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Research Paper

Mapping potential landfill sites for North Sinai cities using spatial multicriteria evaluation

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Abstract The exponential rise in the urban population of the developing countries during the past decades accelerated the urbanization phenomenon and the great need for solid waste management. This fact brought awareness of the necessity to develop efficient solid waste management systems in land use planning. Due to insufficient funds, poor planning and growing needs for solid waste management systems, many Egyptian cities dispose their solid wastes in open sites. In Sinai Peninsula, cities are located either on the coastal zones or in deserts. Motivated by the Government objective in developing the cities of Sinai, this paper tries to participate in finding a solution using a spatial multi-criteria decision support system for locating potential landfill sites for North Sinai cities. Criteria concerning three themes were combined to produce three scenarios. Environmental theme related to soil characteristics; permeability and groundwater as well as vulnerable land cover units, faults and streams. Economic theme includes slope, road network, and power lines. Social theme includes distance from airports, archaeology sites and land aspect. Prioritizing the weight of a specific theme or giving an equal weight to the three themes produced different scenarios. A suitability index map was produced for each case. Comparing the three suitability indexes; zones with the highest values were selected resulting in a set of candidate sites for each city in the investigated region. According to the characteristic of a location, a scenario could be preferred. More than an option resulted and are available to the decision makers according to their strategies and objectives.

1. Introduction

Choosing sanitary landfill suitable locations is a decision that requires an extensive land evaluation process in order to identify the optimum available disposal location. This location must comply with the requirements of the existing governmental regulations and at the same time must minimize economic, environmental, health, and social costs (Siddiqui, 1996). Landfill siting should take into account a wide range of territorial and legal factors in order to reduce negative impacts on the

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environment (Delgado et al., 2008). Such a process also requires consideration of multiple alternative solutions and evaluation criteria. Massive amounts of spatial data are processed for choosing a waste disposal location. Some difficulties emerge from the rigid environmental restrictions. If landfills are not carried out to sufficiently high standards, it will have adverse impacts on the environment. Many of the attributes involved in the process of selection of sanitary landfill sites have a spatial representation, which in the last few years has motivated the predominance of geographical approaches that allow for the integration of multiple attributes using Geographic Information Systems (GIS) (Kontos et al., 2005; Sener et al., 2006; Delgado et al., 2008). The advantages of using GIS for waste disposal and landfill site selection have been demonstrated by various researchers. (Jensen and Christensen, 1986) demonstrate the use of GIS in the selection of solid and hazardous waste disposal sites. GIS was subsequently used by Fatta et al. (1998) for the site selection of an industrial waste facility. (Siddiqui, 1996) presents a method that identifies and ranks potential landfill areas for preliminary site assessment. Recently, several publications have tackled landfill siting problems using GIS and multi-criteria analysis or intelligent system approaches (Kontos et al., 2005, 2003; Al-Jarrah and Abu-Qdais, 2006; Sener et al., 2006; Sumathi et al., 2008; Ehler et al., 1995; Lukasheh et al., 2001). These techniques utilize geographic information systems (GIS) to perform an initial screening of the study region in order to find suitable areas. In addition, these techniques are binary since the final result is a discrimination of the study region in suitable/unsuitable areas. Other siting techniques combine multiple criteria analysis (MCA) and GIS (Minor and Jacobs, 1994; Siddiqui, 1996; Kontos et al., 2005). Suitability mapping involves using a variety of data sources in which weights are assigned to geographical criteria. Data are often imported into a Geographic Information System (GIS), which combines potentially unrelated data in a meaningful manner. The result of these techniques is the evaluation of the suitability for the entire study region based on a suitability index, which is useful in order to make an initial ranking of the most suitable areas (Kontos et al., 2005; Malczewski, 2004, 2006; Janke, 2010). GIS technology has also been combined with AHP and fuzzy set theory; Kontos et al. (2005) describe a spatial method that integrates multiple criteria analysis, GIS, spatial analysis, and spatial statistics with a view to evaluating a region for landfill site selection.

1.1. Location of the study area

Sinai Peninsula is situated between the Gulf of Aqaba and the Gulf of Suez, and is bounded from the north by the Mediterranean Sea. The peninsula is divided into two governorates namely, North Sinai and South Sinai. Sinai is located within the arid belt which dominates the northern part of Africa and extends to the southwest of Asia. In the north it is characterized by the Mediterranean Sea zone that is characterized by arid climatic conditions dominated by a long hot, rainless summer and mild winter. Area of the North Sinai governorate amounts to 27,000 square kilometers. The population as of 2010 Census is 384,000 inhabitants living in eight small cities with low population compared to the Egyptian cities and towns. Such cities are spatially distributed along the Mediterranean and Red sea shores except for Nekhel city which is located in the South of the governorate and in the middle of the Sinai desert. Improving the services of such cities could improve their polarization and help in a balanced distribution of the population in Egypt (See Fig. 1).

2. Materials and methods

A set of criteria was developed by combining an intensive literature review and expert knowledge. Such criteria were based on national and international codes related to site selection of a landfill and considering environmental, social and economic parameters. (Simsek et al., 2006; Baban and Flannagan, 1998), Kontos et al., (2005), Sener et al., 2006; Gemitzi et al., 2007; Delgado et al., 2008) Table 1. A large portion of the data came in the form of analog maps. Such maps were converted to the

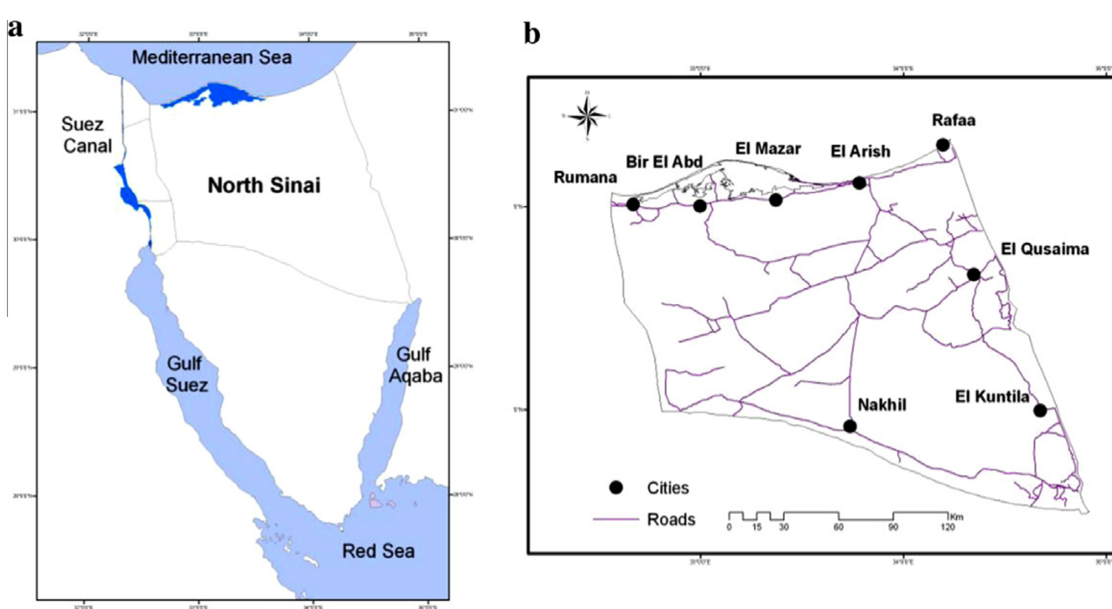

Figure 1 (a) Location of the Sinai Peninsula. (b) Cities and towns of North Sinai.

Table 1 Decision rules for the three themes.

Theme	Factor (units of measure)	Attribute values	Verbal scale	Suitability rating
Environmental	Permeability (cm/s)	$\leqslant 10^{-5}$	Most suitable	10
		10^{-5} and 10^{-3}	Highly suitable	8
		10^{-3} and 0.1	Medium	6
		0.1 and 1.0	Low	4
		1.0	Least suitable	1
	Ground water depth (meters)	$\leqslant 6$	Not suitable	0
		6–25	Least suitable	1
		25–110	Suitable	5
		> 110	Most suitable	10
	Distance to sabkha (kilometers)	$\leqslant 1$	Not suitable	0
		1–28	Least suitable	1
		28–57	Suitable	2
		> 57	Most suitable	10
	Distance to faults (kilometers)	$\leqslant 1$	Not suitable	0
		1–5	Less suitable	5
		> 5	Most suitable	10
	Distance to shores (kilometers)	0–1	Not suitable	0
		1–5	Least suitable	2
		5–10	Suitable	6
		> 10	Most suitable	10
	Distance to protected zones (kilometers)	0–1	Not suitable	0
		1–5		2
		5–10		6
		> 10	Most suitable	10
	Distance to high order streams (kilometers)	$\leqslant 0.5$	Not suitable	0
		0.5–6	Least suitable	1
		6–12	Less suitable	2
		12–19	Suitable	5
		> 19	Most suitable	10
Economic	Distance to cities (kilometers)	< 5	Not suitable	0
		5–10	Most suitable	10
		10–20	Suitable	7
		> 20	Least suitable	3
	Slope of the land (degrees)	$\leqslant 6$	Most suitable	10
		6–10	Highly Suitable	8
		10–15	Suitable	6
		> 15	Least suitable	2
	Distance to power supply (kilometers)	< 0.5	Not suitable	0
		0.5–5	Most suitable	10
		5–10	Suitable	8
		10–20	Marginally suitable	6
		> 20	Least suitable	3
	Accessibility (kilometers)	< 0.5	Not suitable	0
		0.5–2	Most suitable	10
		2–5.5	Suitable	8
		5.5–13	Marginally suitable	6
		> 13	Less suitable	4
Social	Distance to archaeological sites (kilometers)	$\leqslant 1$	Not suitable	0
		0–5	Least suitable	2
		5–10	Suitable	5
		> 10	Most suitable	10
	Distance to Airports (kilometers)	$\leqslant 5$	Not suitable	0
		5–10	Suitable	5
		> 10	Most suitable	10
	Aspect (Azimuth angle)	North	Least suitable	1
		Northeast, Northwest	Leas suitable	2
		East, West	Less suitable	3
		Southeast, Southwest	Suitable	7
		South	Most suitable	10

vector format (line, point, and polygon) and a geographic database was established. All information was projected into WGS_1984 Universal Transverse Mercator UTM zone 36 N. Analysis was conducted in the raster format; using a grid of 100 m.

2.1. Developing the Criteria

Weighted Linear Combination was used for this study. Two types of criteria support the decision-making: constraints and factors. These criteria represent conditions possible to be quantified and contribute for the decision-making (Eastman et al., 1993). In such practice, constraints are used to eliminate certain spatial objects from consideration. Constraints are based on the Boolean criteria (true/false). Factors are criteria, which define some degree of suitability for all the geographic regions. Factors are often grouped into themes according to overall sustainable development objectives. Keshkamat et al., 2009.

2.1.1. Constraints

Constraints were identified and protective buffer zones were designed for shoreline, roads, settlements, high order streams and fault lines. Such buffer zones were generated based on the criteria set by the Egyptian Environmental Affairs Authority (EEAA), while few others were derived from literature review expert knowledge. Constraint images were produced by converting the factor images into a binary image (zero or one values) using ESRI ArcGIS 9.2 Spatial Analyst module and combined by multiplying such binary images. The constraint map ensures the protection of the vulnerable lands as well as avoiding selection of built-up lands.

2.1.2. Factors

The factors were identified based on literature review and expert knowledge and grouped into three main groups (themes), ecological, economic and social themes. Each theme contains a set of related sub-criteria. Expert knowledge, the Analytical Hierarchy Process and the straight rank-sum method, were used to derive the factor weights. Three scenarios were produced by prioritizing themes as explained below.

2.1.2.1. Environmental theme. The environmental theme is considered an important issue due to the special and unique ecological nature. The region is characterized by the Mediterranean Sea shore, Bardaweel Lake and Zaraneik national park with wetlands. In the desert lands, aquifers exist with various depths. Due to the possibility of land and water pollution from a landfill site, the environmental protection objective is achieved in this study through the following factors:

2.1.2.1.1. Permeability. The infiltration rate plays an important role in determining the potential risk of contamination of the groundwater and hence is a key criterion for the development of a landfill at a particular site. Sumathi et al., 2008. The permeability map was based on the surface rock type which varied from fine clay, shale, limestone, sand gravel clay mixture with surface rock permeability that ranges from 0.00001 to 5.5. According to Simsek et al. (2006) permeability less than or equal to 10–5 cm/s has a (maximum suitability), between 10–5 and 10–3 cm/s (high suitability), between 10–3 and 0.1 cm/s (medium suitability), between 0.1 and 1.0 cm/s (low suitability) and 1.0 cm/s (very low suitability). The rock permeability ranged from 0.00001 to 2 Darcy.

2.1.2.1.2. Ground water depth. A landfill site should not be located in areas with shallow ground water depth. To safeguard the ground water from pollution, a groundwater depth surface was created from interpolation of groundwater depth of water wells obtained from the hydro-geological map of Egypt.

2.1.2.1.3. Distance to sabkha. Sabkha and marshes border Lake Bardawil and El Zaraneik as natural protectorate. The area is a breeding shelter for immigrant birds and is preserved as open space for wildlife. A buffer zone of 1 km was established around such sensitive areas. A distance image was then created.

2.1.2.1.4. Distance to faults. Fault zones should be avoided in choosing a location for a landfill that is because fault zones usually are highly porous and permeable zones. These areas

Table 2 Calculation of weights for the economic and social themes.

Factor rank	Factors/themes	$n - \mathrm{r\,j} + 1$	Sum $(n - \mathrm{r\,k} + 1)$	$w_{\mathrm{ij}} = (n - \mathrm{r\,j} + 1)/\mathrm{SUM}(n - \mathrm{r\,k} + 1)$
Weight calculation for factors in economic themes				
1	Distance to urban areas	4	10	0.4
2	Slope	3		0.3
3	Distance to power supply	2		0.2
4	Distance to roads	1		0.1
Weights calculation for factors in social themes				
1	Distance to archeological sites	3	6	0.5
2	Aspect	2		0.33
3	Distance to airport	1		0.17
Weight calculation for environmental scenario				
1	Environmental theme	3	6	0.5
2	Economic theme	2		0.33
3	Social theme	1		0.17
Weights calculation for economic scenario				
1	Economic theme	3	6	0.5
2	Environmental theme	2		0.33
3	Social theme	1		0.17
Equal weight scenario				
Environmental theme			0.33	
Economic theme			0.33	
Social theme			0.33	

act as good conductors for any pollution or contamination agents. A buffer zone of 1 km was created around the fault lines. A distance image was created from faults.

2.1.2.1.5. Distance to shores. Shorelines are ecological and tourism value zones. A protective buffer of 1 km was created away from the shoreline and a distance to shoreline image was created.

2.1.2.1.6. Distance to protected national parks. A protectorate is an environmental sensitive zone, such zones need to maintain esthetics values whenever possible. A protective buffer of 1 km was created around those protectorates. A distance to protectorates image was created.

2.1.2.1.7. Distance to high order streams. Due to the arid nature of the study area, streams with low orders were not considered. Streams were extracted in ESRI ArcGIS 9.2 hydrology model using ASTER digital elevation model .A buffer zone of 500 m was created. A distance image was created.

2.1.2.2. Economic theme. The study region is characterized by limited development activities with various spaces of virgin lands and deserts. Costs of development are minimized through considering the following factors:

2.1.2.2.1. Distance to cities. Cities are the main source of the solid waste. Applying the five kilometers constraint buffer ensures a future extension of a city and avoids nuisance. Yet, after the five kilometers, the closer the landfill to a city, the more economic the transportation of solid waste is. A distance to cities map was created.

2.1.2.2.2. Slope of the terrain. The slope of a land is considered an economic factor in construction of a landfill as high slope lands are more difficult to be managed and therefore will be more costly. The terrain slope angles in North Sinai range between almost 0° in the case of flat lands. Mountainous areas and sand dunes have higher slopes reaching 47°. slope angles less than 6° were considered most suitable, lands less than 10° were highly suitable and less than 15° suitable while lands greater than 15° were least suitable.

2.1.2.2.3. Distance to power supply. As the sustainable development, the proposed landfill sites have to have a power supply source for recycling industry. A distance map was created around power supply lines, where the less the distance from a power supply sources the more suitable the site.

2.1.2.2.4. Accessibility. Solid wastes are daily delivered through one or more collection roads. Buffer zones of 500 m were created around roads. A distance to roads map was created where the less distance from a main road, the better the site.

2.1.2.3. Social theme. The social theme is considered an important issue as the cultural values and social impacts on the

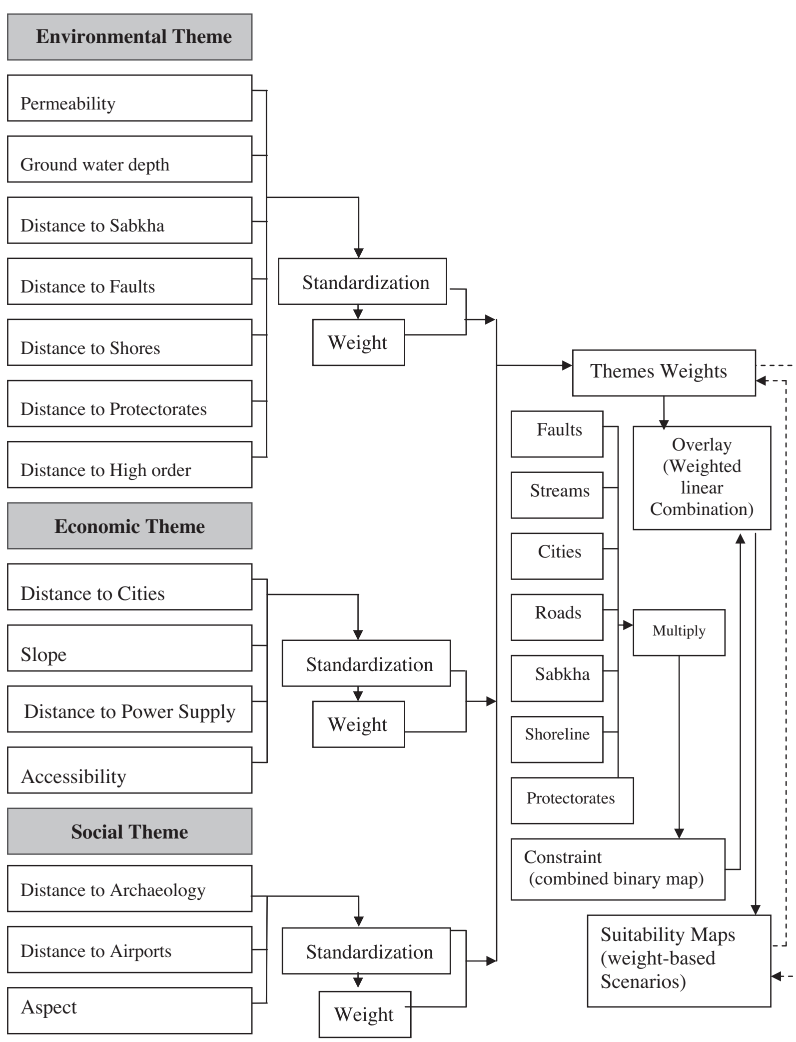

Figure 2 Flow diagram for applied methodology.

inhabitants are considered in such a theme. Social impacts are considered through the following factors as follows:

2.1.2.3.1. Archaeological sites. Sinai Peninsula has a unique history quite rich with its archaeological sites. A protective buffer zone of one kilometer was created around such sites. A distance map was then created around such sites. The more the distance from the archaeological sites, the more suitable the land and vice versa.

2.1.2.3.2. Airports. Based on the literature review, international practice dictates a minimum distance of 3 km from airports (Kontos et al., 2005). A buffer zone of 5 km was considered for this study. A distance map was then created where the more distance the more suitable the site.

2.1.2.3.3. Aspect. The morphological aspect is expressed in degrees based on the parcel azimuth. Most frequently encountered winds in North Sinai are northwest and northeast oriented. Therefore, sites with southern orientations were considered most suitable while northern orientations are least suitable.

2.2. Applying the Weighted Linear Combination for three scenarios

Weighted Overlay is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis (ESRI ArcGis 9.2 Spatial Analysis). Weights emphasize the relative importance of one criterion to another and are often determined by research specialists, stakeholders, or interest groups and/or decision-makers. In general, in the procedure of multicriteria evaluation using a Weighted Linear Combination it is necessary that the weights are normalized; summed to one or 10 or 100. Three scenarios were experimented based on weight impacts; the environmental, the economic scenario and the equal-weight scenarios. First, factors weights were calculated within each theme using two approaches. The environmental theme, weights were calculated using the Analytical hierarchy Process. Soil vulnerable to pollution was represented by the rock permeability factor. Such factor was considered seven times more important than streams, and five times more important than protectorates, shorelines and faults, four times more important than sabkha as these factors being considered as constraints are masked out from the study area. Permeability is considered twice more important than groundwater depth factor. As for the economic and social themes, factor weights were calculated using the straight rank-sum method Table 2 guided by the literature review. Economic and social themes weights were calculated using the straight rank sum method, Eq. (1) Table 2 as follows:

$$W_j = (n - rj + 1)/SUM(n - rk + 1) \quad (1)$$

where W_j is the normalized weight for jth factor, n is number of factors under consideration, rj is the rank position of the factor.

In order to allow comparability, which is essential to multicriteria evaluation, the factor maps are standardized to a common suitability scale that ranges from 1–10 using ESRI ArcGis 9.2 Spatial Analyst.

2.3. Running the multicriteria model

The suitability index was calculated using simple additive weighing (SAW). This is a widely utilized method for the calculation of final grading values in multiple criteria problems; the mathematic formulation of the method is described by Eq. (2) (Kontos et al., 2005).

$$V_i = \sum_{j=1}^{n} W_j v_{ij}, \quad (2)$$

For an area i: V_i is the suitability index, W_j is the relative importance weight of criterion j, $_{ij}$ is the grading value of area i under criterion j, n is the total number of criteria.

Eq. (2) was applied three times in ArcGIS9.2 spatial analyst. Using the three sets of weights resulted in three suitability index scenarios (Fig. 2). The environmental scenario weights were calculated using the straight rank-sum method by giving the environmental theme a first rank order, followed by the economic theme and finally the social theme. Same method was applied to calculate the economic vision and finally equal weights were applied to the equal weights scenario. Each of the three scenarios was reclassified into ten suitability classes where highest pixel values are the most suitable locations. Most suitable sites were selected from each scenario suitability index by choosing the highest pixel values ranging from 7–10. The final site selection decision rules were agreed to be as follows:

1. The site should lie within 5–22 km from a city.
2. Minimum site area should be 1.5 km^2.

Finally, site selection resulted by applying GIS query on the resulting suitability index.

3. Results

Result of applying the Boolean overlay of the constraints layers is a binary map. Such a map identifies all sites that are not

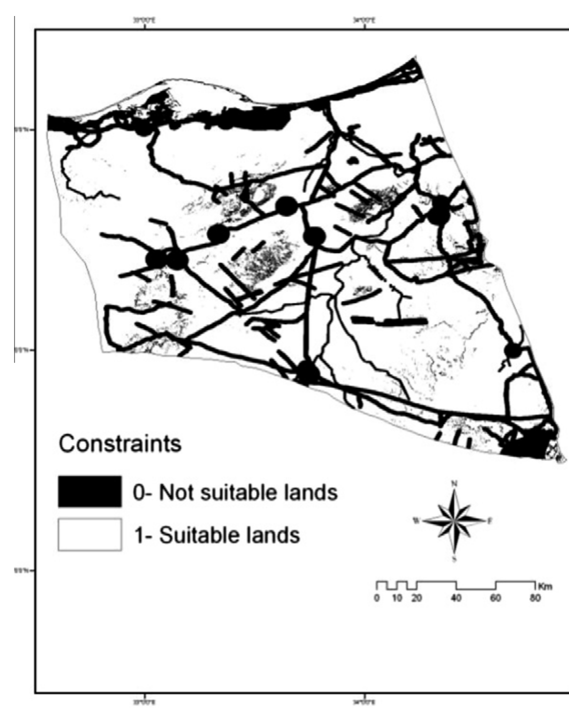

Figure 3 Combined constraints images produced by Boolean overlay.

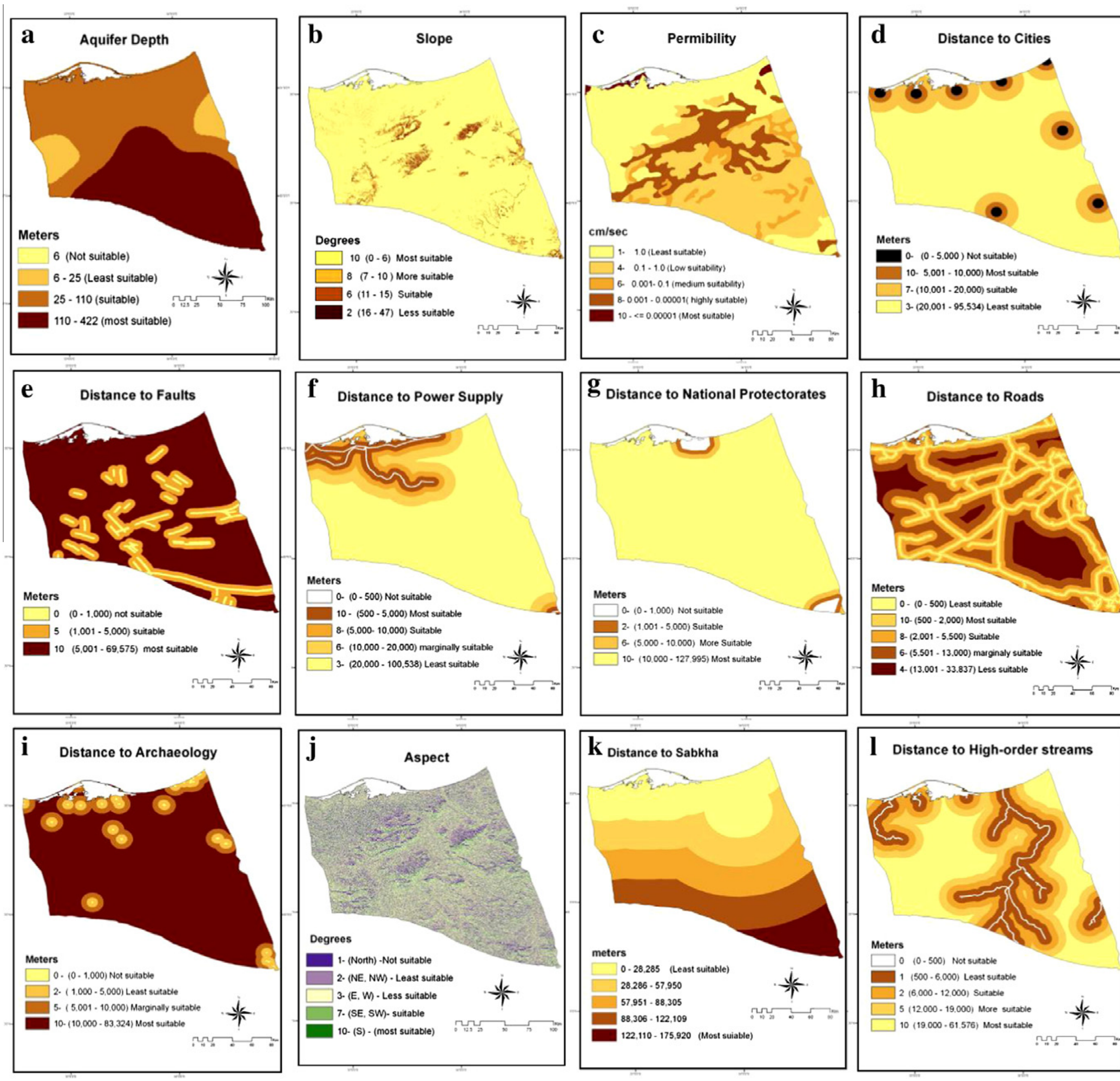

Figure 4 Factors maps: (a) Aquifer depth. (b) Slope. (c) Permeability. (d) Distance to cities. (e) Distance to faults. (f) Distance to power supply. (g) Distance to protectorates. (h) Distance to roads. (i) Distance to archaeology sites. (j) Aspects. (k) Distance to sabkha. (l) Distance to high order streams.

to be changed in landuse and thus are not to be considered in the site selection procedure. Nevertheless such lands have to be modeled in the multicriteria evaluation as constraints and masked out (See Fig. 3).

Use of the multicriteria Weighted Linear Combination for producing the factor maps unveiled the land characteristics reference to such factors. Aquifer depth images reveal that underground water depth increases in the southern zones (Fig. 4a). High slopes in mountainous zones reach 47° in limited middle parts of the investigated area. (Fig. 4b). Land permeability images reveal that most permeable soils exist in the northern zone where the Mediterranean shores and sand dunes exist (Fig. 4c). Distance images express the distance from the main towns (Fig. 4d), distance from linear features and faults (Fig. 4e), distance from power supply (Fig. 4f), distance to protectorates (Fig. 4g), distance to roads (Fig. 4h), distance to archaeological sites (Fig. 4i), and distance to sabkha and railways are depicted in Figs. 4h,i). Land slope aspect angles (Fig. 4h) reveal the flat lands in valleys while various slope angles in azimuth spread among the terrain.

Results of running the Weighted Linear Combination revealed interesting results for each scenario. As such aggregation results in continuous suitability images, such images were reclassified into ten suitability classes for each scenario. Changing the set of weights for the themes changed the trade-off between them. Reducing the weight for a specific

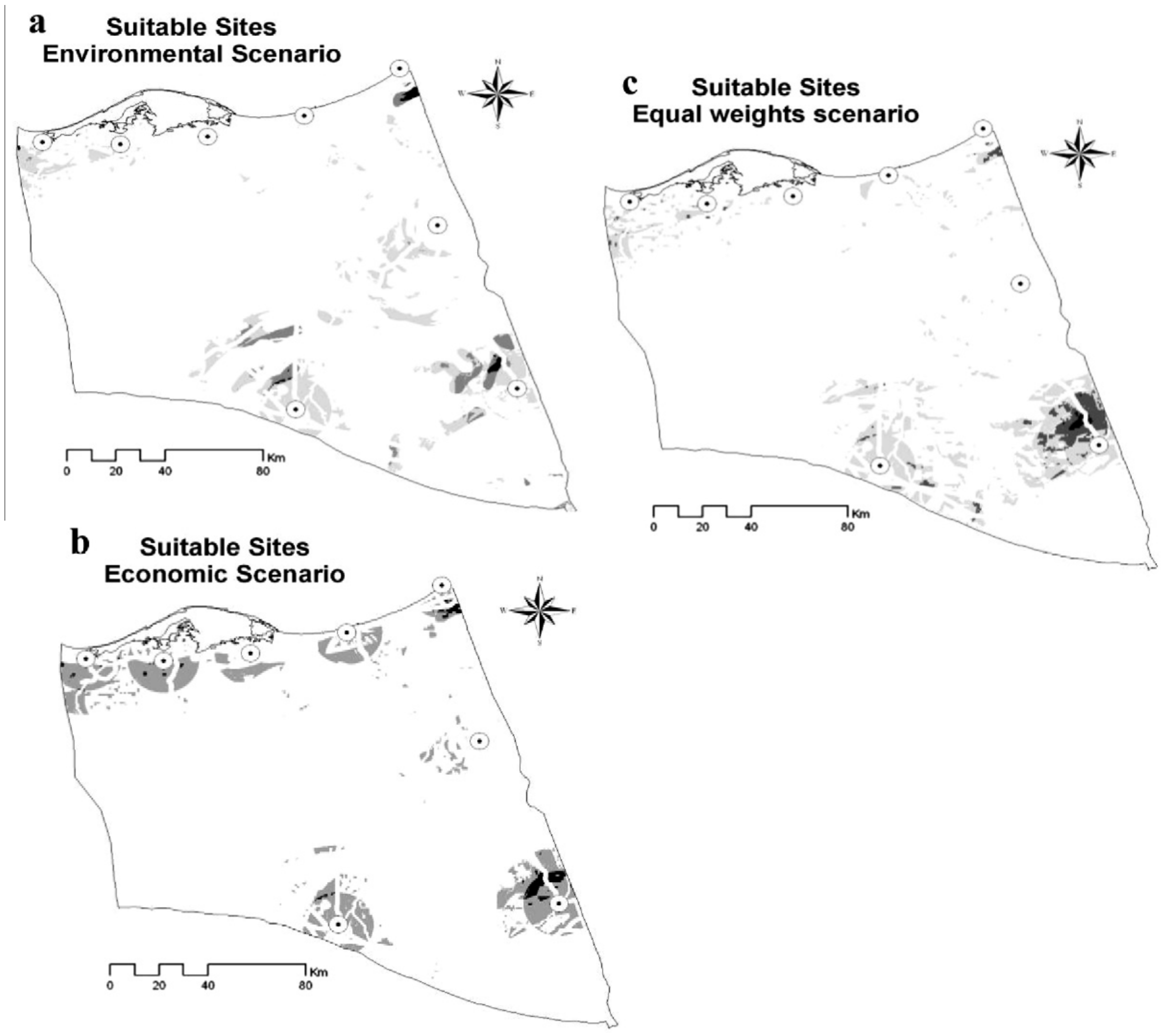

Figure 5 Result: (a) Environmental scenario. (b) Economic scenario (c) Equal weights scenario.

theme means prioritizing another, the results could be explained as follows:

The environmental scenario resulted in a suitability index map where most of the suitable sites are identified in the Southern cities El Qusaima, El Kantella and Nekhel, in addition, suitable sites are found south of Rafah city, (Fig. 5a). In addition some moderately suitable sites lie south of Romana and Beir el Abd cities. The main cause of such a result is the ecological features that exist in the coastal belt of the region. The Bardawil Lake and protectorate which lies north of the cities of Romana, Beir El Abd and El Mazar lowers the suitability values in such scenario that evaluates the ecological theme highest and therefore less suitable zones exist in the northern zones. For the Equal weight scenario, the result revealed extensive suitable zones in the south of the investigated area. The desert cities vicinity shows high suitability. Except for El Arish and Beir El Abd, which have hardly suitable sites in such a scenario, the remaining three coastal cities Rafah, El Mazar and Romana have quite proximate potential zones for a lanfill (Fig. 5b). The Economic scenario resulted in a suitability index map where the desert cities (El Kantella, El Kossayma and Nekhel) are surrounded by vast areas of suitable lands (suitability values of eight and nine). Yet, due to a lower weight given to the environmental theme, this scenario shows suitable sites to the south of most coastal cities (Rumana, Beir El Abd and El Mazar). This result is quite reasonable for a scenario that prioritizes the economic factors reflected by the existence of developed features such as cities, existence of an extensive road network and railroad in addition to proximity to life lines utility (Fig. 5c) (See Table 3).

Using the multicriteria evaluation Weighted Linear Combination is an aggregation procedure that allows retaining the variability from the continuous factors and allows the trade-off between factors. This means that a low suitability value in one factor can be compensated by a high suitability factor for a specific location or pixel. This trade-off is controlled by the relative weights assigned for such factors. The Weighted Linear Combination is an averaging technique that places our analysis exactly halfway between the AND and the OR operations. (Eastman, 2009). The Binary constraints allow masking out areas that should not be considered in the land use decision. Applying such a technique in both coastal and desert zones of Sinai proved to be quite helpful. It facilitated exploring and unveiling the various characteristics of the desert using remotely sensed data and GIS mapping combined with multicriteria analysis techniques. Emphasizing

Table 3 Candidate landfill sites (with high suitability values) for North Sinai Cities.

City		Type	Potential sites for a landfill	
			Distance from city (km)	Potential area (sq km)
1	Romana	Coastal	8.5	3.4
2	Bir El Abd	Coastal	8.3	4.6
3	El Mazaar	Coastal	21	16.1
4	El Arish	Coastal	20	5.7
5	Rafah	Coastal	10	14.8
6	El Qusaima	Desert	13.3	1.5
7	El Kantella	Desert	5.4	27
8	Nekhel	Desert	10	3.6

each of the three scenarios resulted in more than an option for choosing potential sites. Thus based on the nature of the location of a city, a suitable scenario could be preferred. Chang et al., 2007 argues that while GIS offers unique capabilities for automating geospatial analysis for screening all possible sites, data availability can prove to be a limiting factor in its application for the selection of a landfill. The authors agree to a certain extent that the technique needs a lot of information and data, yet, we believe that compared to the traditional techniques used in site selection and urban planning it can bring much more realistic results. Data mining problems can be tackled in developing countries if such a technique is adopted by the decision makers and embedded in the urban planning system.

4. Conclusion

The use of remotely sensed data integrated with spatial multicriteria evaluation in this study proved to be quite feasible. It facilitates the scanning of quite a large region with least costs. The technique provides a land screening that can not only be used in site selection but also in environmental impact assessment of proposed projects. Applying such methodology to identify suitable landfill sites in North Sinai, three possible sets of solutions were possible according to three visions. A follow-up on this research, would be to develop a Decision Support System whereby the user could give different weights to the three parts (environment, social, and economic), depending on particular needs. This could be based on the criteria tree designed in this paper. Such a system can be quite helpful to bridge the gap between decision makers and analysts during discussions of the various visions and priorities.

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