



Landfill site selection using GIS-based multi-criteria evaluation (case study: SaharKhiz Region located in Gilan Province in Iran)

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Abstract

Recognizing potential sites for landfill has increasingly become an important waste management strategy around the world. This study aims to determine municipal solid waste (MSW) landfills in SaharKhiz Region located in Gilan by comparing Fuzzy logic and Boolean logic. Fuzzy logic, which has been used in this research, is based on weighted linear combination (WLC); however, the utilized Boolean logic is considered only to determine the accuracy and validity of every method. At first, the Boolean logic using a geographical information system (GIS) is used to recognize potential and excluded zones, based on zero and one value system. In the next phase, Fuzzy logic is used, between zero and one, to standardize information layers, based on their type (increasing or decreasing). The final weight of every layer was determined using the analytical hierarchy process. Finally, the WLC method was used to integrate layers in the GIS environment to provide the final site suitability map in five classes of Fuzzy membership degree. The results show that Fuzzy logic, based on WLC, has more flexibility to resolve conflicts of human judgment, and it also has higher accuracy than Boolean logic in the selection of optimal landfill sites for MSW in SaharKhiz Region, Gilan Province, based on ecological and socioeconomic parameters.

Keywords Site selection · Municipal solid waste (MSW) · Boolean logic · Fuzzy logic · Analytical hierarchy process (AHP) · Geographical information system (GIS)

Abbreviations

AHP	Analytical hierarchy process
ANP	Analytical network process
EC	Expert choice
EPA	Environmental Protection Agency
GIS	Geographical information system
IDOE	Iran's Department of Environment
MSW	Municipal solid waste
MCDM	Multi-criteria decision making
MCE	Multi-criteria evaluation
MSWDSs	Municipal solid waste disposal sites
OWA	Ordered weighted averaging
SDSS	Spatial decision support system

TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WLC	Weighted linear combination
WOM	Weighted overlay method

1 Introduction

Nowadays, population growth, along with increasing municipal solid waste (MSW) production, plays a remarkable role in environmental pollution. MSW management, to recognize suitable landfill sites, is an indispensable step of environmental planning, where the selection of a landfill

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SN Applied Sciences (2019) 1:1082 | <https://doi.org/10.1007/s42452-019-1109-9>

Received: 31 May 2019 / Accepted: 16 August 2019 / Published online: 24 August 2019

site for disposal of solid waste can assure habitat conservation and promote human health [1]. More importantly, environmental challenges caused by the leakage from MSW, which can potentially contaminate groundwater and surface water resources, are one of the significant and tangible environmental impacts of a landfill site, where appropriate ecological and socioeconomic circumstances, as well as precise engineering design of landfill site, will contribute greatly to reducing leakage and protection of the environment [2]. Selection of optimal landfill sites for MSW is one of the most important principles of urban planning which can be defined as a practical method to attain sustainable urban development. To reduce its environmental impacts, locating a landfill is the basis for sound management of MSW [3]. Regarding the negative environmental impacts of waste disposal on human health and welfare, environmental experts must decide on planning for MSW landfill based on the environmental capacity of land in cooperation with relevant public agencies [4]. Often, environmental negative consequences of landfill site selection are of interest to environmental specialists and related experts; proper site selection of MSW landfill through multi-criteria decision-making (MCDM) method within the framework of ecological capacity assessment can lead to establishing a logical framework. Parameters such as slope, geological formations, soil texture, proximity to surface water, groundwater depth, land use (forest, pastures, farmlands), proximity to population centers, proximity to protected areas, distance from industrial areas, distance from power transmission lines, and distance from access roads all play a pivotal role in selection of MSW landfill [5]. Some of the mentioned parameters have more importance to locating suitable landfills than other parameters, including groundwater depth, proximity to surface water sources, soil texture, type of geological formations, distance from protected areas, and distance from population centers [6]. Geographical information system (GIS) is a useful and high-performance tool in studies pertaining to sanitary landfill site selection, as a spatial decision support system (SDSS) with a strong set of tools to enter, store, display, analyze and model spatial data as well as the ability to handle large volumes of spatial data from different sources [7]. The potential advantage of using GIS for site selection lies within the fact that using GIS not only reduces time and saves money for MSW landfill site selection, but also provides a digital database for long-term monitoring of a landfill [8].

In addition to GIS, MCDM method can be applied to solve landfill site selection problems [9]. MCDM is based on the assumption that decision-making issues should be divided into smaller comprehensible sections that can be analyzed independently, and at the end, those decision-making segments will be integrated in a logical manner

[9]. Integrating GIS and MCDM generates a strong problem-solving tool for spatial issues regarding the selection of MSW landfill [10]. This is because GIS analyzes spatial and descriptive criteria at the same time and turns raw data into valuable information, while MCDM, in turn, addresses ranking and prioritizing of landfill sites by considering ecological parameters [11]. Several studies have been carried out on landfill site selection for MSW in the context of multi-criteria evaluation (MCE) approaches. Osra and Kajjumba [12] applied an integration approach based on GIS and analytical hierarchy process (AHP) to demonstrate pragmatically the connections between the diverse landfill site selection factors in Makkah, Saudi Arabia. They found that this method would be an efficient method to identify the most desirable locations in Makkah [12]. Yildirim and Guler [13] used AHP, GIS, and weighted overlay method (WOM) based on weighted linear combination (WLC) for identification and selection of municipal solid waste disposal sites (MSWDSs) for the Mersin Region in the southeast of Turkey. They classified the suitability map indicating six suitability classes [13]. Torabi Kaveh et al. [14] utilized GIS-based multi-criteria evaluation (MCE) based on the AHP in terms of identifying the appropriate sites for the landfill in the Iranshahr Region. They obtained four suitability classes within the study area were identified [14]. Karimzadeh Motlagh and Sayadi [15] utilized MCDM methods based on WLC and ordered weighted averaging (OWA) and analytical network process (ANP) for the landfill site selection of the Birjand plain. Their research outcomes revealed that the OWA method, in comparison with WLC and ANP, had great potential and flexibility in the modeling of the complex decision-making problems [15]. Abd-El Monsef [16] used GIS, remote sensing, and AHP to identify and locate suitable locations for new landfill sites along coastal desert regions of the Red Sea in Egypt. They found two suitable sites for MSW landfill [16]. Ghobadi et al. [17] undertook an MSW landfill site selection, in Hamedan Province, by integrating GIS and AHP, and they classified areas based on three suitability classes [17]. In the present study, comparison of Fuzzy logic, based on WLC, and Boolean logic, in the ArcGIS 10.3 software environment, was made to select MSW landfill site in SaharKhiz Region in Gilan Province, according to the ecological and socioeconomic parameters.

2 Study area

The study area, SaharKhiz Region, is a part of the coastal zone of the Caspian Sea which is located in Gilan Province. SaharKhiz Region has a latitude of 37°19'N and a longitude of 50°13'E, which is placed 23 to 26 m below sea level. The region's area is 1627.10 km², and the slope

of the land surface is toward the northwest. According to the field observation, the area has a few steep slopes and is mainly used for agriculture [18]. From surface water resources' point of view, there are 11 permanent rivers and 2 permanent lakes in the area, among which Sefidrood and Shamrood are the most important permanent rivers in the area. SaharKhiz Region includes cities such as Rood-sar, Langerood, Lahidjan, Astaneh Ashrafie, and Kia Shahr. Consequently, the study area has a high population density. On the other hand, the important protected habitats in the area, which are rich in flora and fauna, are Boojagh National Park, Amir Kolayeh Wildlife Refuge, Safrabashte Forest Reserve, and some other valuable wetlands. Also, dangerous facilities such as gas pipelines, Kelachay Mine, and Lahidjan Car Factory are located within the studied area [18]. Figure 1 shows the location of SaharKhiz Region in Gilan Province, Iran.

3 Methodology

3.1 Boolean logic

To select the MSW landfill site in SaharKhiz Region, a large number of socioeconomic and ecological parameters are involved. After determining the ecological and socioeconomic sub-criteria in the GIS environment, a common projection coordinate system was determined for all of the layers based on the WGS 84/UTM zone 39 N. Then, by using the Boolean logic method, the constraint criteria reflect the imposed conditions regarding decision-making options. Constraints make it possible to consider the separated spatial options from the rest of the choices; in fact, the constraints contain the criteria in which there is no feasibility for the MSW site selection and should be considered as the separated criteria, including the slopes of more than 15%, areas situated inside floodplains, areas located at a distance of less than 100 m from active faults, areas placed in a distance of less than 1000 m from population centers, etc. [19]. Table 1 shows the layers and standards for landfill site selection regarding Iran's Department of Environment (IDOE) requirement.

3.2 The Fuzzy logic approach based on WLC

The second method which is used in this research is the Fuzzy logic approach based on WLC, one of the most popular MCDM methods, in which standardization of spatial criteria is continuous. At first, standardization of criteria raster layers was used depending on the function type (whether ascending or descending). Since the importance of landfill spatial criteria varies, it is necessary to determine the weights of criteria using AHP before implementing the

WLC method. In the following stage, questionnaires on the priority and importance of ecological and socioeconomic criteria were distributed among environmental experts [20]. One of the most common methods of spatial decision making based on GIS is applying AHP for weighting the criteria and sub-criteria. In order to determine the weight of ecological and socioeconomic criteria and sub-criteria, a pairwise comparison matrix of each element within every level was constructed. This matrix showed the importance of each element against another [17]. Next, experienced environmental experts' comments were used to determine the priorities of every two criteria undergoing pairwise comparison. Finally, the geometric mean of their survey was used as an input to the expert choice (EC) software to determine the final weight of the ecological and socioeconomic sub-criteria [17]. While the AHP process determines the weight of indicator criteria, the rate of inconsistency can be calculated, so experts will be able to make a decision about pairwise judgments. If the rate of judgment inconsistency is equal to or smaller than 10% (0.1), it will be considered acceptable; otherwise, weighting should be repeated [21]. Table 2 shows the preference values for pairwise comparison of criteria and sub-criteria [22].

Following this, each standardized factor was multiplied by the final weight obtained from AHP, and then layers were added together. The final map related to the calculated preference 0–1 is related to the suitable areas. This method is based on Eq. (1) [23], where S represents site suitability of the area, W_i is the final weight of the criteria, X_i is the Fuzzy value of the criteria, and n represents the number of criteria [24].

$$S = \sum_{i=1}^n w_i x_i \quad (1)$$

To integrate the WLC method into the spatial analysis, after preparing the raster maps of the ecological and socioeconomic parameters, a suitable approach for multi-criteria comparison of all the parameters needs to be considered, which is called MCE. In fact, due to the adverse essence of the ecological and socioeconomic parameters, all of the parameters should be chosen in a standard unit, in terms of being compared with each other. WLC method is one of the most fundamental approaches for standardization of data layers between the standard unit of zero and one, based on the standardization formulations for ascending and descending according to the type of data layer [25]. Table 3 shows the threshold values and Fuzzy membership function to standardize of different layers in Fuzzy logic for landfill site selection regarding IDEO requirements. Figure 2 presents several stages of MSW landfill site selection by comparing Boolean logic and Fuzzy logic based on WLC in the studied area.

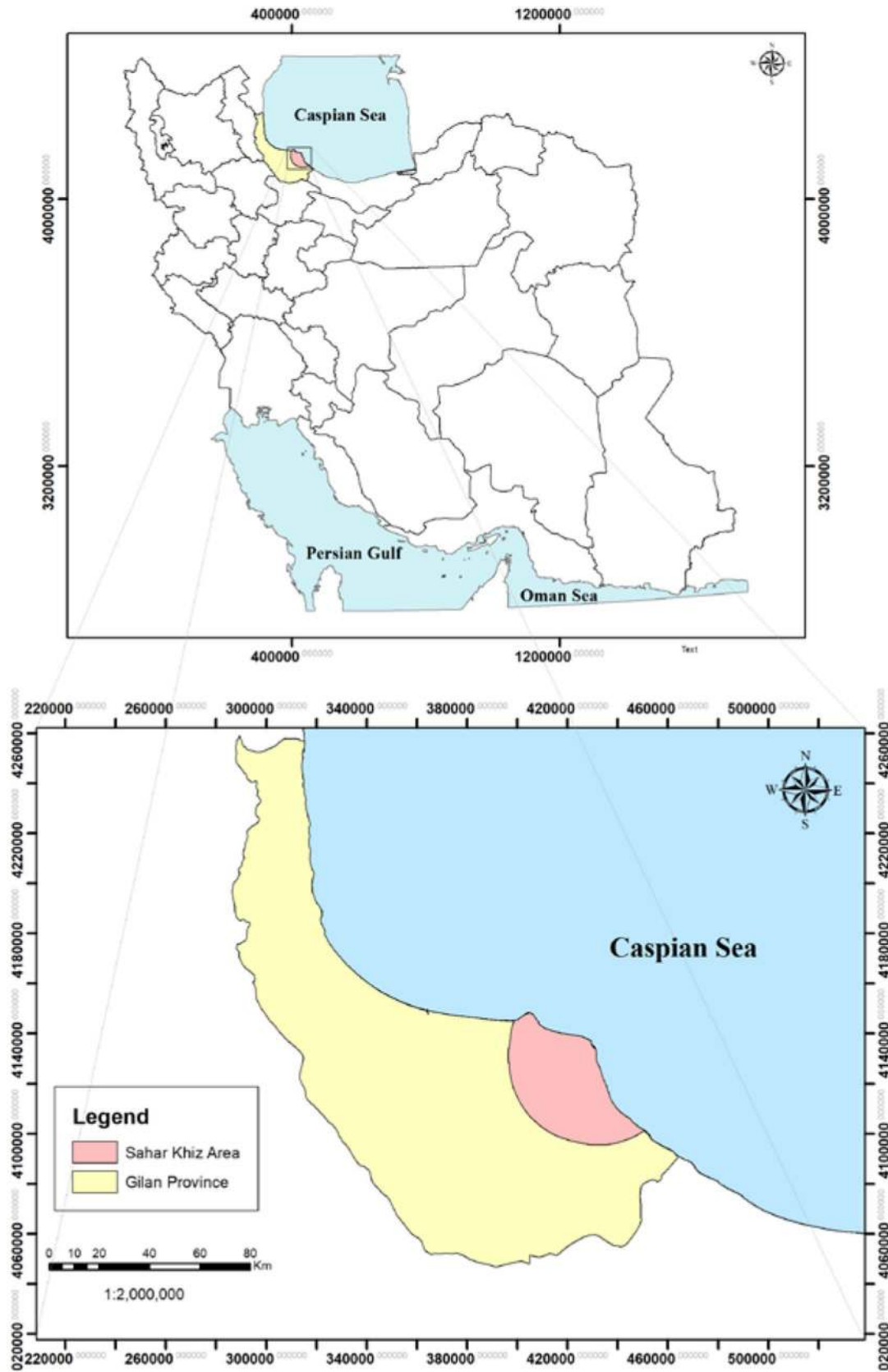


Fig. 1 Location of SaharKhiz Region in Gilan Province, Iran

Table 1 Criteria and standards for the selection of landfill site by using Boolean logic [19]

Row	Ecological and socioeconomic layers	Acceptable standard for landfill site selection	Value
1	Slope (%)	< 15%	1
2	Distance from fault	≥ 200 m	1
3	Flooding	Areas outside the flood plain	1
4	Groundwater depth	≥ 10 m	1
5	Distance from lake	≥ 1000 m	1
6	Distance from river	≥ 1000 m	1
7	Distance from shoreline	≥ 1000 m	1
8	Distance from protected area	≥ 1000 m	1
9	Distance from wetland	≥ 1000 m	1
10	Distance from population centers	≥ 1000 m	1
11	Distance from road	≥ 300 m	1
12	Distance from power transmission line	≥ 100 m	1
13	Distance from gas pipeline	≥ 1000 m	1
14	Distance from industrial	≥ 1000 m	1

Table 2 The preferences values for pairwise comparison [22]

Preferences	Numerical value
Extremely preferred	9
Very strongly preferred	7
Strongly preferred	5
Moderately preferred	3
Equally preferred	1
Moderately preferred	1/3
Strongly preferred	1/5
Very strongly preferred	1/7
Extremely preferred	1/9
Less important between the above intervals	1/8, 1/6, 1/4, 1/2, 8, 6, 4, 2

4 Site Selection Criteria

Generally, selecting a suitable landfill site would minimize the risk to human health as well as decrease the negative effects on the environment. Additionally, it will reduce the costs of waste disposal [26]. The selected areas for landfilling should be close to the source of waste and far from protected areas (wildlife refuges, national parks, natural monument, in addition to protected areas of Iran Department of Environment). Underground water depth in the area must be low, and access to the roads and transport routes should be facile. The area must be flat without any steep slope and far from surface water resources (rivers and lakes) or

Table 3 Threshold values and Fuzzy membership function to standardize the different layers in Fuzzy logic for landfill site selection [19]

Row	Ecological and socioeconomic layers	Threshold value		Type of the Fuzzy membership function	Name of the Fuzzy membership function
		Control line a	Control line b		
1	Slope (%)	15	5	Decreasing	S-shape
2	Distance from fault	200	1000	Increasing	S-shape
3	Groundwater depth	10	100	Increasing	S-shape
4	Distance from lake	1000	2000	Increasing	S-shape
5	Distance from river	1000	2000	Increasing	S-shape
6	Distance from shoreline	1000	2000	Increasing	S-shape
7	Distance from protected area	1000	2000	Increasing	S-shape
8	Distance from wetland	1000	2000	Increasing	S-shape
9	Distance from population centers	1000	2000	Increasing	J-shape
10	Distance from road	1000	300	Decreasing	J-shape
11	Distance from power transmission line	100	1000	Increasing	S-shape
12	Distance from gas pipeline	1000	2000	Increasing	S-shape
13	Distance from industrial	1000	2000	Increasing	S-shape

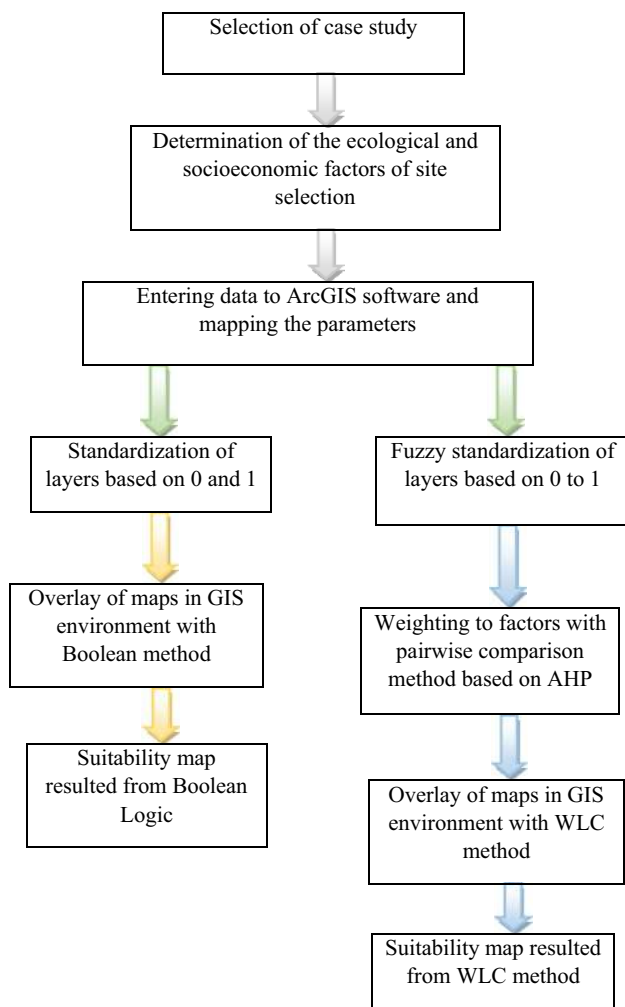


Fig. 2 Stages of MSW landfill site selection by comparing Boolean logic and Fuzzy logic based on WLC in SaharKhiz Region in Gilan Province

areas which are prone to earthquakes and faults. In fact, these areas have more capability for landfill site selection than others [27]. Table 4 shows the list and description of ecological criteria for MSW landfill site selection in SaharKhiz Region, Gilan Province. Table 5 shows the list and description of socioeconomic criteria for MSW landfill site selection in SaharKhiz Region, Gilan Province. To utilize the Fuzzy logic based on WLC, in terms of Iran’s Department of Environment (IDOE), all parameters related to ecological and socioeconomic parameters were standardized between the standard unit of zero and one [28]. Parameters include slope, flood, distance from the fault, distance from protected areas, distance from wetlands, distance from lakes, distance from the coast, distance from population centers, distance from power lines, distance from the gas pipeline, and distance from roads.

5 Results

By using Iran’s Department of Environment (IDOE) regulation for MSW landfill site selection together with environmental experts’ views, which were utilized for ecological and socioeconomic sub-criteria, this study illustrated that ecological sub-criteria such as groundwater depth, distance from surface water resources, and flooding play a key role in landfill site selection. Also, among socioeconomic sub-criteria, distance from population centers (urban and rural) is an important factor for landfill site selection. As a result, if landfill site selection is done correctly and in accordance with environmental assessment (ecological and socioeconomic capacity), the urban environment will be protected, socioeconomic requirements will be met, and it will be in accordance with principles of sustainable development. After final map preparation using Boolean logic, it is shown that about 14.72% (239.53 km²) of SaharKhiz Region in Gilan Province has site suitability, whereas 85.28% (1387.57 km²) has unsuitable properties for landfill site selection. Also, in the final map prepared through Fuzzy logic based on WLC, it was determined that about 2.94% of SaharKhiz Region with an area of 47.83 km² has very low site suitability; 17.31% of the region with an area of 281.73 km² has low site suitability; 35.23% of the region with an area of 573.20 km² has moderate site suitability; 28.65% of the region with an area of 466.23 km² enjoys high site suitability; and 15.77% of the region with an area of 256.65 km² is endowed with very high site suitability for MSW landfill site selection. In this study, standardization of ecological and socioeconomic sub-criteria on a continuous scale (between 0 and 1) is provided by employing Fuzzy logic, and as a result, the relative desirability of suitable areas for MSW landfill can be determined. Furthermore, the capacity of Fuzzy logic based on WLC in terms of allocating different relative weights to any of the ecological and socioeconomic sub-criteria in the process of information layer integration is one of the advantages of this method. Therefore, one can decide on MSW landfill site selection in SaharKhiz Region according to the region’s environmental capacity (region’s ecological and socioeconomic capacity).

As shown in Fig. 3, the local desirability range for MSW landfill site selection is discrete. Figure 3 represents MSW landfill site selection by applying Boolean logic in SaharKhiz Region of Gilan Province. In Fig. 4, site suitability for MSW landfill site selection in SaharKhiz Region is continuous. According to the ecological and socioeconomic parameters, unsuitable sites are scored zero and others are marked between zero and one. One of the most important differences among maps of Boolean

Table 4 List and description of ecological criteria for landfill site selection [29–33]

Ecological criterion	Description
Slope	The area's slope, as a key factor in the production of surface runoff, facilitates pollutant transfer from the landfill into the groundwater and surface water resources. In fact, lands with high slope cause more drilling costs for landfilling. According to studies conducted in other countries on landfill site selection for MSW, slope values of less than 15% are appropriate and those of more than 15% are unsuitable
Flooding	Iran's Department Of Environment (IDOE) regulations for MSW landfill site selection stipulate that floodplains with a return period of 100 years are unsuitable for selection. Therefore, regions that are located outside the scope of floodplains are identified and assessed as suitable areas
Distance from fault	The areas located far away from active faults are suitable areas for landfilling. In fact, faults increase the possibility of groundwater pollution by leachate. According to the IDOE regulations, a distance of more than 200 m from active faults is suitable for MSW landfill site selection
Soil texture	Since lower recharge rates will protect groundwater resources from contamination, locations having impermeable soils provide a more suitable condition for landfill construction. Soil textures such as clay and silt clay are the best alternatives for the locations of landfill due to their low permeability. However, soil properties such as soil composition, hydraulic conductivity, and permeability are contributing factors in transporting contaminants into groundwater. They are therefore key elements that need to be considered for landfill site selection
Geological formations and their structural features	Compact geological formations (without discontinuities) like igneous, metamorphic, and sedimentary rocks have low permeabilities (hydraulic conductivities). Therefore, these formations are the most suitable for landfill site selection
Distance from surface water resources	Contamination of groundwater resources is one of the major concerns of landfill site selection for MSW. According to the IDOE regulations for the purpose of MSW landfill site selection, a minimum distance of 1000 m from surface water (lakes and rivers) must be considered as the suitable distance
Distance from the coast	Coastal areas are regions along which groundwater level is at or near the land surface; also their population density is high. Therefore, distance from coastal regions should be included in landfill site selection studies. According to the IDOE regulations, landfills must have a minimum distance of 1000 m from coastal area
Groundwater depth	Afzali et al. [31] in Khomeinishahr of Isfahan Province considered the depth of more than 10 m vertical distance above the water table as the suitable depth for landfill site selection. Considering the fact that in SaharKhiz Region, depth of groundwater table is close to the surface, so for the sake of aquifer vulnerability, a depth of more than 10 m was selected as the optimal depth
Distance from protected areas and wetlands	Protected areas are sections that have ecological value in terms of protection. These areas are selected to preserve, rehabilitate, and restore the life of plants and animals which have values regarding the biodiversity and genetic diversity. Therefore, according to the IDOE regulations, landfills at a distance of less than 1000 m from protected areas are not allowed

logic and Fuzzy logic approach can be mentioned as being discrete and continuous structures, respectively. Figure 3 shows the final map resulted from Boolean logic, and Fig. 4 shows result from Fuzzy standardization of ecological and socioeconomic sub-criteria for MSW landfill site selection in SaharKhiz Region. Table 6 presents final weights and priorities assigned to the ecological and socioeconomic factors using the AHP method for MSW landfill site selection. In this study, the rate of inconsistency was calculated to be 0.05 in the Expert Choice software environment for ecological and socioeconomic parameters; therefore, judgment consistency was acceptable and weighting was conducted

correctly by experts. Table 7 presents the result of different classes for landfill site selection using Boolean logic. Table 8 shows the result of different classes for landfill site selection using Fuzzy logic based on WLC.

6 Conclusions

In this study, Boolean logic and Fuzzy logic approaches based on WLC were used to select MSW landfill sites in accordance with IDOE regulations. If the ecological and socioeconomic parameters of SaharKhiz Region, such as distance from areas with soil liquefaction, land ownership,

Table 5 List and description of socioeconomic criteria for landfill site selection [29–33]

Socioeconomic criterion	Description
Distance from population centers	Locating a landfill near residential areas can cause negative environmental impacts including odor, noise caused by vehicles and mechanical equipment, traffic, and dust. According to IDOE regulations, landfills at a distance of less than 1000 m from population centers are not allowed
Land use	In studies addressing landfill site selection, barren areas and pastures with very low plant density are suitable for landfill site selection; in turn, forests, rangelands, farmland, and residential areas are the least suitability for landfill
Distance from industries and gas pipeline	Since industrial and mining activities in the vicinity of the landfills increase risks of soil erosion and sedimentation, and as leachate percolation to the surface water and groundwater resources may lead to water pollution, landfills at a distance of less than 1000 m from industrial areas are not allowed
Distance from power transmission lines	In order to prevent damage to power transmission lines, landfills at a distance of less than 1000 m from transmission lines are not allowed
Distance from access roads	Along with MSW landfill site selection process, availability of the access roads to the most important substructures of MSW landfill site selection must be taken into consideration. Moreover, landfill site should not be far from the access roads since this results in higher road construction cost. Based on the IDOE regulations, a 300 m distance from the access roads for MSW landfill site selection will be considered suitable

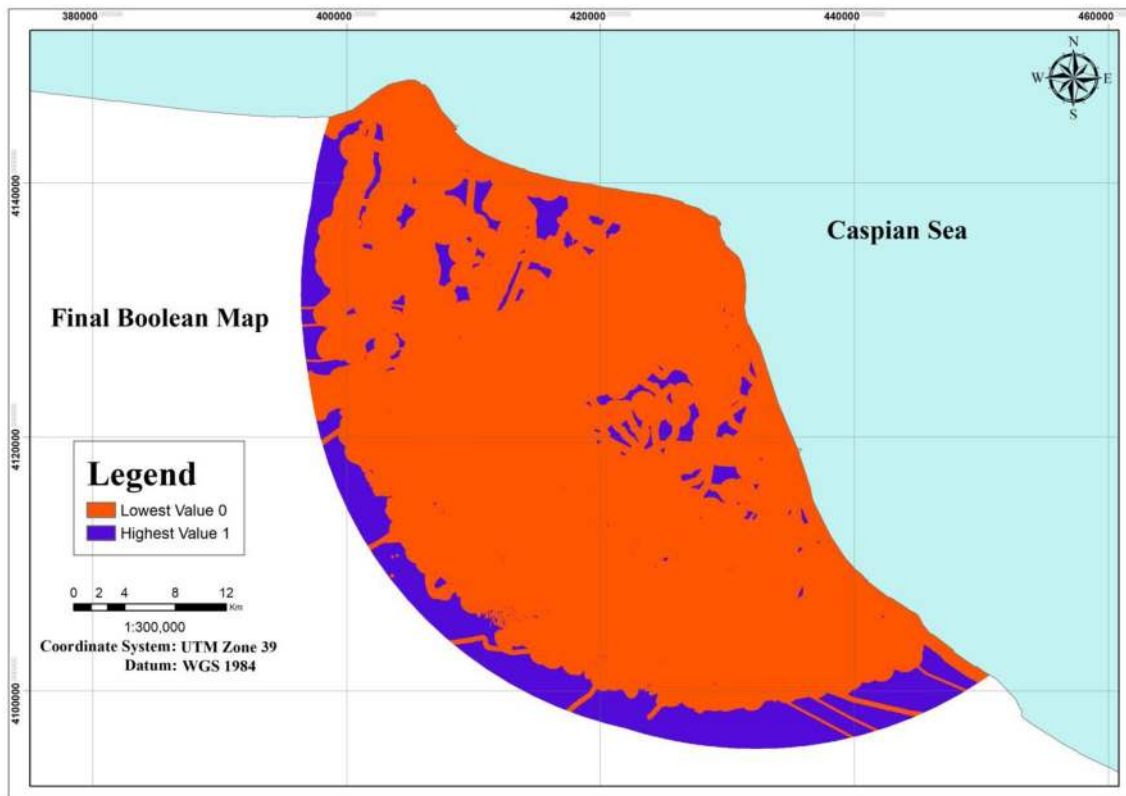


Fig. 3 Final map resulted from Boolean logic

future land use, groundwater vulnerability, and meteorological factors, such as rainfall, are used to determine landfill suitability and assessment, results will have high accuracy. In this study, comparison of Boolean logic and Fuzzy logic approaches, based on WLC, was employed

to locate MSW landfill sites. Fuzzy logic allows standardization of ecological and socioeconomic sub-criteria in a continuous structure, and due to the wide range of suitability classification (between zero and one), experts' ability for the selection of the most appropriate place

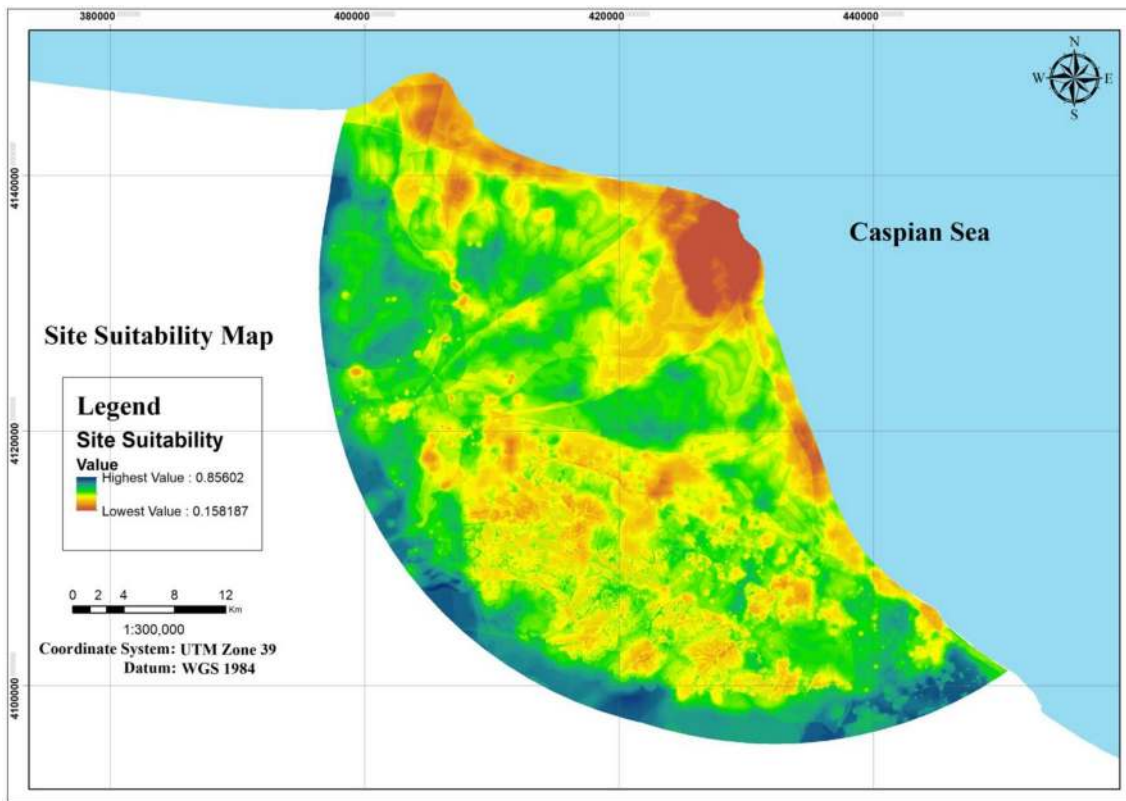


Fig. 4 Final map resulted from Fuzzy logic based on WLC

Table 6 Final weights and priorities assigned to the ecological and socioeconomic factors using AHP method

Ecological and socioeconomic factors	Weight
Groundwater depth	0.135
Distance from lake	0.089
Soil texture	0.085
Distance from protected areas	0.082
Geological formations and their structural features	0.076
Distance from wetland	0.070
Distance from population centers	0.068
Distance from river	0.067
Slope	0.063
Distance from coastal areas	0.056
Flooding	0.046
Land use	0.043
Distance from industries	0.031
Distance from access roads	0.030
Distance from fault	0.026
Distance from gas pipeline	0.018
Distance from power transmission line	0.016
Total	1

Table 7 The result of different classes for landfill site selection using Boolean logic

Class of suitability	Area (km ²)	Percentage of area (%)
Suitable	239.53	14.72
Unsuitable	1387.57	85.28
Sum of suitability	1627.10	100.00

Table 8 The result of different classes for landfill site selection using Fuzzy logic based on WLC

Class of suitability	Area (Km ²)	Percentage of area (%)
Very high	256.65	15.77
High	466.23	28.65
Moderate	573.20	35.23
Low	281.73	17.31
Very low	47.83	2.94
Sum of suitability	1627.10	100.00

for MSW plays a more important role than the Boolean logic. In fact, results from landfill site selection, using this method, have more compatibility with the environmental capacity of SaharKhiz Region (ecological and socioeconomic capacity). Given the ecological sensitivity of the aquifers in the north of Iran, it is recommended that in future research, both the soil textures types and geological formations permeability should be taken into account for MSW landfill site selection. To increase the accuracy of assessment, 1:10,000 scale maps should be produced. This study also recommends taking into account the rules and regulations of the Environmental Protection Agency (EPA) for MSW landfill site selection. In order to provide more accurate results based on ecological and socioeconomic parameters, it is suggested that the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method be used. Its results can be compared with results obtained from Boolean logic and Fuzzy logic based on WLC.

Acknowledgements We would like to express our thanks from Dr. Reza Samadi at energy efficiency organization of Iran for his great consultation in this project.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest and no funding for this project.

Ethical approval Data gathered during questionnaires were anonymized.

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