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ORIGINAL ARTICLE

Geotourism Development in World Heritage of the Lut Desert

Mehran Maghsoudi[1] · Anvar Moradi[1] · Fatemeh Moradipour[1] · Mohammad Ali Nezammahalleh[1]

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Abstract

Geotourism implicitly implies geologic and geomorphologic characteristics as the base for tourism/recreation activities and geographic situations. The Lut desert and its environmental system have many potential and outstanding universal values including the highest and longest yardangs (kaluts) and very high sand dunes and nebkhas. It is necessary to explore and introduce internationally the values of the Lut desert. In this research, we have initially listed tourism attractions of the Lut desert. Subsequently, their scientific, educational, and tourism value, and degradation risks have been evaluated by Brilha (2016) method. The suitable areas for geotourism development have been determined by the fuzzy AHP method and the optimal areas have also been selected and surveyed based on an assessment of geosites. The results of the geosite evaluation of the Lut desert indicate that the geosites of Shur River, mega-yardangs (kaluts), linear dunes, basalt plateau of Gandom Beryan, and the dreamy city of the Lut (Shahr-e Khialy-ye Lut) have the highest values for geotourism. The results of zonation by fuzzy AHP have also indicated that west, northeast, and southeast parts of the Lut have more suitable conditions for geotourism development. Finally, through the integration of the assessments and zoning of suitable areas for geotourism development with a field survey in a new approach, we have selected eight suitable areas for the geotourism development in the Lut desert.

Keywords Geotourism · Geosite · Quantitative assessment · Fuzzy AHP · Lut Desert

Introduction

Geotourism in an academic perspective in world is initiated by 1995 when it was for first defined by Thomas Hose (Hose 2012). Broadly, geotourism is defined as a set of activities, infrastructures, and services to improve the value of geological heritage through tourism (Reynard et al. 2007). Geotourism is a particular kind of tourism in which geosites are greatly considered by visitors. A geosite can be landscape, a variety of landforms, a rock outcrop, and fossil layers or a fossil (Dowling and Newsome 2006). Geotourism is also the best solution for regional development; particularly, rural areas are well conserved for their natural heritages (Rodrigues et al. 2011). Generally, geotourism is a comprehensive kind of sustainable tourism. It contains subjects in different areas of tourism including rural tourism (Clarc and Chabrel 2007; Oliver and Jenkins 2003; Ilbery and Kneafsey 2007; Saxena et al. 2007), cultural heritage tourism (Boyd 2002; Kang and Moscardo 2006; Moscardo and Pearce 1999), tourism society (Blackstock 2005; Joppe 1996), tourism supporting the poor (Ashley and Roe 2002), and ecotourism (Ceballos 1996; Scheyvens 1999). The landforms created from combined processes of biology and geomorphology (Fassoulas et al. 2007) along with cultural, social, and economic added values (Comanescu et al. 2012) have created tourism sites emphasizing geotourism. Therefore, planning and management of geoheritage and geosite have grown in the recent years and attracted the attention of researchers of geodiversity along with biodiversity. There are policies and efforts that, addition to biodiversity, make attempts to conserve the diversity of geological and geomorphologic landforms. The models and methods for assessment of geosites are new and developing (Burlando et al. 2011).

✉ Mehran Maghsoudi
maghsoud@ut.ac.ir

Anvar Moradi
anvar.moradi@ut.ac.ir

Fatemeh Moradipour
moradipour.f@ut.ac.ir

Mohammad Ali Nezammahalleh
mnezammahalleh@ut.ac.ir

[1] Faculty of Geography, University of Tehran, Azin Alley, Vesal Street, Tehran, Iran

Geotourism not only is focused on all the human and natural characteristics of geosites, but it also argues about their performance. This kind of tourism can play a major role in national development and economic diversity through planning based on opportunities and limitations of geotourism (Beigi and Pakzad 2010). Development of sustainable geotourism plays a particular role in regional development. As the aspects of geotourism are really understood, better practical and executive attempts can be made to develop the geographical areas. The situation can be more objective as a region has a variety of unique tourism potentials and also can eliminate poverty in the area. Indeed, to reach the goals of sustainable development in arid and desert regions in environmental and cultural dimensions, it is necessary to consider cultural issues along with introducing the geotourism potentials.

With special natural characteristics, geomorphologic structures, and climate diversity, Iran has spectacular sites for researchers and the public to visit (Sanaiee et al. 2013). Hence, the country has the capability to be introduced as an active area in the execution of geotourism. A large part of Iran (73%) is located in semi-arid, arid, and desert regions. The vast extent of the arid region in the country makes it essential to consider the potential of the region in ecotourism and geotourism. The Iranian arid areas and deserts, particularly the Lut desert, have many geomorphologic and geologic features (Maghsoudi and Emadoldin 2007). There are many local communities in suitable marginal areas of the Lut and the areas have conserved their local cultures for many centuries. Thus, the Lut desert with the various and unique geotourism potentials can be effective to elimination poverty in the region. Felischer (2000) indicated that for tourism development, it is necessary to understand cultural resources and also involve them in cultural planning. Therefore, to achieve the goals of sustainable development in arid and desert areas, it is inevitable to consider the cultural issues in addition to geotourism capabilities. The Lut desert has potential and actual values with outstanding natural features including yardangs with the highest yardangs landforms of the world, very high sand dunes and nebkhas, giant erosion gullies, hydrologic networks, tectonic holes, salt features, desert pavement, and historical of human settlements. The hot pole of the earth in the region makes it more outstanding so that in the years 2004, 2005, 2006, 2007, and 2009, it was the hottest point of the earth (Mildrexler et al. 2011). In 2005, with a temperature up to 70.73 °C, it recorded the hottest temperature of the earth surface. This can be interesting for many scientists.

There are many similar studies in the world about geotourism: Azman et al. (2010) in a review study considered the role of public education in conserving natural and cultural heritages in geoparks. They stated that to improve education programs in the geoparks, it involves the public participation of local communities and monitoring by the communities. Nemanja 2011) in a research in the assessment of geotourism potentials of Lazar's Canyon evaluated geotourism properties of the region by a questionnaire. The results of the study indicated that the region has high geotourism capability. Amorfini et al. (2015) investigated promotion of geologic heritages in the Apuan geopark in Alpes, Italy. The study introduced the most important solutions for the promotion of the geoparks. These solutions are environmental education through the press and websites, participation with universities and research institutes, and some conservation solutions for each geosite. Given the importance of geotourism and its role in tourism planning in the recent decades, many studies have been conducted to quantify the existing values in the geosites (Pralong 2005; Reynard et al. 2007; Periera et al. 2007; Coratza et al. 2008; Comanescu et al. 2012; Kubalikova 2013; Brilha 2016). Many studies have also been carried out in Persia by Iranian researchers about geotourism properties of geosites (Maghsoudi and Emadoldin 2007; Zandmoghadam 2009; Mokhtari 2010; Maghsoudi et al. 2011, 2014; Yamani et al. 2013), the role of geotourism in sustainable development (Amrikazemi 2010; Yazdi and Shafiee 2012; Ildermi et al. 2011; Lotfi et al. 2011), and cultural development of geotourism and sustainable development (Faghihi and Kazemi 2003; Nojavan et al. 2009; Divsalar 2013; Farsani 2014).

The Lut desert is one of the unique deserts of the world in terms of outstanding features. It is inscribed on the world heritage list based on the criteria vii to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance, and viii to be outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features. Landform evolution in Quaternary in this desert represents a particular history of geological and geomorphological changes. Given the high geotourism capabilities of the Lut desert as well as the richness of culture in the local communities, the purpose of this research is to assess the ability of the Lut desert for tourism development. Thus, we have emphasized on geosites and the zonation of optimal areas for the tourism development.

Study Area

The Lut desert, covering 51,800 km^2, is located in southeast part of Iran among three provinces of Kerman, Sistano Baluchestan, and Khorasan-e Jonubi (Fig. 1). The watershed of the Lut is 175,000 km^2. The Lut plain (Dasht-e-Lut), one of the largest and most arid deserts of the world, is an asymmetrical depression. In terms of topography, the Lut can be divided into three parts of northern Lut, southern Lut, and central Lut. The central Lut is an outstanding and extensive part of the desert. The southern boundary of the Lut is a line extended

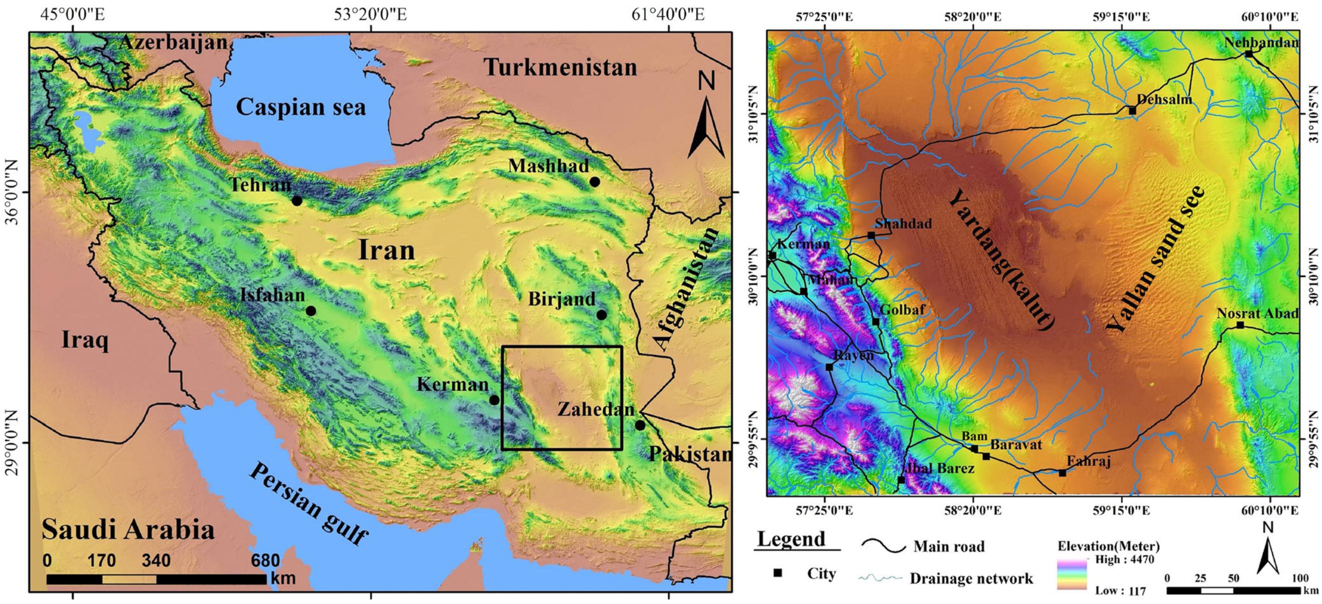

Fig. 1 Location of study area in Iran

from Keshit in the west to Gorg in the east. The southern part of the Lut, called Lut-e-Zangiahmad, is a vast plain in the south part of the Lut in Azar highlands from northern Bam and Bam-Zahedan road. The Lut desert has a variety of characteristics including arid weather conditions as one of the hottest points of the earth surface, a variety of geomorphologic conditions, and scarce vegetation. Based on weather data derived from the Meteorological Organization of Iran, average rainfall in the Lut is less than 50 mm per year and aridity index, according to UNEP definition, is less than 1. The surrounding highlands of the Lut plain represent a resistant mass on which the tectonic and structural factors could not have considerable effects, but only on the marginal sediments. Orogenic activities in the Lut are accompanied by thrust faults, overthrust fault, fracture, and frequent bending. All the structures led to the formation of the Lut depression between the two faults of Naiband in west and Nehbandan in the east (Motamed 1974). The Nehbandan fault in the east made colored mélange rocks along a narrow strip, as one of the oldest geologic formations of the area. Most of the rock extension is related to the third period as a large part of the region is covered by flysches (Taleghani 2009). In the foothills of the Lut desert, there exist some remnants of human settlements from the fourth millennia AD (Mostofi 1972).

Methods

The data used in this research have been gathered from different sources (Table 1). The research have been conducted in six steps: (1) the fundamentals of the subject have been examined by documents; (2) up to 58 geosites have been recognized in the Lut by field works and using aerial photos and satellite images; (3) the listed geosites have been assessed quantitatively by Brilha's (2016) method; (4) to make a zonation for development of suitable areas of geotourism, we have used Delphi method for weighting of criteria and sub-criteria; (5) the areas suitable for development of geotourism have been determined by fuzzy AHP; and (6) finally, the suitable sites for tourism development have been determined based on the results of geosite assessment,

Table 1 List of data

Data	Scale	Source
Geosites	1:50,000	Field survey with GPS
Topography (contour line, DEM, slope, view-shed)	1:50,000	National Geography Organization, Iran
Erosion and land cover map 2014	1:100,000	Organization of Forests, Pasture and Watershed Management, Iran
Road and river map	1:50,000	National Geography Organization (topographic maps), Iran
Cultural places	–	Cultural Heritage Organization, Iran
Population data 2012	–	National Statistical Office, Iran
Water sources (spring, qanat)	1:50,000	Iran Water Resources Management Company
Geology map	1:100,000	Geology Organization, Iran

zonation, and field control. In this research, we have used Expert Choice for AHP analyses and ArcGIS 10.2 for spatial analysis and modeling. Based on the results of geotourism assessment, zonation of suitable areas for geotourism development, and field control, eight regions have eventually been selected for development of sustainable tourism.

Brilha's (2016) Method

This method has been developed by Brilha (2016) to evaluate geological sites, by their scientific value, potential educational and touristic uses, and degradation risk. To make this quantitative evaluation, we have used 4 criteria for science, 12 criteria for education potential, 13 criteria for tourism potential, and 5 criteria for degradation risks (Table 2). Each of the criteria has several parameters (Brilha 2016). In each geosite based on the parameters of each criterion, the scores of 1, 2, and 4 are assigned to scientific value and the scores from 1 to 4 for other values. A parameter can receive zero value. In the values of science, education, tourism, and degradation risks, each of the criteria is assigned different weights based on their relative preferences (Table 2). In the science value, all the criteria and parameters are related to geologic characteristics of a geosite. A geosite can have education value as the diversity of geology elements is resistant enough to be used by students as well as the elements are easily visible to the students in all levels. In such conditions, the geosite has the highest potential educational use (PEU). A geosite can have tourism value as the geologic elements have remarkable spectacular aesthetic properties and can easily be understood by a person without geology background. The existence of proper facilities for visitors is necessary for the geosite. A geosite can have a high value of degradation risks, if its geological features are exposed to damage by nature or human activity, and if the geosites are not legally supported for protection as well as it is not located in the vicinity of active or vulnerable areas. It is noteworthy that the criteria of access and population density have been considered in tourism, education, and degradation risk assessments. In site evaluation, suitable access to the site is an advantage and a disadvantage and risk at the same time in terms of vulnerability (Brilha 2016).

In spite of many published methods about the numerical assessment of sites, so far, there is no general accepted method (Brilha 2016). Usually, quantitative methods are based on several criteria and respective indicators to which different scores or parameters may be assigned. The method presented by Brilha (2016) should be considered as an example that has resulted from a survey and compilation of the best practices and of the author's own experience. Each criterion is characterized by several indicators and each indicator is scored with a numerical parameter. More details about the evaluation process are available in Brilha (2016).

Table 2 Criteria and indices of quantitative evaluation of geosites (Brilha 2016)

Scientific value (SV)

Criteria	Representativeness	Key locality	Scientific knowledge	Integrity	Geological diversity	Rarity	Use limitations
Value	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4
Weight (%)	30	20	5	15	5	15	10

Potential educational use

Criteria	Didactic potential	Geological diversity
Value	1–4	1–4
Weight (%)	20	10

Potential educational and touristic value (shared between these two types of uses)

Criteria	Accessibility	Vulnerability	Use limitations	Safety	Logistics	Density of population	Association with other values	Scenery	Uniqueness	Observation conditions
Value	1–4	1–4	1–4	1–4	1–4	1–4	1–4	1–4	1–4	1–4
Weight (%)	10	10	5	10	5	5	5	E(5)-T(15)	E(5)-T(10)	E(10)-T(5)

Potential touristic

Criteria	Interpretative potential	Economic level	Proximity of recreational areas
value	1–4	1–4	1–4
Weight (%)	10	5	5

Degradation risk

Criteria	Deterioration of geological elements	Accessibility	Legal protection	Proximity to areas/activities with potential to cause degradation	Density of population	Classification of risk
value	1–4	1–4	1–4	1–4	1–4	
Weight (%)	35	15	20	20	10	Low (<200)–medium (201–300)–high (301–400)

Fuzzy AHP Method

After exploration and assessment of geosites, we require a clear planning for development of geotourism in the Lut desert. This involves integration of geographical and environmental aspects of this desert in decision-making process. Thus, we have employed fuzzy AHP method for the geotourism planning and controlled its results using field works.

As an integration of fuzzy set theory and AHP, this method has been widely used to solve the problem of multi-criteria decision-making (MCDM) (Lo and Wen 2010). The method overcomes the subjectivity of decision makers. This enables researchers to obtain accurate values and important factor weights (Bozbura and Beskese 2007). The fuzzy AHP method can also be used for site suitability evaluation for ecotourism (Bunruamkaew and Murayama 2011).

The fuzzy logic was introduced for the first time by Zadeh (1965). In the fuzzy set, zero means no membership of an element in the set and one means the element is completely a member of the set. The operators of AND, OR, Product, Sum, and Gamma are used in modeling (Zadeh 1965). AHP is also a mathematic method for multi-criteria decision-making for analyses of decisions. This method was developed by Saaty (1980) for analysis of complicated decisions with many developed criteria (Saaty 1980).

The fuzzy AHP method in this study was introduced by Chang (1996). The numbers in this method are fuzzy triangular values. The concepts of the fuzzy AHP can be explained by extent analysis. The general stages to implement the fuzzy AHP are as following: (1) hierarchy diagram; (2) definition of fuzzy numbers for pairwise comparison; (3) forming pairwise comparison matrix by fuzzy numbers as follows:

$$\begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \ldots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \ldots & 1 \end{bmatrix} \qquad \tilde{a}_{ij} = \begin{cases} 1 & i = j \\ \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}, \ or\ \tilde{1}^{-1}, \tilde{1}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}, & i \neq j \end{cases}; \tag{1}$$

(4) calculation of Si for each row of the pairwise comparison matrix as follows:

$$s_i = \sum_{i=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{i=1}^{m} M_{gi}^{j} \right]^{-1} \tag{2}$$

In the relation, i represents row number and j column number; M_{gi}^{j} is triangular fuzzy number of pairwise comparison matrix; (5) calculation of the magnitude of S_i values relative to each other, as shown in Fig. 2 :(6) calculation of the weights of criteria and options in pairwise comparison matrix, as follows:

$$d'(A_I) = \text{Min } V\,(s_i \geq S_k) \qquad k = 1, \ldots, n, \quad k \neq i \tag{3}$$

More details about the fuzzy AHP are available in Chang (1996). This study has also conducted a Delphi method based on fuzzy AHP questionnaire survey with 30 expert scholars specializing in the field ecotourism, geomorphology, and geotourism for weighting of criteria and sub-criteria. We have sent 30 provided questionnaires to the experts that 26 cases out of them are acceptable. In addition, for some cases requested for more information, we have conducted the face to face interview with experts based on provided questionnaires.

Results and Discussions

In the studies conducted in Iran, the geosites were inventoried based on available information with no systematic approach to making the list. However, we formed the inventory based on similar properties of formative processes of the landforms with the goal to introduce the geosites. As there are a variety of landforms and geologic formations, we initially introduce the geosites and then explain them in ten groups: nine main groups and one supplementary group.

Location and Properties of Geosites

The Lut desert is a graben in the southeast part of Iran. The Shur River flows all year. The streams originate from eastern and western mountains around the Lut and have created some extensive alluvial fans extended at the end from Yallan Sand Sea (Rig-e Yallan) in the east to Yardangs in the west. Most parts of the Lut is covered by yardangs, sand dunes, and hamadas (Fig. 3). The area of the geomorphologic features of the Lut is represented in Table 3. Some of the geosites in the regions are including Rig-e-Yallan (Yallan Sand Sea), mega-yardangs (kaluts), small yardangs, hamada, Shur River, badlands (miniature mountains), salt polygons, volcanoes and volcanic features like basalt plateau of Gandom Beryan, dreamy city of the Lut (Shahr-e Khialy-ye Lut), and other erosion morphologies (Fig. 4; Table 4). There are some other phenomena like the desert sky as supplementary values to the sites.

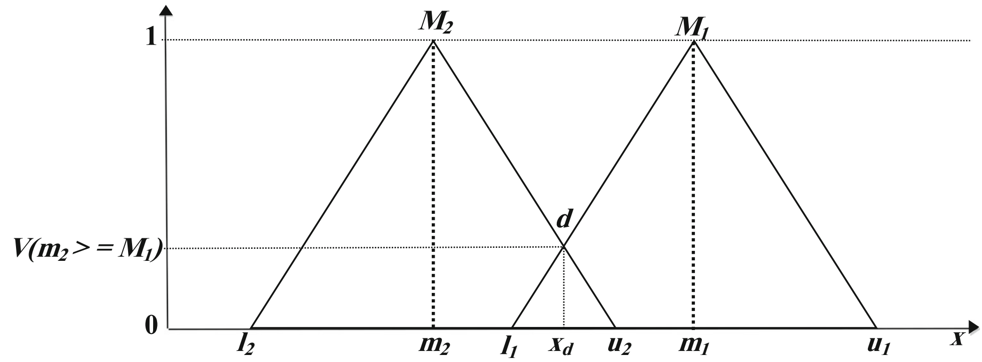

Fig. 2 Magnitude of two fuzzy numbers relative to each other (Chang 1996)

Yallan Sand Sea (Rig-e Yallan)

The Yallan Sand Sea (Rig-e Yallan), more than 10,000 km^2 in area, extends in a rectangular shape with north-south alignment in the east part of the Lut desert (Taleghani 2009). It has a distance of 150 km from north to south and a distance of 70 km from east to west. From west, the erg is limited to the Lut depression; from the north, it is limited to Deh Salm, from east to Nosratabad, and from south and southwest to Lut-e Zangiahmad. The sand dunes of the area are basically transverse dunes with asymmetric linear dunes (Fig. 5a). Most of the accumulation forms like barchans can be observed in east part of the rig, mega-ripple marks and longitudinal dunes in the southwest part, transverse dunes in the east parts, and pyramids and funnel shape dunes in central areas. In some texts, it is mentioned that these dunes are 475 m high with three to five diverging strips (Mahmoudi 1988). In some other deserts of the world, e.g., Badin Jaran Desert, these dunes are up to 500 m high; it seems as the highest in the globe (Walker 1996). Therefore, it can be said that the sand dunes in the Lut similar to those in China are the largest on the earth. In the southern part of the Yallan Sand Sea (Rig-e Yallan), the dunes have a shift in direction and are joined to the west yardangs of the Lut.

It is noteworthy that the accumulation forms of sands in the Yallan Sand Sea (Rig-e Yallan) are also developed in other parts of Lut. Some of these are barchans in west of the Lut near the Pashuiyeh Village, mega-ripples in the corridors of the yardang and southwest of Yallan Sand Sea, longitudinal dunes in north of hamada, and pyramids sand dunes in small ergs in the east part of yardangs. Many of the features are outstanding and unique in the world.

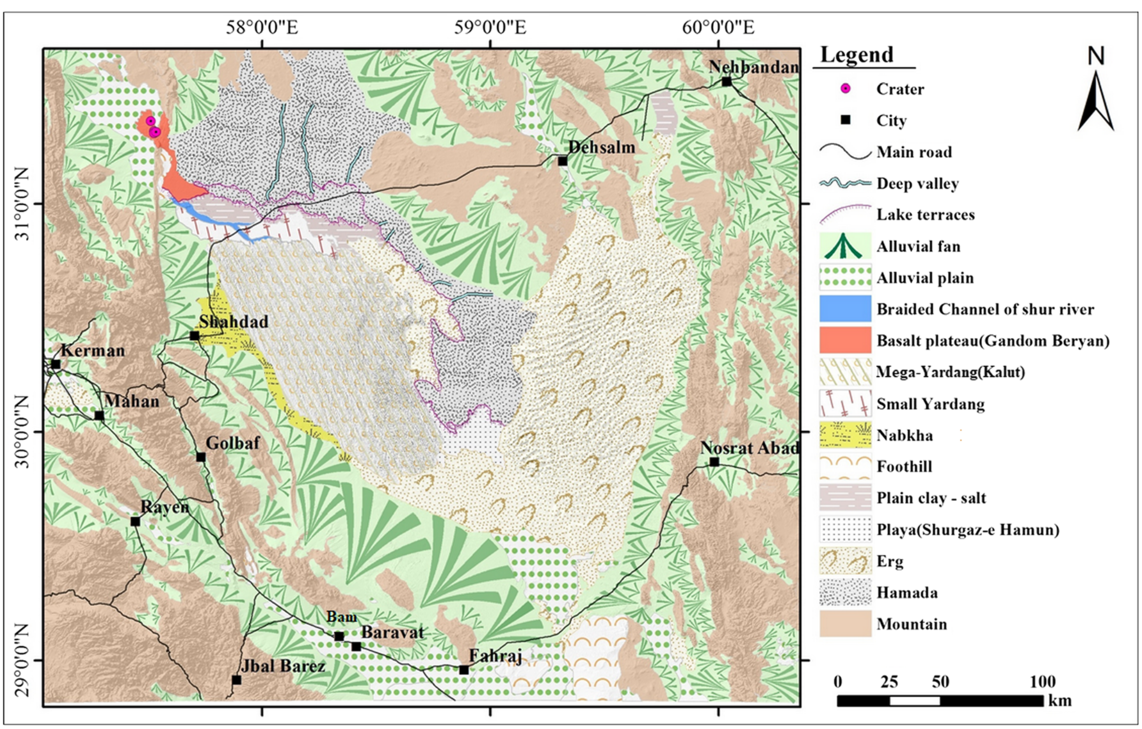

Fig. 3 Geomorphology of the study area

Table 3 Area of the geomorphologic features in Lut desert

Landform	Area (km^2)	Area (%)
Alluvial fan	33,435/41	32/51
Alluvial plain	5432/35	5/28
Braided channel of Shur River	116/19	0/11
Gandom Beryan	358/93	0/35
Hamada	7761/5	7/55
Mega-yardang (kalut)	6619/33	6/44
Small yardang	566/06	0/55
Foothill	1289/28	1/25
Mountain	32,521/53	31/62
Nebkha	817/06	0/79
Plain clay-salt	808/7	0/79
Playa	505/39	0/49
Erg	12,612/63	12/27

Mega-yardangs and Small Yardangs

Wind erosion morphologies are greatly observed in arid and semi-arid areas of the world including Iran, the USA, Egypt, and Peru (Ahmadi 1998; Gudie 2007). The unique outstanding samples of the features are greatly extended as parallel corridors and ridges (Fig. 5b) in southeast Iran in 150 × 170-km dimensions (Ahmadi 1998). These yardangs were mainly formed by late Pleistocene and early Quaternary (Krinesli 2009). The morphologies are configured along the direction of the 120-day winds of Sistan in a real 333° (Krinesli 2009). The highest yardangs of the world with a height of 155 m and the longest of them are formed in the Lut desert. The yardangs are covered by a clay-gypsum layer that prevents the galleys to develop on the steep slopes of the morphologies (Mahmoudi 1988). The clay layer represents the past humid conditions and it is also typical of inactivity of erosion processes on the kalut surfaces (Taleghani 2009).

The yardangs are disappeared next to the salt river of Birjand and are replaced by some small directional forms called kalutak (small yardang) in Persia (Mostofi 1969). This is also the most extensive small yardang plain of Iran. There are also some unique spectacular small yardang (Fig. 5c) in the conjunction of the mega-yardangs and Shur River.

Given that the extent of the small yardangs and their shapes are different from the mega-yardangs and that they are located in great distances from each other (Fig. 1) with aesthetic differences (Fig. 5), we have made separate investigations of them.

Nebkhas and Shadow Dunes

There are many shrubs and tamarisk trees in desert vases as nebkhas surrounded by sandy lands. The nebkhas are usually growing on the even surfaces with high ground water level or

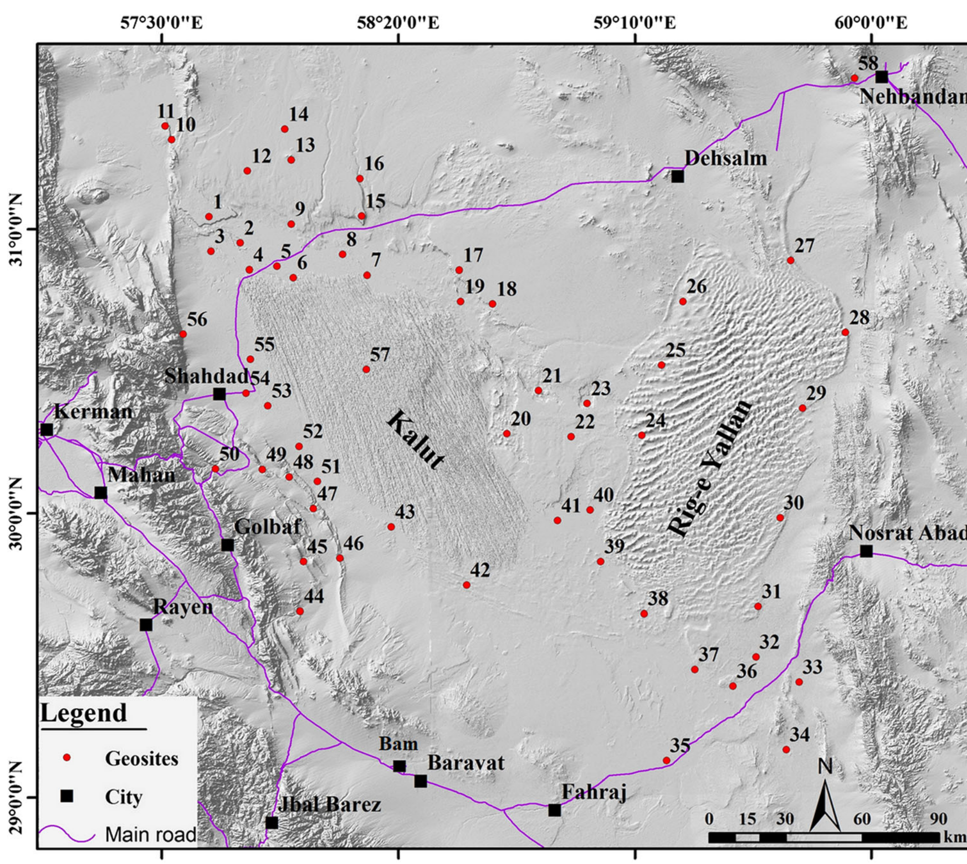

Fig. 4 Location of the geosites in the study

Table 4 Properties of the geosites in the study

Number	Geosite	No. of geosite on map	Number	Geosite	No. of geosite on map
1	Gandom Beryan	1	14	Blank parallel strips	24
2	Small yardang	3, 4, 5, 7, 8	15	Low long dunes	19, 38, 36
3	Shur River	2	16	Parabolic dunes	28, 30
4	Salt crystals and salt rims	6	17	Barchans	29, 31,51, 52
5	Lake terraces	9	18	Nebkha and shadow dunes	34, 35, 43, 53, 54, 55
6	Crater	10, 11	19	Salt polygons	40
7	Hamada	12, 22	20	Mega-yardangs (kaluts)	57
8	Inselberg	13, 14	21	Playa (Shurgaz Hamun)	41
9	Dreamy city of the Lut	15	22	Shurgaz River	33
10	Deep valleys	16, 17, 18, 45, 47, 48, 49	23	Hurmak valley	44
11	Long strips (parallel and crescent)	25, 26, 27, 42	24	Pinnacles	46
12	Playa (Malek Mohammad)	23	25	Badlands (miniature mountains)	50, 56, 58
13	Star dunes	20, 21, 39	26	Mega-ripple mark	32, 37

enough moisture to supply the vegetation cover. The nebkhas are formed by sand, loam, clay, and silt around the shrubs of aphyllouom, Agropyron, and tamarisk (Khosravi 1993). The nebkhas sometimes, 20 m high, are growing in the vicinity of one of the hottest place in the world, Shahdad. The highest and largest nebkhas, more than 10 m high, are located in west part of the Lut (Fig. 5d) (Maghsoudi et al. 2012). The nebkhas are also present in the southwest margin of Yallan Sand Sea (Rig-

Fig. 5 Some of the geosites in the Lut: **a** Yallan Sand Sea (Rig-e Yallan), **b** mega-yardangs (kaluts), **c** small yardang, **d** nebkhas, **e** dreamy city of the Lut (Shahr-e Khialy-ye Lut), and **f** badlands (miniature mountains) of Nehbandan

e Yallan). The shadow dunes as the simplest accumulation forms are about 4 m long (Maghsoudi et al. 2014). The shadow dunes can be observed in different areas of the Lut desert.

Dreamy City of the Lut

The dreamy city of the Lut (Shahr-e Khialy-ye Lut) is one of the manifestations of the Lut desert. It is formed by water and wind erosion through the land surface. During a long time of erosion, the land is sculptured and polished like glossy walls of a destroyed city. These desert features resemble remnants of an abandoned city (Fig. 5e).

Badlands (Miniature Mountains)

In the marginal parts of Nehbandan-Kerman road about 6 km from the city, there are spectacular hills of aesthetic value. These mountains are composed of sediments and without vegetation cover. Some of the small mountains are just 5 m high and make a beautiful scene with cones (Fig. 5f). They are mainly composed of marl and clay deposits created by water erosion and badland development. Some badlands in the west part of the Lut are also created in the same conditions.

Hamada (Desert Pavement)

The geomorphologic conditions of the central part of the Lut are developed as a pebble and sand plain. The severe hot daily temperature decomposes rock outcrops in mountains and left clashed deposits on the plain (Fig. 6a). The fine grains of the deposits are removed by the wind from the plain surface. As a result, the plain surface is covered by pebble and coarse-grained sediments. This hamada plain in the central part of the Lut has a reverse triangular shape that its head is in the south towards Shurgaz Hamun playa (Taleghani 2009). In other parts of Lut, the desert pavement is created where the conditions made it possible.

Fluvial Geosites

The presence of the Shur River in the Lut increased the singularity of the region (Fig. 6b). The river originates from the Khusf and Khorasan-e Jonubi Mountains outside the study area and flows into the area from the northern parts. Along the flow path, the tributaries, 2000 km long, from Ravar Mountains passed the west margin of Gandom Beryan into salt depression. The watershed of the river is 73,760 km^2 in area. Heavy rainfall and severe floods eroded the lands and made deep valleys called alley (Koucheh) by local people. Other tourism attractions in the fluvial features are temporary flows around the Lut, deep valleys amid the Lut formed by water and wind erosion, and gypsum and salt crystals of the river (Fig. 6c).

Playa and Saltland Geosites

Some playas of the Lut are filled with water in winter and losses the water in dry season. Some other playas are always dry without water. These playas can be observed in the end part of the Shur River and Shurgaz Hamun. There are huge areas of saltlands in the Lut, particularly in its south and west parts. Many salt rims and blisters and beautiful salt polygons are formed as a result of evaporation (Kardavani 2007). These

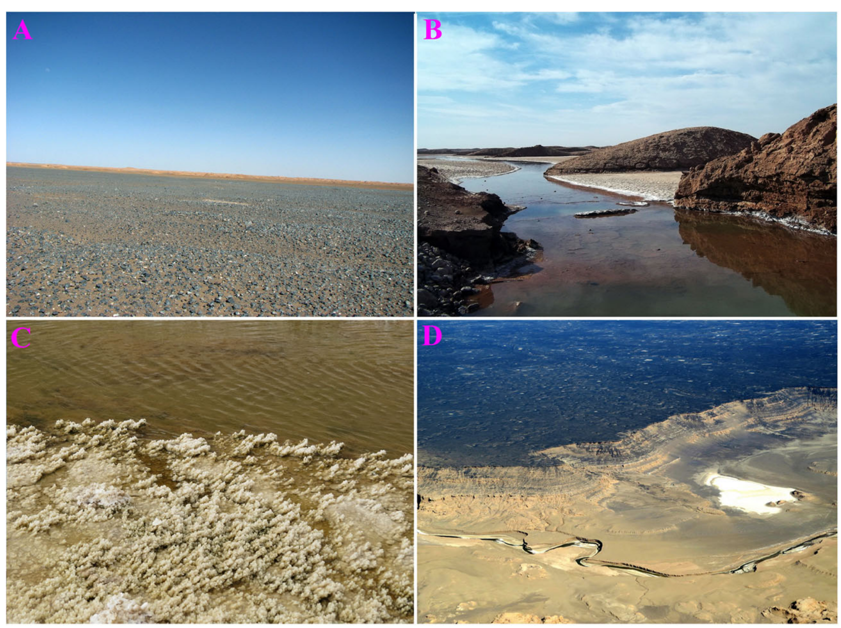

Fig. 6 Some of the geosites of the Lut: **a** hamada, **b** Shur River, **c** salt crystals, and **d** basalt plateau of Gandom Beryan and Shur River

Table 5 Final results of quantitative evaluation of geosites based on Brilha method

Geosites	Geosite number	Scientific value	Educational and/or touristic value	Degradation risk	Classification of degradation risk	Rank
Mega-yardangs (kaluts)	57	360	310	165	Low	1
Shur River	2	355	290	165	Low	2
Blank parallel strips	24	285	280	225	Moderate	3
Gandom Beryan	1	280	265	110	Low	4
Dreamy city of the Lut	15	270	260	220	Moderate	5
Hurmak valley	44	260	265	230	Moderate	6
Badlands (miniature mountains)	58	265	250	165	Low	7
Small yardang	4	260	250	130	Low	8
Nebkhas and shadow dunes	54	255	240	220	Moderate	9
Small yardang	5	250	240	210	Moderate	10
Bird-like barchans	29	245	235	235	Moderate	11
Long strips (parallel and crescent)	42	235	235	120	Low	12
Small yardang	7	255	210	170	Low	13
Badlands (miniature mountains)	56	225	240	215	Moderate	14
Barchans	51	235	225	225	Moderate	15
Small yardang	8	220	230	220	Moderate	16
Star dunes	39	270	180	135	Low	17
Lake terraces	9	260	190	165	Low	18
Pinnacles	46	230	220	255	Moderate	19
Badlands (miniature mountains)	50	215	225	185	Low	20
Nebkha and shadow dunes	55	210	225	210	Moderate	21
Nebkha and shadow dunes	53	205	225	225	Moderate	22
Barchans	31	200	230	185	Low	23
Hamada	12	185	240	160	Low	24
Nebkha and shadow dunes	34	195	230	215	Moderate	25
Nebkha and shadow dunes	43	205	220	175	Low	26
Mega-ripple mark	37	185	235	210	Moderate	27
Barchans	52	215	210	195	Moderate	28
Star dunes	21	260	160	130	Low	29
Star dunes	20	245	175	170	Low	30
Parabolic dunes	30	235	180	120	Low	31
Crater	10	245	170	150	Low	32
Deep valleys	47	210	205	180	Low	33
Deep valleys	45	195	220	200	Moderate	34
Deep valleys	48	210	200	175	Low	35
Salt crystals and salt rims	6	200	200	220	Moderate	36
Mega-ripple mark	32	190	215	230	Moderate	37
Small yardang	3	265	130	185	Low	38
Nebkha and shadow dunes	35	185	205	190	Low	39
Crater	11	230	155	125	Low	40
Parabolic dunes	28	245	140	135	Low	41
Playa (Shurgaz Hamun)	41	220	165	130	Low	42
Long strips (parallel and crescent)	27	215	160	130	Low	43
Low long dunes	36	185	185	215	Moderate	44
Long strips (parallel and crescent)	26	220	150	155	Low	45
Deep valleys	49	180	180	130	Low	46
Deep valleys	16	185	170	115	Low	47
Long strips (parallel and crescent)	25	210	135	135	Low	48

Table 5 (continued)

Geosites	Geosite number	Scientific value	Educational and/or touristic value	Degradation risk	Classification of degradation risk	Rank
Salt polygons	40	185	150	215	Moderate	49
Shurgaz River	33	185	150	240	Moderate	50
Playa (Malek Mohammad)	23	180	140	130	Low	51
Hamada	22	160	155	125	Low	52
Low long dunes	19	165	145	155	Low	53
Deep valleys	17	165	130	80	Low	54
Low long dunes	38	145	125	170	Low	55
Deep valleys	18	150	115	80	Low	56
Inselberg	14	130	110	115	Low	57
Inselberg	13	145	90	105	Low	58

features can mainly be observed in Shurgaz Hamun region, the end part of Shur River.

Volcanic Geosites

There are about 40 Quaternary volcanic cones in the desert. The cones are dwarf circular peaks or volcanic craters (Motamed 1974). The flow of volcanic lavas makes some cones and basalt plateau in the area. One of the most outstanding surfaces resulted from the volcanic activity is basalt plateau of Gandom Beryan region (Fig. 6d). The Gandom Beryan surface is 48 km long, 10 km wide, and 480 km^2 in area (Maheri 2000).

Other Geosites and Supplementary Values

There are many other geosites in the study area that could be considered as geotourism attractions:

- Some of the geosites include ventifact s and polished rocks, which can be seen in almost all of the area, but mainly in the west of the Lut and central hamada.
- Salt rims and blisters are around Shur River as spectacular features.
- Inselbergs are observed in central hamada. Old and recent alluvial fans are developed around the Lut on the marginal plains. Human life flourished on the surface of these fans and the end of the alluvial fans is the end of human communities' contact with the desert (Negaresh 1990).
- There are pinnacles in the vicinity of Keshit village.
- Deflation hollows are frequently observed in the Rig-e Yallan region.
- The sky of the Lut has supplementary value for the area. As the desert sky is completely devoid of urban lights and cloud, it can be helpful for visiting the celestial bodies and stars, and it may be a good place to establish observatory stations.

Evaluation of the Geosites Based on Brilha Method

After the geosites have been identified and listed, the required information is gathered and evaluated by Brilha method (Brilha 2016). The results of the criteria of scientific, educational, and/or touristic value, and degradation risks are presented in Table 5.

Subsequently, the ranking has been made based on total scores so that the scores of each geosite in scientific, education, and/or tourism criteria have been added together to obtain the rank of each geosite. It is noteworthy that one geosite may have high scientific value but it may have low tourism value due to the absence of infrastructure, hard access, etc.

The quantitative evaluation of the geosites based on Brilha method indicates that in the scientific criterion, the mega-yardangs have got the highest score as the first. The high score of mega-yardangs in scientific criterion results from a proper exhibition of the geologic processes in this area; use of the geosite in international science, with important studies in high-ranking journals (e.g., Goudie 2007; Ehsani and Quiel 2008; Goudie 2013); diversity of the geologic features; and conservation of the geologic features. The geosite is unique in international level and there is no limitation for field work and sampling. The geosites of Shur River (score 355), blank parallel strips in Yallan Sand Sea (score 285), Gandom Beryan (score 280), and the Dreamy City of the Lut (Shahr-e Khialy-ye Lut) (score 270) are in the following ranks in terms of scientific criterion. The geosites of deep valleys and inselbergs with 150 and 145 are in the final ranks in scientific values (Table 5). In terms of educational and/or touristic value, the geosite of mega-yardang has the first rank with 310 scores. This may be due to low vulnerability, the suitable access to the geosite, no limitation for use of the visitors, use as a tourism destination, the presence of other geosites in the proximity of the geosite, proper visibility, good display of geologic features, and educational potential

Table 6 Criteria and sub-criteria effective in geotourism development and final weights in the hierarchy analysis

Factors	Criteria	Unit	Suitability rating				Final weight
			Suitable	Moderate	Marginal	Not suitable	
Landscape/naturalness	Visibility	Value range	Near	Middle	Far	Not visible	0.046
	Land use/cover	Class	High	Moderate	Marginal	Not	0.102
Topography	Elevation	Meter	900–2100	2100–3500	>3500	57–900	0.024
	Slope	Degree	0–5	5–25	25–35	>35	0.096
Accessibility	Proximity to cultural sites	Kilometer	0–20	20–40	40–60	>60	0.135
	Distance from roads	Kilometer	0–5	5–15	15–25	>25	0.166
Water resources	Distance from rivers (permanent and seasonal)	Kilometer	0–5	5–15	15–25	>25	0.129
	Proximity to qanat and spring	Kilometer	0–2	2–4	4–8	>8	0.198
Geology	Erosion	Class	Not/low	Moderate	Marginal	Much	0.38
	Proximity to geosites	Kilometer	0–3	3–6	6–10	>10	0.154

of the site for all education levels. The geosites of Shur River and blank parallel strips with scores of 290 and 280, respectively, are in the following ranks. The inselbergs, number 14, and deep valleys and inselbergs, number 13, have final ranks with the scores of 115, 110, and 90, respectively (Table 5). The evaluation of degradation risks indicated that there are 20 geosites in average degradation risk and 38 geosites with low degradation risks (Table 5).

Suitable Areas for Geotourism Development

Prioritization of resources and attractions of the region enable the accurate decision-making for geotourism development. This research has attempted to identify the principal and effective factors and determine the most suitable areas for geotourism development using fuzzy AHP model. Studying the authenticated literature,

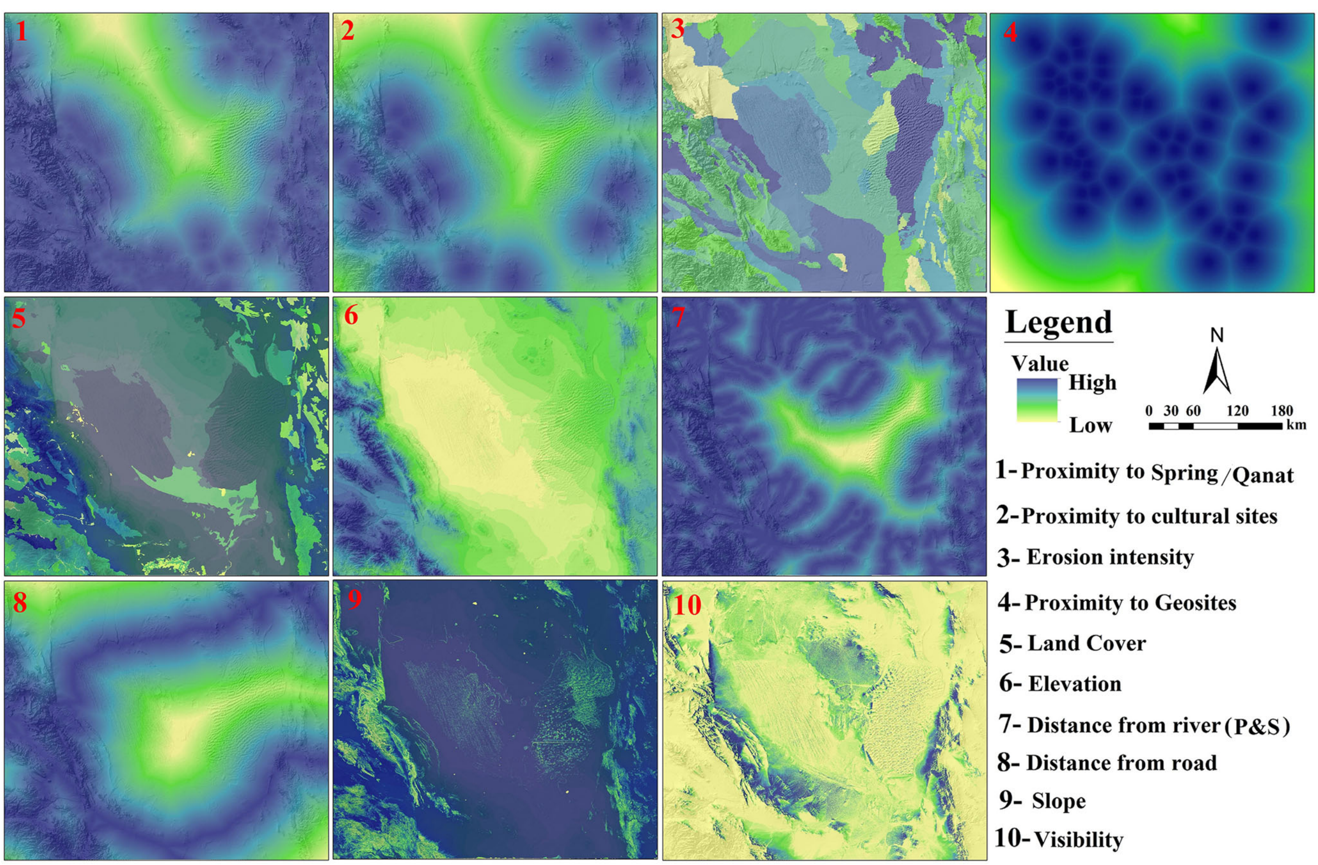

Fig. 7 Maps of the criteria for analysis of suitable areas for geotourism development

exploring present conditions of the environment, and interviews with experts of geomorphology, ecotourism, and geotourism, we have determined five criteria and ten sub-criteria effective on the geotourism (Table 6). Subsequently, the GIS map of each sub-criteria has been determined and fuzzified (Fig. 7). The data of the maps have been classified into four classes of FAO for further assessment (Sadasivuni et al. 2009; Tienwong 2008). The four classes are very suitable (0.8–1), relatively suitable (0.4–0.8), nearly suitable (0.2–0.4), and non-suitable (0–0.2). The criteria have been weighted based on their preferences by fuzzy AHP. These weights have been introduced to expert choice to get the final weights (Table 5). According to Saaty (1980), the consistency ratio index of the weights must be less than 0.1. In this study, the consistency index is 0.06 based on Eq. 4. Finally, the relative weights of each criterion in each fuzzy layer have been included in ARC GIS10.2 and the final execution of fuzzy model has been conducted by gamma 0.9.

$$CR = \frac{CI}{RI} \quad (4)$$

where CR is the consistency ratio, CI is the consistency index, and RI is the consistency index of a randomly generated comparison matrix.

The results of zonation for suitable areas to develop geotourism in the Lut desert (Fig. 8), the areas in the west, northeast, and southeast have more suitable conditions. In this figure, the more colored areas (in blue) represent the areas more suitable for geotourism development. The region is ranged from more suitable areas (blue) to less suitable (yellow). According to the results, the areas near Shahdad, Dehsalm, Nehbandan, and Nosratabad are the most suitable path to visit the region. The suitable areas are also with 5 km of roads, 20 km of cities and villages, and 2 km of springs and qanats, and also 2 km of rivers and temporary streams. In the contrary, the unsuitable areas are located long distances from water resources and residential areas and inappropriate landscapes. Therefore, the areas of all layers according to the score they received are included in the range from suitable to unsuitable.

Visiting Sites and Paths

The possibility of easy access to the geosites is one of the important advantages for geotourism development in desert areas. However, not all the infrastructures are available in the Lut to exploit all its advantages for educational, tourism, and scientific purposes. Hence, with the results obtained from the zonation of geotourism

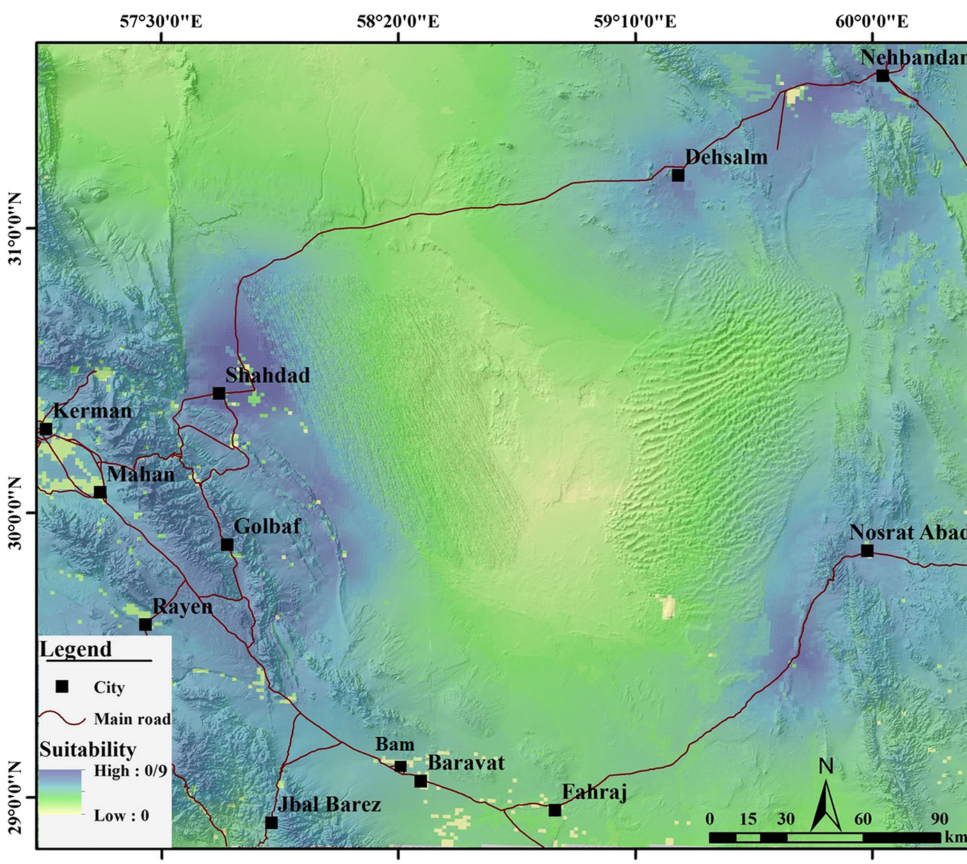

Fig. 8 The map of suitable areas for geotourism development in the Lut

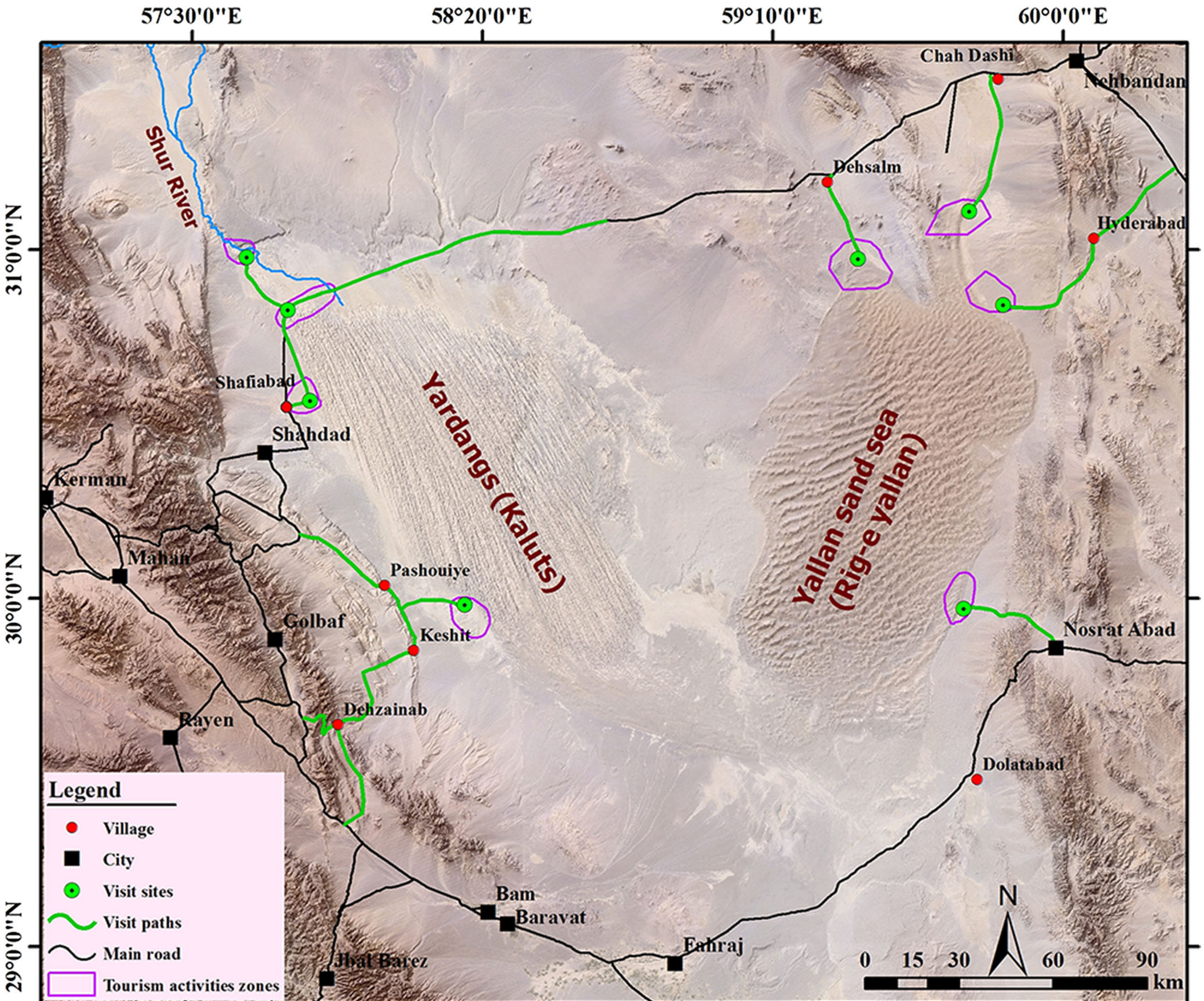

Fig. 9 The optimal areas and sites for geotourism development in the Lut

development areas, quantitative evaluation of the geosites, and field survey, we have determined eight regions and access paths to them that have optimized conditions for the development of stable tourism (Fig. 9). These regions and paths are as follows:

1- Nehbandan-Martian mountain or badlands–Chah Dashi–Dehsalm–Yallan Sand Sea (Rig-e Yallan)
2- Nehbandan–badlands (miniature mountains)–Chah Dashi–Yallan Sand Sea (Rig-e Yallan)
3- Nehbandan–Heydarabad–alluvial fans–Yallan Sand Sea (Rig-e Yallan)
4- Zahedan–Nosratabad–alluvial fans–Yallan Sand Sea (Rig-e Yallan)
5- Bam–Dehzeynab–Hormak Valley–Keshit–(Kerman–Mahan–Keshit)–the Lut desert (mega-yardangs, barchans, nebkhas)
6- Kerman–Mahan–Shahdad–yardang–small yardang (kalutak)
7- Kerman–Mahan–Shahdad–Shafiabad–nebkhas–Shur River
8- Kerman–Mahan–Shahdad–Shafiabad–nebkhas–Shur River–small yardang–Gandom Beryan

Conclusion

This research is a comprehensive approach to geotourism development through identification and evaluation of geosites. A collection of key parameters has been considered by reviewing expert information and previous researches for geotourism potential assessment. The distance to geosites has been considered as a novel criterion in the assessment of suitable areas for geotourism development. The main problem in decision-making theory is the way of assigning weights to the preferences and the complexity in giving priority values to the criteria (Tewodros 2010). Therefore, in this study, we have combined the two approaches to quantitative evaluation of geosites and multi-criteria decision-making by GIS technology to determine the suitable areas for geotourism development. As there are many effective criteria in the quantitative assessment of the geosites, it is possible to cover the weaknesses of decision-making criteria in geotourism studies. This combination along with field survey and control is a comprehensive novel approach to finding suitable paths, sites, and the areas for the purpose. This approach can also be used for assessment of geotourism capability. It can also be helpful for decision support systems and sustainable geotourism planning in the future. The results of evaluation of the geosites in the Lut indicated that the geosites of mega-yardangs, Shur River, Yallan Sand Sea, badlands of west Nehbandan, Gandom Beryan, and the dreamy city of the Lut (Shahr-e Khialy-ye Lut) have received the highest scores for geotourism development. It is noteworthy that other geosites with high scores by Brilha method are in the next ranks. Therefore, the Lut desert, with unique geosites, has the capability to develop geotourism. Furthermore, some supplementary attractions such as beautiful desert sky have increased the tourism potential of the Lut desert. Suitable areas for geotourism development have been determined based on fuzzy AHP for better management and planning. The results have indicated that west part of the Lut and northeast and southeast parts have more suitable conditions for geotourism development. Through zonation of geotourism suitable areas and field survey and control, eight suitable access paths have been specified for geotourism development and sustainable tourism. It can be suggested to establish required tourism facilities and services in the areas as well as provide tableau to introduce these features to visitors for guidance and education purposes.

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