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QUANTITATIVE MAPPING AND ASSESSMENT OF ENVIRONMENTALLY SENSITIVE AREAS TO DESERTIFICATION IN CENTRAL IRAN

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ABSTRACT

Desertification is one of the main environmental and also social and economic problems facing Iran. Seventeen out of 31 Iranian provinces, which are home to approximately 70% of the total population, are affected by desertification. This study aimed to use geographic information system (GIS) and fuzzy logic for mapping environmentally sensitive areas to desertification based on Mediterranean Desertification and Land Use approach in Isfahan province, central Iran. Six desertification indicators including climate, soil, vegetation, soil erosion, groundwater, and management and policy quality were used to determine various types of environmentally sensitive areas to desertification. Seventeen desertification indices affecting the quality of each indicator were spatially mapped and assigned a value between 0 and 1 using a fuzzy logic option of ArcSDM3 software in GIS environment. Results showed that a 21·7% of the study area was classified as critical, 70% as fragile and 5·5% as potential, and 2·9% of the area was not affected by desertification. In the town of Borkhar, 64·2% of the area was classified as critical, followed by the towns of Isfahan and Nayin with 40·2% and 31·8%, respectively. Results at provincial scale indicated that the climate indicator and humidity index with a weighting mean of 0·71 and 0·77 were the most affective factors in the desertification of the study area. The developed model in this study can be used for mapping desertification status in other 16 provinces that contain desert areas. These assessments provide a GIS-based desertification database that Iran as a member of the United Nation Convention to Combat Desertification can use to report the condition of desertification at national scale. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: desertification; UNCCD; MEDALUS; GIS; central Iran

INTRODUCTION

Desertification is defined by the United Nation Convention to Combat Desertification (UNCCD) as 'land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. It occurs all around the world especially in dry lands, which cover about 41% (6,150 million hectares) of the land (Kassas, 1995).

Arid and semi-arid lands cover more than 70% of Iran and are very prone to desertification. Iran includes 31 provinces with a land area of about 1·64 million square kilometres and an annual temperature ranging from −20 to +40°C. The amount of annual precipitation is approximately 1,200 mm in the north and less than 100 mm in the central regions (NAP, 2005). According to the land use/cover map of Iran; deserts, rangelands, agricultural lands, forests and residential areas cover 20%, 55%, 11%, 8% and 6%, respectively (NAP, 2005). Eco-climatic classification shows that 85% of Iran is stratified under dry land categories (Le Houérou, 1992). It is estimated that about 20% of the country has been affected by desertification processes (Pakparvar, 1998). According to the Bureau of Desert Affairs of Iran, 17 provinces have desert areas that are home to approximately 70% of the total population of the country. There are many causes for arid land degradation, and they vary from one place to another. The main causes of desertification in Iran are water resource depletion, population pressure, excessive grazing, wrong management practices and climatic factors (NAP, 2005).

Iran was one of the first countries to sign the UNCCD in 1996 and became a member of the convention. Since then, several desertification assessment and monitoring projects have been conducted at different scales (Amiraslani, 2005), but the systematic spatial mapping based on scientific technique has not been carried out so far. Therefore, desertification status mapping of the entire country is needed.

Many models of desertification have been presented and applied for assessing and monitoring this phenomenon, and also their advantages and disadvantages have been discussed in previous studies (FAO/UNEP, 1984; Babaev, 1985; Vogt *et al*., 2011). According to the results of the food and agriculture organization and united nations environment programme's (FAO/UNEP) model, about 70% of dry lands have been globally affected by desertification (UNEP, 1992). ICD is an Iranian Classification of Desertification (ICD) model that was developed by Ekhtesasi and Mohajeri in 1995 for assessing desertification in dry lands of Iran. The main advantage of this model is that it has been developed on the basis of natural and anthropogenic characteristics of Iran's deserts. The ICD approach classifies the severity of desertification to five classes: slight, low, moderate, severe and very severe. The results of applying ICD to parts of central Iran showed that about 75% of desertification in this region has been caused by anthropogenic factors (Ekhtesasi & Mohajeri, 1995).

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Arid and semi-arid lands are affected by desertification due to interaction of natural and anthropogenic indicators (Winslow *et al*., 2011). Thus, in the desertification modelling, it is important to assign for each indicator its own weight in the desertification process and to merge all indicators to determine the most sensitive areas to desertification. The Mediterranean Desertification and Land Use (MEDALUS) project's model applies a geometrical average of indicators to identify the sensitivity of land to desertification. In this approach, when several indicators of an area have high value, that area will be classified as a highly sensitive region (Kosmas *et al*., 1999). The model uses four quality indicators including climate, soil, vegetation and management and their parameters to map different types of environmentally sensitive areas (ESAs) to desertification. A number of studies have applied this model in arid and semi-arid areas of Iran (Farajzadeh & Egbal, 2007; Sepehr *et al*., 2007) and in other countries such as Spain and Italy (Basso *et al*., 2000; Lavado Contador *et al*., 2009; Ladisa *et al*., 2010; Salvati & Bajocco, 2011). According to the results of these studies, this approach has some advantages over other desertification models such as simplicity, applicability, availability of data for the parameters, adaptability to the environment and last but not least the spatial distribution mapping of the parameters using remote sensing and GIS.

The MEDALUS model uses a quantitative classification scheme ranging from 1 to 2 to classify the sensitivity of land to desertification for all individual indices, indicators and the final desertification map. The value of 1 is assigned to the area of least sensitivity, the value of 2 is assigned to areas with the most sensitivity and values between 1 and 2 show relative sensitivity. Because many criteria have continuous rather than discrete values, the intention of the current study was to use fuzzy logic for assessing the severity of desertification in the study area (Zadeh, 1965; Baja *et al*., 2002). Therefore, the output maps provide continuous spatial distribution of desertification indices and indicators.

To date, no research has evaluated the potential of the MEDALUS model for spatial mapping of desertification at provincial level in Iran. Neither has any work examined the usefulness of fuzzy logic in desertification mapping at this scale. Therefore, the main objectives of this study were to (i) provide general information on the desertification of Isfahan province; (ii) identify the main indices and indicators of desertification based on fuzzy classification; and (iii) identify ESAs to desertification in the region.

MATERIALS AND METHODS

Study Area

The Isfahan province with 107,045 km^2 is located in central Iran and lies between latitudes 30°42′N and 34°27′N and longitudes 49°38′E to 55°32′E (Figure 1). The climate in the study area is characterised by hot summers and cold winters. The mean daily maximum temperature ranges from 35°C in summer to approximately 17°C in winter, and the mean daily minimum temperature ranges from 15°C in summer to about 5°C in winter. The mean annual evaporation rate is 2,500 mm. Winds are usually from the southeast in the north and southwest in the south of the study area. Rainfall is highly variable from year to year in this region. It varies across the province from less than 100 mm in the east to about

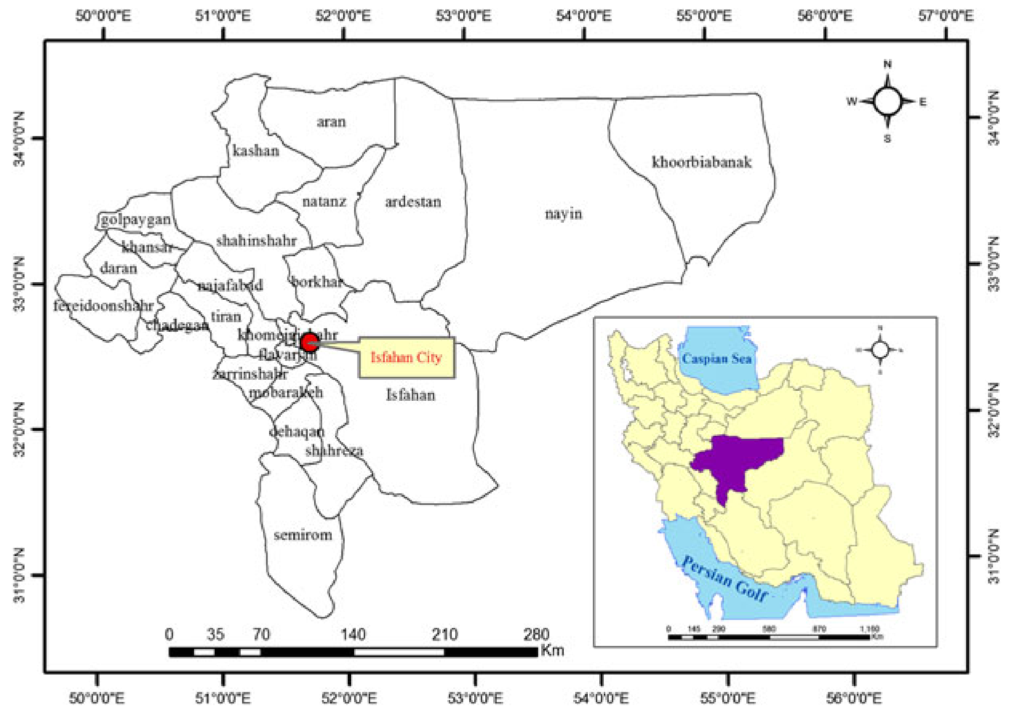

Figure 1. Location of Isfahan province in central Iran. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

450 mm in the west. The Isfahan province is surrounded by the Dasht-e-Kavir desert in the east and north and the Zagros Mountains in the west and south. The Zagros Mountains produce a Fohn effect that reduce the rainfall in the Isfahan region and then cause desert-like conditions. The water resources of Isfahan province are coming from rivers (e.g. Zayandeh-Rood), springs, wells and qanats.

Desertification Assessment

There is much information for desertification assessment, but to assess this phenomenon in an effective way, it needs to select and use some simple and available key indicators and indices to tackle this complex process (Rubio & Bochet, 1998). In this study, six indicators and 17 indices were chosen on the basis of previous studies (Zehtabian *et al*., 2005; Sepehr *et al*., 2007; Nateqi *et al*., 2010), field works and expert knowledge. To map desertification, the following algorithm is adapted from the MEDALUS methodology (Equation 1):

$$D_S = (W_C \times W_S \times W_V \times W_{Er} \times W_G \times W_M)^{\frac{1}{6}} \qquad (1)$$

Where: D_S is the desertification severity, W_C is the climate quality indicator, W_S is the soil quality indicator, W_V is the vegetation quality indicator, W_{Er} is the soil erosion quality indicator, W_G is the groundwater quality indicator and W_M is the management and policy quality indicator. After calculating the desertification severity, it was classified in four broad classes as low (0–0·25), moderate (0·25–0·5), severe (0·5–0·75) and very severe (0·75–1) based on the values ranging from 0 to 1. To identify the different degrees of desertification sensitivity, ESAs to desertification of Isfahan province were determined on the basis of the D_S map and the MEDALUS model as follows: [$D_S > 0{\cdot}75$ = critical(3), $0{\cdot}65 < D_S < 0{\cdot}75$ = critical(2), $0{\cdot}55 < D_S < 0{\cdot}65$ = critical(1), $0{\cdot}45 < D_S < 0{\cdot}55$ = fragile(3), $0{\cdot}35 < D_S < 0{\cdot}45$ = fragile(2), $0{\cdot}25 < D_S < 0{\cdot}35$ = fragile(1), $0{\cdot}15 < D_S < 0{\cdot}25$ = potential(p), $D_S < 0{\cdot}15$ = nonsensitive].

Equation 1 indicates that the geometric mean of the six indicators including climate quality, soil quality, vegetation quality, soil erosion quality, groundwater quality, and management and policy quality is used to determine the severity of desertification. A similar approach was applied to map each indicator using related desertification indices in geographic information system (GIS) environment. The climate quality was calculated through rainfall and evaporation data on a number of 43 meteorological stations and also Transu humidity index as follows (Equation 2):

$$I = P/E \qquad (2)$$

Where: P is the average annual rainfall and E is the average evaporation. Two soil and three vegetation indices including soil texture and soil waterlogging, plant cover percentage, plant erosion protection and plant drought resistance were considered in this study. The soil erosion quality was calculated on the basis of wind and water erosion classes using Iran Research Institute of Forests and Rangelands (IRIFR) and Bureau of Land Management (BLM) techniques, respectively. Nine parameters of the IRIFR method including lithology, morphology and relief, wind velocity, soil characteristics, type and plant cover percentage, wind erosion features, soil moisture, type and distribution of sandy dunes, and land use and land management were applied to characterise affected areas by wind erosion in the geomorphological units of desert regions that were modified in this study (Ekhtesasi & Ahmadi, 1995; Bureau of Desert Affairs, 2011). In the BLM method, seven parameters were considered including soil movement, surface litter, gravel and rock cover, land cover, rill erosion, channel erosion and gully erosion (BLM, 1973). Electrical conductivity, sodium adsorption ratio, chloride rate and total dissolved solid indices were used to assess the groundwater quality (Wilcox, 1955; Abdullahi, 2010). For assessing management and policy quality, the quality of agricultural and irrigation practices in agricultural lands and grazing intensity in rangelands and also vegetation rehabilitation policy were considered in the region (Cerdà *et al*., 2009; Amiri & Arzani, 2010; Bureau of Desert Affairs, 2011; Weber & Horst, 2011; García Orenes *et al*., 2013). Table I demonstrates the classes and quantitative scores of the considered indices.

In this study, GIS software was used to produce a raster map (pixel size = 50×50 m = 2,500 m^2) for each index. For this purpose, among different geostatistical techniques, a technique with minimum error was selected to map climate and groundwater indices. The remaining indices of soil, vegetation, soil erosion, and management and policy indicators were assigned a value between 1 and 10 based on the classes presented in Table I. To determine the effect of each index on desertification, the raster layers were classified using a fuzzy logic option of ArcSDM3 extension in GIS environment (Sawatzky *et al*., 2009). Then, the desertification map and ESAs map to the desertification of the region were calculated by integrating all six fuzzy-based raster maps of the indicators using Equation 1. Finally, the desertification and ESAs map were classified into four severity classes (i.e. low, moderate, severe and very severe) and eight sensitivity classes (i.e. critical 3, critical 2, critical 1, fragile 3, fragile 2, fragile 1, potential, nonsensitive or nonaffected area), respectively. Figure 2 shows a summary of mapping ESAs to desertification in Isfahan.

RESULTS AND DISCUSSION

Figure 3 shows the spatial distribution of the desertification of six quality indicators based on the MEDALUS methodology and fuzzy classification at provincial scale. The map values range from 0 to 1, representing high and low desertification, respectively. With the use of fuzzy logic, the output map represents a continuous spatial distribution of the indicator rather than a categorical value. In this study, the climate and groundwater indicators and also their indices were continuous; therefore, the related maps were produced using geostatistical tools in GIS environment. To have comparable

Table I. Classes and assigned weights for the 17 desertification indices in Isfahan province

Classes and assigned weights

Climate quality (W_C) = (Rainfall × Evaporation × Humidity Index)$^{1/3}$

	Average annual rainfall (mm)	Annual evaporation (mm)	Humidity index	Assigned weight (applied to all the 17 indices)
1	<71	>3,000	0·023	1
2	71–100	2,801–300	0·03	0·9
3	01–150	2,601–2,800	0·1	0·8
4	151–200	2,401–2,600	0·15	0·7
5	201–250	2,201–2,400	0·2	0·6
6	251–300	2,001–2,200	0·3	0·5
7	301–350	1,901–2,000	0·4	0·4
8	351–400	1,801–1,900	0·5	0·3
9	401–600	1,701–1,800	0·6	0·2
10	>600	<1,700	0·75	0·1

Soil quality (W_S) = (Soil Texture × Soil Drainage)$^{1/2}$

	Soil texture and depth (from playas to mountains)	Soil drainage (land unit)
1	Very clayey-deep-extremely sandy	3·6
2	Very clayey-clayey-deep	2·6
3	Clayey-deep	3·7, 3·5, 1·5, 1·4, 4·3
4	Clayey-medium clayey-deep	7·1, 6·1, 1·4, C4
5	Clayey-loamy-moderate	8·2, 2·4
6	Loamy-moderate	3·8, 4·7, 2·7, C2
7	Loamy-shallow	5·3, 5·1, 8·1, 3·8, 3·5, 2·2, 2·1, C1
8	Loamy-very shallow	1·9, 3·3,1·3, 2·3, 1·3, 3·2, 1·5, C3, urban area
9	Clayey-shallow	X4, X2, 2·9, 3·1
10	Rock	X1, 2·1

Vegetation quality (W_V) = (Vegetation Cover × Drought Resistance × Erosion Protection)$^{1/3}$

	Vegetation cover (%)	Drought resistance	Erosion protection
1	SL–TK–K–SS	Dry farming	Dry farming
2	BL	Irrigated farming	Irrigated farming
3	SD	R3 (west of region)	Orchard + irrigated farming
4	R3	R2–R3 (east of region)	R3 (east of region)
5	Rock (R3)	R1	R3 (west of region)
6	F3	Orchard	Orchard–R2
7	Rock	F3	R1
8	R2–PF	F2	PF
9	F2	F1	F2–F3
10	R1–orchard	PF	F1

Soil erosion quality (W_{Er}) = (Water Erosion × Wind Erosion)$^{1/2}$

	Water erosion (BLM)	Wind erosion (IRIFR)
1	V (very high)	V
2	IV + V	IV + V
3	IV (high)	IV
4	III + IV	III + IV
5	III (moderate)	III
6	II + III	II + III
7	II (low)	II
8	I + II	I + II
9	I (very low)	I
10	<I	<I

Groundwater quality (W_G) = (EC × SAR × TDS × CL)$^{1/4}$

	EC (μmmhos cm^{-1})	*SAR*	*TDS*	*CL* (g L^{-1})
1	>8,000	>36	>8,000	>175
2	5,001–8,000	33·1–36	2,001–8,000	150·1–175
3	3,501–5,000	30·1–33	1,751–2,000	125·1–150
4	2,251–3,500	26·1–30	1,501–1,750	100·1–125
5	1,501–2,250	22·1–26	1,251–1,500	75·1–100
6	751–1,500	18·1–22	1,001–1,250	50·1–75

(*Continues*)

Table I. (Continued)

Classes and assigned weights				
7	401–750	14·1–18	751–1,000	35·1–50
8	301–400	10·1–14	501–750	25·1–35
9	250–300	5–10	250–500	15–25
10	<250	<5	<250	<15

Management and policy quality (W_M) = (Grazing Intensity × Rehabilitation Practices × Agricultural and Irrigation Quality)$^{1/3}$

	Grazing intensity(available livestock/allowable livestock)	Rehabilitation practices
1	>2·7	Degradation of sensitive areas to erosion due to anthropogenic activities
2	24–27	Degradation of nonsensitive areas to erosion due to anthropogenic activities
3	2·1–2·3	Rehabilitation practices are not applied to sensitive areas to erosion
4	1·9–2	Rehabilitation practices are not applied to moderately sensitive areas to erosion
5	1·6–1·8	Rehabilitation practices are not applied to nonsensitive areas to erosion
6	1·3–1·5	Less than 30% under rehabilitation practices
7	1·1–1·2	Less than 30–50 under rehabilitation practices
8	0·5–1	Less than 50–70 under rehabilitation practices
9	0·2–0·4	More than 70% under rehabilitation practices
10	<0·2	Complete rehabilitation practices are applied

	Agricultural and irrigation quality
1	Unattended agricultural lands
2	Improved varieties are used, fertilizers and pesticides are applied, cultivation is highly mechanised, the land is not under fallow, use of traditional irrigation methods, irrigation with poor quality of water
3	Improved varieties are used, fertilizers and pesticides are applied, cultivation is highly mechanised, the land is not under fallow, use of modern irrigation methods, irrigation with poor quality of water
4	Improved varieties are used, fertilizers and pesticides are applied, cultivation is highly mechanised, the land is not under adequate fallow, use of modern irrigation methods, irrigation with poor quality of water
5	Improved varieties are used, fertilizers and pesticides are applied, mechanisation is restricted to the most important such as sowing, the land remains under fallow, use of traditional irrigation methods, irrigation with poor quality of water
6	Improved varieties are used, fertilizers and pesticides are applied, mechanisation is restricted to the most important such as sowing, the land remains under fallow, use of modern irrigation methods, irrigation with poor quality of water
7	Local plant varieties are used, fertilizers and pesticides are not applied, mechanisation is limited, the land remains under fallow, use of traditional irrigation methods, irrigation with poor quality of water
8	Local plant varieties are used, fertilizers and pesticides are not applied, mechanisation is limited, the land remains under fallow, use of traditional irrigation methods, irrigation with poor quality of water
9	Local plant varieties are used, fertilizers and pesticides are not applied, mechanisation is limited, the land remains under fallow, use of modern irrigation methods, irrigation with poor quality of water
10	Local plant varieties are used, fertilizers and pesticides are not applied, mechanisation is limited, the land remains under fallow, use of modern irrigation methods, irrigation with high quality of water

SL, salt pan; TK, clayey facies in playa; K, Kavir; SS, sand sheets; BL, bare land; SD, sand dunes; R3, low-density rangeland; F3, very open forest; R2, medium density rangeland; PF. plantation forest; F2, medium density forest; R1, high density rangeland; F1, high density forest. EC, electrical conductivity; SAR, sodium adsorption ratio; TDS, total dissolved solids; and CL, chloride rate; BLM, Bureau of Land Management; IRIFR, Iran Research Institute of Forests and Rangelands.

maps of continuous and discrete (i.e. soil, vegetation, soil erosion and management quality) indicators and indices, the produced maps were classified using the fuzzy logic option of ArcSDM3 software.

To show the effect of desertification in a comparable and simple way, the final fuzzy-based indicator maps were categorised into four suitable desertification severity classes including low, moderate, severe and very severe. As Figure 4 (a) shows, about 1·15% is in low class, 8·35% in moderate class, 34·07% in severe class and 56·43% in very severe class of climate quality. The majority of Isfahan province is characterised by severe and very severe conditions (90·5%), and more than half of the area (56·43%) is of very severe class. The main reason for this harsh climate conditions in the area is the low amount of precipitation and the high amount of evaporation. The amount of rainfall decreases from west to east around 82%. About 53·65% of the study area is characterised with high amount of evaporation (more than 2,500 mm y^{-1}) and with humidity index less than 0·05.

The soil quality indicator (Figure 4(b)) demonstrates that around 48·86% of the province is in moderate class, and the majority of severe and very severe classes lie in the northern and eastern parts of the study area. The very severe desertification class is attributed to lowland plains where soil drainage is weak and soil salinity and alkalinity is higher (Singh, 2009). In these areas, the groundwater level is shallow, therefore, increases salinisation and consequently desertification of the province especially in the marginal lands of Gavkhouni playa, Dagh-e-Sorkh playa, Maranjab playa and Siahkoh playa.

Figure 4(c) shows that more than 80% of vegetation indicator is in severe and very severe classes and about 19·8% is in

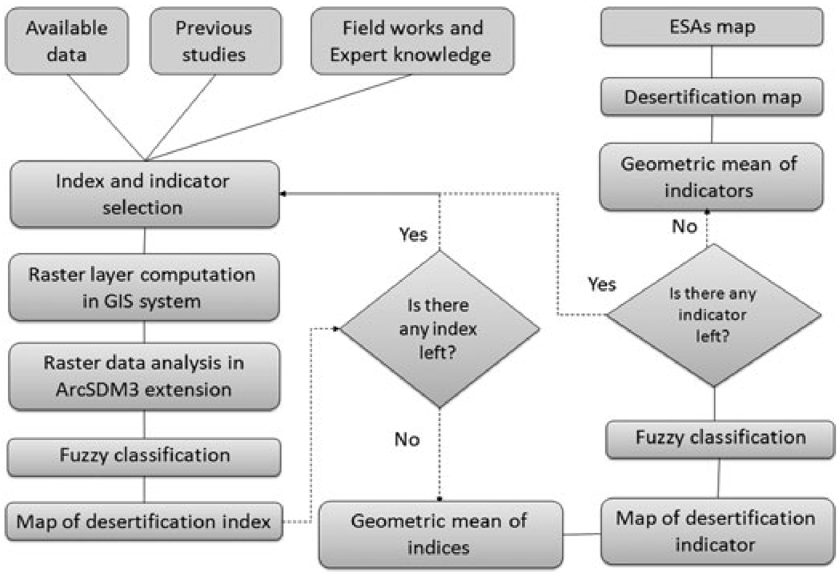

Figure 2. Flow chart of mapping environmentally sensitive areas (ESAs) to desertification in Isfahan province.

moderate and low classes. Most of the study area especially central, northern and eastern parts is not well vegetated, and wind erosion due to harsh climate condition is dominant in these regions. The high quality and high density of rangeland and forest (*Quercus brantti*) perennial vegetation cover protect land from water erosion in the west and south of the study area. As it can be seen from Figure 4 that the desertification class is low in these areas and also in some patches in the east, north and north-east of the region due to *Haloxylon* spp. plantations, although this class only covers around 5·5% of the province. The high quality of vegetation cover is mainly distributed in semi-steppe regions in the west and south, and from west to east, the vegetation cover decreases and steppe regions with *Artemisia* spp. are dominant. Livestock grazing is the main land-use activity in the semi-steppe rangelands of the study area. In these areas, heavy grazing often occurs and results in a dramatic decline of vegetation cover, leading to soil erosion and rangeland desertification (Arnalds & Archer, 2000; Lin *et al.*, 2010). For example, grazing intensity in the rangelands of Golpaygan town is approximately 2·6 times greater than acceptable level (Table I), which may cause the extinction of many plant species in the region.

Soil erosion status calculated from the IRIFR and BLM models is shown in Figure 4(d). Low wind erosion in the south and west corresponds with areas where vegetation cover quality is higher due to semi-arid climate. Wind erosion is also low in mountainous and *Holoxylon* spp. plantation areas. In contrast with wind erosion, water erosion is higher in the west and south and it decreases from west to east. According to the wind and water erosion maps, 7·98% of the region has been classified as very severe, 7·31% as severe, 43·76% as moderate and 40·95% as low class of wind erosion, and the results for water erosion were 0·59%, 12·15%, 56·06% and 31·21%, respectively. Because of Iran's climate and topographic conditions, 75 and 20 million hectares are affected by water and wind erosion, respectively (NAP, 2005), and the average national rate of water erosion has been reported from 15 to 45 Mg ha^{-1} (Jalalian *et al.*, 1997).

The effect of groundwater quality on desertification was evaluated on the basis of electrical conductivity, chloride rate, sodium adsorption ratio and total dissolved solid indices (Figure 4(e)). In the study area, these indices range from 228·2 to 10,533·8, 0·02 to 157·6, 0·23 to 36·4 and 140·7 to 12,497·1, respectively. The quality of groundwater decreases from west to east and also from south to north especially in playas where the groundwater level is shallow and nonclastic minerals are dominated. Therefore, in the south and west, low desertification class with 26·76% of the study area is dominated.

Flood irrigation is one of the most common techniques in Isfahan province in which 70% of water is lost through evaporation (Karimkoshteh & Haghiri, 2004). This system has increased soil salinisation and desert-like conditions in the region. Because of the overexploitation of underground water for agricultural purposes, a major decline in the water table of Isfahan's plains has occurred and caused an increase in land subsidence in the region. For example, there is an annual decline of 1·33 m (24 m from 1991 to 2009) in the level of water table in the Mahyar region of Shahreza town. In general, it can be said that most of the plains in Iran are threatened by land subsidence. Figure 4 (f) shows the impact of management and policy on desertification in Isfahan province. Most of the area (67%) has been classified as moderate and low classes of desertification, and about one-third of the region includes very severe and severe classes. In general, the intensity of land use from east to west increases; therefore, most of the low desertification class is located in the eastern regions that

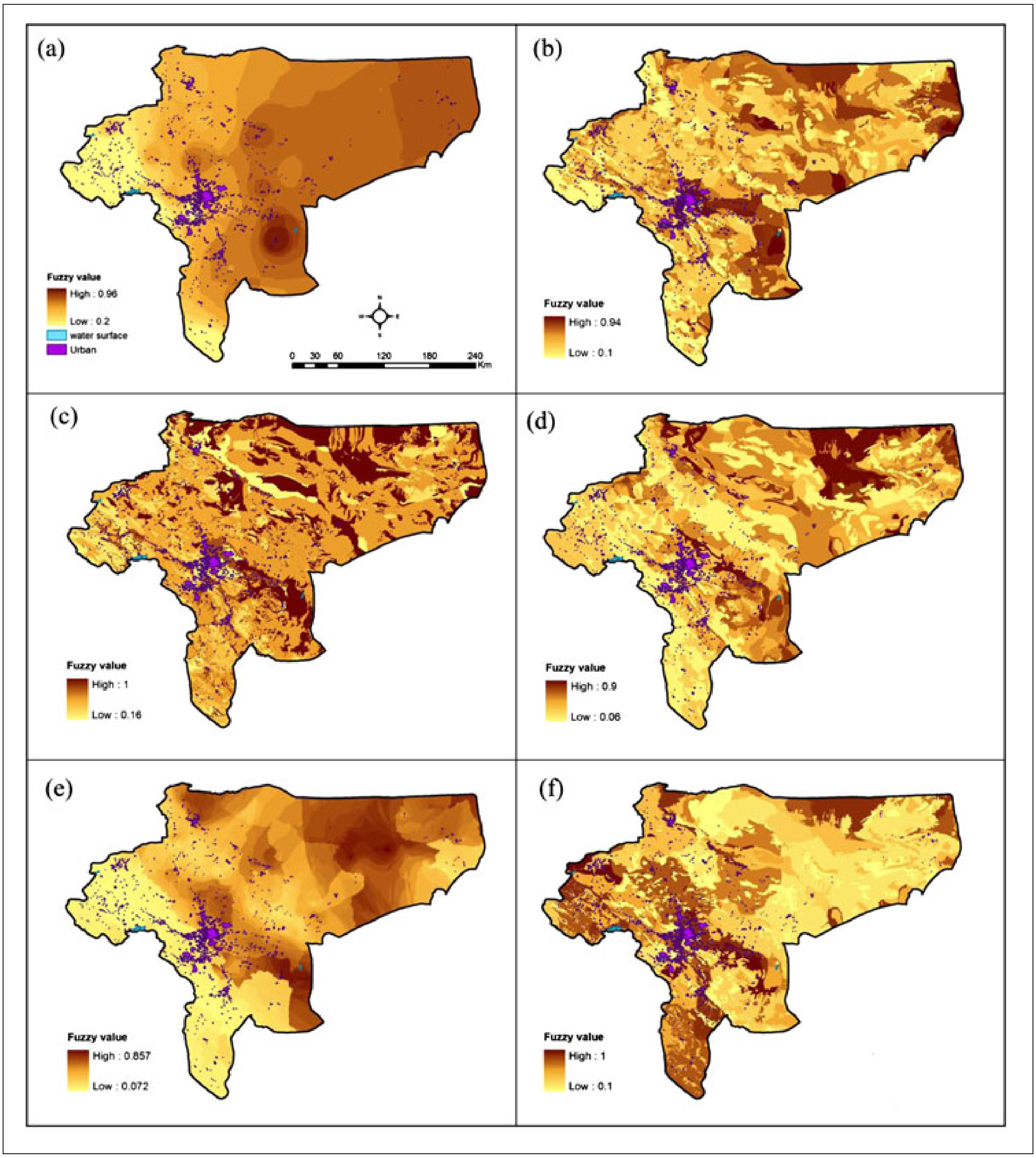

Figure 3. Fuzzy classification of quality indicators: (a) climate, (b) soil, (c) vegetation, (d) soil erosion, (e) groundwater and (f) management and policy. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

are dominated by harsh climate conditions. The main reason for high degradation in the west and south where high quality rangelands and forests are located is the high grazing intensity, which has been dramatically increased in recent years.

Another example of human-induced land degradation in the study area is located approximately 25 km in the east of Isfahan town in Segzi plain (Figure 5(b)). This plain with an area of 40,000 ha is a hot spot of wind erosion, and also, it is an important source of gypsum. About 120 trucks transport gypsum soils to the 70 gypsum furnaces every day. These furnaces are located in the direction of east and north-east winds that transport dust particles to the surrounding areas and Isfahan city in summer season causing health, social and economic problems (Bureau of Desert Affairs, 2011; Keramat *et al*., 2011; Requier Desjardins *et al*., 2011). Before starting gypsum exploitation, most of the plain was covered by pebbles and gravels called ‘desert pavement’ (Ekhtesasi & Sepehr, 2009). This natural mulch is very important in desert regions with sparse vegetation cover and protects soil from wind erosion. Therefore, the hazard of soil blowing and dust is

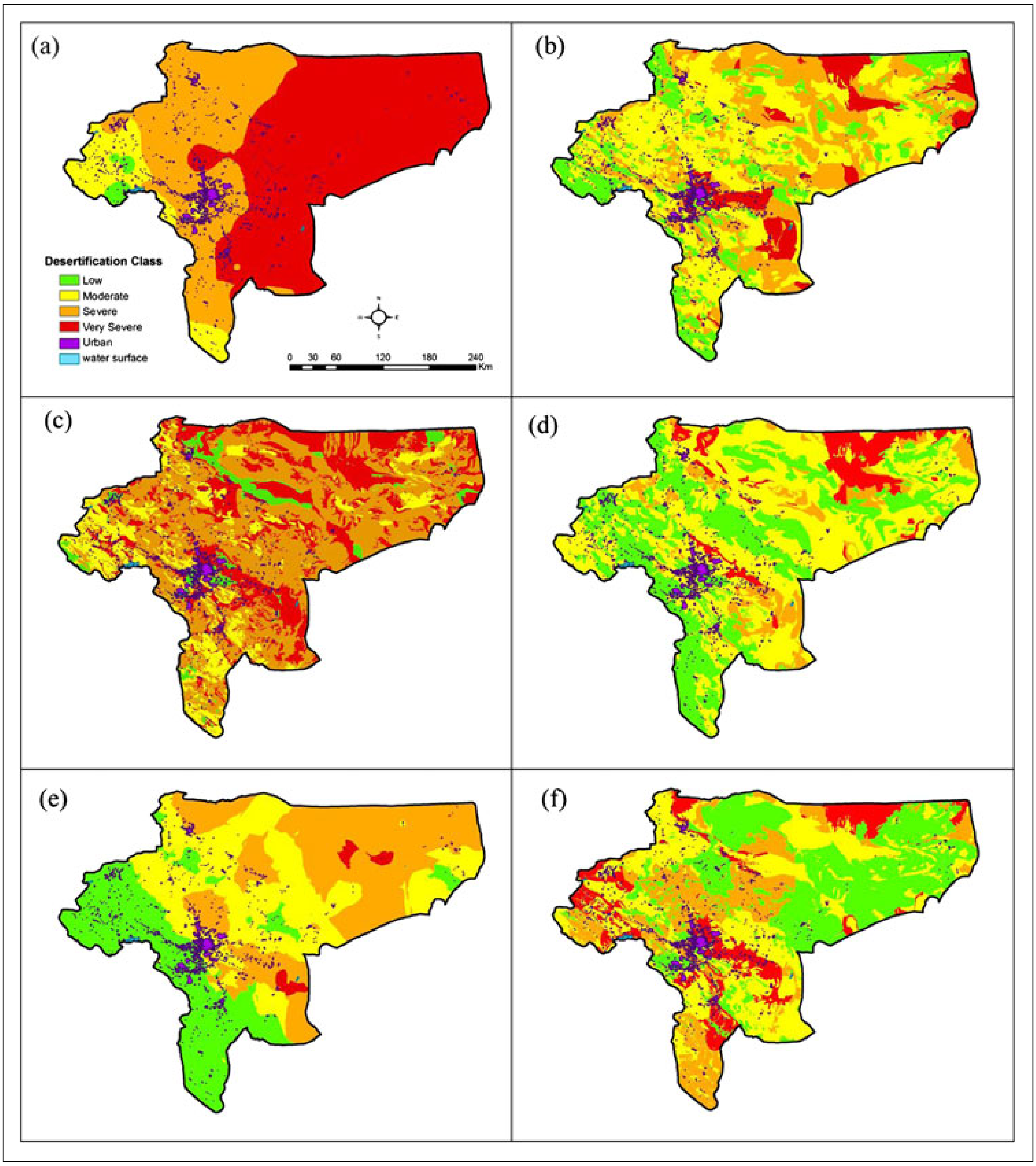

Figure 4. Spatial distribution of desertification classes for quality indicators: (a) climate, (b) soil, (c) vegetation, (d) soil erosion, (e) groundwater and (f) management and policy. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

slight where the surface is protected by a layer of closely packed pebbles or rock fragments.

Because of the complexity of desertification, its assessment and monitoring is difficult. Although in this study six indicators with 17 indices were considered and assessed to map desertification, the selection of input factors is an open question (Rubio & Bochet, 1998; Sommer *et al*., 2011). Thus, extracted desertification classes are not absolute ones, and the map can change as other indicators are introduced. In other words, the final desertification map depends highly on the selection of indicator and availability of suitable data, and these issues must be considered in modelling studies (Chasek *et al*., 2011). According to the results of this study, the MEDALUS model due to its flexibility to accept new indicators and weights and also because of its GIS-based characteristic appears to be a suitable model for studying desertification process in the region.

Table II shows the desertification classes and the percentage of area covered by each indicator. According to the table, the very severe desertification class of climate indicator covers

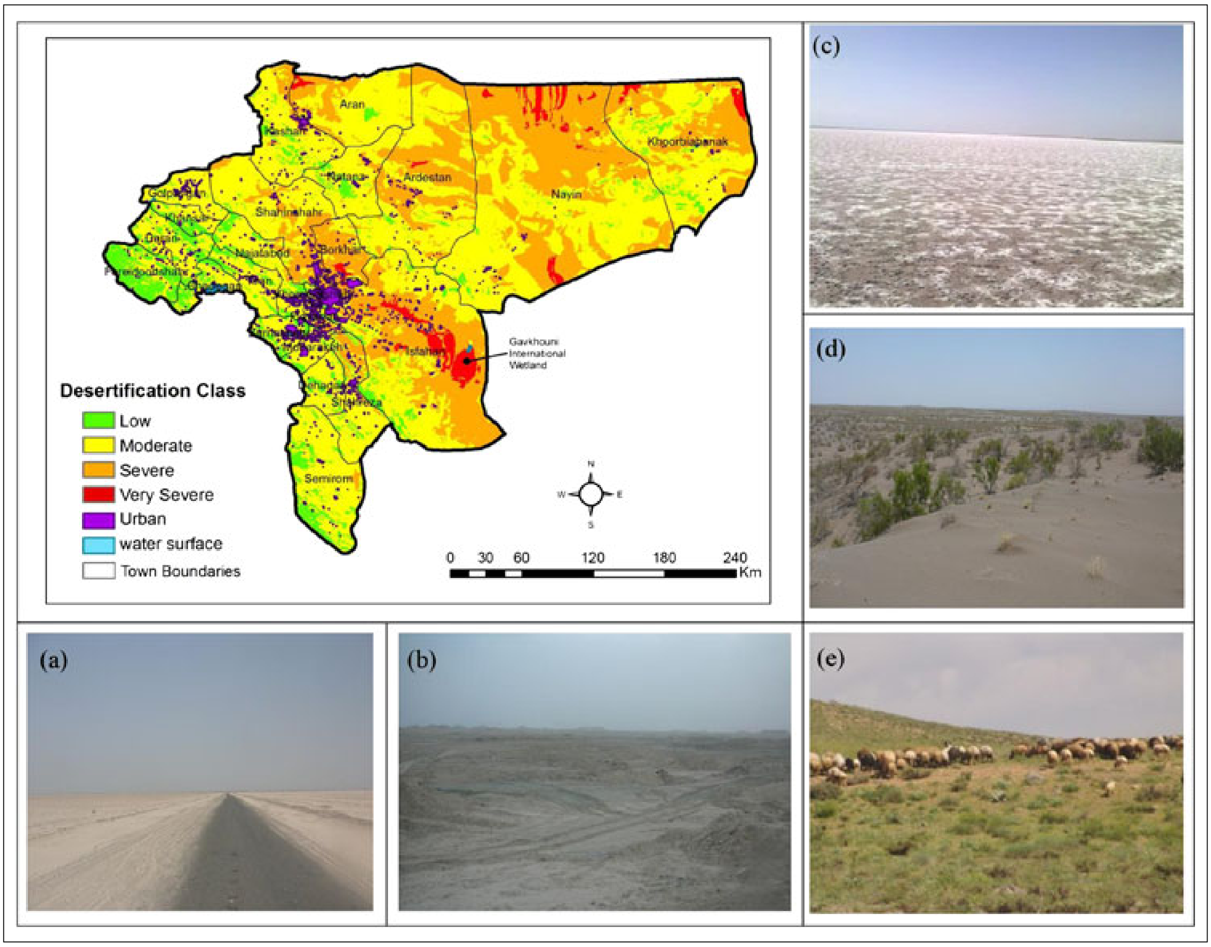

Figure 5. Spatial distribution of desertification status with severity classes in Isfahan province. Photographs: (a) wind erosion in Isfahan town, Segzi plain; (b) Gypsum mine and land degradation in Isfahan town, Segzi plain; (c) Dagh-e-Sorkh salt pan in the north of Ardestan town; (d) *Holoxylon* spp. plantation in the north of Ardestan town; and (e) medium density rangeland in Fredounshahr town. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

more than 56%, and the low desertification class of this indicator comprises around 1% of the study area.

To obtain a single desertification map of the study area, all six indicators were combined, and then, the severity of desertification similar to the indicators was classified as low, moderate, severe and very severe. Results showed that 9·49% (1·01 million hectares) of Isfahan province has been affected by low desertification, 56·4% (6·04 million hectares) by moderate, 31·74% (3·4 million hectares) by severe and 2·33% (0·25 million hectares) by very severe (Figure 5, Table II).

Table II. The percentage areas of desertification indicators and status in Isfahan province

Indicator class	Desertification severity			
	Low	Moderate	Severe	Very severe
Climate	1·15	8·35	34·07	56·43
Groundwater	26·76	31·28	37·2	4·21
Vegetation	5·43	14·44	51·64	28·4
Soil	10·31	48·86	31·34	9·48
Soil erosion	31·20	46·46	13·64	8·7
Management and policy	33·26	33·93	20·05	12·76
Desertification status	9·49	56·44	31·74	2·33

Figure 6 shows ESAs to desertification and their extent in Isfahan province. A 21·72% of the study area is classified as critical, 70·01% as fragile and 5·51% as potential, and 2·89% of the area is not affected by desertification. Figure 6 indicates that most of the sensitive areas to desertification are located in eastern parts of the province. For example, in the town of Borkhar, 64·21% of the area is classified as critical, followed by the towns of Isfahan, Nayin, Aran, Khoorobiabanak and Ardestan where the critical class of desertification comprises 40·2%, 31·8%, 24·9%, 23·6% and 19·9%, respectively. On the other hand, in the western towns of Isfahan province, the desertification sensitivity is vice versa. For example, in the town of Fridounshahr, no affected area to desertification was observed. It is clear that no affected or potential area does not necessarily mean zero degradation. Table III shows the dominant desertification indicators, indices

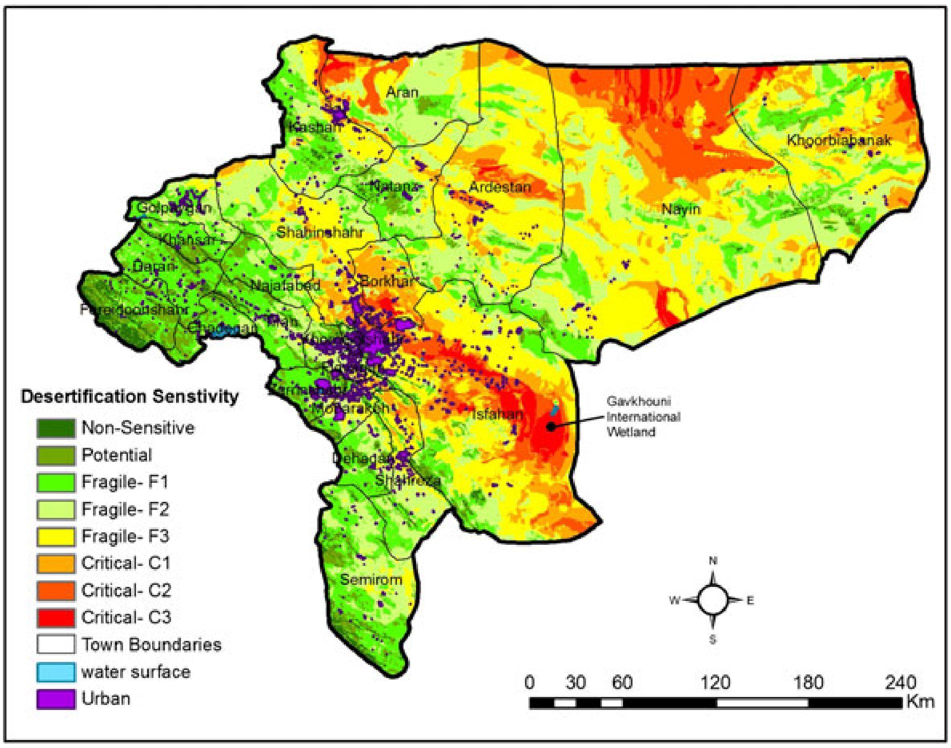

Figure 6. Spatial distribution of various types of environmentally sensitive areas to desertification in Isfahan province. The percentage areas of ESAs include critical 3 (2·89), critical 2 (5·51), critical 1 (17·8), fragile 3 (24·45), fragile 2 (27·64), fragile 1 (11·31), potential (7·95) and nonsensitive (2·46).

and types of ESAs to desertification in the 23 towns of Isfahan province.

The results of comparisons between the six desertification indicators and 17 indices at provincial scale showed that the climate quality indicator and humidity index with a weighting mean of 0·71 and 0·77 were the most affective factors in the desertification of the study area (Figure 7).

Table III. Comparisons of desertification indices, indicators and ESAs classes in the towns of Isfahan province

Dominant ESAs type	Dominant indicator(s)	Dominant index	Town	No.
Fragile 2	Vegetation, climate	Underground water decline	Aran	1
Fragile 3	Vegetation, climate	TDS	Ardestan	2
Fragile 1	Vegetation, policy and management	Grazing intensity	Chadegan	3
Fragile 1	Vegetation, policy and management	Humidity index	Dehagan	4
Nonsensitive	Vegetation, policy and management	Grazing intensity	Feredoonshahr	5
Fragile 2	Soil, policy and management	Grazing intensity	Falavarjan	6
Fragile 2	Vegetation, policy and management	Grazing intensity	Golpayegan	7
Fragile 2	Vegetation, climate	Humidity index	Kashan	8
Fragile 1	Vegetation, policy and management	Tolerance to drought	Khansar	9
Fragile 2	Soil, climate	Humidity index	Khomeinishahr	10
Fragile 3	Vegetation, climate	Rainfall	Khoorobiabanak	11
Fragile 2	Vegetation, climate	Grazing intensity	Mobarakeh	12
Fragile 1	Vegetation, climate	Humidity index	Najafabad	13
Fragile 2	Vegetation, climate	Humidity index, underground water decline	Natanz	14
Fragile 3	Climate, groundwater	TDS	Nayen	15
Fragile 1	Climate, policy and management	Grazing intensity	Semirom	16
Fragile 2	Vegetation, climate	Underground water decline	Shahinshahr	17
Fragile 2	Climate, policy and management	Grazing intensity	Shahreza	18
Fragile 1	Vegetation, climate	Vegetation tolerance to drought	Tiran	19
Fragile 1	Vegetation, climate	Humidity index	Zarrinshahr	20
Fragile 1	Vegetation, policy and management	Grazing intensity	Daran	21
Fragile 3	Vegetation, climate	TDS	Isfahan	22
Critical 1	Vegetation, climate	TDS	Borkhar	23

ESAs, environmentally sensitive areas; TDS, total dissolved solids.

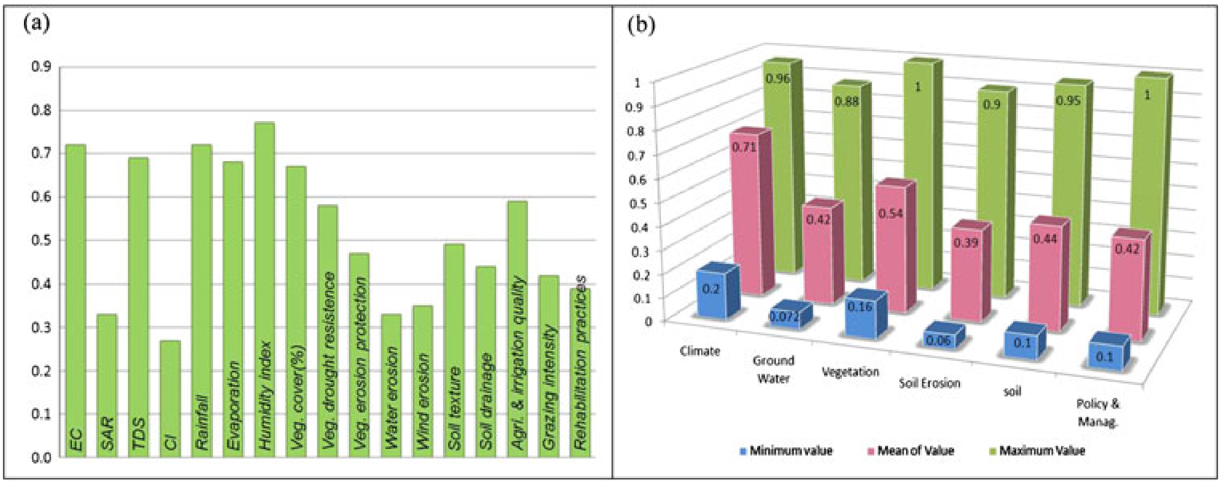

Figure 7. (a) Comparisons of the weighting mean of desertification indices and (b) comparisons of minimum, maximum and mean scores of desertification indicators. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

CONCLUSIONS

Arid and semi-arid regions of Iran are undergoing rapid desertification in response to climatic variations and anthropogenic disturbances. Although Iran, as a member of UNCCD, has executed many desertification assessment and monitoring projects to combat with this crisis, it seems these activities in comparison with rate of degradation in the country are not adequate. In this study, to map ESAs to desertification of Isfahan province with 107·045 km^2, a regional model was developed on the basis of the MEDALUS method and fuzzy logic in GIS environment. Results indicated that Isfahan province is very sensitive to desertification, and more than 91% of its area is sensitive to and affected by desertification. According to the results, the marginal lands of Gavekhouni International Wetland have been classified as critical to desertification and can be an important dust source at regional, national and international scales in the near future. Therefore, the map of ESAs can be used as a very useful tool for making better decisions for the future of the region.

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