

# Assessing desertification by using soil indices

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**Abstract** Desertification generally refers to land degradation in arid, semiarid, and dry semi-humid climatic zones. It involves five principal processes: vegetation degradation, water erosion, wind erosion, salinization and waterlogging, and soil crusting and compaction. The aim of this study is assessing desertification using soil criteria. For this purpose, nine indices including sodium absorption ratio (SAR), soil gypsum percentage, soil texture, the content of  $\text{HCO}_3^-$ , the percentage of the organic matter, electrical conductivity (EC), pH, the content of the soil sodium, and chloride were used. The soil samples were taken in the north of Zayandeh-Rood River in Isfahan province of Iran, using soil data randomly sampled in a depth of 0–20 cm. After assessing the normality of the samples using Kolmogorov-Smirnov test, indices were imported into GIS environment and interpolated with IDW and normal and discrete kriging methods for delineating soil characteristics maps based on MEDALUS model. In this model, the data were firstly changed from 100 to 200. Thus 100 and 200 are estimated as the best and worst quality, respectively. Then the

final map of soil criteria has been created by geometric mean of its indicators. The results showed that the maximum area is related to the medium class of desertification and is equal to 44,746 ha. The areas of severe and very severe classes of desertification are equal to 30,949 and 351 ha, respectively. The results also revealed that the indices of the organic matter and soil gypsum percentage are the most influential indices which affect desertification phenomenon.

**Keywords** MEDALUS · GIS · Desertification · Soil · Isfahan

## Introduction

Desertification is generally understood to refer to land degradation in arid, semiarid, and dry semi-humid climatic zones (UNEP 1992). It involves five principal processes: vegetation degradation, water erosion, wind erosion, salinization and waterlogging, and soil crusting and compaction (Dregne 1998). Among these, soil degradation means displacement of soil material driven by water and wind erosion, and internal deterioration caused by physical and chemical processes, such as salinization and nutrient loss (Takar et al. 1990; Zobeck 1991). Desertification is not a new issue in Iran. It is a natural process in most parts of the country. Dry land ecosystems cover more than 85% Iran's land, of which desertified and desert lands account for 34 million ha [FRW (Forest, Range, and Watershed Management Organization) 2004]. The Mediterranean Desertification and Land Use (MEDALUS; European Commission 1999) (Kosmas et al. 1999) methodology identifies regions that are environmentally sensitive areas (ESAs). In this model, different types of ESAs to desertification can be analyzed in terms of various parameters such as landforms, soil, geology, vegetation, climate, and human actions. Each of these parameters is grouped into various

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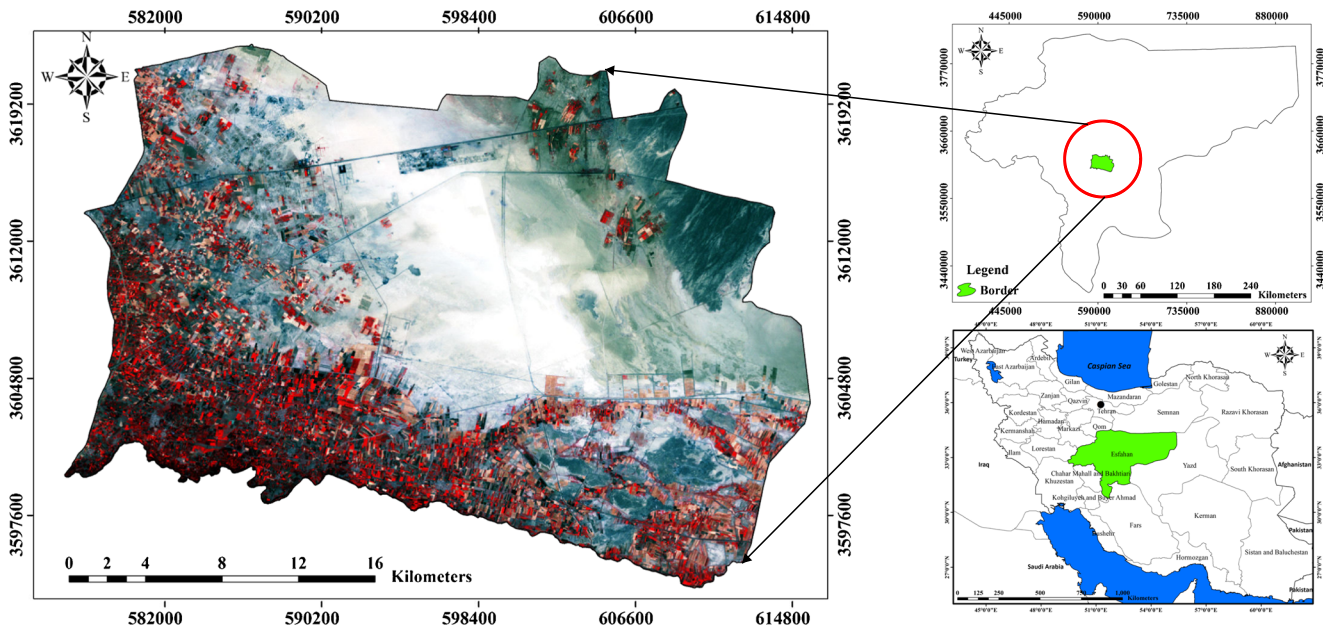
uniform classes and a weighting factor is assigned to each class. Then four layers are evaluated including: soil quality, climate quality, vegetation quality, and management quality. Determining indices for each layer, the ESAs to desertification can be defined using combination of four quality layers. The data which describe the four main layers is introduced in a regional geographical information system (GIS) and overlaid due to the developed algorithm, which takes the geometric mean to compile maps of ESAs to desertification (Basso et al. 1999). Several studies have been conducted to evaluate the effect of soil conditions on desertification phenomenon using MEDALUS model referred to various cases. In assessment of desertification in southern part of Italy, Ladisa et al. (2002) used six major criterion including soil, climate, vegetation, land use, management, and human pressure criterion. They concluded that climate is the most important criterion in area desertification. Castellano and Valone (2007) examined the pressure effect, the infiltration rate of the soil, and soil characteristic changes on desertification phenomenon in Arizona. They concluded that soil characteristic variation, the most important factor affecting the desertification, would be highly intensified toward changing the physical and chemical properties such as soil salinity, soil structure collapse, and loss of organic matter, increasing desertification. As a result, soil characteristics are most affected by desertification in arid and semiarid areas. Sepehr et al. (2007) measured the effect of soil indices in Larestan desertification in Fars using MEDALUS model, such indices as the gravel cover, soil texture, soil depth, soil organic matter,

drainage, and electrical conductivity were used. The results showed that approximately 66.2% is in average level and 33.4% is in low level in terms of soil quality. Albaladejo et al. (1988), Yong Zhong et al. (2004), Amezketta (2006), Castellano and Valone (2007), and Lian Zhou et al. (2008) investigated the effect of soil properties and other factors on the phenomenon of desertification, such as vegetation, water pressure, and water content in the distribution and intensity of desertification phenomenon. They concluded that soil characteristics have the greatest effect on this phenomenon. The main purpose of this study was to determine the most important soil indices on desertification intensity in arid and semi-arid areas.

## Material and methods

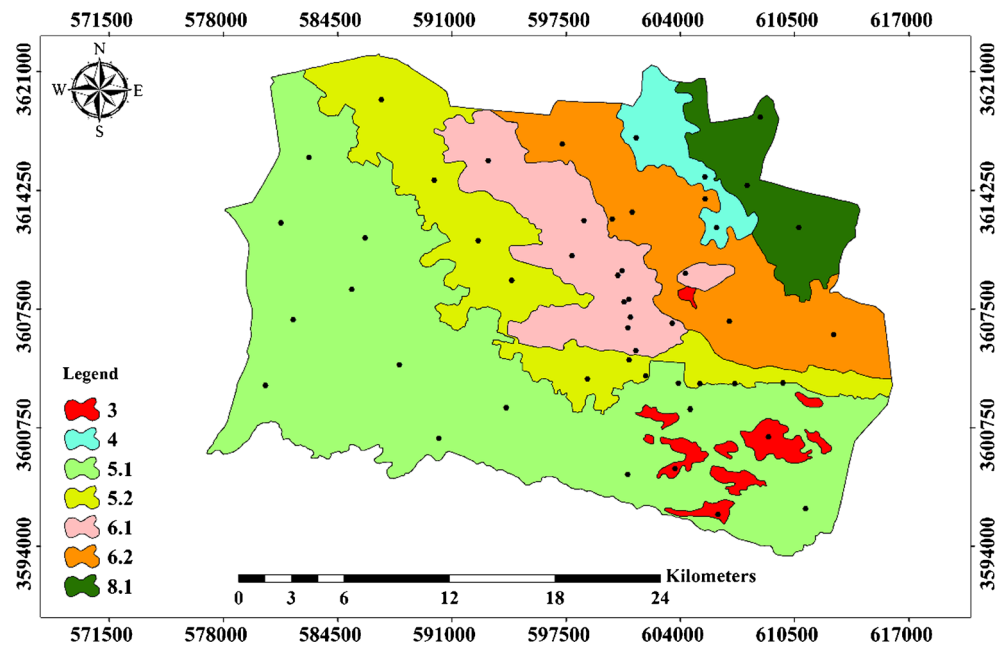
### The study area

The study area is the Segzi Plain located in north of the Zayandeh-Rood River in Isfahan Province, Iran ( $52^{\circ} 15' 43''$ – $52^{\circ} 53' 43''$  E and  $32^{\circ} 27' 24''$ – $32^{\circ} 41' 21''$  N) and covers an area of about 112,167 ha. Figure 1 shows the study area on a map of Iran. Furthermore, due to hydrological assumptions, there is a big river in south of area and 38 wells. According to FAO (1988), the main soil orders of the plain are Fluvisols, Regosols, Cambisols, Gypsisols, and Solonchaks. Given soil taxonomy (2010), there are Entisols and Aridisols (USDA 2010). The region has a semiarid climate with an average



**Fig. 1** Location of the study area in Iran and Isfahan

**Fig. 2** Map of the physiologic units in the study area



annual rainfall of 125.5 mm and an average annual temperature of 15 °C. The average annual evaporation was estimated as 2920 mm with Thornthwaite method. Agriculture land, salty, rural and industrial land, and sand mine are land uses in the study area.

The data was firstly plotted on topographic and geomorphology maps. Soil samples were sampled in physiographic units (Fig. 2). A total of 50 soil samples were collected from five physiographic units and seven land units (Table 1) (each sample is from a point, not composite points). These samples

were taken from a depth of 0–20 cm in order to have a random sampling. After drying in air, soil samples were passed through a 2-mm sieve. Markers were determined by soil texture (percentage of sand, silt, and clay) using gauging method (Jacob and Clarke 2002), the amount of gypsum was obtained by using drying methods (w.t), the bicarbonate was measured through titration method, and electrical conductivity of saturation extracts was obtained by EC meter model 3310. The pH was calculated using pH meter model 744 metrohm, the organic matter was measured by wet oxidation of the method

**Table 1** Characteristics of the physiographic units in the study area (Karimzadeh 2002)

Characteristics	Name	No.	Number of sample in each unit	Area (ha)
Physiographic units are old (they belong to Quaternary Period), they have been worn by the process of water erosion and their remnant are appeared as topographic relief rougher and heterogeneous.	High plateaus and terraces	3	3	1819
Flat plains have been created by accumulation of fine sediments, which have been transported from the foot of the mountains	Piedmont- alluvial plains	4	3	2580
River creates this unit during overflows and this unit is near the river	River alluvial plains	5.1	13	35,584
River creates this unit during overflows and this unit is away from the river	River alluvial plains	5.2	9	12,024
They are located with low or concave slope in the center of the intermountain plains with runoff from surrounding lands	Lowlands	6.1	13	8309
They are located with low or concave slope in the center of the intermountain plains with high groundwater level and drainage problems	Lowlands	6.2	6	10,966
Foothill slopes are at hillsides, in which coarse and fine sediments are transferred into them using streams from the catchment area.	Gravelly alluvial fans	8.1	3	4761

**Table 2** The statistical characteristics of soil indices

Index	Number	Minimum	Maximum	Average	C. V.	Skewness	Elongation
pH	50	7.4	8.9	8.0	0.3	0.5	-0.5
OM (%) (organic matter)	50	0.0	1.6	0.5	0.4	0.7	0.7
EC (ds/m)	50	2.5	174.7	62.6	53.7	0.5	-1.0
Cl (mg/l) (chloride)	50	17.5	2766.0	956.2	877.9	0.5	-1.1
Gypsum (%)	50	1.2	16.5	9.9	4.4	-0.2	-1.1
HCO <sub>3</sub> <sup>-</sup> (meq/l)	50	5.0	30.0	17.5	5.3	-0.5	0.3
Na (ppm)	50	4	10,945.5	3017.5	3114.2	0.9	-0.4
SAR	50	0.3	2688.2	652.8	783.6	1.1	-0.07
Texture	50	108.0	167.0	124.9	19.1	1.4	0.4

Walcott St. Furthermore, amount of sodium was estimated using the flame photometry and chloride with titration method using silver nitrate in the soil, and the sodium adsorption ratio was finally measured (Sparks et al. 1996).

We first calculated the primary statistical data including mean, minimum, maximum, mean standard error, median, mode, variance, skewness, and elongation of data to prepare the soil map by using geostatistics method (Table 2). The Kolmogorov-Smirnov method was used to investigate the normality of data. Due to data normalization, there is no conversion operation here. The change view patterns were subsequently drawn for soil parameter using GS+ software and then the best change view pattern was chosen. In this study,

interpolation was performed using one of the three kriging methods based on the spatial structure including ordinary, simple, and universal kriging. The best method was selected based upon such parameters as ME, RMSE, ASE, and MSE.

## Methods

The main soil indices were selected and used in the GIS environment to assess desertification intensity. Indices classification are also presented in Tables 3 and 4. A quantitative classification scheme was used to evaluate individual indices values ranging from 100 to 200 throughout the model as well

**Table 3** Classes of Soil indices (Basso et al. 1999)

Index	Class	Explain	Score	Index	Class	Explain	Score
Na (mg/l)	1	< 1000	100–124	HCO <sub>3</sub> <sup>-</sup> (meq/l)	1	< 15	100–124
	2	1000–5000	125–149		2	15–20	125–149
	3	5000–8000	150–174		3	20–25	150–174
	4	> 8000	175–200		4	> 25	175–200
EC (ds/m)	1	<10	100–119	Cl (meq/l)	1	<100	100–119
	2	10–50	120–139		2	100–1000	120–139
	3	50–100	140–159		3	1000–2000	140–159
	4	100–150	160–179		4	2000–2500	160–179
	5	>150	180–200		5	>2500	180–200
Texture	1	Loam, silt	100–124	Gypsum (%)	1	0–5	100–124
	2	Clay, fine sand	125–149		2	5–10	125–149
	3	Fine and coarse sand	150–174		3	10–15	150–174
	4	Very coarse sand	175–200		4	>15	175–200
SAR	1	<50	100–119	O.M (%)	1	1.5–2	100–119
	2	50–500	120–139		2	1–1.5	120–139
	3	500–1000	140–159		3	0.5–1	140–159
	4	1000–1500	160–179		4	0.2–0.5	160–179
	5	>1500	180–200		5	<0.2	180–200
pH	1	7<					
	2	7.5–8.3					
	3	8.3>					

**Table 4** Classification of indices (Basso et al. 1999)

Class	Range	Class	Range
Low	100–125	Severe (B)	140–145
Moderate (A)	125–130	Very severe (A)	145–150
Moderate (B)	130–135	Very severe (B)	>150
Severe (A)	135–140		

as the final classification of desertification sensitive areas (ESAs). The value “100” was assigned to areas of least sensitivity, and the value “200” was assigned to areas with the most sensitivity to desertification. Values between 100 and 200 reflect relative vulnerability (Basso et al. 1999; Khanamani 2011).

In succeeding, each of the layers was scored based on MEDALUS model, and the final characteristic maps were then generated using soil geometric mean indices. The proposed formula of preparing soil conditions is as follows (Basso et al. 1999):

$$W_s = (W_{EC} * W_{SAR} * W_T * W_{Cl} * W_{Na} * W_G * W_{O.M} * W_{pH} * W_H)^{1/9} \tag{1}$$

where  $W_s$  is soil criterion and  $W_{EC}$ ,  $W_{SAR}$ ,  $W_T$ ,  $W_{Cl}$ ,  $W_{Na}$ ,  $W_G$ ,  $W_{O.M}$ ,  $W_{pH}$ , and  $W_H$  are defined as soil electrical conductivity (EC), sodium absorption ratio (SAR), texture index, the sodium content, the chloride content, gypsum percentage, the organic matter percentage, pH, and the content of  $HCO_3^-$ , respectively.

Soil indices criterion and soil criterion classification are showed in Tables 2 and 3.

**Geostatistical analysis**

According to the simplest definition, geostatistic is, in fact, an interpolation method in which the criteria used for interpolation or estimation is the minimization of the variance estimation (Hohn 1988). Interpolation is the estimation of the unknown continuous variable based on the known samples in the region (Lu and Wong 2008). Geostatistical estimation is one of the most accurate methods of estimation, because it analyzes many factors such as the distance between points, anisotropy, and spatial variability. But this method has a high volume of calculations causing the increase of calculation time in large operations (Hirsche et al. 1998). Geostatistical analysis investigates the variable phenomena in space and time. The sample analysis was collected from different locations in order to produce a steady level (Johnston et al. 2001). Geostatistical analysis is looking for a way to describe the spatial coherence and collecting statistical and definitive tools and modeling of these changes. The basic assumption of spatial-statistical analysis is that close observation requires

greater statistical correlation than far away observation. It should be noted that, access to accurate and efficient results through these analyzes develops when the data were normally distributed and as it is possible to be fixed and their mean and variances do not vary in space (Bohling 2005).

**Variogram**

Variogram is one of the most important concepts of the geostatistics field, in which, all definitions and concepts are often explained based on the concept. Variogram is used to determine the spatial correlation of a variable in the sampling intervals as well as extraction of the necessary parameters at the interpolation steps (Shabani et al. 2011). Variogram is the first step in modeling the spatial structure used in the kriging. The main purpose of establishing the semi-variogram is to identify variability of variables in relation to terms of the spatial distance. Variogram is calculated by the following equation (Webster and Oliver 2000).

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i) - z(x_{i+h})]^2$$

Where:

- $\gamma(h)$  is the value of the semi-variogram of the two points located with the distance of  $h$  from each other.
- $n$  is the number of two points, where they are located with the distance of  $h$  from each other.
- $z(x_i)$  is the observed value of the variable at the point  $x$ .
- $z(x_{i+h})$  The observed value of the variable that is located with the distance of  $h$  from  $x$ .

The increase in distance of ( $h$ ) increases the value of  $\gamma(h)$  in the variogram curve. It means that the situation continues till a certain distance obtained, where its amount remains fixed. In this study, inverse distance weights (IDW) and kriging methods are used to investigate the soil indices.

**Statistical analyzes**

Normal distribution of the parameters is the first condition in using ordinary kriging to mapping (Sepehr et al. 2007). Statistical analysis was performed using SPSS 21.0 (IBM Corp. 2012). The normal distribution of the data was measured through Kolmogorov-Smirnov test. Finally, the correlation between indignant (Pearson and Spearman) was determined ( $P$  value >0.05). All of the indicators except soil texture are normally distributed at  $\alpha = 0.01$  level. Thus, the inverse distance weighting method was used for soil texture map, but ordinary kriging and inverse distance weighted were used for other indices.

In this study, the variogram model was used to illustrate the spatial correlation between different data of the soil criteria

**Table 5** Nugget effect and sill variogram parameters for fitted variogram of EC

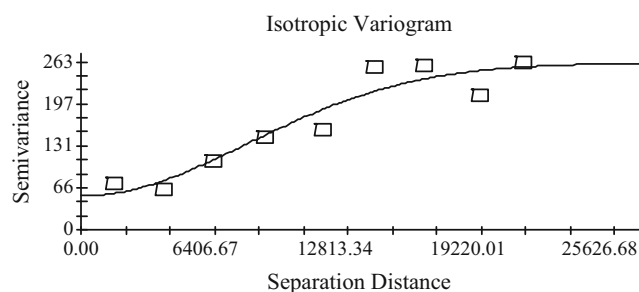
Model	Nugget Co	Sill Co + C	Proportion Co/Co + C	Range parameter Ao	$R^2$
Spherical	22.8	256.3	0.91	22,700.0	0.87
Gaussian	52.8	260.7	0.79	11,320.0	0.90
Linear	47.5	275.6	0.82	21,295.1	0.85
Exponential	23.0	356.9	0.93	17,610.0	0.86
Linear to sill	48.1	348.9	0.86	28,180.0	0.85

(Table 5). A variogram was used to fit the data of each parameter representing the spatial correlation among those which are more favorable than other variograms. For this purpose, the ratio between the nugget effect and sill variogram was calculated. If the ratio of nugget effect on the sill variogram is less than 0.25, there is a strong spatial correlation among the data (Tuominen et al. 2003; Zahedi Amiri 1998). If the ratio is in between 0.25 and 0.75, the spatial correlation is in average and if it is more than 0.75%, there is a low or no spatial correlation (Co/Co + C) in between the data (Tuominen et al. 2003; Zahedi Amiri 1998). Therefore, the ratio was used to select the best model of variograms. Due to the parameters obtained for the fitted variograms of soil criteria, Gaussian variogram with 0.90  $R^2$  has modeled the best correlation among the data and it was, then after, used for the interpolation. Linear, spherical, Linear to sill, and exponential variograms had the ratio of 0.85, 0.87, 0.85, and 0.86, respectively. Figure 3 shows the Gaussian variogram used to fit the data.

Maps of the indicators were developed using geostatistical methods in Arc-GIS 9.3 software (Sepehr et al. 2007).

## Results and discussion

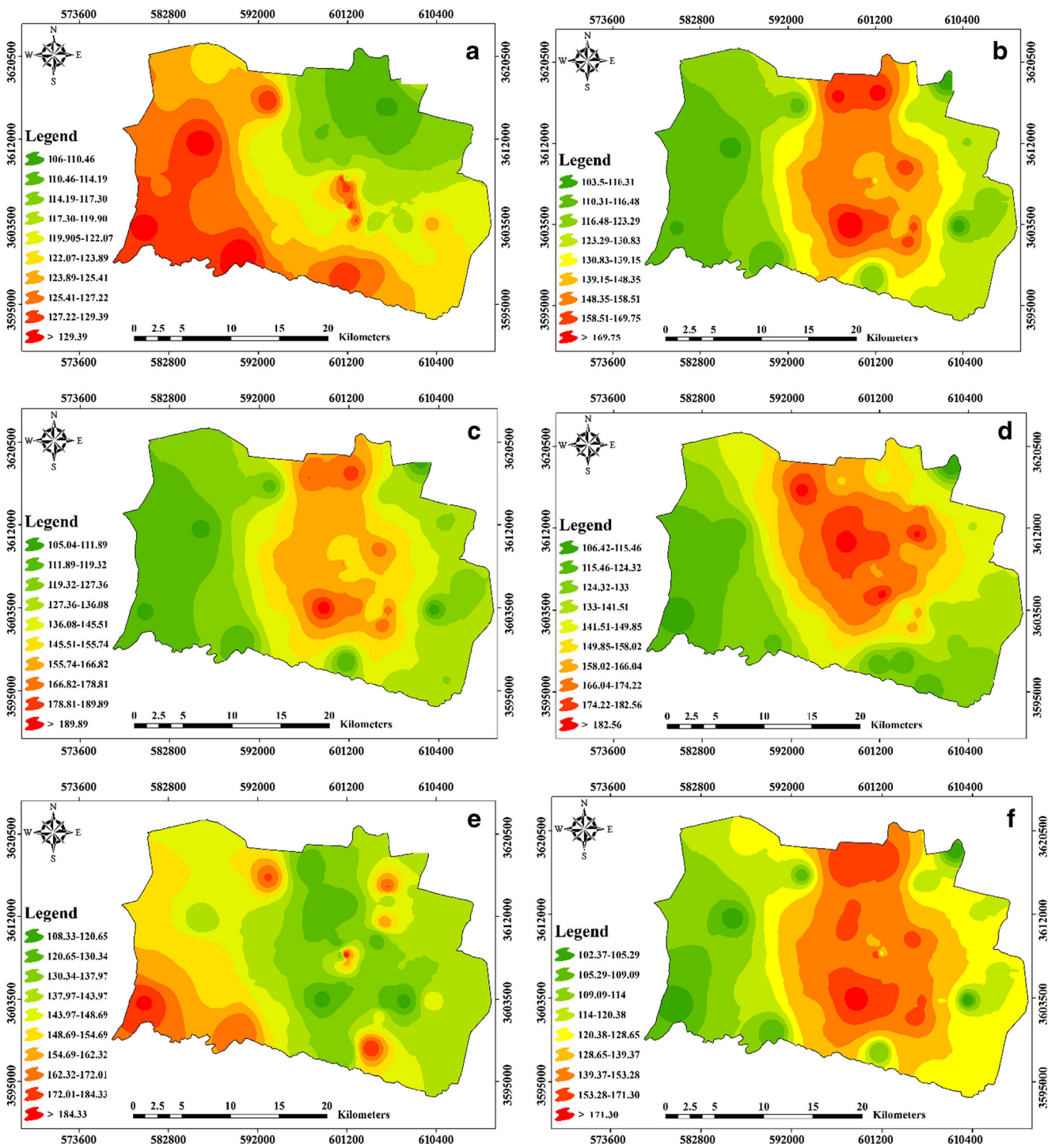
According to the results, soil conditions were classified as moderate, severe, and very severe classes in the area of Segzi in terms of severity of desertification. At the maximum level, 44,746 ha are in moderate class, 30,949 ha in severe, and 351 ha is classified in very severe class of desertification. According to the soil map of the study area (Fig. 4), degradation conditions are high in the land units 6.1 (playa landform) due to the accumulation of salts in the soil, wind erosion severity, and groundwater decreasing; it was located in very severe class of

**Fig. 3** Fitted variogram of the EC by Gaussian method

desertification. Plant cover has formed rough surface in soil surface. However, because the 6.1 unit has vegetation less than 2%, the rough surface is not occurring at the soil surface and the wind directly hits the soil surface and dries soil rapidly. The regional average wind speed (8 m/s), is much higher than the threshold velocity of wind erosion (4.5 m/s), and severity of wind erosion is considerably high in this area.

Soil organic matter percentage, gypsum percentage, soil salinity, and sodium adsorption ratio of the soil had the highest effect among the indices used to measure the soil parameters on Segzi Plain desertification. Data on soil surface properties are shown in Table 6. Since each unit has a different texture classes, the predominant soil texture data are listed in this table.

According to Table 6, physiographic units 6 have the worst situation of soil degradation. That is because of the high salinity and alkalinity of soils in this unit. The soil gypsum percentage is high in this unit, which can be sometimes more than 70%. Therefore, these soils are susceptible to erosion. Salt accumulation led to eliminate ecosystem and crop productivity since elevated salt concentrations can inhibit plant establishment and growth. To maintain water uptake from a saline soil, plants must be osmotically adjusted, which is accomplished by either taking up salts and compartmentalizing them within plant tissues or synthesizing organic solutes (D'Odorico et al. 2013). Given the importance of soil criterion as well as inappropriate landform soil conditions of desertification, vegetation growth is also inappropriate. Thus, this will be further influenced on the soil conditions, which is named as the indirect and increasing effect. Different soil conditions have also affected the amount of water and wind erosion. Thus, if the soil structure is not coherent, soil will be susceptible to erosion, sodium and salinity (EC) is high, organic matter content is low, and gypsum content is high, and etc., leading to soil structure collapse. Soil will, therefore, be susceptible to wind erosion; thus the erosion rate rises sharply (Basso et al. 1999). The organic matter varies from 0.042 to 2.52% in soil. The minimum amount of organic matter is estimated as 0.042 percentage in the 6.1 unit. Since there is no vegetation cover in this area, the soil organic carbon will be low. The highest O.M is 2.52% located in the agricultural land that results from the return of crop residues to the soil and manure of livestock that are used here. Lian Zhou et al. (2008) analyzed reciprocal effects of desertification, soil



**Fig. 4** Soil map Classification (where **a** is soil texture, **b** chloride, **c** electrical conductivity (EC), **d** soil gypsum percentage, **e** content of  $\text{HCO}_3^-$ , **f** content of the soil sodium, **g** percentage of the organic matter, **h** pH, **j** sodium absorption ratio (SAR), and **k** is final soil map)

organic matter, and nitrogen on northern part of China; they concluded that the plant growth was reduced due to lack of organic matter of the soil, and thus influence the desertification phenomenon. According to their results, agricultural lands and pastures with adequate coverage have the highest content of regional organic matter. Soil salinity and gypsum content of the soil are the most important factors influencing

the desertification phenomenon (Basso et al. 1999). Soil gypsum with high salt, which is added to the soil surface, causes the soil surface to become very light (Fig. 4). Thus, high soil erodibility in late winter to early summer is due to the peak of the dry surface soil. Furthermore, it coincides with the maximum amount of wind erosion as we observed that wind erosion is extremely high in the area in these months. In

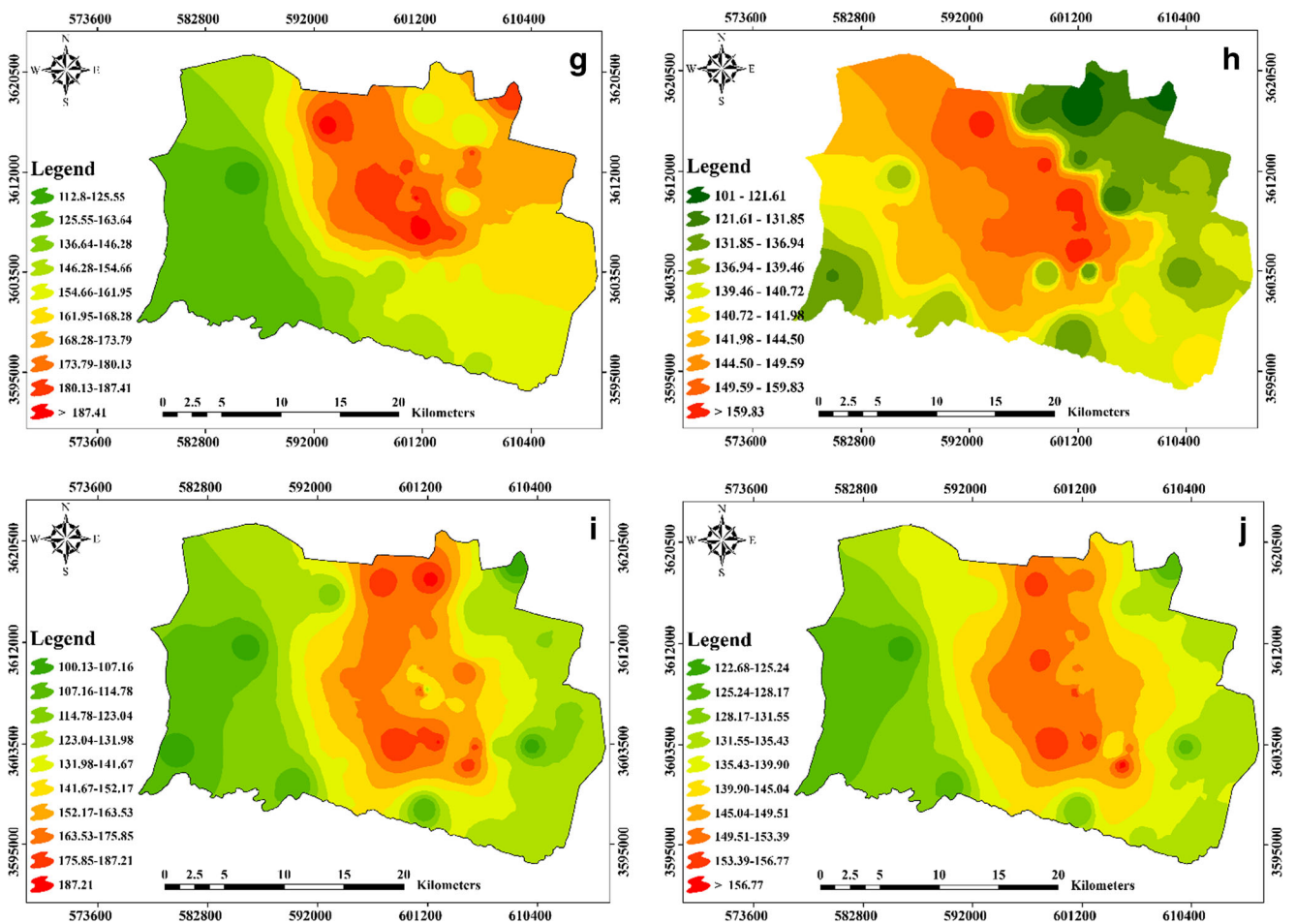


Fig. 4 continued.

evaluation of desertification in the Zarin-dasht in Fars province by MEDALUS model, Farajzadeh and Nik Egbal (2007) concluded that among soil indicators, soil salinity index (EC) has the greatest effect on desertification area. Also, high soil salinity decreases osmotic potential in soil and due to lack of sufficient moisture in the soil, reduces the available water to be absorbed by plant roots and while more than half of the area is devoid of vegetation, the wind can easily contact with soil

causing soil erosion. High percentage of gypsum in the region (average percent 57.16) also causes loss of soil structure and soil surface density become light (Ahmadi 2011), due to the increase of soil erosion. Albaladejo et al. (1988) studied effective criterion on desertification phenomenon and concluded that soil is the most important criterion influencing desertification. The highest salinity is observed at 5.2 units, which include agriculture abandonment. In this unit, the use of poor

**Table 6** Average real soil indices data for each land unit in the study area

Land unit	pH	Na (ppm)	OM (%)	EC (ds/cm)	HCO3 (meq/l)	CL (meq/l)	Gypsum (%)	SAR	Texture
3	7.9	1569	0.7	44.1	21.7	495	5.1	212	Sandy clay loam
4	7.9	3689	0.6	78.8	21.7	1257	10.6	936	Silt loam
5.1	7.9	1129	0.9	23.7	20.0	326	5.9	242	Clay loam
5.2	8.0	4150	0.6	78.9	15.2	1226	10.8	732	Clay loam
6.1	8.5	4503	0.2	91.3	15.8	1424	14.3	1097	Sandy clay loam
6.2	7.9	3813	0.3	83.2	15.5	1284	11.9	813	Clay loam
8.1	7.7	553	0.3	19.9	18.1	234	6.3	104	Sandy clay loam



water quality for irrigation of the farm land increases the soil salinity. These abandoned lands and cultures of the surrounding lands usually evolve to a desert and rangelands are spread.

## Summary and conclusion

Using GIS spatial interpolation data analysis has particular importance, since many of the maps used in GIS operations are being manufactured by interpolation. In fact, the smooth and continuous production models of the spatial and temporal distribution of data through interpolation is possible. In local climate, soil criterion is the most significant factor affecting vegetation condition. Furthermore, vegetation condition directly influences on the status and severity of the erosion (water and wind). In this case, presence of vegetation, in addition to windbreaker effect, leads to varied surface roughness layer and prevented the incidence by the wind directly in the soil. As a result of the high level of salt and gypsum in the soil, soil structure collapses and surface materials become lightweight, these are the factors causing an increase in soil erodibility, consequently, erosion can be severe. It can also be concluded that in the desert, toward the center of the plain, land degradation is increasing. As a result, the soil criterion acts as the main factor influencing the erosion and desertification conditions. The desertification of the region can be studied with the same conditions and can be evaluated by soil criterion. Soil conditions can also be improved by performing operations such as proper drainage, carminative construction, and planting salt tolerant crops.

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