief (Stone and Dugundji 1965) and microtopography (Herzfeld et al. 2000) are variously used to characterize roughness. In general, roughness is a direction-rated variation of the Earth's surface, measured perpendicular to the ground. In this study, we used Vector Ruggedness Measure (Sappington et al. 2007).

Height and spacing of sand dunes

Slip face length is used to characterize high sand dunes (Bourke et al. 2006; Bourke et al. 2008), and this is known as the most appropriate method to calculate the height of sand dunes. This method is best suited to features where slip faces are clearly identified (Bourke et al. 2006). Pye and Tsoar (2008) say that laboratory experiments have shown that the angle of repose for medium-fine sands varies from 30.5° to 35.45°, but is typically 32°–34° (Allen 1970; Carrigy 1970). On the other hand, various researchers consider 30°–34° as the angle of repose in sand seas (Bagnold 1941; Sharp 1963).

In order to obtain the height of sand dunes in the region, we used a set of systematically sampled transects to improve the accuracy both in horizontal and vertical directions (Fig. 3). Then a set of points were chosen that represented sand dunes in Kashan Erg. Finally, the height of sand dunes was calculated using the elevation data of cross-sections (Al-Masrahy and

Table 2 Area of sand dunes showing different types in Kashan Erg

Type of sand dunes	Area (km^2)	Percentage
Compound	412	42.47
Fixed	306	31.54
Transverse	144.9	14.93
Linear	40	4.12
Barchan-Bookliye	38	3.91
Star	29	2.98
Sum	969.9	100

Mountney 2013) extracted from Google Earth (Fig. 4). Some of them were checked with field data (Tavakoli Fard 2012).

Because sand dunes are sometimes above sand deposits, a sand thickness map was obtained using an interpolation method in Kashan Erg. For the sand thickness map, we used starting points of sand deposition (Fig. 4) in the Erg and made a sand thickness map with Inverse Distance Weighted (IDW) method. In the next step, for calculating accurate height of sand dunes, we used minus order in 3D Analyst Tools between sand thickness map and DEM. For calculating sand dune spacing, we used the distance between two sand dunes based on Al-Masrahy and Mountney (2013)'s research as shown in Fig. 5.

Wind analysis

In this research, wind data were obtained from Iran Meteorological Organization for five stations (Ardestan, Qom, Garmsar, Jangalbani Badrood and Kashan). For analysis of wind data, we used the formula designed by Fryberger (1979) which is used widely in desert environments (e.g. Fryberger 1979; Carson and MacLean 1986; Havholm and Kocurek 1988; Sweet 1992; Bullard et al.

Table 4 Correlation coefficient matrix between accuracy of DEM and sand dunes elevation

Value	GCP	NCC DEM	SRTM DEM	ASTER DEM
GCP	1	0.986	0.995	0.997
NCC DEM	0.986	1	0.986	0.986
SRTM DEM	0.995	0.986	1	0.994
ASTER DEM	0.997	0.986	0.994	1

1996; Pearce and Walker 2005; Mesbahzadeh and Ahmadi 2012; Al-Awadhi and Al-Dousari 2013; Zhang et al. 2015; Hesp et al. 2016).

$$Q = U^2(U-U_t) \times t \quad (1)$$

where Q is a proportionate amount of sand drift, U is average wind velocity at 10 m height, U_t is impact threshold wind velocity and t is time wind blew, expressed as a percentage in a wind summary. Fryberger (1979) mentions that values derived from this formula by substitution reflect the sand-moving capacity of wind for the time period of the wind summary. These are herein known as drift potentials (DP), which are numerically expressed in vector units (VU).

$$\text{RDD} = \text{Arc} \ \tan(C/D) \quad (2)$$

$$C = \sum(\text{VU}) \sin(\theta) \quad (3)$$

$$D = \sum(\text{VU}) \cos(\theta) \quad (4)$$

$$\text{RDP} = \sqrt{(C^2 + D^2)} \quad (5)$$

$$\text{UDI} = \text{RDP}/\text{DP} \quad (6)$$

where θ is the angle measured clockwise from 0° (north) and VU is the drift potential in each wind-direction class.

For performing calculations, it is assumed that the dunes of sand particles are formed with an average grain size of 0.30–

Table 3 Classification accuracy of discriminant function with (a) NCC, (b) ASTER and (c) SRTM

Original group	Count	Predicted group membership (percentage)																	
		Compound			Fixed			Transverse			Linear			Barchan-Bookliye			Star		
		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Compound	1702	38.8	46.9	0	17.9	35.3	0	20.5	2.8	0	22.7	9.2	99.9	0.1	5.8	0.1	6.8	4.8	0
Fixed	1377	9.6	24.5	0	47.0	55.9	0.5	32.2	3.2	0	10.0	9.4	98.7	0.2	7.0	0.7	6.2	3.7	0
Transverse	454	0	25.8	0	0	54.4	0	100	2.4	0	0	9.3	99.7	0	8.0	0.3	12.5	6.5	0
Linear	153	26.1	36.3	0	22.9	40.1	0	24.2	5.7	0	26.8	8.9	100	0	8.9	0	9.7	2.9	0
Barchan-Bookliye	60	26.2	33.9	0	21.5	50.0	0	32.3	3.2	0	15.4	3.2	92.0	4.6	9.7	8	1.4	4.3	0
Star	43	16.8	38.2	0	17.6	52.1	0.1	28.9	6.2	0	19.8	7.3	93.3	1.7	8.4	2	14.4	7.8	0

52.0% of original grouped cases correctly classified with NCC. 45.2% of original grouped cases correctly classified with ASTER. 1.6% of original grouped cases correctly classified with SRTM

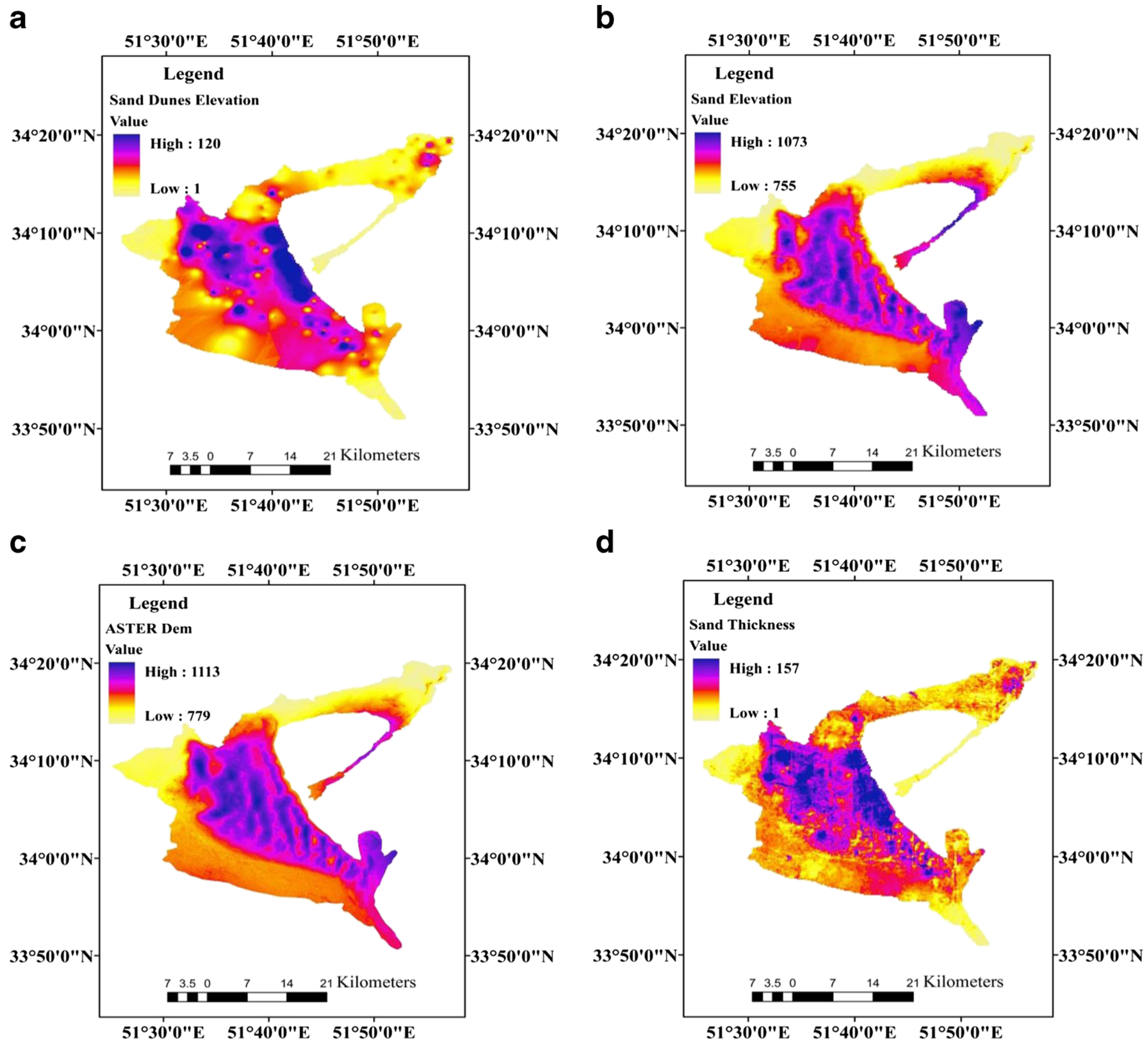

Fig. 6 **a** Sand dune elevation map made with elevation point of sand dunes (red point in Fig.3). **b** Sand elevation map made with point elevation of sand deposition (blue point in Fig. 3). **c** ASTER DEM downloaded from USGS. **d** Sand thickness map made from minus raster of ASTER DEM and sand elevation, and shows that sand dunes may sometimes form on top of the sand

0.25 mm (Fryberger 1979). This assumption is considered good for most of the world's arid regions (Ahlbrandt 1979). Also, the results of field studies prove this assumption in Kashan Erg (Tavakoli Fard 2012). This assumption may not be able to predict DP with great accuracy, but it may be appropriate to compare different sand seas of the world (Fryberger 1979). Wind data threshold is considered 11.6 knots for particles with average 0.30 mm diameter, surface roughness factor of 10 m elevation (Belly 1964), and wind data threshold of 12 knots (Fryberger 1979). Finally, wind data analysis was done using WR Plot view 7.0 and MATLAB 2013 Software for assessment.

Table 5 Elevation classes of sand dunes

Elevation classes	<30	30–50	50–70	70–100	100–120	>120
Area (km^2)	516.41	96.93	55.50	100.20	61.94	105
Percentage (%)	55.4	10.3	5.9	10.6	6.6	11.2

Statistical analysis (discriminant analysis)

Discriminant analysis is a classifying technique that differentiates distinct populations by using a number of independent attributes. It was developed by Fisher (1936) to solve a taxonomic problem. The method uses a classifying function to assign samples individually to one of two or more populations (Cohen et al. 2013). Discriminant analysis has been used with sand sea analyses (Moiola et al. 1974; Moiola and Spencer 1979; Lancaster 1981; Edwards and Zubillaga 2005).

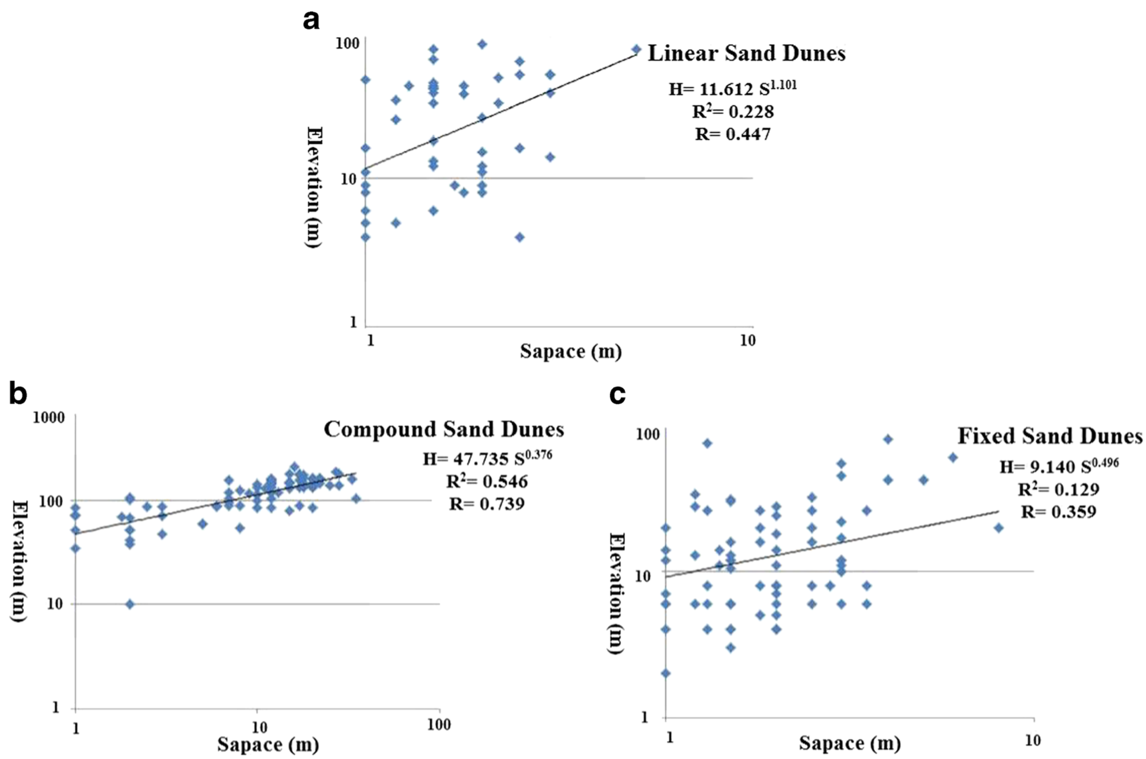

Fig. 7 Statistical analysis between height and space of sand dunes in Kashan Erg

Results and discussion

After visual interpretation of Google Earth images, we checked the boundaries of sand dune types against field studies for zoning of sand dune types. Results show that the most compound sand dunes are located in the heart of the Erg and the lowest area has a star sand dune in the center of the Erg. Table 2 shows the different types of sand dunes in Kasahn Erg.

The results of discriminant analysis show NCC DEM (10 m) has high percentage (52%) classification accuracy of discriminant function, while ASTER DEM and SRTM DEM have 45.2 and 1.6%, respectively (Table 3). Parameters used in discriminant analysis have a direct relationship with the accuracy of DEM. Thus, NCC DEM (10 m) with higher pixel resolution can be better for classification of geomorphometry parameters. Significant difference was shown between SRTM DEM, NCC DEM and ASTER DEM. Blumberg (2006) mentioned that the dune spacing and heights extracted from the SRTM DEM tended to be in overall agreement with those reported in the literature for ASTER DEM. However in this research, SRTM DEM did not show such agreement.

Table 6 Relation between dune height and spacing in Kashan sand sea and other sand seas

Locality		Power function exponent	Correlation coefficient
Namib sand sea	Crescentic	0.97	0.83
	Compound linear	0.54	0.66
	Complex linear	1.72	0.72
	Star	1.20	0.62
Skeleton Coast dune field	Crescentic grain desert	1.20	0.95
	Crescentic	0.58	0.76
	Star	1.70	0.75
Simpson-Strzelecki dune field- linear		1.06	0.67
Great Sandy Desert-linear		0.52	0.70
Southwest Kalahari- linear		1.10	0.81
Kashan Erg	Linear	1.101	0.477
	Fixed	0.496	0.359
	Compound (barchan)	0.376	0.739

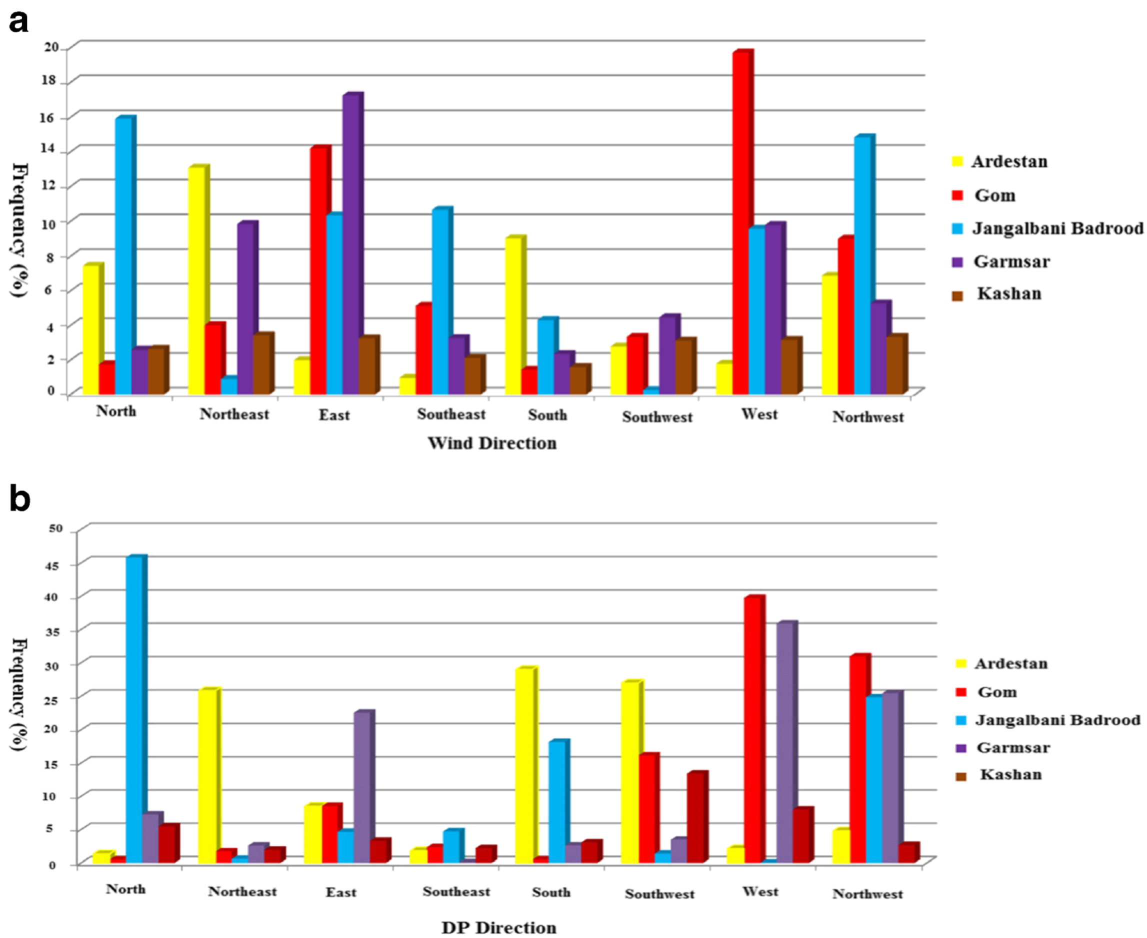

Fig. 8 **a** Relation between wind direction and frequency in stations near Kashan Erg. **b** Relation between DP direction and frequency in stations near Kashan Erg

Results of the slope map show that internal convexity has the most value and the western region has the lowest value. Overall, 82% of region is located in slope of less than 10%, so this area is a location of deposition of sand and was suitable for sand dune formation.

In order to assess changes in geomorphometry parameters, we used radar charts of slope (%), surface area ratio, roughness and general curvature as shown in Fig. 5. In fixed sand dunes, with biological activities, decrease in height of sand dunes due to slope is less than in other areas. On the other hand, star and compound sand dunes are higher compared to other types and they had steeper slopes than other sand dunes. Changes in roughness show that the lowest value is in star sand dunes although this value is not correct. But in other sand dunes, it follows a reasonable trend. Changes in curvature show that linear and transverse sand dunes were formed in concave shape and so it can be concluded that sand dunes with low height form in concave shape.

Table 7 Calculation of sand rose graph indices in stations

Station	Sand rose graph indices			
	DP	RDP	RDD	UDI
Ardestan	263 (medium)	72	277	0.273 (low)
Garmsar	199 (low)	13	116	0.08 (low)
Gom	224 (medium)	139	99	0.623 (medium)
Jangalbani Badrood	442 (high)	188	166	0.42 (medium)
Kashan	40 (low)	14	26	0.35 (medium)

Results of comparison with Ground Control Points (GCP) from National Cartographic Center of Iran showed that elevation value of ASTER DEM (RMSE = 4.25 m) is better than NCC DEM (RMSE = 8.65 m) and SRTM DEM (5.62 m). It can be interpreted that NCC DEM in the Erg region is not accurate for assessing the height of sand dunes. Table 4 shows the matrix of correlation coefficients between accuracy of DEM and sand dune elevation.

Figure 6 shows sand dunes elevation, ASTER DEM, sand elevation and sad thickness in Kashan 246 Erg.

Elevation classes of sand dunes also are shown in Table 5, so that the most classes belong to sand dunes with elevation less than 30 m and sand dunes with elevation more than 120 m had formed.

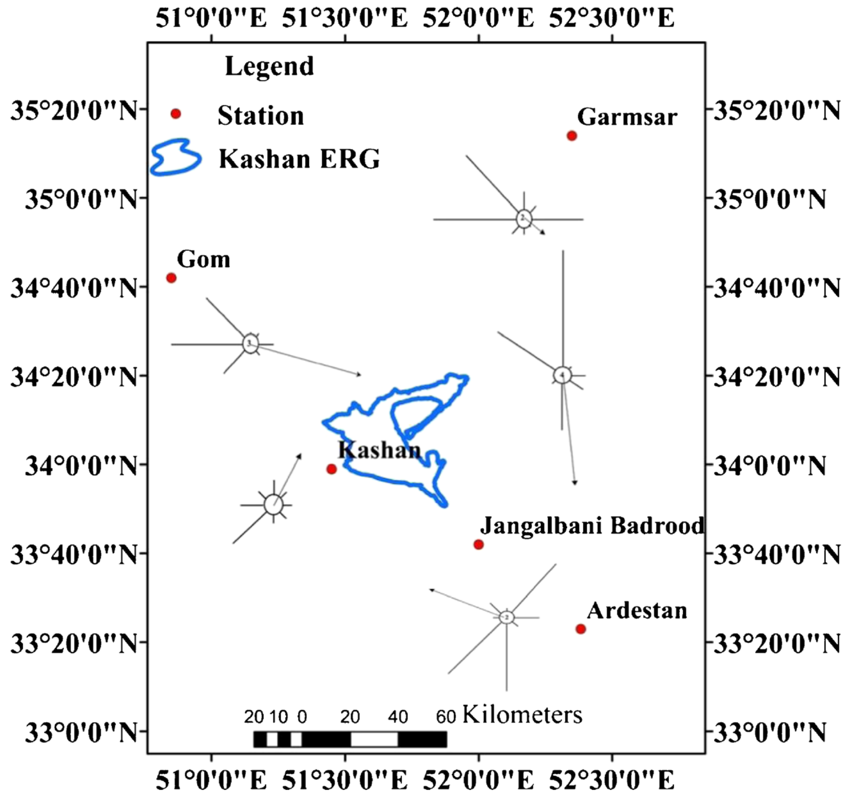

Fig. 9 Effect of wind data on Kashan Erg in relation to sand rose graph

Study of the relations between sand dunes and elevation in Kashan Erg shows that there is a significant correlation in compound sand dune (99%), fixed sand dune (99%) and linear sand dunes (95%). Figure 7 also shows statistical analysis between spacing and elevation of sand dunes in Kashan Erg. On the other hand, world sand sea data from Lancaster (1988) compares with records from Kashan Erg. It is clear that there are close similarities between linear sand dunes in Kashan sand sea and linear sand dunes in other desert environments such as Simpson-Strzelecki, Great Sandy and Southwest Kalahari deserts (Table 6).

Comparing the spacing of fixed, linear and compound sand dunes indicates that fixed sand dunes were formed in closer spacing than linear and compound sand dunes. The spacing in compound sand dunes is very different compared to linear and fixed sand dunes. This change in sand dunes could be interpreted from the beginning of the Erg as well as wind power decrease in the center of the Erg.

Results of WR Plot view 7.0 are summarized in Fig. 9. Calculation of wind database from Fryberger (1979) is shown in Fig. 8 and Table 7, so each station is shown in a different wind regime.

Figure 9 shows effects of stations on Kashan Erg. Because there is no literature comparing wind data in Iran and other terrestrial sand seas, Fig. 10 shows five stations near Kashan Erg in central Iran with other stations that Fryberger (1979) researched. Our finding indicates that Kashan station is the nearest in sand sea and has low DP (40VU).

Wind regime studies in stations showed that Kashan station tends to form linear dunes, which is clear in Fig. 1 and Fig. 4. Jangalbani Badrood and Ardestan stations also tend to form linear dunes. Low areas of central Kashan Erg had been observed with star dunes. It can be interpreted that star dunes are under the influence of Garmsar station. However, because Garmsar station is far away from the Kashan sand sea, it can be interpreted that star sand dunes have been under the influence of wind regimes in an older geological time. Our studies on changes in height of sand dunes follow the results of Porter (1986)'s model in sedimentation of Ergs.

Finally, analysis of wind data showed that all stations have wind erosion potential in a low-medium class (Table 7). Field studies showed that wind erosion was not a strong hazard in the region.

Conclusion

Although the extent of dune fields is nearly 20% of the total area of drylands, very few studies and research have been conducted in these areas. To have knowledge of dune activity and morphology, detailed wind data and field studies are needed which are time consuming and costly in arid regions. Over the past decade, because of developments in computer sciences, access to digital spatial geomorphometry data has become easier and is suitable for studying earth surface features. In this research, we used a conjunctive approach using

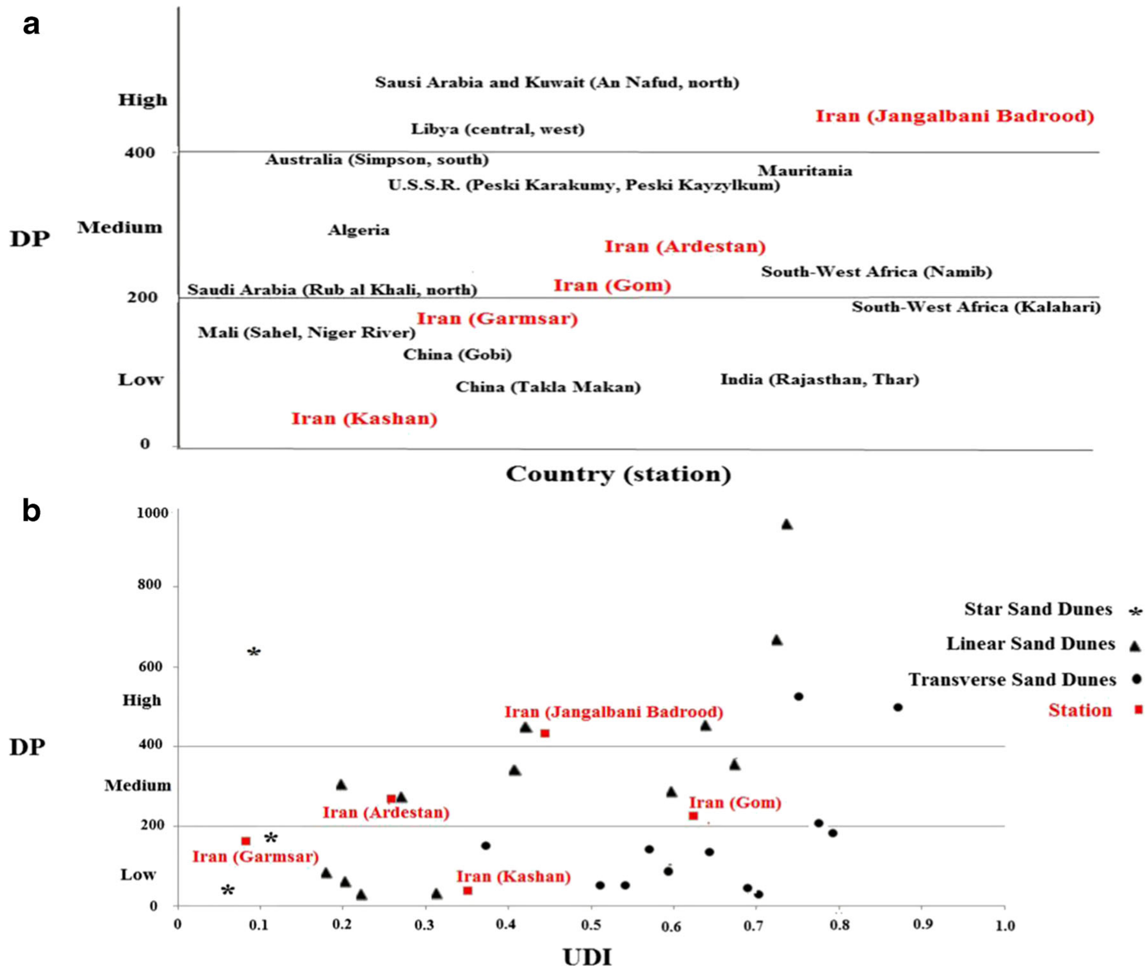

Fig. 10 Comparison of wind data in Iran (Kashan Erg) and other terrestrial sand seas

geomorphometry and wind data analysis to find the effects of sand-fixing projects on dune morphology and separation. We studied active and inactive dune types in a large sand sea located in north central Iran.

Our finding reveals that using DEM, we can estimate the sand elevation in a desert environment with an acceptable accuracy and economy. The high elevated dunes were found in the central section of the Kashan Erg with high sand thickness. Results of wind data analysis from a station close to the erg showed different wind regimes explaining the formation of various dune types around the erg. Based on Fryberger (1979)'s method and by comparison with other sand seas, Kashan Erg can be categorized into the low-medium class of sand drift potential. Linear sand dunes in the studied erg followed the global trend and showed a significant relationship between space and height. In order to establish a universal database on geomorphometry indices for separating various sand dunes, more research is needed. Such research findings can develop our knowledge on quantitative classification of arid landforms which may be better than using visual examination and field study.

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