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النمذجة المستندة إلى نظم المعلومات الجغرافية للاختيار المناسب لمواقع دفن النفايات

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الخلاصة

هذا البحث يقدم تقييم لنموذج معايير نظام المعلومات الجغرافية مع الأخذ بعين الاعتبار جوانب الاستدامة لبحث مدى ملائمة موقع الردم على أساس طريقتين للتحليل؛ النوعية والكمية. للتحليل النوعي لاختيار المواقع ينقسم الى 3 مستويات: المجموعات الاستدامة (البيئية، الاقتصادية، الاجتماعية)، ثم كل مجموعة تحتوي على معايير نظام المعلومات الجغرافي، ولكل معيار تقسيمات توصيفية. قدم التحليل النوعي لاختيار مردم معتمدا بالتصميم على نظام المعلومات الجغرافي الى ثلاث سيناريوهات لتعكس اهميه جوانب الاستدامة. السيناريو الاول يميل للمعايير البيئة والسيناريو الثاني يعطي اهميه متساوية لمجموعات الاستدامة في حين ان السيناريو الثالث يركز على الجانب الاقتصادي والاجتماعي. العملية الهرمية التحليلية بالتكامل مع نظام المعلومات الجغرافية قدمت حساب الثقل للمعايير وقيمة نقاط لتقسيماتها لكل معيار. معدل كتلة النفايات الصلبة في هذي الدراسة تم تقديره بمعدل 1.59كيلوجرام لكل فرد باليوم في الكويت. تم تصفية نتائج التحليل النوعي بعد أخذ نتيجة التحليل الكمي لتعطي هيكل متكامل يشكل استدامه الموقع على أساس تفضيلات المكان والحجم. نتيجة تحليل النوعي المأخوذة من نظام المعلومات الجغرافي رتب المواقع موفقا لمايلي: الاعلى (فوق 90 ٪)، متوسط (50 الى- 90 ٪)، منخفض (اقل من 50 ٪)، وغير مناسب تماما (0 ٪). توضح نتائج التحليل الكمي ان المناطق المستدامة تحتاج ما بين 3 الى 18 كيلومتر مربع وفقا لتصميم مردم يستقبل النفايات لفترة 20 عام. تم استخدام العاملان (عمق المردم وحده الأوزان المتراصة) لتحديد المساحة المحتاجة لتصميم مردم نفايات المستدام بالاعتماد على معدل كتله النفايات الصلبة. نتيجة سيناريوهات التحليل النوعي والكمي حددت 3 مناطق (في جنوب الكويت ومنطقه في الشمال). في حين ان باقي المناطق المرشحة لتكون مرادم كانت قريبه من المناطق السكنية والطرق الرئيسية بشكل عام. هذا البحث أوجد المساحة المحتاجة لسنة إضافية لمكب النفايات المصمم خصيصا لاستقبال النفايات لمدة 20 عام بحيث كان يتراوح مابين 0.2 الى 1 كيلومتر مربع بالاعتماد على معدل وحده الأوزان المتراصة 8،26 كيلو نيوتن لكل متر مربع وعمق المردم.

GIS-Based Modeling for Appropriate Selection of Landfill Sites

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ABSTRACT

This paper provides a macro-evaluation of a geographic information system (GIS) criteria analysis model to select the appropriate landfill sites based on quality and quantity analysis. The qualitative analysis breaks down into three levels of evaluation. The 1st level is sustainability groups (environmental and socioeconomic), 2nd level includes GIS criteria, and 3rd level has classes for each criterion. The quality analysis provides three scenarios to reflect the importance of sustainability aspects. An analytical hierarchal process (AHP) integrated with GIS data provides weights and scores for criteria and their classes. The rate of solid waste generation for Kuwait has an average of 1.59 kg per capita per day. The quality analysis from GIS-based modeling revealed that the sites were ranked as highly (>90%), moderately (50–90%), lowly suitable (< 50%), and unsuitable sites (0%). The results of the quantity analysis demonstrated that sustainable areas need between 3 and 18 km^2 for landfills designed to last 20 years. Two factors, landfill depth and compacted unit weight, were used to determine the area needed to design a sustainable landfill based on the rate of solid waste generated. The quality and quantity analyses of the three scenarios provided three significant sites (south of Kuwait and one site north of Kuwait). The remaining candidate sites were close to urban areas and major roads. The area needed per year for landfills designed for over 20 years ranged between 0.2 and 1.0 km^2 based on the average compacted unit weight, 8.26 KN/m^3, and landfill depth variable.

Keywords: Geographic Information System, landfill sites, waste quantity and quality, environmental, socioeconomic, analytical hierarchal process, solid waste.

hierarchal process (AHP) is a multicriteria decision analysis method that used to reduce the complex process to a series of simple levels to provide an optimum solution (Malczewski, 1999; Ohman et al., 2007). The AHP was earlier introduced by Saaty (1980) to set the weights for criteria by a pairwise comparison method. The integration of GIS and AHP is a good approach to solve and reduce the complexity of selecting sites for landfills (Alanbari et al., 2014; Al Raisi et al., 2014; Basagaoglu et al., 1997; Chen et al., 2010; Minor & Jacobs, 1994; Nas et al., 2010; Saeed et al., 2012; Sener et al., 2006; Siddiqui et al., 1996). ArcGIS is software that has the capability to analyze, manipulate, and display outcomes. MSW disposal includes reuse, recycling, and recovery. The less environmentally preferable option, is landfill disposal. Nonetheless, it is still the most common practice of MSW disposal globally (Hoornweg & Bhada-Tata, 2012).

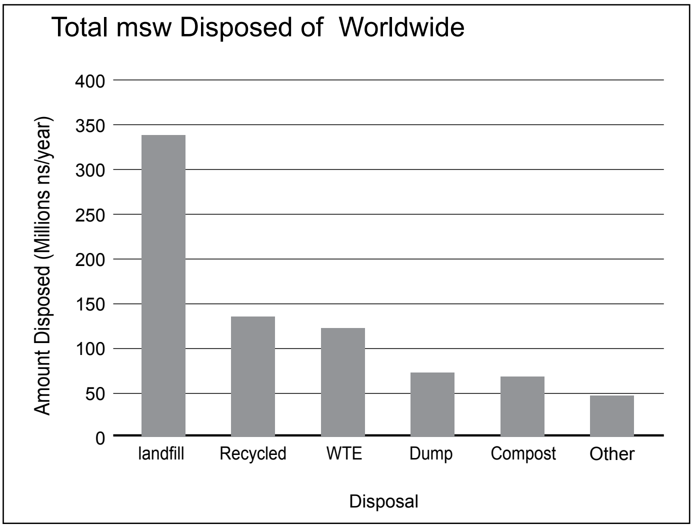

Figure 1 Options for MSW Disposal worldwide (Source: Hoornweg & Bhada-Tata, 2012)

MUNICIPAL SOLID WASTES AND LANDFILL SITES IN KUWAIT

Landfill disposal is the main disposal method of MSW in Kuwait, though small amounts of MSW are recycled (Al-Jarallah & Aleisa, 2014; Hamoda, 2016; Koushki et al., 2002, 2004). Table 1 shows the three baseline studies of MSW composition in Kuwait (Al-Jarallah & Alesia, 2014; Koushki & Al-Khaleefi, 1998; Hamoda, 2016). Those studies found that about half of the MSW in Kuwait is organic content. Kuwait has 16 dumping sites; 3 are active and the others are closed. None of these 16 dumping sites have a sanitary design. Figure 2 shows the location of the opened and closed dumping sites. All the dumping sites are concentrated in the eastern and western areas of Kuwait which quite near from residential areas. Dumping sites occupy 45.5 km^2 of land in Kuwait, which is expected to be 60 km^2 in 2025 (Alsulaili et al., 2014; Industrial Bank of Kuwait, 2010).

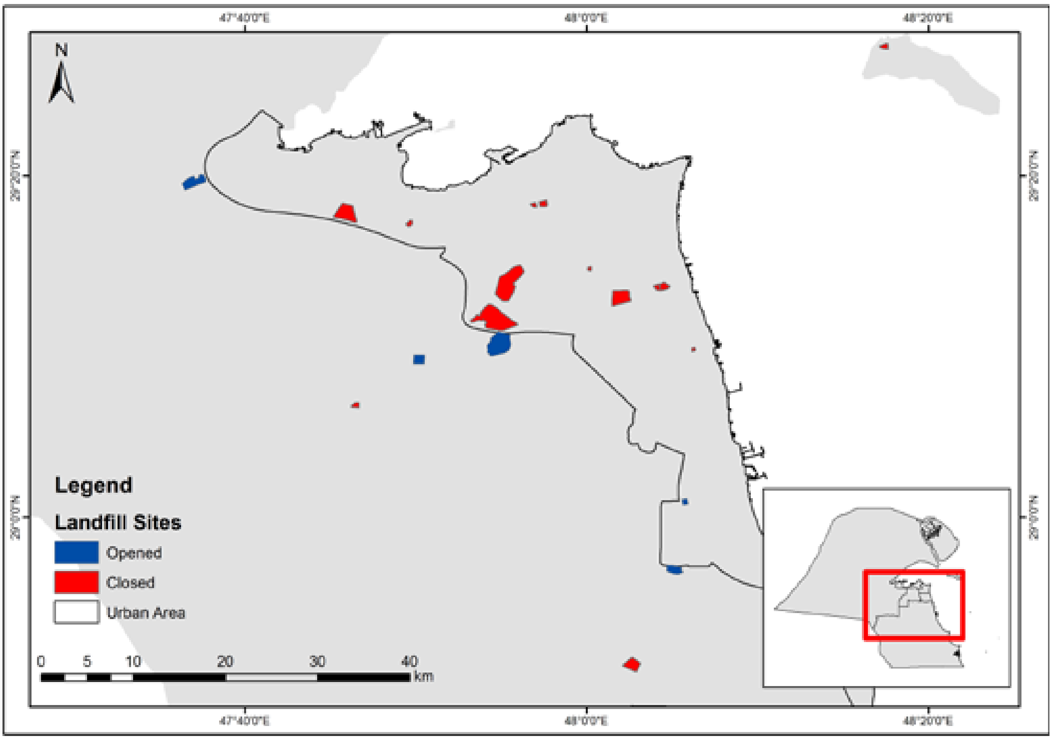

Figure 2 Closed and Open Dumping Sites in Kuwait

Table 1: Composition of MSW in Kuwait

Waste Types	**Al-Jarallah & Aleisa (2014)**	**Koushki & Al-Khaleefi (1998)**	**Hamoda (2016)**
Wood and sanitary	10.05%	N.A	5%
Paper and corrugated fibers	15.07%	18.60%	8.00%
PET bottles and film	18.19%	13.40%	10.00%
Organic	45.80%	51.10%	55.00%
Metals	3.95%	5.00%	9.00%
Glass	6.09%	4.50%	4.00%
Others	N.A	7.40%	9.00%

Figure 3 shows population and MSW data (Kuwait Central Statistical Bureau, 2014). As shown in the figure, both the population and MSW generation have been growing. The population grew by 58% and MSW generation by 77% between 2004 and 2014. The average MSW generation per capita per day increased from 0.96 to 1.44 kg/p/day. . The predicated total solid waste mass can determined from equation (y1) in figure 3.

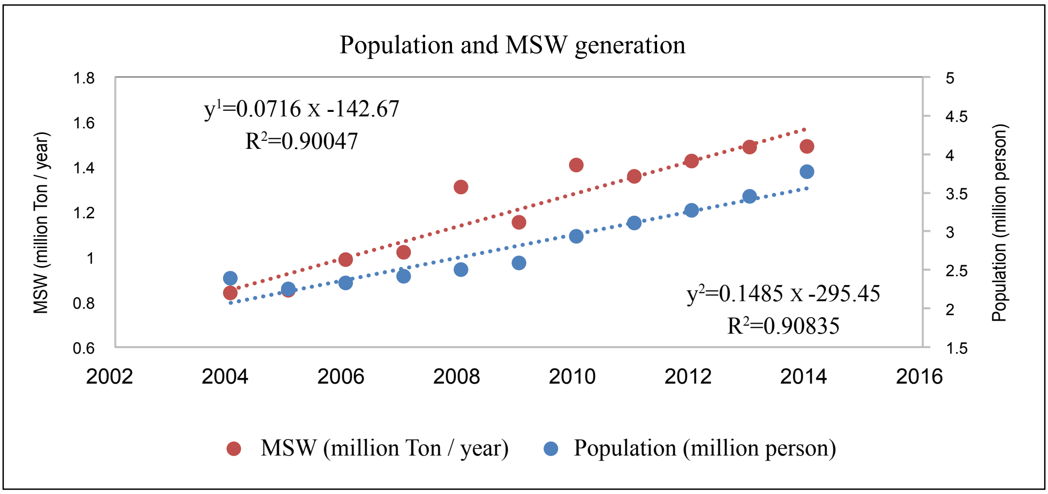

Figure 3 Population vs. MSW generation between years 2004 and 2014

Unit Weight (KN/m^3) and Mass of MSW (Tons)

According to the United Nations Environment Program (UNEP, 2005), MSW densities vary between 700 and 1,000 kg/m^3 (0.7 tons/m^3 to 1.0 tons/m^3) after compaction on-site. According to the Mississippi Department of Environmental Quality (2016), the compacted MSW density is 750 to 1,250 lb/yr^3 (0.445 ton/m^3 to 0.742 ton/m^3). Hanson et al. (2010) reported that compaction density of MSW in the field ranges between 5.7 KN/m^3 and 8.2 KN/m^3 (0.57 tons/m^3 and 0.82 tons/m^3) depending on moisture content and seasonal variations. In this paper, average densities of compacted MSW between 0.65 and 1.0 tons/m^3 are considered in this study.

Multicriteria Decision Analysis and GIS Criteria

Integrating multicriteria decision analysis (MCDA) into the GIS framework can provide proper processes and classification by turning data into numeric based on the influence of factors in the site selection analysis (Khan & Samadder, 2014; Saeed et al., 2012). The GIS framework is a powerful tool that can deal with spatial decision-making data. Saaty (1980) developed the pairwise comparison method within the framework of the AHP to find relative importance weights. The pairwise comparison method in the AHP was performed alongside GIS for the selection of a suitable landfill site (Siddiqui et al., 1996). In the context of MCDA, many methods have been used to find weights, but the advantage of the pairwise comparison method proposed by Saaty (1980) was over others, such as multicriteria decision analysis, that it allows the decision-makers to establish preferences based on their priorities. The pairwise comparison method developed by Saaty within the context of the AHP has the ability to measure the consistency and relation between variables in a pairwise matrix to achieve the target (AlRukaibi et al., 2016). In this study, criteria were selected based on a review of the literature that had the same circumstances and environmental scope of study (Al-Yaqout et al., 2002; Eskandari et al., 2012; Eskandari et al., 2015; Khan & Samadder, 2014; Kontos et al., 2003; Lunkapis et al., 2010; Nas et al., 2010; Sumathi et al., 2008; Vasiljević et al., 2012). Furthermore, many recommendations for criteria to be considered in this study emerged in a discussion on prioritization with decision-makers in the Kuwaiti government. This study provides alternative, suitable sites for landfills by integrating GIS and MCDA based on the MSW generated within a designated period of 20 years.

The methodological structure for Sustainable, Suitable Sites for Landfills

The mechanisms of landfill site selection in this study depend on two parallel approaches: quantitative and qualitative analyses. Designing the capacity and lifetime span for landfills involves a quantitative analysis. This is a technical approach that has to overcome many obstacles, such as closing a landfill before the expected time and classifying solid waste in the landfill. The qualitative analysis considers the selection factors that influence a landfill site's suitability. Selection factors involve environmental, social, and economic aspects. Overall, the output of the selection of suitable sites for landfills provides the appropriate capacity and the desired criteria in terms of their impact on location of landfill sites.

Quantitative Analysis

this analysis considers the sizes of landfill areas and lifetime spans. The challenging task is to keep a landfill open for receiving a quantity of solid waste for a certain designated period. The analysis used the following parameters as inputs: growth rate of population, uncompacted density, depth of landfill, and solid waste generation rate. Sharma and Reddy (2004) used equations (1) and (2) to estimate the volume of waste generated and calculate the required area for a landfill.

$$V = \frac{R}{D\,(1-\frac{P}{100})} CV \qquad (1)$$

$$A = \left[\frac{(V)}{d}\right] + 1 \qquad (2)$$

$$where: CV = 1 + \frac{Soil\ Cover\ Thickness}{d}$$

V: volume of compacted solid waste + cover soil (km^3/period)

R: predicted solid waste generated for a certain designated period (kg/period)

D: uncompacted density of solid waste (kg/m^3)

P: percent volume reduction per unit volume achieved from solid- waste compaction

d: landfill depth below the ground (m)

A: landfill area needed (km^2/ period)

Accordingly, for the purpose of this study we developed a graph to estimate the total area of landfill needed for the predicted solid waste mass equation (R) for a 20-year period. Solid waste mass was multiplied by gravity, 9.81, to be expressed in units of KN/period. Equation (1) modified the compacted unit weight (KN/m^3) instead of the uncompacted density, and the soil-cover thickness was assumed to be 1 m. Equation (2) was updated by adding 1 km^2 as a buffer around landfill sites to protect the surrounding areas. Two variables were used as inputs: 1) the compacted unit weight and 2) the depth of the landfill below ground. Alternative depths were proposed between 5 and 25 m below ground.

Qualitative Analysis

The selection of suitable sites for landfills is a complex problem that necessitates a comprehensive structure, such as the AHP, that can break down the factors influencing the hierarchy selection. The qualitative analysis is a GIS-based model for separating the sites into 4 significant categories, unsuitable, lowly suitable, moderately suitable, and highly suitable sites, based on a set of criteria. the target of qualitative analysis is to identify the most suitable sites for selection. This study is significant because it selects factors related to aspects of sustainability. According to the sustainability classification, environmental and socioeconomic factors are the main criteria that characterize suitable sites for landfills. Each criterion can be measured in order to evaluate the site selection problem. The criteria allow rating of sites for finding sustainable landfill-suitable sites (SLSS) based on qualitative analysis. The quality analysis for GIS based model provides 3 scenarios to reflect the importance of sustainability aspects. The first scenario leans more on environmental criteria, the second scenario gives equal importance to both sustainability groups, and the third scenario gives more weight to socioeconomic criteria

Integration of the AHP Method and GIS Criteria to Influence Landfill Location

Based on location quality, the qualitative analysis combines the GIS framework with the AHP method to provide an optimal solution for landfill location. The GIS can turn the thematic layer into numerical values that can be further analyzed by GIS processing tools. The AHP is a multicriteria decision analysis method composed of complex selection processes for sorting sustainable landfills into 3 hierarchal levels. The AHP is able to classify the target based on group variables, sets of criteria, and spatial attributes. Then, the pairwise comparison method is used to find the relative importance weights for each aspect at all 3 hierarchal levels. The hierarchal structure consists of 3 levels of evaluation. First, the top hierarchal level has environmental and socioeconomic groups. This level is the target of SLSS. Each group has 4 criteria that represent the second hierarchal level. The environmental group's criteria are 1) depth of the ground to the water table, 2) transmissivity, 3) total dissolved solids (TDS) in groundwater, and 4) groundwater fields. The selection criteria in the environmental group are protecting groundwater quality and quantity from the impact of landfill. Criteria in the socioeconomic group consider the impact of landfill sitting on people and economies. The selection criteria of socioeconomic groups are 1) land cover, 2) residential and urban areas, 3) transportation networks, and 4) elevation slope. The third hierarchal level contains the rating for each criterion classified into 4 classes: a) constraints (unsuitable), 2) low suitability, 3) medium suitability, and 4) high suitability. The constraints class enforces the selection process to extract the unsuitable sites expressed in the form of Boolean logic, where the value of 0 is excluded and 1 denotes candidates (Malczewski, 1999). Suitable sites satisfy the constraints conditions, which are excluded, while the other 3 classes classify the candidate sites. They rank the suitability of sites based on relative importance scores.

GIS Criteria Specification

The process of quality analysis for the selection of an SLSS is carried out based on a set of 8 sustainability criteria: those with high environmental impact and socioeconomic-related factors, such as transportation and residential lands. Some criteria were used based on the recommendation of Al-yaqout et al. (2002) and Moeinaddini et al. (2010), whose studies had a similar scope to this one. Moeinaddini et al. (2010) used the permeability of groundwater as a criterion in landfill selection. The present analysis used the transmissivity criterion instead of permeability to prevent the pollution of groundwater. The criteria in the socioeconomic group have human and economic impacts. For example, the distance of a landfill from roads and residential areas and the land cover are critical factors in the selection analysis that affect the cost of location and transportation of solid wastes (Nas et al., 2008). Additionally, elevation slope is critical for landfill sitting. ArcGIS tools were used to geoprocess the raw data of environmental and socioeconomic criteria in the selection processes. All 8 criteria were designed to be used as GIS map layers with a raster format. The spatial attributes of the data are that they contain raster map layers. Each criterion in the environmental and socioeconomic groups has 4 significant classes. They describe and rank the spatial attributes of criteria for the suitability of sites, with one class constrained and 3 classes rating the candidate sites. The classifications are as follows: Class 4 contains high suitability features, class 3 contains medium suitability features, class 2 contains low suitability features, and class 1 represents the unsuitable condition.

Environmental Group Criteria

The environmental suitability of sites for landfills was characterized by depth to water table, groundwater field locations, and physical aspects of the groundwater, such as TDS and transmissivity. The vertical distance from the ground to the water table took priority in this selection process. The water table, TDS, and transmissivity data were provided by the Kuwait Institute of Scientific Research (KISR) and the Ministry of Electricity and Water (MEW). Water table data were represented as point features in ArcGIS software, which measured the depth from the ground to the water table. Water table point feature data were interpolated using Krining interpolation, an interpolation method that estimates depth-to-water-table values for each cell using the value and distance of nearby points (ESRI Inc., 2010). The outcome of interpolation is a raster for water tables with a cell size of 15 by 15 m. To avoid pollution from transportation, depth-to-water-table criteria reject landfills sitting 15 m from ground level, which represents the 1st class (constrained; Eskandari et al., 2015; Moeinaddini et al., 2010). The ranges between 15 m and 60 m, 60 m and 100 m, and greater than 100 m are represented as 2nd class, 3rd class, and 4th class, respectively. The same procedure was carried out for TDS and transmissivity data to represent them as raster data. TDS criteria and transmissivity criteria data were classified for the concentration of groundwater less than 500 mg/l and a cross-section rate of groundwater greater than 1,000 m^2/hr as constrained (1st class). Transmissivity values less than 250 m^2/hr are preferable for the high-suitability class due to the low rate for contamination transport and groundwater. The high-suitability class for TDS represents a concentration of groundwater greater than 5,000 mg/L, which is considered undrinkable and tends to be saline water. The other classes for TDS and transmissivity criteria are shown in Table 5. Groundwater fields (GW fields) are represented as polygon features in ArcGIS software. Multiple buffer zones have been created surrounding groundwater fields by using the buffer tool in the ArcGIS framework. The areas of groundwater fields are constrained (1st class), and the other 3 classes are buffered with 1 km, 4 km, and more than 5 km, respectively.

Socioeconomic Group Criteria

The socioeconomic group utilized 4 criteria due to the availability of data and the preference of decision-makers in the Municipality of Kuwait and the Ministry of Public Works (MPW). A slope criterion was derived from the digital elevation model (DEM) using spatial analysis in ArcGIS. The slope is the percent rate of change between each surrounded cell on the raster map (ESRI, 2010). A slope criterion is relevant to landfill sitting, and a moderate slope is a preferable to avoid excavation and drainage (low slope) and filling up the soil (high slope; Kao & Lin, 1996). Ratings for slope values were adjusted according to Kuwait's terrain, in which the occurrence of unsuitable slope (very high) is greater than 5% and represents the constrained class (1st class). The other 3 classes were classified as follows: 2nd class 0–0.5% (flat slope), 3rd class 0.5–3% (moderate slope), and 4th class 3–5% (high slope). The land cover criterion included government facilities and occupied areas that are restricted only to landfill sitting. The urban area criterion restricted residential areas with buffers of 250 m around them. Land cover and urban criteria were reclassified from a polygon feature to a raster format. The buffer tool in ArcGIS was used to identify the 2nd, 3rd, and 4th classes for land cover and urban criteria. Road criteria were a polyline feature in ArcGIS format and an important factor in the economic selection process. To rate the classes of road criteria, a buffer zone was applied for major roads with values of 2 km, 4 km, and 6 km. The restrictions on road criteria for landfill sitting were to not be located very close to major roads (250 m buffer) and to not be located more than 6 km from major roads. For details, Table 5 briefly describes the criteria, their classes, and their spatial attributes.

Pairwise Comparison Method for GIS Criteria

Relative importance weights are essential for deciding which criteria are more important than others in finding suitable sites for landfills within certain circumstances. The pairwise comparison method in the AHP was used to establish weights for all parameters in the 3 hierarchal levels. The computation of relative weights in the qualitative analysis was carried out for the group level, criteria level, and class level, and the weight scores were determined for all classes belonging to each criterion. The combination of GIS map layers and the pairwise comparison method in the AHP provided the to determine the relative importance in the 3 hierarchal levels by determining scores for classes and criteria and assigning different scenarios for the environmental and socioeconomic preferences.

First, each criterion had 4 classes. The 1st class had a 0 score because it is a constraint class, and the 3 other classes' score values were determined using the pairwise comparison method. For comparison, Saaty's (1980) 9-point scale is indicated in Figure 4, and the 3 classes for each criterion were compared against each other to find their rating scores. For example, based on judgments of decision-makers, if class 2 was much more important (scale: 5) than class 3 for suitable sites, class 3 would be indicated as less important (scale: 1/5) than class 2. The pairwise comparison process was continued for other classes in the same criterion based on judgments of decision-makers. This led to having a pairwise comparison matrix for each criterion that had 3 rows by 3 columns.

The second stage examined 4 criteria regarding environmental aspects and 4 criteria regarding socioeconomic aspects to determine their importance weights. For each group, each criterion was compared against the others to find the relative importance. The high-priority environmental criteria, which were given high importance, were the weights for depth of the water table and groundwater fields. For the socioeconomic group, the main concerns were urban areas and elevation slopes. Comparing the criteria for each group to find their importance weights led to having 2 matrices with the 4 criteria organized in rows and columns.

For the final stage, a pairwise comparison was made between two components, environmental and socioeconomic groups. To provide suitable sites for a landfill, 3 scenarios were run with the following conditions:

1. Environmental factors as more important than socioeconomic factors, at 75% to 25%, respectively
2. Environmental factors as equally important to socioeconomic factors, at 50% and 50%, respectively
3. Environmental factors as less important than socioeconomic factors, at 25% to 75%, respectively

A final check was performed for each matrix by calculating the consistency ratio (CR). Saaty (1980) defined the consistency ratio as the index that represents the randomness of the matrix, CR ≤ 0.1, which indicates that it is acceptable and the comparisons between criteria are consistent. Otherwise, the comparison should be repeated with different preferences (Saaty, 1980).

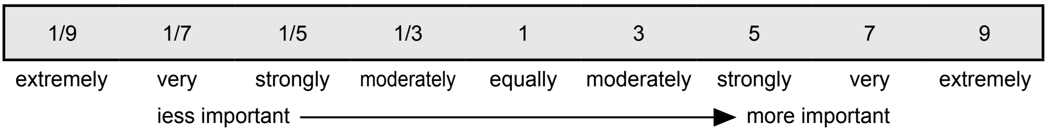

Figure 4 The 9-point rating scale of Saaty's (1980) pairwise comparison

The GIS Model Design

The process of finding suitable sites depended on 8 GIS criteria that were classified evenly for environmental and socioeconomic groups. Each GIS criteria layer has 15 m by 15 m cell size. They were used as inputs in ArcGIS software using a quality analysis procedure to provide GIS outcomes of desired suitability for the landfill site. The significance of suitable sites for landfills in this study was the setup for sustainability preferences. This depends on environmental and socioeconomic group scenarios ($\boldsymbol{S_G}$), and the 3 scenarios provided different visions. For 8 GIS criteria rasters, each criterion had weight ($\boldsymbol{W_n}$) with respect to the other criteria, and criteria were classified into 4 classes. Then, reclassification was done for each class to assign it a score value ($\boldsymbol{x_{nm}}$), shown in Table 5. All constraint classes (1st class) that had a 0 score ($\boldsymbol{C_n}$) were merged by a union tool in ArcGIS to represent unsuitable sites for landfills for all of Kuwait; the rest of the areas were suitable potential locations for landfills. The overlay tool in ArcGIS software was used to find the SLSS. The suitability of a site for a landfill in qualitative analysis was determined by the following equation for each pixel after modifying the suitability equation of Eastman (1999) by adding the scenario's parameter:

$$\mathbf{SLSS} = \sum_1^G \boldsymbol{S_{G,i}} \left(\sum_1^n \boldsymbol{w_n} \cdot \boldsymbol{x_{n,m}}\right) \prod_1^n \boldsymbol{C_n} \quad (3)$$

where G: number of sustainability groups, total of 2 groups

i: scenario number for $S_{G=1,i}$ and $S_{G=2,i}$

S: scenario % for $S_{G=1}$ and $S_{G=2}$

G: number of sustainability groups, total of 2 groups

w: weight assigned for criterion n

n: number of criteria per group

m: number of classes (2nd, 3rd, and 4th classes)

xnm: score value classes (2nd, 3rd, and 4th classes) for criterion n

C: constraint class for criterion x_1 (1st class)

The quantitative analysis provided the required areas for landfills based on growth rate, uncompacted density, depth of landfill, and solid waste rate. The GIS outcomes of SLSS by quality analysis were filtered by the results of the quantitative analysis. Overall, the final sites for landfills were examined for quality sitting (qualitative analysis) and area capacity (quantitative analysis).

GIS Criteria Standardization

The outcomes of the SLSS equation provided a GIS raster map with cells ranging between minimum and maximum values. In order to set a comparable standard, the 3 scenarios were provided by equation (3). The final outcomes were transferred to comparable units based on a percent basis. Equation (4) was used to standardize the suitability of sites in the various scenarios.

$$\mathbf{SLSS}_{\text{scenario}(i)}\ (\%) = \frac{(\mathbf{SLSS}_{\boldsymbol{i}}) - (\mathbf{SLSS}_{\boldsymbol{min}})}{(\mathbf{SLSS}_{\boldsymbol{max}}) - (\mathbf{SLSS}_{\boldsymbol{min}})} * 100 \quad (4)$$

where (i): the number of scenarios

$SLSS_i$: the outcome for SLSS

$SLSS_{max}$: the maximum outcome for SLSS

$SLSS_{min}$: the minimum outcome for SLSS

In the context of standardizing the outcomes for site suitability, the overall classification for the selection of an SLSS was based on the following:

- Unsuitable: [SLSS (i) %] = 0
- Low Suitability: [SLSS(i) %] below 50%
- Medium Suitability: [SLSS(i) %] between 50 and 90%
- High Suitability: [SLSS(i) %] between 90 and 100%

Results of Weighting GIS Criteria

The pairwise comparison method was used for determining the importance weights (W_n) on the criteria level and scores (X_m) on the class level. In the criteria level there were 2 matrices, as shown in Tables 2 and 3, for environmental and socioeconomic groups, respectively. For instance, the pairwise criteria comparison indicated that the depth to the water table was strongly (5 points) more important than transmissivity. Table 4 shows that for each criterion there was a pairwise comparison matrix between classes. The judgments for rating the 3 classes for each criterion depended on decision-makers in the Municipality of Kuwait and the priority for suitable sites for landfills. Based on the pairwise comparison preferences, criteria in both matrices were reliable and consistent, and this satisfied Saaty's (1980) condition for $C_R = 0$. To rate the classes of each criterion, 8 pairwise comparison matrices were set up to determine classes 2, 3, and 4, while class 1 has a score of 0 because it was the constraint. The consistency index (C_R) for pairwise comparison matrices at the class level was below 10%. The evaluation of a criterion and its classes provides weights and score values, as shown in Table 5. Driving criteria leads to defining suitable sites for landfills that have high weights, such as depth to groundwater (W_1: 52%) in environmental groups and the impact of distance to urban areas (W_2: 45%) in socioeconomic groups. Together, the elevation slope and impact of distance to roads has a total weight of 47%. Based on Table 5, the high suitability of the depth to groundwater class is between 15 m and 60 m; digging below ground over 60 m is less suitable due to its association with a high cost of excavation and other water quality issues. The medium suitability class for both groundwater fields and land-cover facilities is between 1 km and 5 km because the impact of this range of buffer is not considered a high indicator for suitability. Overall, the 3 different scenarios provide different visions based on the approaches of the decision-makers. For instance, the 2nd scenario gives equal importance to both groups, while the other scenarios provide high weights for one group over another.

Table 2 Pairwise Comparison Matrix for Environmental Criteria

Environmental	Depth to Water	Transmissivity	TDS	GW Fields
Depth to Water	1.0	5.0	5.0	2.0
Transmissivity	0.2	1.0	1.0	0.3
TDS	0.2	1.0	1.0	0.3
GW Fields	0.5	3.0	3.0	1.0
			Cr	**0.00**

Table 3 Pairwise Comparison Matrix for Socioeconomic Criteria

Socioeconomic	Land cover	Urban	Roads	Slope
Land cover	1.0	0.2	0.3	0.3
Urban	5.0	1.0	2.0	2.0
Roads	3.0	0.5	1.0	1.0
Slope	3.0	0.5	1.0	1.0
			Cr	**0.00**

Table 4 Pairwise Comparison Matrices to Derive the Class Scores for Each Criterion

Depth to Water (m)	**15–60**	**60–100**	**>100**
15–60	1	3	9
60–100	0	1	3
> 100	0	0	1

CR = 0

Land cover (km)	**0–1**	**1–5**	**>5**
0–1	1	0	0
1–5	9	1	3
> 5	7	0	1

CR = 0.07

Transmissivity (m^2 /d)	**<250**	**250–500**	**500–1,000**
< 250	1	2	7
250–500	1	1	4
500–1000	0	0	1

CR = 0

Urban (km)	**0.250–10**	**10 – 20**	**>20**
0.250–10	1	3	9
10–20	0	1	7
>20	0	0	1

CR = 0.07

TDS (mg/L)	**500–1,000**	**1,000–5,000**	**>5,000**
500–1,000	1	1	0
1,000–5,000	2	1	0
>5,000	6	3	1

CR = 0

Roads (km)	**0.250–2**	**2–4**	**4–6**
0.250–2	1	2	9
2–4	1	1	5
4–6	0	0	1

GW Fields (km)	**0–1**	**1–5**	**>5**
0–1	1	0	0
1–5	9	1	3
> 5	5	0	1

CR = 0.03

Slope (%)	**0–0.5**	**1–3**	**3–5**
0–0.5	1	0	0
1– 3	9	1	7
3–5	3	0	1

CR = 0.07

Results for Sustainable, Suitable Landfill Sites

The hierarchal structure of the AHP simplifies the processes of selecting suitable sites for landfills to 3 levels of evaluations by breaking down the concept of sustainability into 2 groups and the factors into influencing criteria that have classes describing the spatial attributes. The setup of 3 scenarios indicates the suitability of sites based on the preferences of decision-makers. Figures 5 and 6 show the GIS criteria outcomes for the environmental and socioeconomic groups, with 4 colors describing the 4 classes. The overlay analysis tool in ArcGIS software used Equation 3 then standardized it using Equation 4 to provide 3 scenarios based on the input of 8 GIS criteria with their score classes and weights. The area has an SLSS index of >= 90%, which is considered a highly suitable site for a landfill. Scenario 1 provides the significant outcomes shown in Figure 7, which are highly suitable sites for landfills close to urban areas, while scenario 3 has large sites in the south of Kuwait. Scenario 2 provides an ideal option, with some areas north and south of Kuwait in addition to sites close to urban areas. Overall, the GIS raster of SLSS outcomes stored 8 layers with their weights based on the various scenario conditions.

Landfill Sizing Capacity Results

The capacity of the area needed was designed based on the compacted unit weight and the depth of the landfill. Figure 8 provides alternative decisions between the two input variables for a 20-year period and suggests that the area desired could be designed for 2 to 17 km^2. The equation for the mass of MSW (R) generated, as shown in Figure 2, was 46.43 million tons for a 20-year period. For instance, if the compacted unit weight was 7 KN/m^3 and the depth was 10 m, then the area needed for landfills with a time span of 20 years would be 7.2 km^2.

Table 5 Final Weights for Criteria and Scores for the Classes of 3 Scenarios Proposed

Group	**Criteria**		**Class Score** x_{nm}	**Criteria Weight (%)**		
				Scenario 1	**Scenario 2**	**Scenario 3**
G_1 : Environmental	Depth to Water (m)		x	39	26	13
	W_1: 52	Class 1 (Unsuitable): < 15	0	Constraint		
		Class 2 (Low Suitability):): > 100	8	3	2	1
		Class 3 (Medium Suitability): 60–100	23	9	6	3
		Class 4 (High Suitability15–60	69	27	18	9
	Transmissivity (m^2/hr.)		x	7.5	5.0	2.5
	W_2 :10	Class 1 (Unsuitable): > 1,000	0	Constraint		
		Class 2 (Low Suitability): 500–1,000	8	0.6	0.4	0.2
		Class 3 (Medium Suitability): 250–500	32	2.4	1.6	0.8
		Class 4 (High Suitability): <250	60	4.5	3	1.5
	TDS (mg/L)		x	7.5	5.0	2.5
	W_3:10	Class 1 (Unsuitable): < 500	0	Constraint		
		Class 2 (Low Suitability): 500–1,000	11	0.8	0.6	0.3
		Class 3 (Medium Suitability): 1,000–5,000	22	1.7	1.1	0.5
		Class 4 (High Suitability): >5,000	67	5.0	3.3	1.7
	GW Fields (km)		x	21	14.0	7
	W_4 :28	Class 1 (Unsuitable): Field area	0	Constraint		
		Class 2 (Low Suitability): 0–1	6	1.3	0.9	0.4
		Class 3 (Medium Suitability): > 5	27	5.7	3.7	1.9
		Class 4 (High Suitability): 1–5	67	14	9.4	4.7
G_2 : Socioeconomic	Land Cover (km)		x	2	4.0	6
	W_1 :8	Class 1 (Unsuitable): Facility area	0	Constraint		
		Class 2 (Low Suitability): 0–1	6	0.1	0.2	0.3
		Class 3 (Medium Suitability): > 5	29	0.6	1.2	1.8
		Class 4 (High Suitability): 1–5	65	1.3	2.6	3.9
	Urban Area (km)		x	11.2	22.5	33.8
	W_2 :45	Class 1 (Unsuitable): Urban zone and 250 m buffer	0	Constraint		
		Class 2 (Low Suitability): >20	6	0.7	1.3	1.9
		Class 3 (Medium Suitability): 10–20	29	3.2	6.6	9.9
		Class 4 (High Suitability): 250 m –10	65	7.3	14.6	22
	Roads (km)		x	5.9	11.75	17.6
	W_3 :23.5	Class 1 (Unsuitable): buffer < 250 m and > 6 Km	0	Constraint		
		Class 2 (Low Suitability): 4 – 6	6	0.4	0.7	1.1
		Class 3 (Medium Suitability): 2–4	32	1.9	3.8	5.6
		Class 4 (High Suitability): 250m–2 and 4–6	62	3.6	7.25	10.8
	Slope (%)		x	5.9	11.75	17.6
	W_4 :23.5	Class 1 (Unsuitable): > 5	0	Constraint		
		Class 2 (Low Suitability): 0–$\frac{1}{2}$	7	0.4	0.8	1.2
		Class 3 (Medium Suitability): 3–5	15	0.9	1.75	2.7
		Class 4 (High Suitability): $\frac{1}{2}$–3	78	4.6	9.2	13.7

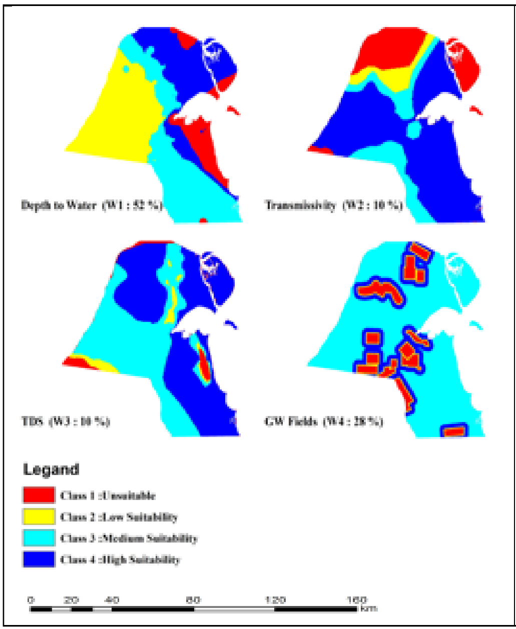

Figure 5 The GIS criteria outcome for the environmental group.

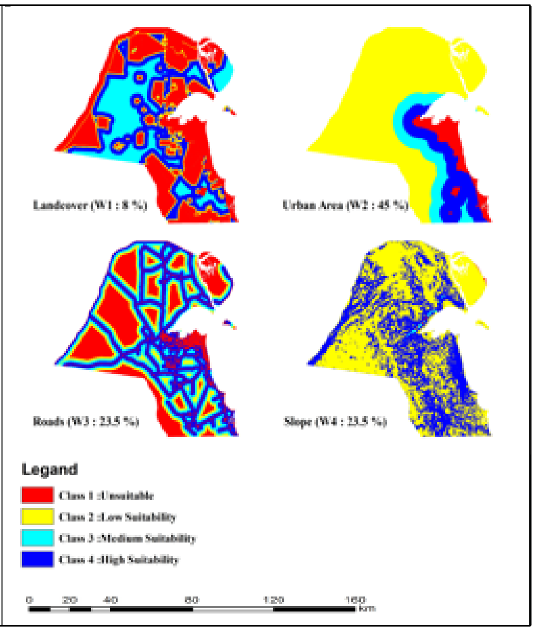

Figure 6 The GIS criteria outcome for the socioeconomic group

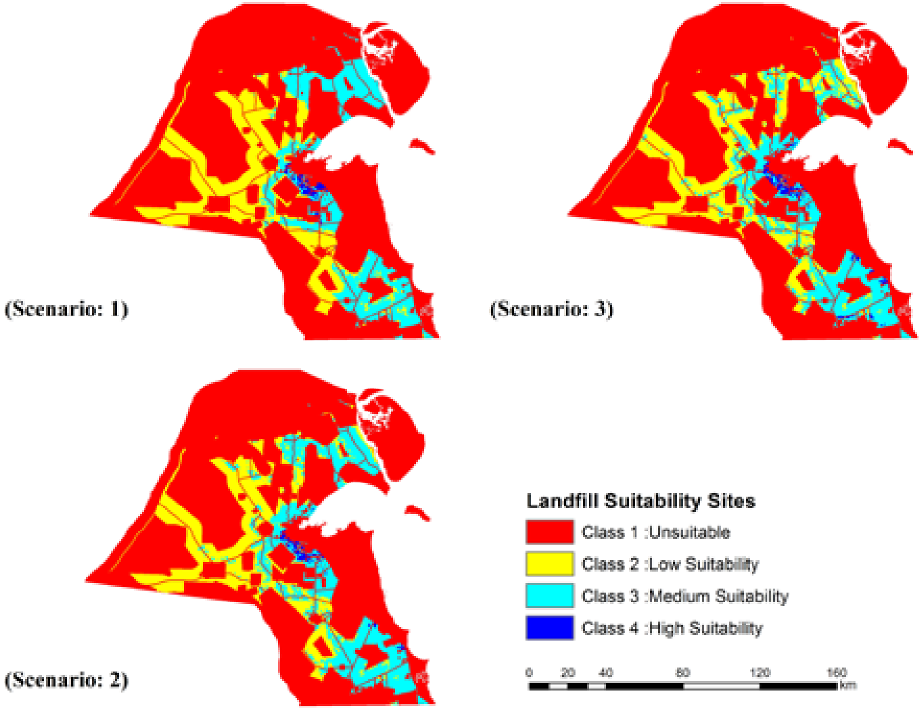

Figure 7 The SLSS outcome for the 3 different scenarios

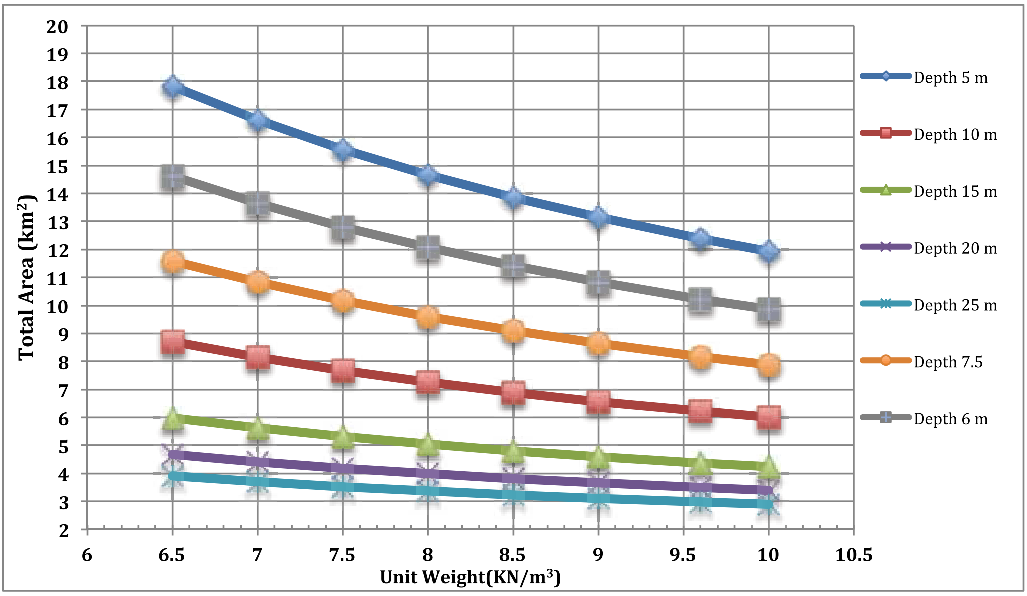

Figure 8 Estimation of landfill area (km^2) for a 20-year life span

The outcomes of SLSS Scenarios

The results of the 3 scenarios developed to investigate sustainable, suitable sites for landfills in areas with an SLSS index value of >= 90% were filtered based on the outcomes in Figure 8. Highly suitable outcomes that required a total area between 2 and 17 km^2 were selected to be sites for landfills. A buffer area parameter was added to the equation for surrounding the candidate landfill sites with 1 km^2 to reach the minimum area needed, which is from 3 km^2 up to 18 km^2 based on two variables, unit weight and depth of landfill below ground. Figures 9, 10, and 11 are the outcomes of the 3 scenarios based on qualitative and quantitative analyses. The criteria specification and characterization of each suitable site for a landfill were assigned the color blue and had an SLSS index >= 90%, as shown in Tables 6, 7, and 8 for the 1st, 2nd, and 3rd scenarios, respectively.

For the outcome of the 1st scenario, the area with ID 5 in Figure 9 has a total area of 14 km^2 while the depth to the groundwater table is 25 m. Based on Figure 8, the landfill depth could be between 5 and 6 m with a compacted unit weight between 6.5 and 8.5 KN/m^3. The location with ID 6 has a total area of 19.8 km^2 with excellent values for elevation slope (1%) and depth to groundwater (42 m). The site with ID 6 has a total area that can provide 2 sites for landfills; an estimation of the area needed from Figure 8 is 9.9 km^2 for each site, and the landfill depth could be 6 m, while the compacted unit weight would be 10 KN/m^3. The sites with ID 4 and 7 have a total area of about 7.5 km^2, and the landfill depth could be up to 10 m, while the compacted unit weights could be between 6.5 and 7 KN/m^3. The other sites have a total area between approximately 3 and 4.7 km^2 and could have landfill depths from 15 to 25 m.

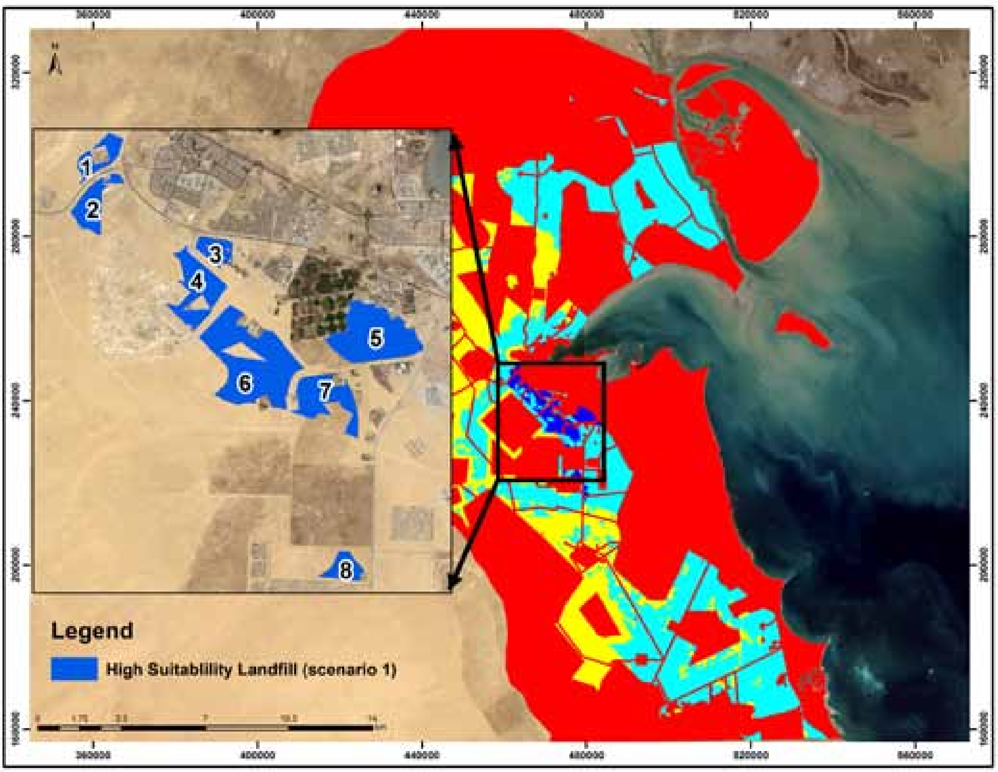

Figure 9 The SLSS outcome after being filtered by quantitative analysis for 1st scenario

Table 6 The Criteria Specification of each Suitable Site of the1st SLSS Scenario

Site ID	Area (km^2)	Environmental Criteria				Socioeconomic Criteria				GW Depth (m)	Slope (%)
		Depth to GW (Score Class)	Transmissivity (Score Class)	TDS (Score Class)	Aquifer (Score Class)	Land Cover (Score Class)	Urban (Score Class)	Roads (Score Class)	Slope (Score Class)		
1	3.0	69	60	22	67	6	65	62	78	55	2
2	4.6	69	60	22	67	6	65	62	78	53	1.2
3	2.7	69	32	22	67	65	65	62	67	40	0.7
4	7.6	69	32	22	67	65	65	62	78	50	0.6
5	14.0	69	60	67	67	65	65	62	7	25	0.4
6	19.8	69	32	67	67	65	65	62	78	42	1
7	7.5	69	60	67	67	65	65	62	78	42	0.7
8	2.8	69	60	67	67	6	29	62	78	55	0.6

The significant outcome of the 2nd scenario, shown in Figure 10, is that there are 2 sites generated south of the urban areas of Kuwait, ID 9 and ID 10, and there is 1 site close to the urban areas, ID 6, with total areas of 3.3, 5, and 4 km^2, respectively. The depth to groundwater at site ID 9 is 20 m from the ground, and the depth of the landfill, based on Figure 8, should be 25 m. This result leads to the rejection of site ID 9 because the depth of the landfill exceeds the depth of the water table. The results of site ID 10 were estimated from Figure 8, and the depth of the landfill is 15 m with a compacted unit weight of 8 KN/m^3. Site ID 10 is near major roads and supports new cities south of Kuwait. Site ID 6 could receive solid waste volume with a depth of landfill between 20 m and 25 m based on compacted unit weight.

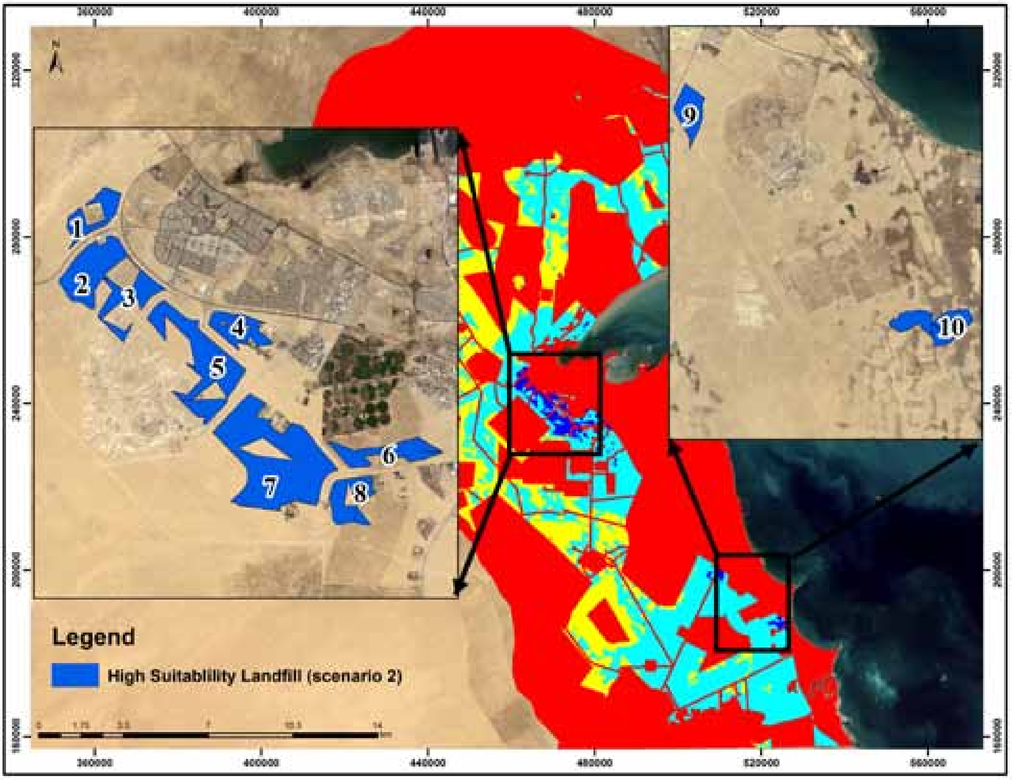

Figure 10 The SLSS outcome after filtering by quantitative analysis for the 2nd scenario

Table 7 The Criteria Specification of Each Suitable Site of the 2nd SLSS Scenario

Site ID	Area (km²)	Environmental Criteria				Socioeconomic Criteria				GW Depth (m)	Slope (%)
		Depth to GW (Score Class)	Transmissivity (Score Class)	TDS (Score Class)	Aquifer (Score Class)	Land Cover (Score Class)	Urban (Score Class)	Roads (Score Class)	Slope (Score Class)		
1	3.0	69	60	22	67	6	65	62	78	55	1
2	6.4	69	60	29	67	65	65	62	78	45	1
3	3.5	69	32	22	67	6	65	62	78	45	1.5
4	3.4	69	32	22	67	65	65	62	78	40	0.7
5	9.8	69	32	22	67	65	65	62	78	48	0.8
6	4.0	69	60	67	67	65	65	62	78	40	0.6
7	18.9	69	32	67	67	65	65	62	78	42	1
8	3.8	69	60	67	67	6	65	62	78	42	0.6
9	3.3	69	60	67	27	65	65	62	78	20	0.9
10	5.0	69	60	67	27	65	65	62	78	45	0.75

The 3rd scenario considered the economic and social impacts in determining the site suitability for a landfill by giving a higher weight to the socioeconomic criteria. Figure 11 shows that there are 3 sites located near the agriculture area of Wafra City—IDs 12, 13, and 14—that could have a landfill depth between 20 and 25 m. The depth to groundwater is 88 m below ground, which leads to difficulty in having to monitor wells. Site ID 5 has a 10 m landfill depth with a high compacted unit weight, while site ID 3 has a 15 m landfill depth with a minimum compacted unit weight. Sites with IDs 2, 4, 7, and 9 have a capacity area between 3.4 and 4 km^2 and could have a landfill depth between 20 and 25 m. Two sites, IDs 6 and 8, have huge areas that can be used for many landfill sites. The landfill depth at site ID 1 could be either 20 m with 9.3 KN/m^3 in compacted unit weight or 25 m with 7.2 KN/m^3 in compacted unit weight. This site is in the north urban area of Kuwait and close to a residential area under construction, Almutla'a City. Both site IDs 10 and 11 have the same characterization as site IDs 9 and 10 in the 2nd scenario. Overall, the best candidate sites can be found in the 2nd scenario because of the equal importance weights for the main sustainability groups.

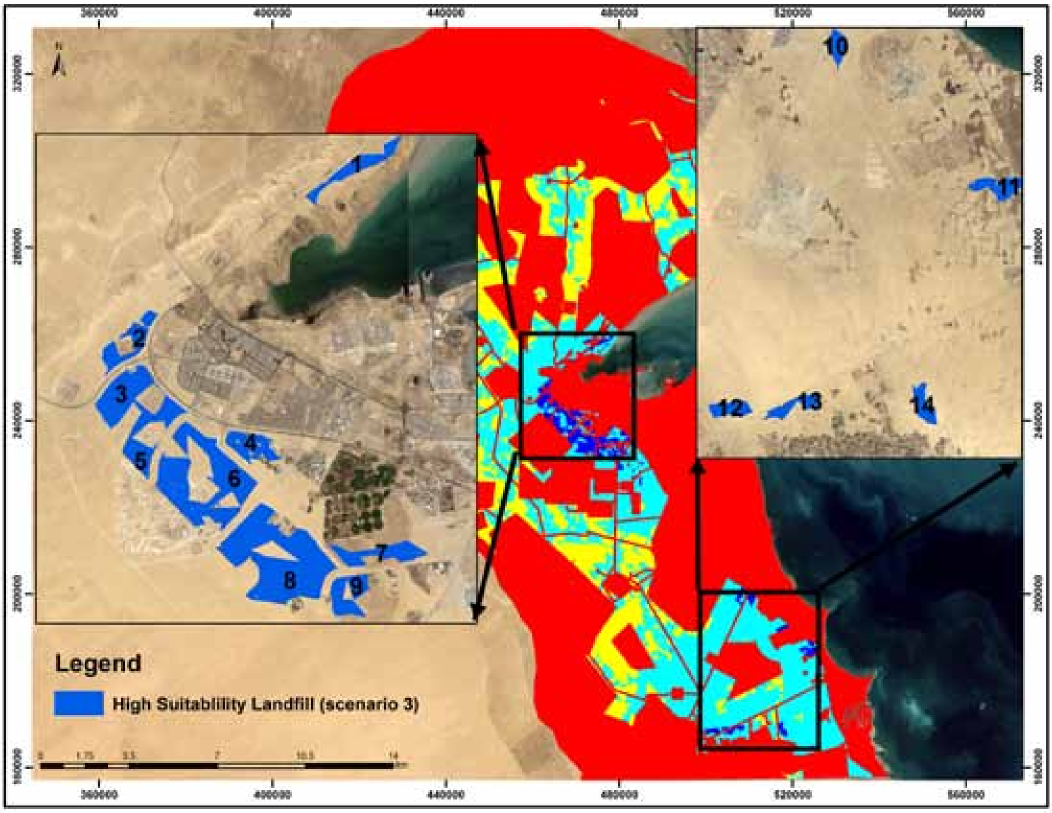

Figure 11 The SLSS outcome after filtering by quantitative analysis for the 3rd scenario

Table 8 The Criteria Specification of Each Suitable Site for the 3rd SLSS Scenario

Site ID	Area (km^2)	Environmental Criteria				Socioeconomic Criteria				GW Depth (m)	Slope (%)
		Depth to GW (Score Class)	Transmissivity (Score Class)	TDS (Score Class)	Aquifer (Score Class)	Land Cover (Score Class)	Urban (Score Class)	Roads (Score Class)	Slope (Score Class)		
1	3.6	69	60	22	27	65	65	62	78	39	2
2	3.6	69	60	22	6	65	65	62	78	55	2
3	6.2	69	60	22	67	6	65	62	78	53	1
4	3.4	69	32	22	67	65	65	62	67	40	1
5	5.6	69	32	22	6	65	65	62	78	45	1
6	15.9	69	32	22	67	65	65	62	78	50	1
7	4.0	69	60	67	67	65	65	62	78	40	1
8	20.6	69	32	67	67	65	65	62	78	42	1
9	3.8	69	60	67	67	6	65	62	78	42	1
10	3.3	69	60	67	27	65	65	62	78	20	1
11	5.0	69	60	67	27	65	65	62	78	45	1
12	3.6	23	60	67	67	65	65	62	78	88	1
13	3.9	23	60	67	67	65	65	62	78	89	1
14	3.7	23	60	67	67	65	65	62	78	88	1

Conclusion

This study provided a sustainable methodology based on two analyses. First, a qualitative analysis ranked the sites by suitability according to the sustainability criteria weights. Consequently, a GIS framework model in combination with the AHP provided a sustainable structure with 3 levels of evaluation for landfill locational sites. The pairwise comparison method in the context of an AHP was used to determine the relative impact weights based on experts and decision-makers in Kuwait. The outcomes of the GIS-based model were run with 3 different scenarios to reflect the decision-makers' preferences. Then, the quantitative analysis restricted the candidate sites based on the outcomes for area suitability for landfills. The estimation of landfill area was determined by two variables: the depth of the landfill and compacted unit weight. Overall, the results indicated that solid waste predicates designing a landfill for 20 years that requires an area between 3 and 18 km^2 depending on the two inputs. The significant outcomes of the GIS model (qualitative analysis) after filtering by quantitative analysis are as follows: The socioeconomic scenario (3rd scenario) provided 5 sites in south Kuwait and 1 site in north Kuwait; the environmental scenario (1st scenario) provided 8 sites close to urban areas of Kuwait; and the 2nd scenario balanced the preferences between environmental and socioeconomic groups and provided 10 sites. This leads to the conclusion in Figure 12, which describes the relationship by extending the landfill operation for 1 year, requiring an increase in the capacity of landfills based on an average compacted unit weight of 8.26 KN/m^3 and the designed depth of landfills. The authors used 1.59 kg per capita per day as the input for solid waste generated. This study was a baseline for determining sustainable areas for landfills and supporting the mechanisms of site selection based on a set of sustainability criteria. A future suggestion is to consider recycling solid waste to reduce the gross area needed for landfills.

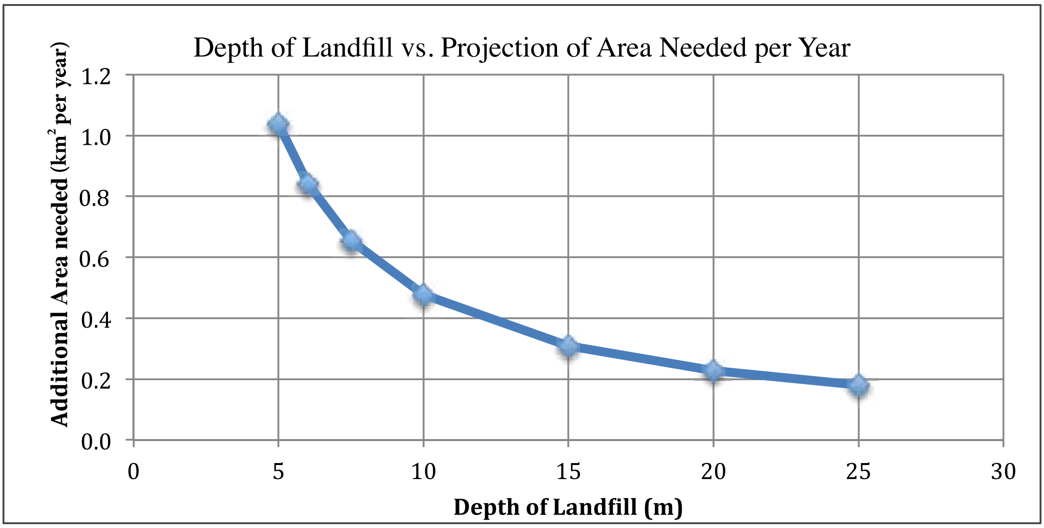

Figure 12 Additional area needed per year based on an average compacted unit weight of 8.26 KN/m^3

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