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ORIGINAL ARTICLE

Evaluating Boolean, AHP and WLC methods for the selection of waste landfill sites using GIS and satellite images

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Abstract The city of Saqqez has a population of 140,000 people, making it one of the largest cities in Iran. Population growth, consumerism, and change in eating habits, such as the increased use of packaged products, is causing the accumulation of waste in this city to increase. In this study, the selection of a waste landfill site for Saqqez focused on 13 layers of geography information that was used by the IDRISI and Arc GIS software. Different models of the analytic multi-criteria decision-making process, such as an analytical hierarchy process (AHP), weighted linear combination (WLC), and Boolean logic, were used to manage layers to establish specific databases for urban waste landfills. Satellite images (Landsat ETM^{+} and SPOT 5), proposed sites and a land use map of the study area were also used. The results of this study indicated that two methods (AHP and WLC) in the early stages had better decision-making powers for locating landfill sites when compared to Boolean logic. Overlapping and compounding the similarities between these models in Arc GIS software, a 74-ha site was found. This site will be able to accept 130 tons of waste per day for the next 20 years.

Keywords Waste landfill · GIS models · Satellite images · Municipal solid waste · Saqqez City

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Introduction

Cities are combinations of complex phenomena, whose components are closely connected to each other in an organized way so that a problem with a single element may cause deficiencies in the whole system. Humans influence their environment and are affected by its consequences, indicating a strongly reciprocal relationship between humans and the environment (Ruhl 1997).

Over the years, the management of municipal solid waste (MSW) has been improved through the installation of various schemes, the development of new treatment technologies and the implementation of economic instruments (Reinhart and Basel Al-Yousfi 1996). Despite such progress, solid waste problems still impose increasing pressures on cities and remain a major challenge for urban environmental management. Locating and finding a proper place for waste landfills is an important part of urban solid waste management systems (Belevi and Baccini 1989). Different criteria and factors are involved in selecting a proper site for a healthy urban solid waste landfill. The components of MSW management include reducing waste, re-using, recycling, energy recovery, incineration and landfilling (Noori et al. 2008). Even if a combination of the actions mentioned above or other management techniques are utilized and if policies of waste reduction and reuse are applied, the existence of a sanitary landfill is necessary for any MSW management system (Tchobanoglous 2009).

GIS can recognize, correlate and analyze the spatial relationships between mapped phenomena, thereby enabling policy makers to link disparate sources of information, perform sophisticated analysis, visualize trends, project outcomes and create long-term planning goals (Malczewski 2004; Sharifi et al. 2009). On the other hand, ground monitoring schemes require intensive efforts and costs, and are sometimes difficult to achieve for large areas. GIS supported by remote sensing technology has been introduced to waste landfill management to monitor the effects of landfill sites on the environment. The potential advantage of a GIS-based approach and remote sensing techniques arises from the fact that they not only reduce the time and cost of site selection, but they also provide a digital data bank for the long-term monitoring of a site (Thoso 2007; Ottavianelli et al. 2005). Many studies have demonstrated the effectiveness of applying visual interpretation techniques to airborne data.

Other advantages of applying GIS and remote sensing techniques in the landfill siting process may include the following:

- Selection of an objective exclusion zone according to a set of provided screening criteria and comparing different factors and selecting the best site for a waste landfill.
- Zoning and buffering.
- Performing 'what if' data analysis and investigating different potential scenarios related to population growth and area development, as well as checking the importance of various influencing factors.
- Handling and correlating large amounts of complex geographical data.
- Visualization of the results through graphical representation (Sumathi et al. 2008).

With regards to waste management, site selection studies reported in the literature cover the allocation of urban solid waste landfills (Lane and McDonald 1983; Chang and Wang 1995; Lober 1995; Siddiqui et al. 1996; Kao et al. 1996; Leao et al. 2001; Kontos et al. 2005; Al-Jarrah and Abu-Qdais 2006; Yonezawa 2009) and hazardous solid waste centers (Canter 1991; Koo et al. 1991).

Garofalo and Wobber (1974) suggested using aerial photographs for solid waste management and planning. Philipson et al. (1988) tested the suitability of SPOT satellite images for monitoring land cover changes that could impact the investigation of landfills. Barnaba et al. (1991) described a procedure for performing comprehensive inventories of waste disposal sites over areas in Suffolk County (New York, United States) based on historical aerial photographs. Brivio et al. (1993) applied the spatial autocorrelation method to Landsat TM data and concluded that it was an effective tool for producing an inventory and assessment of waste disposal sites. Siddiqui et al. (1996) presented an analytic hierarchy method to locate sites for waste disposal by GIS. In their study, they investigated four scales of proximity, which were in proximity to town, kind of land usage, soil limitations (includes slope, tissue, permeability, and depth of the bedrock) and the depth of ground water, to select a site selection in Cleveland, Oklahoma, and measure weight using a binary comparison method.

Shrivastava and Nathawat (2003), in their research in the town of Ransi, selected five sites of different sizes to contain the waste of this medium-sized town. They used geographic information systems and remote sensing techniques, acknowledged environmental preconditions, such as geology, faults, slopes, type of base rock, soil, surface waters and the depth of ground water, urban centers, current communication networks, distance from airports and the use of these systems by weighting indices.

Kamran (2008) used three methods, Boolean, Index Overlay and Fuzzy Logic, for data integration in a hazardous material disposal center located in eastern Azarbaijan, Iran. In this study, binary maps and Boolean operators were utilized to identify areas for landfill center construction; 71 % of Tabriz County fell in this area. Factor maps were integrated using index overlay methods and fuzzy operators to determine suitable locations for building a disposal center in the remaining area. The results showed that 0.12 and 0.17 % of the study area was selected as suitable by index overlay and the fuzzy logic model, respectively.

Moeinaddini et al. (2010) delineated MSW in Karaj by using weighted linear combination (WLC) method and spatial cluster analysis (SCA) in a GIS environment. In their study, they utilized an analytical hierarchy process (AHP) method to select the best site for a waste landfill in Karaj. Their result showed that 6 % of the study area was suitable for building a landfill.

Donevska et al. (2011) used two methods of fuzzy logic, AHP and GIS, to select a site for a hazardous landfill in the Polog Region of Macedonia. A fuzzy set theory was used to standardize criteria using different fuzzy membership functions while AHP was used to establish the relative importance of the criteria. Their results showed that the least suitable area for a landfill covered 1.0 % of the total area, when environmental and economic objectives were valued equally. The most suitable area for a landfill was 1.8 % of the area when economic objectives were given a higher value.

Gorsevski et al. (2011) presented a GIS-based multicriteria decision analysis approach for evaluating the suitability of an area for a landfill site in the Polog Region of Macedonia. Fuzzy membership functions used for standardizing multi-criteria decision frameworks considered environmental and economic factors. AHP was used to assign attribute weights, while the OWA operator function was used to generate a wide range of decision alternatives for addressing uncertainty associated with interactions between multiple criteria. The results from this study demonstrated that the aim of the approach was not to find a single "optimal" solution, but to show other strengths associated with the weighting flexibility of the OWA approach.

The literature suggests that countries around the world have successfully applied GIS and remote sensing to their urban waste management planning processes. In addition, the utilization of sophisticated GIS methods is an innovation in the landfill siting process, giving some efforts in the analysis of the results, showing that the tools provided by GIS and spatial statistics are very important.

The main difference between previous studies and the present study is there has been no comprehensive study to date involving the application and evaluation of various spatial models with the aid of GIS and satellite data in the city of Saqqez. Therefore, there is a significant demand for landfill siting generated by Boolean, AHP and WLC models in Saqqez with a high decision-making power for locating landfill sites.

The aim of this paper was to demonstrate the use of GIS models and remote sensing techniques to identify areas which were suitable for reasonable, convenient, and administratively transparent waste landfills in Saqqez using Boolean, AHP and WLC in a GIS environment. This evaluation involves three main steps. The first step involves identification of categories of the causative factors responsible for identifying possible landfill locations based on geographical information systems and satellite images. The second step estimates the relative contribution of these categories in establishing a relation between the categories and the selected sites. Finally, the significant or the most influential sites were determined for assessment of the best GIS model for this particular study.

Materials and methods

Study area

Saqqez is located between 46°13′ and 46°16′ east longitude and 36°11′ and 36°15′ north latitude in the northwest part of the Iranian Province of Kurdistan. It covers approximately 1,474.8 ha (Fig. 1). The 2006 census reported that the city's population was 135,037; however, its current population is about 145,000 (Iranian Statistics Center 2006). The vegetated area in the city covers about 118 ha and buildings cover 618.26 ha. The average elevation is 1,496 m above mean sea level. Saqqez is classified as a mountainous area, which is not surprising as it is located in the Zagros Mountains and it runs from the southeast to the northwest. This area is about 15.5 % of the province of Kurdistan. The difference in height between the highest elevation point (Chehel-Cheshme Mountain, 3,173 m) and the lowest elevation point (Simineh-Rood basin, 1,150 m above mean sea level) is about 2,023 m. The Saqqez River (Chom Saqqez) emanates from the western mountains (Gardaneh Khan) and continues its path across the city flowing northeast (Shahabi et al. 2012).

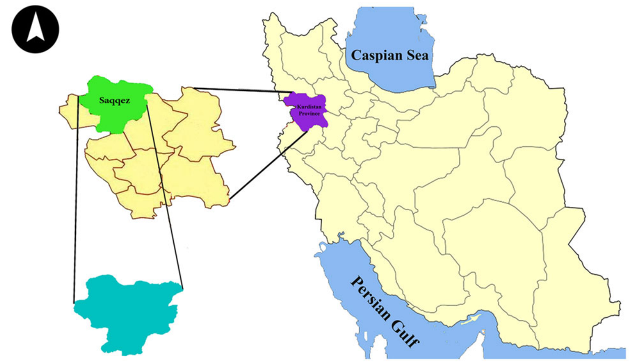

Fig. 1 The location of the study area in Kurdistan province, Iran

The amount of waste generated by Saqqez is between 100 and 140 tons per day on average. The major sources of waste in Saqqez are corruptible materials, plastic, construction trash and hospital waste. A qualitative analysis indicated that the solid waste generated in Saqqez contains a relatively high percentage of organic matter (60–65 % dry weight; Shahabi et al. 2012). The current situation in the city is that recycling diverts about 20 % of waste, while the rest of the waste is disposed of at the Badrabad site, which was launched in 1991 and covers 6 ha. Unfortunately, it lacks the perfect standards for sanitary landfilling (Shahabi 2008). Given the increasing population and the subsequent increase in waste generation, the city will need a new landfill in the coming years.

Ground-based data collection and used software

In order to identify possible landfill locations using geographical information systems, the effective factors, criteria, and limitations should be provided as map layers and then processed and analyzed. In this study, additional data were derived from hard copy maps by scanning and digitizing them. Topographic maps of 1:50,000 were used. The slope and aspect within the study area was obtained from a digital elevation model (DEM). A map of communication and power lines extracted from Landsat ETM^{+} imagery dated the 11th of July, 2009, was obtained from the United States Geological Survey (USGS). These were used as overlays to show topographic details in relation to the digitized road network. Additional information layers consisted of a groundwater layer, a surface water layer, distance to wells, distance from urban centers and airports, supported centers, fault maps (extracted from geology maps), geologic map in 1:100,000 scale, a land use map, and an erosion map (using PSIAC model by nine layers). The geologic map was provided by the Geological Survey of Iran and the land use maps were created from a satellite SPOT 5 image from the 11th July, 2010, that was obtained from the Iranian Space Agency.

The software selected to determine the positioning process needed to be able to support a raster model and multi-feature decision-making principles in addition to vector models (Moeinaddini et al. 2010). As a result, Arc GIS 9.2 (ESRI; Redlands, CA, USA), and IDRISI 15 were selected for the analysis of multi-featured operations. During the course of this study, Autodesk Map software was used to create numeral, modifying, and provide layers. Map Source was used to download data from GPS (Shahabi 2008).

Digital maps, satellite images and spatial datasets

Images captured at almost the same time were used to avoid significant seasonal changes in the surface of the land and vegetation. Many remote sensing studies have addressed the importance of the atmospheric correction for the calculation of the vegetation indices and land surface temperatures (Ou et al. 2002; Jensen 2005; Hadjimitsis et al. 2010). Atmospheric corrections can be either absolute or relative. Although relative corrections are easier to implement, absolute corrections provide better results, if sensor parameters and weather conditions can be obtained (Paolini et al. 2006).

The spectrum characteristics of land use types are diverse. For example, the different types of land use are represented by gray wave bands, and different land use types can perform differently in the same wave band. The boundaries of the land use types (called space characteristics) can be confirmed by determining its shape, position, and the relationship between these two elements (Pearlman and Said 2011).

In this study, ERDAS IMAGINE 8.7 (Leica Geosystems, Atlanta, USA) software was used for image processing. A digital elevation model (DEM) of Saqqez was extracted from a 1:50,000 scale topographic map. In order to integrate the satellite and DEM data, the DEM was co-registered to the satellite image using the Universal Transverse Mercator (UTM) reference system. The spheroid and datum were also referenced to WGS 84. The road networks (vector), satellite, and DEM data were exported into ERDAS VIRTUAL GIS for 3D processing of the landscape to show areas that may be suitable for landfill sites for Saqqez and the surrounding area. All the buffering operations and the final selection of the appropriate sites was completed using ESRI ARC GIS Spatial Analyst extension software.

The coefficients of the linear transformation equations were obtained by linear regression employing several control points across the study area, derived from the 1:50,000 digital topographic map. Subsequently, a root mean square error (RMSE) evaluation was performed to assess the accuracy of the image compared to the map. The RMSEs for the transformed image and standardized maps were smaller than 1 pixel. The resolution of the multi-spectral image was further enhanced using the 15-m panchromatic band. The principal component analysis (PCA) is an ordinary technique that applies a linear transformation to original data (Jensen 2005). PCA is normally used for dimension reduction of a response matrix and to retain the dominant information in the data. PCA is closely related to singular value decomposition and proper orthogonal decomposition. Figure 2 is a flowchart that shows the progression of this study.

In this study, three models were used to select sites for waste landfills for the city of Saqqez. These three models were Boolean logic, AHP and WLC.

Boolean logic

Boolean logic transforms related information from each input map into binary form (True or False) or (0 and 1) and is defined by Eq. 1:

$$C = \{1 \text{ if class } A > \text{ or } < X\} \text{ and } C = \text{class } A > \text{ or } < X. \quad (1)$$

Boolean logic recognizes the class of each map. In this method, it is assumed that a site is suitable for a waste landfill. The number of classes is determined based on whether the desired stipulation is correct or incorrect and the final output expression is applied to each variable (Ghose et al. 2006). These variables were applied repeatedly to the specification of two classes. These classes were 0 and 1 for the desired site and the output of a new map (Higgs 2006). The output map had two polygons, which were used in that condition. Boolean Logic is mostly used in the early screening stages or in stages where unusable options for usable alternatives are divided (Kamran 2008). Boolean logic theory is used when parameter maps are classified into Boolean suitable (yes) and Boolean unsuitable (no) (Malczewski 1999). This process involves the logical combination of binary maps created from the application of conditional operators. If the criteria and guidelines are a

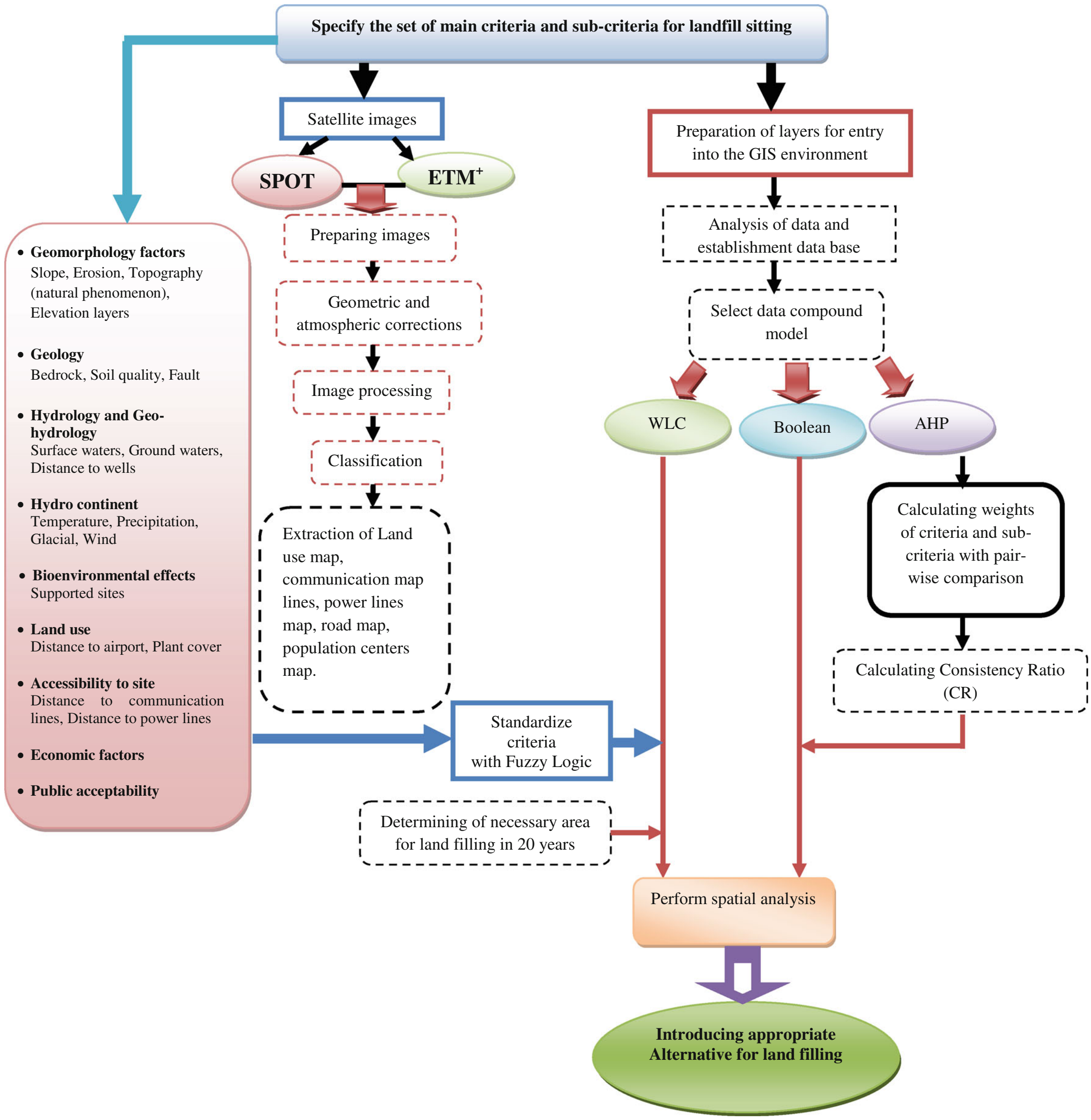

Fig. 2 Framework of the methods and processes

set of deterministic rules, this method is a practical and easy approach. The output is a binary map because each location is either satisfactory or not.

Analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) was presented by Saaty. It is based on three principles: refraction, comparative judgment, and the synthesis of priorities. The principle of refraction is needed to place decision-making problems into hierarchical forms. Each element in the resulting hierarchical structures is placed in special levels by considering their origin in higher levels. The synthesis principle represented the priorities for each site using a determined proportion scale for the different levels in a hierarchy and creates a compound set of priorities for elements at the lower levels of a hierarchy (i.e., options). The defining principle consists of following stages (Saaty 2008):

1. Produce a binary comparative matrix:
   (a) This method creates a basic scale with values from 1 to 9 to determine the extent of the relative priorities of two criteria (Table 1).
2. Measuring criterion weight: this stage includes the following steps:
   (a) Sum of the values for each column in the binary comparative matrix. Divide each matrix component by the total of its column. The resulting

Table 1 Comparing the binary scale

Definition	Extent of importance
Equal importance	1
Equal to average importance	2
Average importance	3
Average to strong importance	4
Strong importance	5
Strong to very strong importance	6
Very strong importance	7
Very strong or super strong importance	8
Super strong importance	9

matrix is called a "Normalized binary comparative matrix".

(b) Measure the mean of components in each row of the normalized binary comparative matrix.

3. Estimating agreement ratio.
4. This stage includes the following steps:

(a) Determine the total weighted vector by multiplying the weight of the first scale in the first column of the main binary comparative matrix, then multiply the second scale in the second column, the third scale in the third column of the main matrix and finally, find the sum of these values.

(b) Determine the agreement vector by dividing the weight vector by the scale weights which were previously specified.

Weighted linear combination method (WLC)

The weighted linear combination method (WLC) is the most common technique for analyzing multi-scale evaluations. This technique also is called a "scoring method". This method is based on the content of the weight average. The analyzer or decision-maker is based on the "relative importance" weighted directly to the scales. By multiplying the relative weight by the feature value, a final measure can be obtained for each option (such as picture element in spatial analysis). After specifying the final value for each option, alternatives, which have higher values, will be the best option for the desired purpose (Malczewski 2004). Determining the proportion for a specific operation or evaluating the potential of a particular occurrence is considered to be a desired purpose. In this method, decision-making principles calculated the value of each A_i options using Eq. (2):

$$A_i = \sum_{j=1}^{n} W_j \times X_{ij}. \tag{2}$$

In this equation, W_j is the j criterion weight; X_{ij} is a value, which accepted i place in relation to j criterion. In other words, this value can indicate the appropriate degree of the i location in relation to j criterion; n is the total number of criteria and A_i is a value, which will attach to the i location. In this method, the total weight should be equal to 1; otherwise, in last stage A_i should be divided by the total of all weights, thus the A_i output will be between 0 and 1. Higher or lower amounts of output can be due to an appropriate or inappropriate option, weight normalizing can be omitted. In the end, the ideal option will be the one that has higher amount of A_i (Malczewski 1999).

Results and discussion

The evaluation criteria used for landfill sites were classified into nine categories, which were the geomorphology, geology, hydrology and geohydrology, hydro-continent, bioenvironmental effects, land use, accessibility to site, economic factors, and public acceptability (Fig. 2).

In the field of solid waste management, the identification of landfill sites for solid waste disposal remains a critical management issue and the selection of a suitable site should be based on a number of considerations (Sumathi et al. 2008; Sharifi et al. 2009). In this study, the land use map was generated using the image interpretation and classification of the satellite SPOT 5 image of Saqqez with a 10-m resolution (Fig. 3).

Subsequently, the thematic maps illustrating habitation, sensitive sites and waste lands were derived from land use maps using standard procedures. Six categories of criteria were identified from the land use maps, namely barren land and pasture, military land, Saqqez River, urban areas, irrigated farmland, and rain fed farmland (Supplementary Figure 1).

In order to determine the area of land that will be required for the waste landfill in Saqqez, the following factors were taken into consideration:

(1) rate of population growth,
(2) annual waste production,
(3) density of pressed substance,
(4) elevation and form of repulsion location (Moeinaddini et al. 2010).

Increases in waste production parallel population growth. As a result, the rate of population growth can be used as the rate of increasing waste production. The

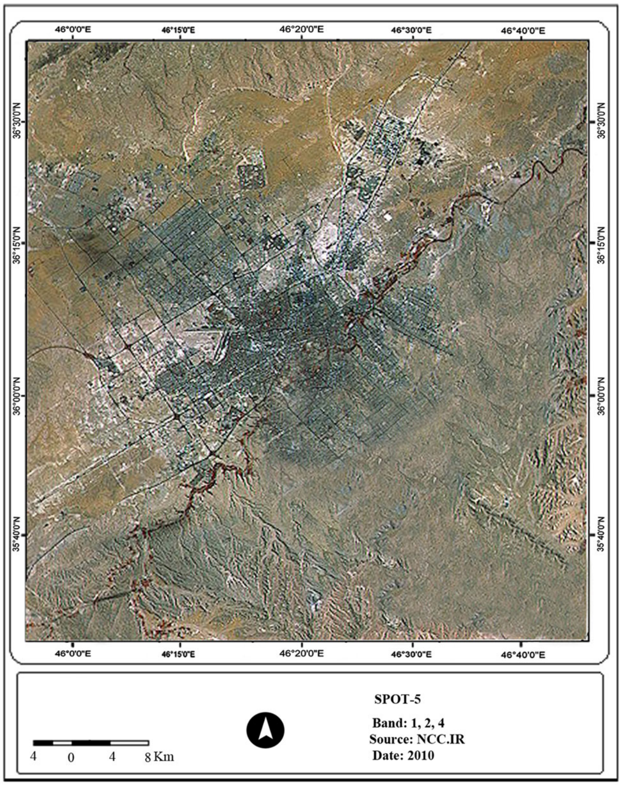

Fig. 3 Satellite SPOT 5 imagery of Saqqez with 10 m resolution in 11th July 2010 was obtained from the national organization of Iran space

population of the city of Saqqez in 1995 was 115,394 people. In 2005, the population had increased to 133,331. The extent of population growth can be determined using Eq. (3):

$$P_{2005} = P_{1995}(1 + r)^{10}, \tag{3}$$

where P_{1995} is the population in 1995, P_{2005} is the population in 2005 and r is the extent of the population growth. In this case, population growth was equal to 1.4 %. The average daily waste production in Saqqez is 130 tons, and the annual average of waste production is 47,450 tons. In total, the annual waste production amounts to 94,900 tons.

As stated above, increasing waste runs parallel to population growth and according to a 20-year planning term for burying place, content of waste produced in a 20-year term is measured as following:

Weight of produced waste = 949,000 tons over the 20-year period.

Volume of waste produced in 20 years = 282,700 (m^3).

Now, if the elevation of the landfill site averages 10 m above the surface of the earth and 5 m below the surface of the earth, then at least 50 ha of land will be needed for a landfill site.

Table 2 Criterion limits to standardize maps (Boolean logic)

Rank	Map layer	Acceptable extent for site selection of waste disposal	Value
1	Slope	<15 %	1
2	Erosion	<100	1
3	Distance to fault	<100	1
4	Distance to Saqqez	Between 30–50 km	1
5	Depth to ground water	<20 m	1
6	Distance to surface water	<300 m	1
7	Distance to wells	<100 m	1
8	Distance to airport	<2,000 m	1
9	Distance to population center	<1,000 m	1
10	Distance to supported regions	<150 m	1
11	Distance to agricultural lands and gardens	<200 m	1
12	Distance to road	<300 m	1
13	Distance to power transition lines	<100 m	1

Integrating informational layers and determining proper place for waste landfill in each model

Standardizing map layers

To locate and compound maps, layers should be standardized. This means that decision-making principles should be used to transform layers into scales that will allow for all the layers to be combined. In this case, three methods, Boolean, AHP, and WLC were used.

Standardizing Boolean maps

Supplementary Figure 2 shows 13 layers including: slope, erosion, depth of ground water, distance to faults, distance to surface water, distance to wells, distance to supported regions, distance to airport, distance to agricultural lands (including gardens), distance to roads, distance to power transition lines, distance to population centers and distance to the city of Saqqez.

A value of 1 indicated acceptable conditions for a site and a value of 0 indicated unacceptable conditions at a site (Table 2).

Standardizing maps using an analytic hierarchy process

To perform this method, the criterion was compared according to scores shown in Table 3. The relative importance of each criterion was determined with couple ratios and entered into a matrix. Then, the weights and consistency ratio (CR) were measured. If the CR was lower than 0.1, then the CR was adjusted to an acceptable value by changing the binary comparative matrix. Due to the weakness of Arc GIS software in measuring weights and consistency ratios, this task was performed in the WEIGHT module of IDRISI software. Saaty indicated that matrices with CR ratings greater than 0.1 should be re-evaluated. In this study, a ratio of 0.02 was obtained, which indicated that the results were acceptable.

Standardizing fuzzy maps

In fuzzy logic, each location was chosen based on observations of the desired criterion that established membership values which demonstrated the suitability of the site. A site with higher membership values was more suitable. Compared to Boolean logic, which has problems with definite and precise scales, fuzzy logic uses values between 0 and 1 in each classified layer. A value of 1 indicates higher acceptability and a value of 0 indicates lower acceptability (Malczewski 2004).

In addition to the scale selection process used to create fuzzy maps, other types of fuzzy functions should be investigated and more suitable functions selected for the criterion. Sigmoidal, linear, and J-shape are considered to be the most eminent functions. These functions exist in the IDRISI software. The IDRISI software also allows users to define a function according to their needs.

In this study, the sigmoidal function was used (see Supplementary Figure 3; Table 4) because it was a commonly used function. When the relationship between the value and the fuzzy membership did not follow any of the sigmoidal functions, a user-defined function was used (Eastman 2003). The control points in the sigmoidal function are shown in Supplementary Figure 3.

When "monotonically increasing" or "monotonically decreasing" curves are chosen, only two control points were needed to define the fuzzy set membership function. In the first case, they were point a and point b, while in the second case they were point c and point d.

When the "symmetric" curve was chosen, however, all four control points were needed and must be entered in the following order: a, b, c and d (Eastman 2003). For example, "Distance to fault" (Table 4) with a symmetric function had inflection values of either $c = 100$, d or $b = 1{,}000$.

The map layers were standardized using the fuzzy approach that was relevant to the criteria. Standardization in the 0–255 range was performed, with 0 as the least and 255 as the maximum suitability rate for each criterion (Moeinaddini et al. 2010).

To apply fuzzy functions in the GIS environment in this study, all the map layers were digitized or imported and

Table 3 Weighting of criteria using binary comparative method

	Erosion	Slope	*D* fault	*D* ground water	*D* Surface Water	*D* wells	*D* roads	*D* Saqqez	*D* population centers	Land use	*D* power transition	*D* airport	*D* protection	Criterion weight
Erosion	1													0.0103
Slope	0.33	1												0.0167
D fault	0.33	0.5	1											0.0183
D ground water	0.2	0.33	0.33	1										0.0321
D surface water	0.2	0.33	0.33	1	1									0.0321
D well	0.2	0.33	0.33	0.5	0.5	1								0.0435
D roads	0.2	0.33	0.33	0.5	0.5	1	1							0.0435
D Saqqez	0.2	0.33	0.33	0.5	0.5	1	1	1						0.0435
D population centers	0.2	0.33	0.33	0.5	0.5	1	1	1	1					0.0435
Lands usage	0.1429	0.2	0.2	0.33	0.33	0.5	0.5	0.5	0.5	1				0.0747
D power transition	0.1429	0.2	0.2	0.33	0.33	0.5	0.5	0.5	0.5	0.5	1			0.0747
D airport	0.1429	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.5	1		0.1062
D protection	0.1429	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.5	1	1	0.1062

D distance

Table 4 Threshold limit and type of fuzzy logic to standardize criterion maps in fuzzy logic

Row	Criterion name	Control options (threshold values)		Type of fuzzy function	Name of fuzzy function
		a or *c*	*b* or *d*		
1	Slope (%)	3	40	Reductive	Sigmoidal
2	Distance to fault (m)	100	1,000	Additive	Sigmoidal
3	Distance to Saqqez (km)	5	32	Reductive	J-shape
4	Distance to surface water (m)	150	600	Additive	Sigmoidal
5	Distance to roads (m)	100	1,000	Reductive	Sigmoidal
6	Distance to population centers (m)	500	3,000	Additive	J-shape
7	Distance to airport (km)	1	7	Additive	J-shape
8	Distance to wells (m)	150	600	Additive	Sigmoidal
9	Distance to supported regions (m)	100	1,000	Additive	J-shape
10	Distance to farmlands and gardens (m)	0	250	Additive	J-shape
11	Depth to ground waters (m)	10	30	Additive	Sigmoidal
12	Distance to power transition lines (m)	100	1,000	Additive	Sigmoidal

converted to a raster format with a 30 m pixel size. Determining the threshold limit was another factor in standardizing fuzzy maps that is also referred to as a "control point." Increasing or decreasing functions should be considered during function selection (Gorsevski et al. 2011; Kemal Korucu and Erdagi 2012). The purpose of a decreasing function is minimizing and descending. The purpose of an increasing function is maximizing or ascending. For example, in the case of groundwaters, a higher depth is more suitable. Thus, in this case, an increase in function was used. Table 4 demonstrates threshold values and types of fuzzy function used to standardize criterion maps using fuzzy logic.

Integrating layers using decision-making principles MADM

After the maps were standardized, the integration stage for the layers could start looking for suitable landfill sites. To integrate these layers, the Boolean, WLC, and AHP methods were used and their stages are described in the following section.

Integration using Boolean logic

Integration using the Boolean method is possible using layers and restriction maps. This integration process is actually considered to be an overlaying method. Either the overlay module or the MAP CALCULATOR module was used and there was no need to scale weights. The map that showed the best sites was prepared by taking all the land and categorizing it using GROUP module. The areas of these regions were measured using AREA operations. Areas greater than 50 m^2 were classified as being acceptable and a final map was created (see Fig. 4; Supplementary Figure 4).

Integration by AHP method

In the AHP method, the locating operation was performed using the MAP CALCULATOR menu. In this method, the

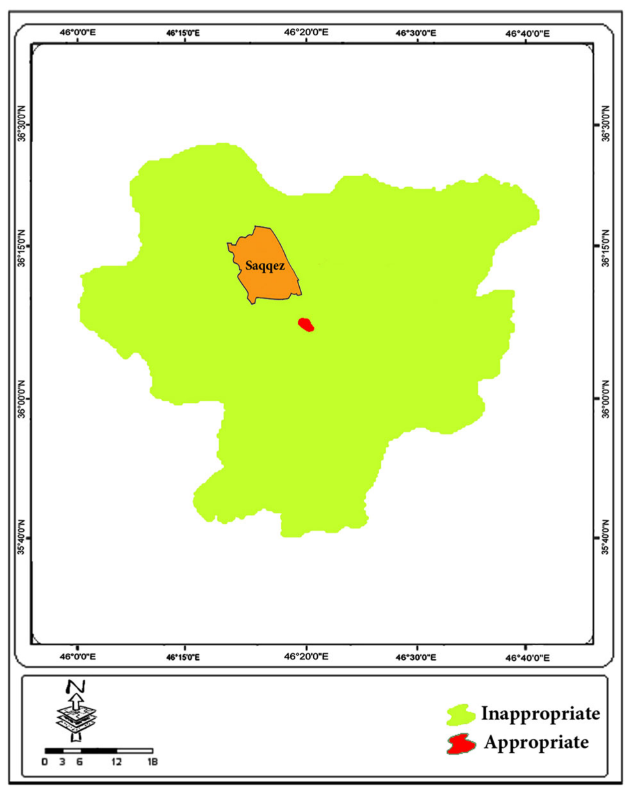

Fig. 4 Final map of located sites of waste landfill using Boolean method

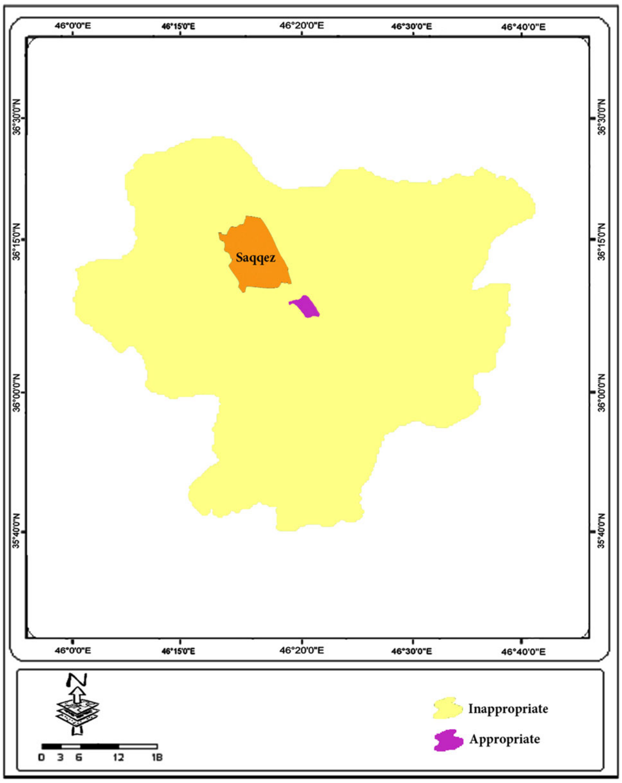

Fig. 5 Final map of located sites of waste landfill using Analytic Hierarchy Process method

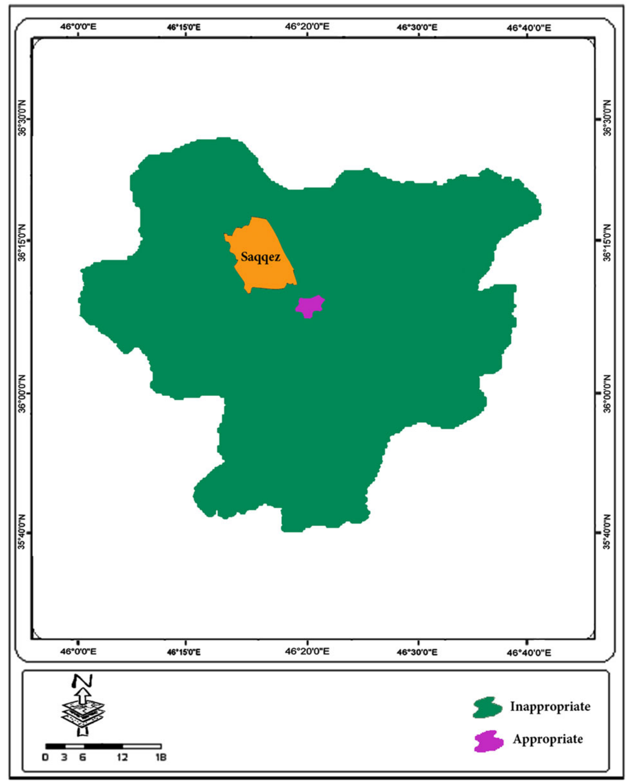

Fig. 6 Final map of located sites of waste landfill using weighted linear combination method

criterion weights used in Table 3 were applied. The result was a map containing five classes. Next, the area of each site was measured using the AREA menu. Finally, sites with areas greater than 50 m^2 were classified as acceptable lands and a final map was provided (see Fig. 5; Supplementary Figure 5).

Integration by WLC

The broad capacities of IDRISI software for multi-criteria decision-making analysis made it useful for performing fuzzy integrations and selecting appropriate sites for waste landfills. In this stage, the use of MCE menus and the WLC option, limitations and criterion maps were integrated by apply corresponding weights as criterion weights. The results of this integration were demonstrated as primitive and final maps. Finally, sites with areas over 50 m^2 were labeled as being excellent sites for potential landfills see Fig. 6; Supplementary Figure 6).

Final map preparation

Finally, after different factors in the selection of waste landfill sites for Saqqez and taking into account important geomorphologic, four sites were found that would be appropriate landfill sites. The characteristics of each of the four sites are discussed in Table 5.

The results of the Boolean, AHP, and WLC methods were compared and by overlaying them on each other, the final landfill site for Saqqez was selected. Figure 7 shows the four sites and old landfill site on the Landsat ETM$^+$ imagery of 11th July 2009 by using combination of bands 2, 3 and 4.

According to all main and secondary criteria mentioned in Table 5 and with regard to performed field observations among the four sites obtained from the three applied models, Site 1, with an area of 74 ha and close to a municipal asphalt factory, was recommended as the best landfill site for the city of Saqqez (Fig. 8).

Conclusion

Site 1 was close to a municipal asphalt factory, and located $X = 4{,}007{,}226$ (north) and $Y = 616{,}226$ (east). According to the results of the three models, and the role of different geomorphologic factors, Site 1 was selected as the best alternative for a waste landfill site because this location had a slope of less than 10 %. Site 1 had a combination of sand and clay soil. The faults at this site were far from other

Table 5 Features of four obtained sites for waste disposal of Saqqez

Prior group	Evaluation components	Site number 1	Site number 2	Site number 3	Site number 4
Geomorphologic	Slope (%)	4	13	8	18
	Erosion	Very low	Much	Medium	Very much
	Topography (natural phenomenon)	Field with gentle slope	Valley	Surface with average slope	Field with long slope
	Elevation layers (m)				
Geology	Bedrock	Andesite	Shale and lime	Andesite and clay	Sandstone and lime
	Soil quality	Gravel-Clay	Gravel	Gravel-Clay	Clay
	Fault (m)	500	100	300	80
Hydrology and geohydrology	Surface waters (m)	800	150	900	100
	Ground waters (m)	35	10	25	7
	Distance to wells (m)	300	180	350	100
Hydro-continent	Temperature (°C) Minimum # Maximum	5–10 # 15–20	2.5–5 # 10–15	10–15 # 25–35	2.5–5 # 10–15
	Precipitation (mm in year)	350–400	300–400	350–400	300–400
	Glacial (day)	138	138	138	138
	Wind (kilometer in hour)	7–10	3–5	5–7	3–5
Bioenvironmental effects	Supported sites (km)	25	38	30	49
Land use	Airport (km)	2	3	5	8
	Land cover	Rain fed farmland	Barren land and pasture	Rain fed farmland	Barren land and pasture
Favorable public health and safety		Favorable	Favorable	Favorable	Favorable
Accessibility to site	Communication lines (m)	80–120	200–350	120–180	400–800
	Power lines (m)	2,000	1,500	3,000	300
Economic factors		Excellent	Medium	Good	Medium
Public acceptability		Excellent	Bad	Good	Medium

major and minor faults. The hydrologic and hydrogeology factors indicated that Site 1 had better conditions than the other locations because of its distance from surface water (800 m), groundwater (25–35 m), and wells (300 m). Site 1 had minimum temperatures of 5–10 °C and maximum temperatures of 15–20 °C, which placed it in a very desirable class. Mean precipitation was 350–400 mm a year.

Each of the four sites had 138 cold days a year indicating that they faced average conditions according to the standard landfill qualifications. The intensity of the prevailing winds at Site 1 was from between 7 and 10 km. This placed it in a very good class according to the standards. In the case of environmental factors, Site 1 is in a desirable location. According to the satellite SPOT 5 image from the 11th July 2010, and the final land use map, Site 1 is in the rain fed farmland class and is away from high-quality agricultural lands and fruit gardens. In the case of future urban development, Site 1 is in an excellent location according to the general and more in-depth plans of the city, because it is situated in a different direction than the city's anticipated future development. In terms of accessibility, Site 1 is 3 km from the Saqqez–Marivan road and 8 km from Saqqez. It is 2 km away from the airport. These factors mean that it is an excellent place for a landfill site. The 74 ha contained in Site 1 means that it will remain useful for next 15–20 years. Based on public acceptance, Site 1 was the most satisfactory site of the residents of Saqqez.

The results of this study demonstrated the ability of geographical information systems and satellite images to model and help locate potential waste landfill sites. The models demonstrated that certain location options, choices limitations, and a range of criteria values, revealed that Boolean logic had lower confidence levels and less flexibility than the other two methods. This method was not suitable for the area investigated in this study, which has specific ecological and environmental conditions, because lands were chosen according to absolute and certain criteria. Decision-making ability is effected according to criteria value limits and will increase through changes in these limits. In the AHP method, the ability of decision-makers was enhanced by the wide range of classifications and useful activities that can be performed to reduce economic and environmental costs. The WLC method used

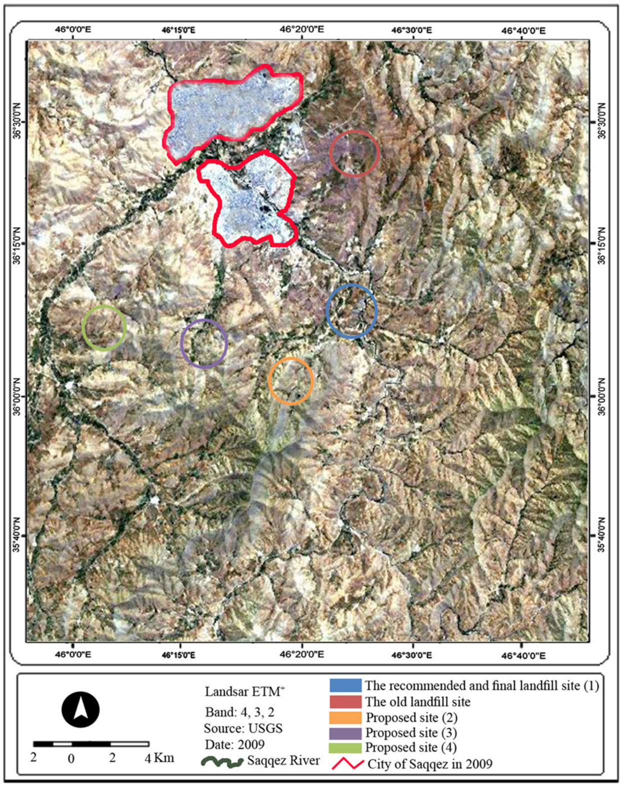

Fig. 7 Four sites were found for waste landfill of saqqez and old landfill site on the Landsat ETM+ imagery of 58611th July 2009 by using combination of bands 2, 3 and 4

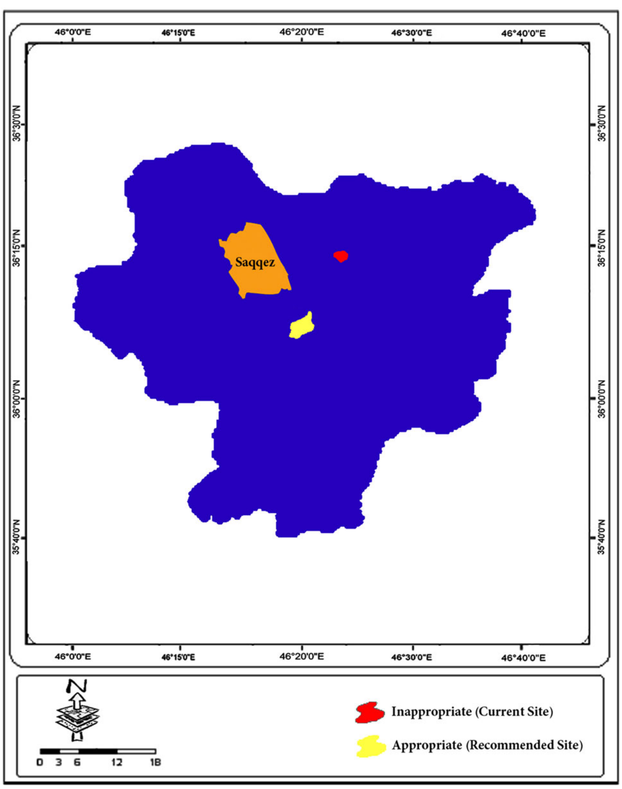

Fig. 8 Current and recommended site for waste landfill of Saqqez

weighting to allow decision-makers to apply the most important factors thought to have the most influence on the locating process. The results of the WLC site selection were improved by its better segregation powers.

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