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Macro and micro geo-spatial environment consideration for landfill site selection in Sharjah, United Arab Emirates

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Abstract Waste management involves various procedures and resources for proper handling of waste materials in compliance with health codes and environmental regulations. Landfills are one of the oldest, most convenient, and cheapest methods to deposit waste. However, landfill utilization involves social, environmental, geotechnical, cost, and restrictive regulation considerations. For instance, landfills are considered a source of hazardous air pollutants that can cause health and environmental problems related to landfill gas and non-methanic organic compounds. The increasing number of sensors and availability of remotely sensed images along with rapid development of spatial technology are helping with effective landfill site selection. The present study used fuzzy membership and the analytical hierarchy process (AHP) in a geo-spatial environment for landfill site selection in the city of Sharjah, United Arab Emirates. Macro- and micro-level factors were considered; the macro-level contained social and economic factors, while the micro-level accounted for geo-environmental factors. The weighted spatial layers were combined to generate landfill suitability and overall suitability index maps. Sensitivity analysis was then carried out to rectify initial theoretical weights. The results showed that 30.25% of the study area had a high suitability index for landfill sites in the Sharjah, and the most suitable site was selected based on weighted factors. The developed fuzzy-AHP methodology can be applied in neighboring regions with similar geo-natural conditions.

Keywords Waste management · Remote sensing · Macro and micro · Fuzzy membership · AHP · GIS

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Introduction

Solid waste management challenges municipal authorities to account for all processes of handling waste materials while considering health codes and environmental regulations. Landfills can present several health and environmental problems due to the treatment of different wastes in substantial amounts. Residents near landfills are exposed to possible inhalation of landfill gas and particles, ingestion of contaminated food as well as drinking water from polluted wells with leachates, and skin contact with contaminated soil (Davoli et al. 2010). Therefore, one of the most sensitive factors in waste management is selection of the most suitable landfill site. Other factors that affect landfill site selection are availability of land, a country's regulations,

environmental awareness, and increasing amounts of waste production, especially in fast-growing countries (Khan and Samadder 2014; Abd-El Monsef 2015; Soltani et al. 2015). Selection of the most appropriate location for a landfill usually includes social, economic, and environmental aspects (Demesouka et al. 2013; Ghobadi et al. 2013), and social factors have been considered the greatest obstacle in locating disposal facilities. For instance, the overwhelming social sentiment of "not in my back yard" often pressures decision makers involved in the site selection process (Şener et al. 2006; Wang et al. 2009). The influential economic factors include the costs associated with development and operation of a landfill site, while the environmental factors relate to the biophysical environment and ecology of the surrounding area (Wang et al. 2009).

Clearly, many factors are involved in landfill site selection decisions and need to be integrated properly through different techniques. Multicriteria decision analysis (MCDA) is a branch of a general class of models that have been used for several waste management problems including selection of locations for waste sites (Merkhofer and Keeney 1987; Briggs et al. 1990). These models optimize decision-making problems utilizing several criteria. The integration of a geographic information system (GIS) and MCDA creates an ideal tool for selection of landfill sites since a GIS can manage large volumes of spatial data from many sources and provides efficient presentation of the data, while MCDA produces consistent weighting of potential landfill areas considering a number of criteria. During the past two decades, several studies were conducted on landfill site selection using GIS modeling (Wang et al. 2009; Şener et al. 2010; Abujayyab et al. 2016). Research has shown that GIS modeling for landfill selection usually involves four main stages: (1) determination of constraints and factors involved in the selection process, (2) preparation and processing of spatial data where various data models (raster and vector) can be integrated and analyzed within a specific procedure, (3) generation of a suitability index map based on certain decision rules, and (4) implementation of sensitivity analysis to define the robustness of the generated model. Different methods have been implemented for landfill site selection, such as the ordered weighted average (Gorsevski et al. 2012), weighted linear combination (Mahini and Gholamalifard 2006), fuzzy logic methodology (Ekmekçioĝlu et al. 2010), and analytical hierarchy process (AHP) (Rahmat et al. 2017).

AHP is an analytical tool that enables researchers to assign weights to tangible and intangible criteria. This method has been widely used in landfill selection processes and is based on three principles: decomposition, comparative judgment, and synthesization of priorities (Saaty 1977). Generally, AHP has the ability to be used subjectively while minimizing inconsistency in judgment, which is considered as one of its advantages over other available methodologies. Also, AHP is usually implemented to provide practical solutions for multicriteria decision-making problems (Chang et al. 2008). The difficulty of this method of landfill site selection usually appears in the estimation of the input data and their preferences. Nonetheless, several studies have been performed in different countries on the selection of landfill location using AHP methodology (Kara and Doratli 2012; Alavi et al. 2013; Yunus et al. 2015; Abujayyab et al. 2016). In these studies, the most important component was determination of the various factors affecting the landfill site selection process. The AHP technique was then utilized to properly assign weights to the various factors based on their importance for landfill location. For example, Yunus et al. (2015) implemented a landfill site selection process by integrating AHP and GIS for spatial data processing and then determined the most optimal location for a future landfill site. Likewise, Şener and others (2010) combined GIS with AHP to address the complexity of landfill site selection in Konya, Turkey.

Following assignment of weights to the various factors based on importance, the different classes within each factor must be evaluated properly according to their suitability for landfill location. Fuzzy membership can be used to determine how suitable a certain location is for being selected as a landfill site. Fuzzy membership values range from 0 to 1, with 0 being the least suitable and 1 being the most suitable. Fuzzy logic provides a wide set of fuzzy membership functions, which includes linear, large, small, and near functions (Cox 1999). Fuzzy membership functions are selected for each factor to best describe its contribution in the landfill site selection process. The advantage of using fuzzy membership for evaluating the various classes in each factor is that it can appropriately handle the uncertainty and imprecision involved in converting the linguistic and non-numeric descriptions into degrees of membership (Cox 1999). In a study conducted by Ekmekçioĝlu et al. (2010) on disposal method and site selection, the authors performed fuzzy multicriteria analysis based

on its ability to manipulate vague qualitative data as well as present suitability results with different membership degrees. In another study, Chang et al. (2008) utilized GIS in combination with fuzzy multicriteria decision making for landfill site selection. Their analysis was performed by first utilizing GIS for the initial screening process and then implementing fuzzy multicriteria decision making for the final selection of the most suitable sites for landfill location.

In the present study, the city of Sharjah in the United Arab Emirates (UAE) was considered as a potential landfill site. Such a study is important for Sharjah due to its rapid population growth, city expansion, and urbanization, which collectively threaten to overwhelm the current landfill. The current municipal landfill is located in the Al Saj'ah area of the city; it opened in 2009 and processed around 2.5 million tons of waste during its first year. For urban planning purposes, it is important to begin considering a new municipal solid waste landfill location to support city expansion and increased waste. Thus, this study sought to

a. Investigate a suitable location for a landfill site in the city of Sharjah, considering the existence of only one current landfill site alongside the significant population increase and urbanization.
b. Identify and map related economic, social, and geo-environmental factors and their weighted contribution in determining the most appropriate landfill site.
c. Utilize fuzzy membership along with weighted overlay analysis to prepare a landfill suitability index map.
d. Perform a sensitivity analysis and identify the most sensitive factors in the selection of a landfill site.

This study responds to the need to find another suitable location for a landfill to support waste management in Sharjah (Al-Ruzouq et al. 2017). In addition, the results of this study address a gap in the literature by presenting a methodology that can be applied in neighboring regions with similar geo-natural conditions.

This paper provides a description of the study area, followed by a discussion of the proposed methodology applied to prepare the landfill suitability index map, including the methodology framework, spatial data collection and processing, and fuzzy membership and weighted overlay elements. The paper then presents the major findings and a discussion of the results and

concludes with a summary of the findings and recommendations for future research.

Study area

The study area was the city of Sharjah, located in the United Arad Emirates. Sharjah City occupies approximately 235.5 km^2 of the total area of the UAE, which is 83,600 km^2. The city is located along the northern coast of the Arabian Gulf and has a central coordinate of 25.3° N and 55.5° E. Figure 1 shows the location of the study area and surrounding region. Sharjah has experienced significant population growth in the last few decades and thus is considered a fast-growing city in the UAE with a population of 1.4 million per 2015 census records. This population growth and urbanization in the city, particularly during the last 10 years, drives the need to find another suitable location for a landfill to support waste management (Al-Ruzouq et al. 2017).

The geomorphologic features of the study area are mainly characterized by mountains, alluvial planes, and sand dune fields (Elmahdy and Mohamed 2014; Abdelfattah and Pain 2012). In terms of weather conditions, Sharjah has typical Middle East weather, with an average temperature of 40 °C during the summer and a comfortably mild winter with an average temperature of 30 °C. The average rainfall of the city is approximately 100 mm/year, and rainfall typically does not exceed 40 mm/year in dry years and 200 mm/year in rainy years (Shanableh and Al-Ruzouq 2014).

Materials and methods

This section presents the methodology framework, spatial data collection and processing, and AHP weights and fuzzy membership functions utilized in this study.

Methodology framework

Various studies (Chang et al. 2008; Gbanie et al. 2013; Rezazadeh et al. 2014; Yunus et al. 2015) have shown that social and economic factors are relatively more significant than environmental factors in determining landfill sites. Based on this finding, the selected factors in this study were grouped into macro- and micro-levels. The macro-level group contained economic and social factors, while the micro-level group consisted of
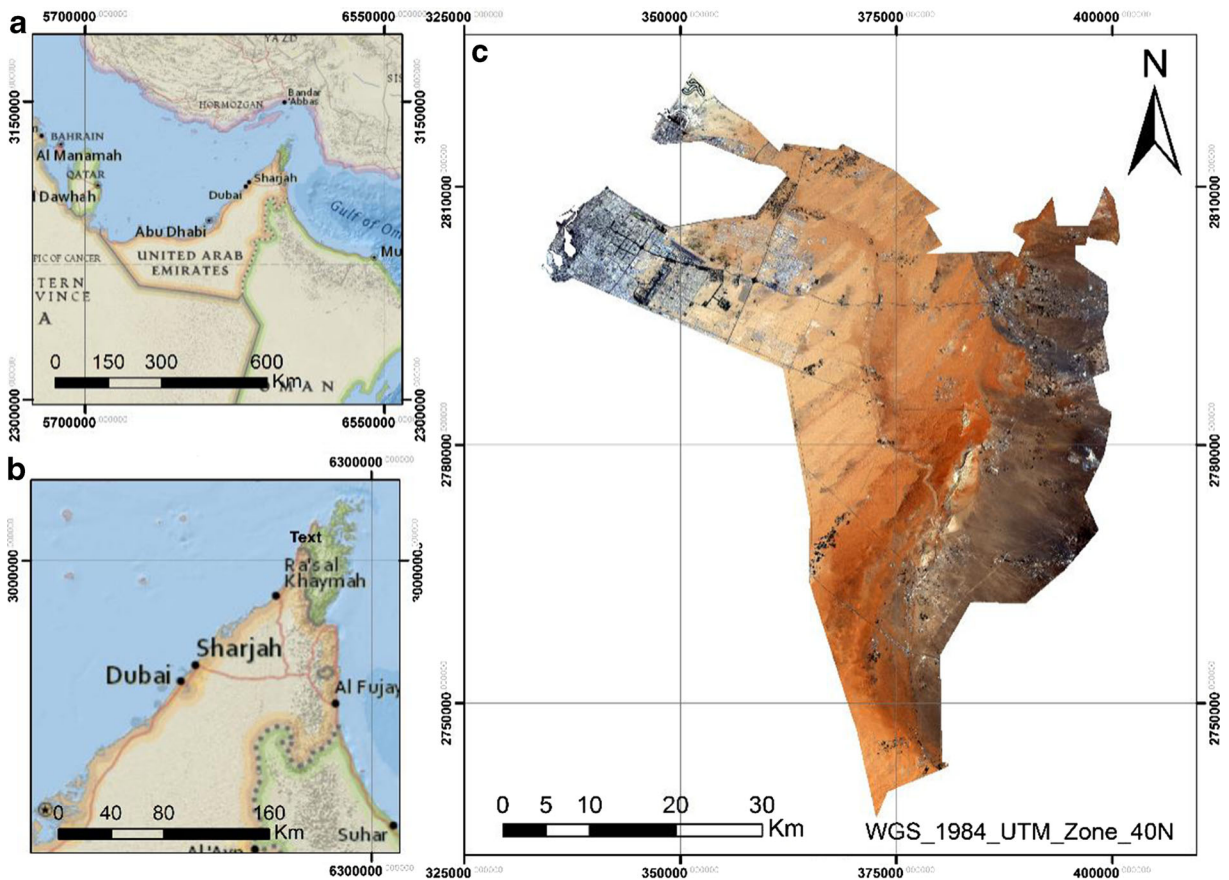
Fig. 1 Study area location: **a** map of the United Arab Emirates and surrounding area, **b** map of the northern emirates, and **c** map of the city of Sharjah

environmental factors. Criteria weights were determined based on the importance of the criteria for landfill site selection and were obtained based on expert judgment, relevant studies, and country legislation. The present work used a fuzzy-AHP methodology in association with GIS. The selection process included mainly determination of fuzzy membership for the various factors along with their respective weights by developing an AHP pair-wise comparison matrix that accounted for any inconsistencies. The process resulted in a final suitability map that distinguished the potential areas based on their suitability index class for landfill site selection.

The different steps involved in preparation of input maps to generate an overall landfill suitability index map along with the considered factors are shown in Fig. 2. The process of landfill site selection started with data collection and preparation. Landsat-8 images were obtained and downloaded from the United States Geological Survey (USGS) website and prepared for

processing after mosaicking and clipping using ArcMap 10.1. Data processing involved mainly digitizing notable features such as residential areas, roads, and hydrology streams. It also involved performing Euclidean distance and image classification. The influencing factors were categorized into macro- and micro-levels as discussed previously, and then, the AHP methodology was implemented for pair-wise comparison. AHP has a scaling system that ranges from 1 to 9. Table 1 shows the adopted Saaty's scale for AHP modeling.

Weighing of the various factors was organized in a square matrix with a value of 1 in all of its diagonal elements. The relative importance of the factors was then determined from the principal eigenvalue and the corresponding normalized right eigenvector of the AHP comparison matrix. To check for consistency of the matrix with the assigned values, consistency measurements were performed through calculating the consistency index, randomized index, and consistency ratio. If the consistency ratio failed to reach a threshold level
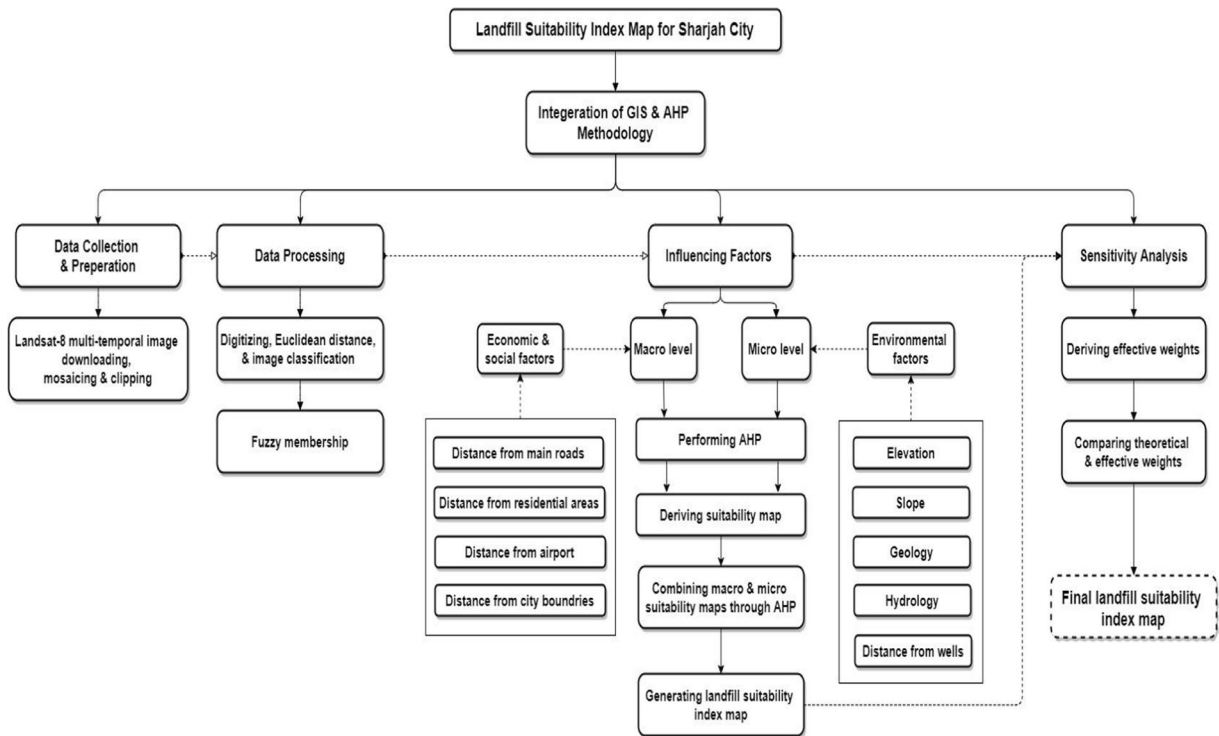
Fig. 2 Flowchart of the implemented methodology and considered factors for landfill site selection

(CR < 0.1), the factors were re-compared to maintain the matrix consistency. The following formulas were used for consistency measurements (Saaty 1977):

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (1)$$

$$RI = \frac{1.98 \ (n-1)}{n} \qquad (2)$$

$$CR = \frac{CI}{RI} \qquad (3)$$

where CI is the consistency index, RI is the randomized index, CR is the consistency ratio, and n is the order of the compression matrix.

After generating a suitability index map for the macro- and micro-levels, researchers assigned each map a certain weight that reflected its contribution to the landfill selection and then combined the maps utilizing the map algebra tool in ArcMap 10.1. In order to refine the initial weights assigned to the influencing factors, a sensitivity analysis was performed and a new landfill suitability index map was developed based on the obtained effective weights.

Spatial data collection and processing

The study considered utilization of Landsat-8 satellite images with 11 spectral bands. The spatial resolution of

Table 1 Adopted Saaty's scale system used in AHP model (Saaty 1977)

Intensity of importance	Definition	Explanation
1	Equal importance	Equal contribution of two activities
2	Intermediate value between 1 and 3	Compromise is needed
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Intermediate value between 3 and 5	Compromise is needed
5	Strong importance	Experience and judgment strongly favor one activity over another

the first 9 bands was 30 m, while bands 10 and 11 had 100-m spatial resolution. The date of acquisition of the satellite images was August 11, 2016. Landsat-8 satellite images were chosen due to their time availability, accessibility, and multispectral bands along with their moderate spatial resolution.

The input maps included herein show the distance from main roads, residential areas, the airport, city boundaries, and wells, along with the elevation, slope, geology, and hydrology of the area. These data were collected, prepared, and processed in a GIS environment. Some of the parameters were collected and implemented directly in the analysis, such as topology (obtained from USGS), hydrology streams, and well location (obtained from Sharjah Electricity and Water Authority [SEWA]). Parameters such as geology, slope, main roads, and residential areas were processed before being included in the analysis. Geology layer was generated through supervised image classification while considering data provided by SEWA as a ground truth. Slope layer was derived from the topology layer, while main roads and residential areas were determined by digitization using polylines and polygons.

AHP factor weights and fuzzy membership

For the process of landfill site selection, nine factors were selected, grouped in macro- and micro-levels, and then utilized for pair-wise comparison, as shown in Tables 2 and 3. It is important to note that two factors from the macro level—distance from airport and distance from boundaries—were considered as constraints for selecting landfill location. For consistency measurements, the required consistency was satisfied (CR < 0.1) with a CR value equal to 0.0036 and 0.0250 for the macro- and micro-levels, respectively. The macro-level included the main factors influencing the process of landfill site selection; therefore, it was given a higher

Table 2 AHP pair-wise comparison matrix: macro-level factors

Criterion	DMR	DRA	DA	DB	Weight
DMR	1	1/2	2	2	0.257
DRA	2	1	4	3	0.477
DA	½	1/4	1	1	0.128
DB	½	1/3	1	1	0.138

DMR distance from main roads, *DRA* distance from residential areas, *DA* distance from airport, *DB* distance from boundaries

Table 3 AHP pair-wise comparison matrix: micro-level factors

Criterion	E	S	G	H	DW	Weight
E	1	1/2	1/2	1/2	1/3	0.097
S	2	1	1/2	1	1/2	0.159
G	2	2	1	2	1/2	0.241
H	2	1	1/2	1	1/2	0.159
DW	3	2	2	2	1	0.345

E elevation, *S* slope, *G* geology, *H* hydrology, *DW* distance from wells

weight compared to the micro-level when generating the overall suitability index map. The highest weights were associated with distance from residential areas, distance from roads, distance from wells, and the geology layer since those are the main factors influencing landfill site selection (Gorsevski et al. 2012; Gbanie et al. 2013).

An explanation of each of the factors considered in this study is provided below.

Distance from main roads Distance from roads is a crucial factor in the selection process of a landfill site due to esthetic concerns and construction costs (Uyan 2014). Roads should connect to the site to decrease costs of making new road connections. Also, this aspect must be considered to avoid any landfill vehicles interfering in the current traffic and to facilitate transportation. The near fuzzy membership type was selected to represent distance from roads for landfill suitability. Low degrees of membership were assigned to the very close and very far areas from the main roads. In contrast, areas with intermediate distance from roads were given the highest membership degrees, as shown in Table 4. A road suitability map was then generated based on the selected fuzzy membership and the weight of the layer, as shown in Fig. 3.

Distance from residential areas Landfill sites should be located at certain distances from residential areas due to odor, esthetics, dust, noise, reduced property value, and health concerns (Tagaris et al. 2003). According to Giusti (2009), there is a relation between proximity to landfill sites and ill health. Also, an increased risk of birth defects and cancers exists for residents living close to landfill sites. Usually, buffers may range between 150 and 5000 m for residential areas based on a country's laws and regulations. In this study, a buffer zone of 1000 m was considered as a minimum. The residential areas were determined through digitizing Landsat-8

Table 4 Criteria weights and sub-criteria fuzzy membership functions of the macro and micro levels

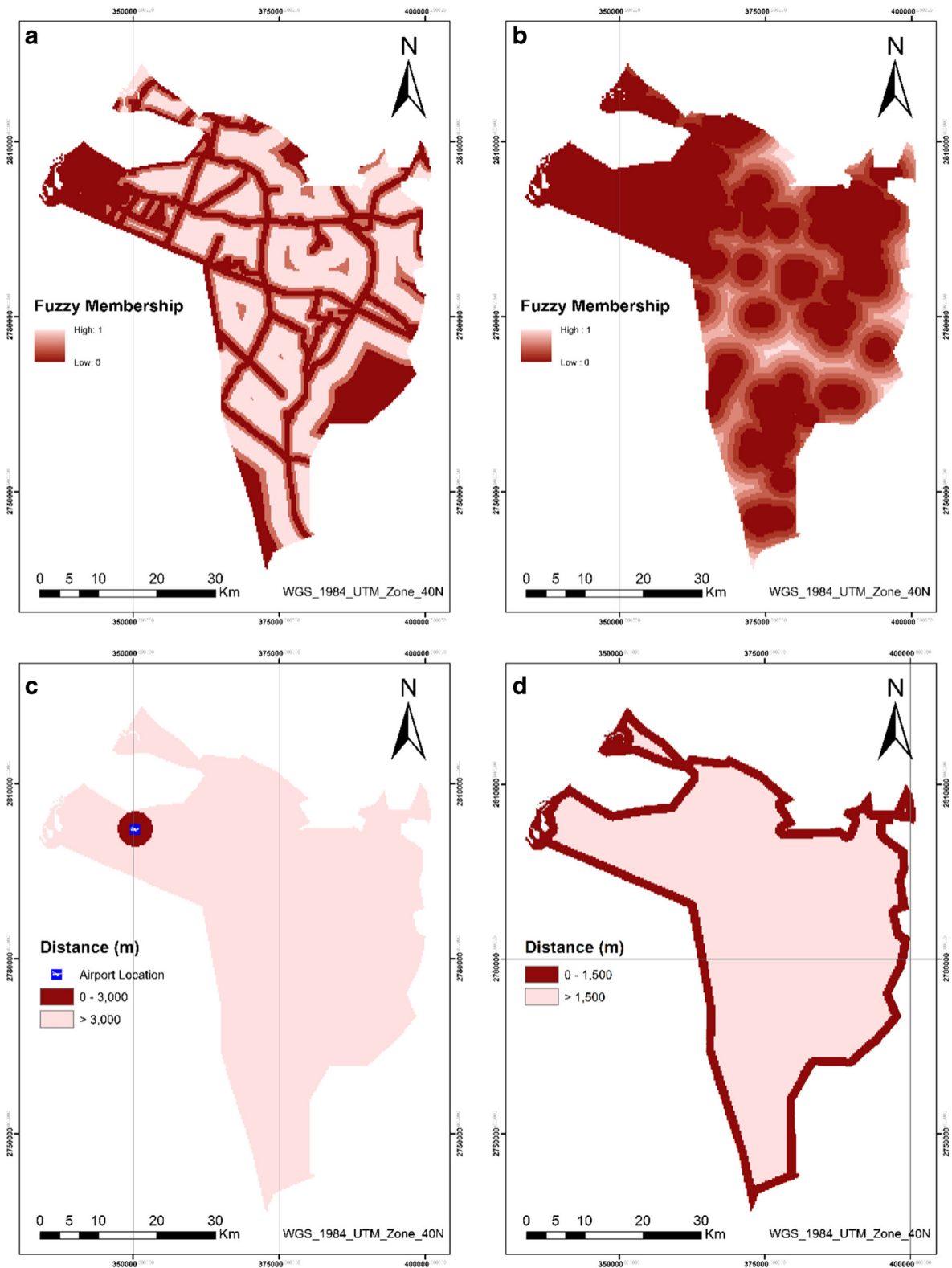| Factor Level	Criteria	Criteria Weight	Sub-Criteria	Fuzzy Membership
Macro	Distance from main roads	25.7%	< 500 500–1000 1000–2000 2000–3000 3000–4000 4000–5000 5000–6000 > 6000	
	Distance from residential areas	47.7%	< 1000 1000–2000 2000–3000 3000–4000 4000–5000 5000–6000 6000–7000 7000–8000	
	Distance from airport	12.8%	< 3000 > 3000	
	Distance from city boundaries	13.8%	< 1500 > 1500	
Micro	Elevation	9.7%	0–50 50–100 100–200 200–300 300–400 > 400	
	Slope	15.9%	0–2 degree 2–5 degree 5–10 degree 10–15 degree 15–20 degree > 20 degree	
	Geology	24.1%	Limestone Vegetation Alluvium Sand	
	Hydrology	15.9%	0–1000 1000–3000 3000–5000 5000–7000 > 7000	
	Distance from wells	34.5%	0–300 300–500 500–1000 1000–2000 2000–3000 > 3000	

Fig. 3 Suitability index map for macro-level factors: **a** main roads, **b** residential areas, **c** airport constraint, and **d** boundary constraint

images with 30-m resolution. Euclidean distance was then applied to the digitized map and a new reclassified map was generated. The degrees of membership of the various classes were represented by a linear increasing fuzzy membership function according to their suitability for landfill location (Table 4).

Distance from airport Based on a country's laws and regulations and previous relevant studies, landfill sites should be located away from an airport. In this study, a buffer zone of 3000 m around the Sharjah airport was considered a restricted area and was assigned zero membership degree. Any area located farther than 3000 m from the airport was considered a suitable location and received a full membership degree equal to 1 (Table 4 and Fig. 3).

Distance from city boundaries Based on a country's laws and regulations, a landfill should be located sufficiently far from the boundaries of a city. In this study, a minimum of 1500 m from the Sharjah city boundaries was considered in the landfill selection process (Fig. 3).

Elevation Elevated lands increase construction costs and could become a burden for vehicles transporting waste to landfill sites (Gbanie et al. 2013). Elevation in the city of Sharjah was divided into six different classes. The suitability of the various elevation classes was represented by a linear decreasing membership function, as shown in Table 4. Sharjah has a slight to moderate elevation, and areas with less than 200 m were considered the most suitable for landfill location (Fig. 4).

Slope Land slope contributes to the landfill selection process due to its impacts on soil water content, surface and subsurface flow, runoff rates, and erosion potential (Gorsevski et al. 2012). It is a basic parameter for constructing and operating landfill sites. Very steep areas and very flat areas are considered unsuitable for landfill location due to the cost of leveling and the risk of drainage runoff (Gbanie et al. 2013). In this study, the slope was derived from the digital elevation model and expressed in degrees. The slope layer was reclassified into six classes, and a near fuzzy membership type was selected to represent the suitability of the various classes within the slope layer, as shown in Table 4. Areas that are very flat and very

steep were considered unsuitable for locating the landfill and therefore were given zero degree of membership.

Geology Field studies, consultations with SEWA personnel, and relevant literature studies were conducted to generate a geology map that basically reflects the surface soil layer for the study area. The geology map was developed through a supervised image classification technique. The different soil formations in the study area were grouped into four classes: limestone, vegetation, alluvium, and sand, which covers most of the area (Fig. 4). Limestone, vegetation, and alluvium are considered unsuitable for landfill sites due to their potential for water adsorption (Şener et al. 2010). Sandy soil has percolation potential and therefore was considered moderately suitable (Table 4). It is important to note that proper replacement of the soil upper layer should be considered before locating a landfill in sandy soil to prevent leachates from percolating down to the ground water.

Hydrology The hydrology factor considered the main water streams indicating the surface water in the city of Sharjah. Water streams were located by SEWA. Surface water contamination is a major concern in landfill site selection, and a landfill should be located far away from any body of water (Gbanie et al. 2013). A hydrology suitability map was generated by applying the Euclidean distance function to measure the outward distances from the water buffer zones (Fig. 4). The area within 1000 m from water streams was considered a restricted zone and was given zero membership degree. A linear increasing fuzzy membership function was utilized to represent the suitability of the area for landfill location considering distance from water streams (Table 4).

Distance from wells To protect groundwater wells from runoff and leaching of a landfill, the proximity of a landfill to groundwater wells becomes a crucial consideration (Chang et al. 2008). The locations of groundwater wells in the study area were obtained from SEWA. A restricted area of 300 m from each groundwater well was given zero membership degree. Higher degrees of membership were assigned to areas far from the wells. A linear increasing fuzzy membership function was used to represent the suitability of the various areas based on the distance from wells for the landfill site (Table 4 and Fig. 4).
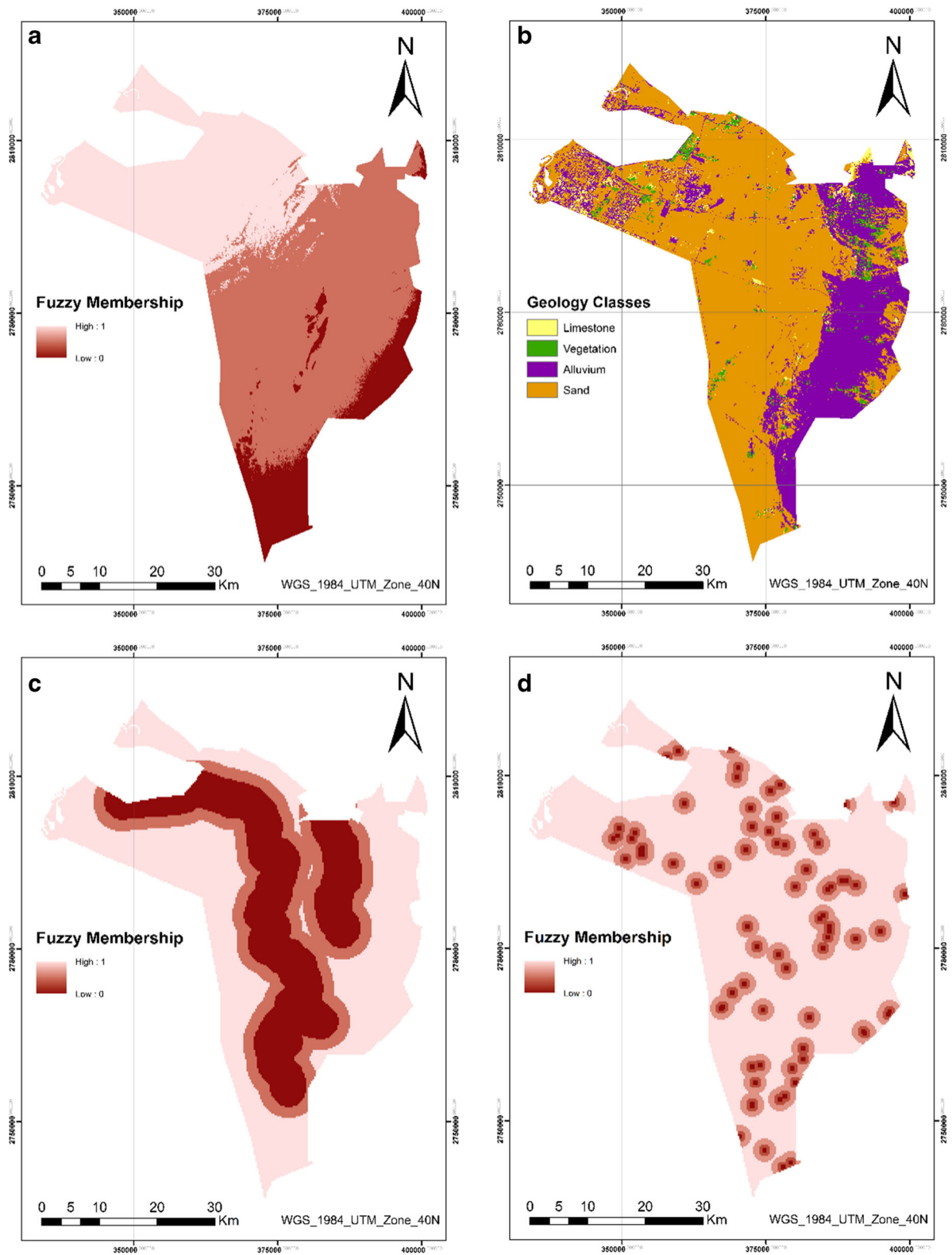
Fig. 4 Suitability index map for micro-level factors: **a** elevation, **b** geology, **c** hydrology, and **d** distance from wells
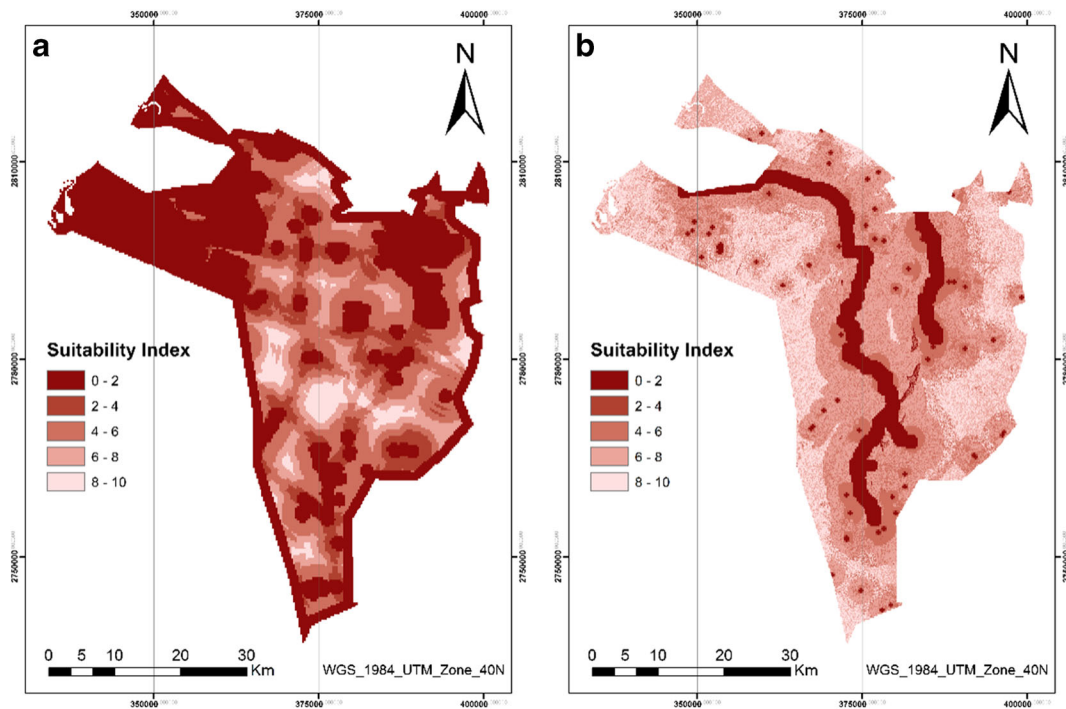
Fig. 5 Suitability index map: **a** macro-level and **b** micro-level

Table 4 summarizes the weights attached to the selected criteria and the fuzzy membership of each factor. It is important to note that the sub-criteria were represented by the most appropriate fuzzy membership function, with zero membership degree for the least suitable areas and full membership degree for the most suitable areas.

Results and discussion

This section discusses the generation of landfill suitability index maps for the macro- and micro-levels. These maps were then combined and an overall suitability index map was developed. Finally, a sensitivity analysis was performed to rectify the initial weights associated with the influencing factors, and then, a final landfill suitability index map was obtained.

Landfill suitability index map

The fuzzy-AHP methodology described earlier was applied to the macro- and micro-level factors, and then, a final suitability map was generated utilizing the weighted overlay tool. The factors were grouped into two levels due to their distinguishable

contribution to the landfill selection process. It was decided that assigning weights for factors similar in nature would be more reasonable than evaluating all the factors together. Such categorization would result in better processing of data and higher refinement of the results. The macro-level factors led to the most suitable sites, and then, the micro-level factors helped refine the initial results accordingly.

A module that contained the spatial layered maps with their respective sub-criteria was developed individually for the macro- and micro-levels. The module was used to generate the suitability index map for each factor through multiplying the weight of the factor by its sub-criteria fuzzy membership; then, aggregated cell values for the different criteria were used to produce a suitability index map for the macro- and micro-levels (Fig. 5). The macro-level was assigned 70% of the total weight for generating the suitability index map. Meanwhile, a weight of 30% was reserved for the micro-level factors. As illustrated previously (Fig. 2), both maps were then combined to produce an overall suitability index map. The suitability map showed that 3.25% of Sharjah City had a very high suitability index for landfill location, while 19.98% had a high suitability index, 19.34% had a moderate suitability index, 0.82% had a low suitability index, and 56.61% had a very low suitability index.

Table 5 Comparison between initial weights and effective weights of the macro- and micro-level factors

Factor level	Criterion	Initial weight	Effective weight			
			Minimum	Maximum	Mean	Standard deviation
Macro	Distance from main roads	25.65	11.00	61.00	30.27	7.50
	Distance from residential areas	47.74	0.00	72.00	32.81	22.73
	Distance from airport	12.83	0.00	37.00	19.85	4.91
	Distance from city boundaries	13.78	0.00	37.00	17.08	8.74
Micro	Elevation	9.67	4.00	31.00	9.42	4.30
	Slope	15.89	6.00	50.00	17.97	5.67
	Geology	24.09	7.00	51.00	19.50	6.18
	Hydrology	15.89	0.00	44.00	14.34	8.45
	Distance from wells	34.47	15.00	108.00	38.78	13.35

Sensitivity analysis

In geographical analysis, studying the effects of variations of the inputs on the outputs of that analysis is known as geographical sensitivity analysis. Sensitivity analysis includes map removal sensitivity that measures the sensitivity of removing one or more parameters from the suitability analysis in the final suitability map (Lodwick et al. 1990). Meanwhile, single-parameter sensitivity identifies the impact of each parameter on the final suitability map (Napolitano and Fabbri 1996). In this study, a single-parameter sensitivity analysis was carried out to compare the initial weights assigned to the influencing factors for landfill selection and the effective weights obtained from the suitability index map. In other words, the single-parameter sensitivity analysis was performed to assess the impact of each factor on the final landfill suitability map. The effective weights of the parameters were calculated using the following equations (Napolitano and Fabbri 1996):

$$LSI = W_{macro} ((DMR_W \times DMR_r) + (DRA_W \times DRA_r) + (DA_W \times DA_r) + (DB_W \times DB_r)) \tag{4}$$

$$+ W_{micro}((E_W \times E_r) + (S_W \times S_r) + (G_W \times G_r) + (H_W \times H_r) + (DW_W \times DW_r))$$

where LSI is the landfill suitability index, DMR is the distance from main roads, DRA is the distance from residential areas, DA is the distance from airport, DB is the distance from boundaries, E is the elevation, S is the slope, G is the geology, H is the hydrology, and DW is the distance from wells.

$$W_{eff} = \frac{P_w \times P_r}{LSI} \times 100 \tag{5}$$

where W_{eff} is the parameter's effective weight, P_w and P_r are the parameter's weight and rate, respectively, and LSI is the landfill suitability index as calculated in eq. (4).

The statistics of the computed effective weights for the macro- and micro-level factors are shown in Table 5. The effective weights for most factors diverged from the initial assigned theoretical weights. The effective weights of distance from main roads, distance from airport, distance from boundaries, slope, and distance from wells were increased by 4.62, 7.02, 3.30, 2.08, and 4.31, respectively. In contrast, distance from residential areas, elevation, geology, and hydrology were decreased by 14.93, 0.25, 4.59, and 1.55, respectively. Therefore, it was concluded that distance from residential areas and distance from wells had the highest impact on landfill site selection at both the macro- and micro-levels. Results of the effective weights obtained from the single-parameter sensitivity analysis were used to generate a new landfill suitability index map for the city of Sharjah, as shown in Fig. 6a. Thus, the coverage of each suitability index class was changed. This final suitability index map showed that 7.47% of Sharjah City had a very high suitability index, 30.25% had a high suitability index, 5.67% had a moderate suitability index, 0% had a low suitability index, and 56.61% had a very low suitability index.
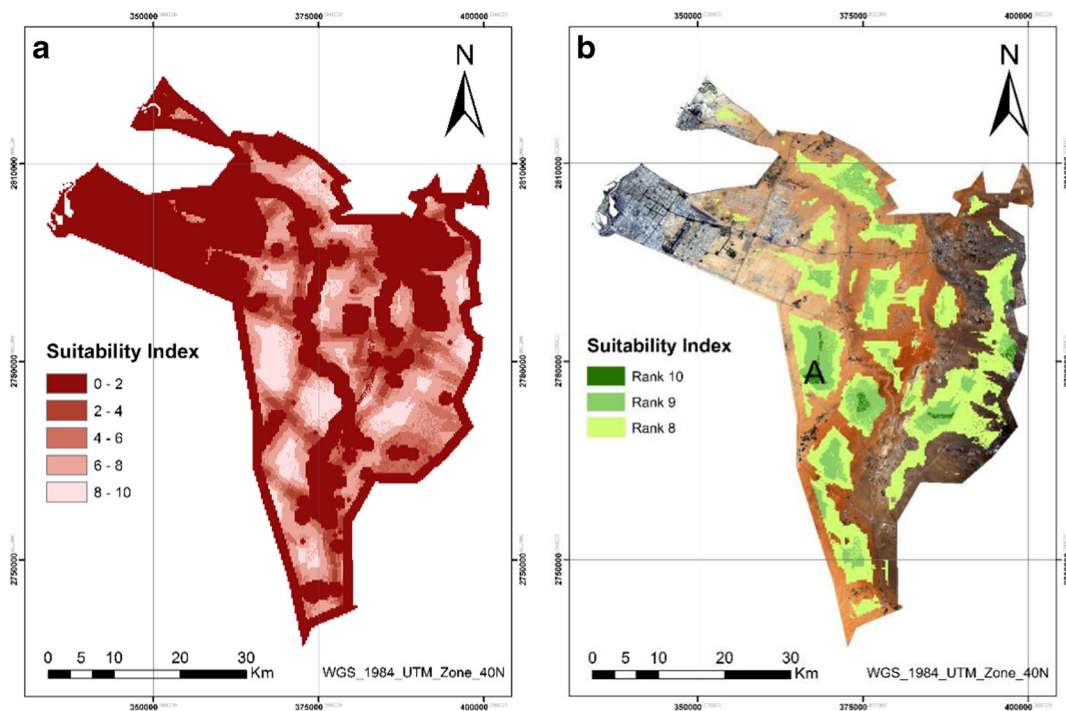
Fig. 6 Final landfill suitability index map after sensitivity analysis: **a** locations with all suitability indexes and **b** locations with very high suitability index

The most suitable sites for locating a landfill in the city of Sharjah are displayed in Fig. 6b. The map includes sites with a suitability index of 8, 9, and 10. These sites had the most appropriate features for a landfill location after considering the influencing factors and constraints maintained in this study. Ultimately, location (A) in Fig. 6b was selected as the most suitable site for the landfill due to its closeness to the main roads; suitable distance from residential areas, the airport, city boundaries, hydrology streams, and wells; relatively low elevation and slope; and geological characterization as sandy soil. In addition, the selected location covers a reasonable area compared to other suitable sites for locating the landfill.

Conclusion and future work

Selecting the most appropriate location for a landfill is a challenging process in waste management, and improper selection can result in health problems and underground water contamination. The selection process usually includes social, economic, and environmental considerations. Managing and controlling these aspects clearly increase the significance of the process. The

primary objective of this study was to develop and utilize a fuzzy-AHP methodology for landfill site selection in the city of Sharjah. The combination of fuzzy membership functions and the AHP technique in a GIS environment allowed for mapping landfill suitability indexes of different areas. This methodology can be applied in neighboring regions with similar geo-natural conditions.

The outcomes of this research present the most suitable areas for landfill sites in Sharjah. A sensitivity analysis was conducted to account for deviation between the theoretical and effective weights of the influencing factors, and coverage of each suitability index class varied accordingly. The results showed that 7.47% of the total area in Sharjah has a very high suitability index for landfill location. Utilizing fuzzy membership for suitability representation of the various classes within each factor is important to account for the uncertainty in modeling problems such as landfill site selection. For future work, considering more factors that influence the process of landfill site selection and determining factor weights based on surveys completed by experts could lead to more reasonable weighing criteria. In addition, utilization of high-resolution images could significantly improve the selection process for suitable

sites. Finally, better validation of results may be achieved through collecting ground truth data.

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