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Combining geographic information system, multicriteria evaluation techniques and fuzzy logic in siting MSW landfills

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Abstract This study presents a methodology for siting municipal solid waste landfills, coupling geographic information systems (GIS), fuzzy logic, and multicriteria evaluation techniques. Both exclusionary and non-exclusionary criteria are used. Factors, i.e., non-exclusionary criteria, are divided in two distinct groups which do not have the same level of trade off. The first group comprises factors related to the physical environment, which cannot be expressed in terms of monetary cost and, therefore, they do not easily trade off. The second group includes those factors related to human activities, i.e., socioeconomic factors, which can be expressed as financial cost, thus showing a high level of trade off. GIS are used for geographic data acquisition and processing. The analytical hierarchy process (AHP) is the multicriteria evaluation technique used, enhanced with fuzzy factor standardization. Besides assigning weights to factors through the AHP, control over the level of risk and trade off in the sit-

ing process is achieved through a second set of weights, i.e., order weights, applied to factors in each factor group, on a pixel-by-pixel basis, thus taking into account the local site characteristics. The method has been applied to Evros prefecture (NE Greece), an area of approximately 4,000 km². The siting methodology results in two intermediate suitability maps, one related to environmental and the other to socioeconomic criteria. Combination of the two intermediate maps results in the final composite suitability map for landfill siting.

Keywords MSW landfill siting · Multicriteria evaluation · Geographic information systems · Analytical hierarchy process · Order weighted average

Introduction

Siting a MSW landfill is a challenging task, as most of the times various controversial parameters should be considered. Geographic information system (GIS) can offer significant help in handling this problem. The analytical hierarchy process (AHP) (Saaty 1977;

Pavlikakis and Tsihrintzis 2003) has been incorporated in the GIS technology producing a flexible way of combining various criteria in the siting process (Siddiqui et al. 1996; Kontos et al. 2003). Several studies have been focused on this subject, including evaluation of many factors and aggregation of these factors in many different ways (Kao and Lin 1996; Lin and Kao

1998; Lukashev et al. 2001; Kontos et al. 2003; Sener et al. 2006).

This study presents a method of determining site suitability for construction of MSW landfills, using the AHP, combined with fuzzy function standardization and ordered weighted averaging (OWA) techniques (Eastman 2003), in a GIS environment. An attempt has been made to apply the OWA technique in a real case, and the results of this relatively new and experimental technique are presented in the following paragraphs.

The procedure analyzes criteria of two types, i.e., constraints (exclusionary criteria) and factors (non-exclusionary criteria). Constraints limit the analysis to particular geographic areas, i.e., they differentiate areas that can be considered suitable for landfill siting by assigning an index value of 1 from those that in no case can be considered suitable and receive an index value of 0. In contrast, factors are criteria that define some degree of suitability for all geographic regions. They define areas or alternatives in terms of a continuous measure of suitability. Individual factor scores may either receive high scores, thus enhancing, or receive low scores, thus detracting from the overall suitability of an alternative (Eastman 2003). The aggregation procedure plays a crucial role on the degree each factor influences the final suitability determination. Factors can be standardized in a number of ways depending upon the individual criteria and the form of aggregation used.

In the study 18 criteria are examined, divided into three main groups, according to how they are considered to influence the landfill site suitability: (1) constraints; (2) factors relevant to environmental concerns; (3) factors relevant to socioeconomic and design parameters. Constraints do not participate in the weight assignment process, whereas all factors in groups 2 and 3, are assigned factor weights, according to their relative importance, based on the AHP (Saaty 1977).

Besides assigning weights to factors, a second set of weights, order weights, has been applied for the different rank-order positions of factors at every location (pixel). The order weights first modify the degree to which factor weights have influence in the aggregation procedure (Eastman 2003), thus they govern the overall level of risk and trade off in the suitability determination.

The methodology has been applied to Evros prefecture (northeast Greece), an area of approximately 4,000 km² (Fig. 1). For each one of the two factor groups an intermediate MSW landfill site suitability map was created; the two maps were then combined in order to produce the final suitability map for landfill siting.

Methodology and study area description

In the present study an overlay and index method of assigning MSW landfill site suitability is presented.

Eighteen criteria are involved in the computation process, distinguished in three main groups. The first group includes constraining criteria that limit the analysis to particular geographic areas. The second group comprises factors relevant to environmental parameters, whereas the third group comprises factors relevant to socioeconomic and design parameters. The examined criteria were selected based on the relevant international literature and were adapted to the Greek and European Union law.

Nine constraining criteria are evaluated: (1) residential areas (RA); (2) land uses (LU); (3) highways and railways (HR); (4) environmentally protected areas (EPA); (5) important aquifers (IA); (6) surface water bodies (SWB); (7) springs and wells (SW); (8) exceptional geological conditions (GEO); and (9) distance from country borders and the coastline (DCB). Three factors relevant to the environment are analyzed: (1) hydrogeology (HDG); (2) hydrology (HDR); (3) distance from water bodies (DWB). Six factors relevant to socioeconomic and design parameters are examined: (1) proximity to residential areas (PRA); (2) site access (SA); (3) type of land use (TLU); (4) proximity to waste production centers (PWPC); (5) site orientation (SO); and (6) slope of the land surface (SLS).



Fig. 1 Location map of the study area

The methodology was applied to the prefecture of Evros, located in the northeast continental part of Greece (Fig. 1). The region has an area of 4,000 km². It is a rural part of the country, with a population of 151,000 people (according to census data provided by the Greek National Statistical Service for the year 2001) distributed in villages and small towns all over the area. The projected population for 2020, using an average annual population increase of 0.5%, is 161,000. Agriculture and stock farming are the main activities of the population. Administratively, the study area is divided into 13 municipalities, each currently having at least one non-sanitary landfill, while still there is no legal MSW landfill for Evros prefecture.

The study area was discretized using a grid cell size of 30 m×30 m. Initially all factors in groups 2 and 3 were quantified in a 0–255-byte scale, using fuzzy membership functions, and were introduced into the process as map layers. This particular scaling is used because it provides the maximum differentiation possible while analyzing data in byte type, requiring thus half the computer disk space needed for the normal 2-byte integer files (Eastman 2003). Zero is assigned to the least suitable areas for landfill siting and 255 to the most suitable ones, transforming the different measurement units of the factor images into comparable suitability values. In this process, sigmoidal (“s-shaped”) fuzzy membership functions, specified for each factor, are used, i.e., monotonically increasing, monotonically decreasing, or symmetrical. The sigmoidal membership function is perhaps the most commonly used function in fuzzy set theory (Eastman 2003), offering a gradual variation from non-membership, i.e., 0, to complete membership, i.e., 1. The sigmoidal membership function, can be specified by four parameters (*a*: membership rises above 0; *b*: membership becomes 1; *c*: membership falls below 1; *d*: membership becomes 0). It is expressed as:

$$\mu(x) = \cos^2 a \tag{1}$$

where, in the case of a monotonically decreasing function:

$$a = \frac{x - c}{d - c} \times \frac{\pi}{2} \tag{1a}$$

when $x < c$, $\mu(x) = 1$.

In the case of a monotonically increasing function:

$$a = \left(\frac{1 - (x - a)}{(b - a)} \right) \times \frac{\pi}{2} \tag{1b}$$

when $x > b$, $\mu(x) = 1$.

Constraining criteria of group 1 remain as Boolean images, dividing the study area in two land categories, i.e., suitable (suitability index 1) and unsuitable (suitability index 0).

The mathematical formulation for area selection, using exclusionary criteria only, is:

$$SI = \prod_{j=1}^K b_j \tag{2}$$

where: SI = overall suitability index value (0 or 1); b_j = suitability index value for each constraining criterion (0 or 1); K = number of constraining criteria.

In each factor group, weights were assigned according to how important each factor is considered to be. The mathematical formulation for the assignment of the overall suitability index, applying both exclusionary (constraints) and non-exclusionary (factors) criteria, is:

$$SI = \sum_{i=1}^N w_i x_i \times \prod_{j=1}^K b_j \tag{3}$$

where: SI = overall suitability index value; w_i = weight of factor i ; x_i = criterion score of factor i ; b_j = criterion score of constraint j ; N = number of factors; K = number of constraining criteria.

To make the process of assigning factor weights more objective, a pairwise comparison is applied, in which only two criteria are considered at a time; thus, it becomes more likely to produce a robust set of criteria weights (Eastman 2003). The implemented technique of factor pairwise comparison was developed by Saaty (1977) in the context of a decision-making process known as the AHP (Pavlikakis and Tsihrintzis 2003). In the procedure of multicriteria evaluation in the present study, using the weighted linear combination described above, it is necessary that the assigned factor weights sum to 1. In Saaty’s (1977) technique, factor weights can be derived by taking the principal eigenvector of the square reciprocal matrix of pairwise comparisons between the criteria, as shown in the example presented in Table 1, where the weight assignment process for a six-factor problem is presented. Only the lower-left triangular half is actually filled in, since the upper-right triangular half is equal to the reciprocal of the corresponding entries in the lower-left. The cells in the matrix contain the evaluation for each possible pair of comparisons. To rate each pairwise comparison and to fill in the matrix cells, one moves from column to column from left to right. In each cell the relative importance of the row variable to its corresponding column variable is considered. Variables are rated according to the 9-point scale shown in Table 1.

The comparisons concern the relative importance of the two criteria involved in determining suitability for the stated objective (Eastman 2003). An index of consistency, known as consistency ratio (CR) (Saaty 1977), can be produced, since the complete pairwise comparison matrix contains multiple paths by which the relative importance of criteria can be assessed, thus determining

Table 1 Pairwise comparison matrix for a six-factor problem

	PRA	SA	TLU	PWPC	SO	SLS	Calculated factor weights
PRA	1	1	1/3	3	3	1	0.1623
SA	1	1	1/3	1	5	1	0.1506
TLU	3	3	1	5	3	3	0.3784
PWPC	1/3	1	1/5	1	3	1/3	0.0920
SO	1/3	1/5	1/3	1/3	1	1/3	0.0545
SLS	1	1	1/3	3	3	1	0.1623

9: relative to the column variable, the row variable is extremely more important
7: relative to the column variable, the row variable is very strongly more important
5: relative to the column variable, the row variable is strongly more important
3: relative to the column variable, the row variable is moderately more important
1: relative to the column variable, the row variable is equally important
1/3: relative to the column variable, the row variable is moderately less important
1/5: relative to the column variable, the row variable is strongly less important
1/7: relative to the column variable, the row variable is very strongly less important
1/9: relative to the column variable, the row variable is extremely less important
Consistency ratio = 0.07

Order weights	0.175	0.170	0.165	0.165	0.165	0.160
Rank	1st	2nd	3rd	4th	5th	6th

the degree of consistency that has been used in developing the ratings. The CR indicates the probability that the matrix ratings are randomly generated. Saaty (1977) indicates that matrices with CR ratings greater than 0.10 should be re-evaluated. In addition to the overall CR, it is also possible to analyze the matrix to determine where the inconsistencies arise (Eastman 2003).

Additionally, one more set of weights, order weights, has been applied to each group of factors analyzed, following a procedure known as OWA (Eastman 2003). Order weights are quite different from factor weights. They do not apply to any specific factor. Instead, they are applied on a pixel-by-pixel basis to factor scores as determined by their rank ordering across factors at each location (pixel). Order weight 1 is assigned to the lowest-ranked factor for that pixel (i.e., the factor with the lowest score), order weight 2 to the next higher-ranked factor for that pixel, and so forth. In that way, a single-order weight can be applied to pixels from any of the various factors depending upon their relative rank order. This procedure offers the possibility to adjust the computations, according to how risky or how strict the decision is desired to be. Taking as an example factor group 2, including factors related to the environmental criteria, i.e., hydrogeology (HDG), hydrology (HDR), distance from water bodies (DWB), the assignment of order weights could have the results shown in Table 2.

In the first case, weight is distributed evenly among all factors regardless of their rank-order position. The result is moderate in terms of risk, allowing the full trade off between factors, and is placed in the middle between the Boolean AND and OR operation. It is identical to the result produced by assignment of factor weights only and no order weights. In the second case, the factor with the lowest score, i.e., the less suitable, receives all the

weight, regardless of the factor weights assigned. The result incorporates the lowest level of risk and no trade off, as all the pixels in the study area were assigned the value of the lowest suitability factor, thus limiting to a high extent the suitable areas. The result will closely resemble the AND (minimum) operation used in the constraining criteria. In addition, because no rank-order position other than the minimum is given any weight, there can be no trade off between factors and the minimum factor alone determines the final outcome. On the contrary, the third case, assigns all weight to the factor with the highest suitability score in each pixel, resulting in pixel values equal to the highest suitability factor. The result is very similar to the Boolean OR (maximum) aggregating operation.

Skewing of order weights toward either factor with the lowest or highest score results in all possible cases between risk and trade off, or between the AND and OR operation. Altering order weights in terms of their skew and dispersion results in an almost infinite range of

Table 2 Example of order weight assignment

Moderate level of risk – moderate strict decision – full trade off			
Factors	HDG	HGR	DWB
Order weights	0.33	0.33	0.33
Rank	1st	2nd	3rd
Low Level of Risk – very strict decision – no trade off			
Factors	HDG	HGR	DWB
Order weights	1	0	0
Rank	1st	2nd	3rd
High Level of Risk – no strict decision – no trade off			
Factors	HDG	HGR	DWB
Order weights	0	0	1
Rank	1st	2nd	3rd

possible solutions (Eastman 2003) to the MSW landfill siting problem.

When analyzing a problem, such as sanitary landfill siting, it is clear that the factors involved in the problem do not have the same level of trade off. Factors relevant to the costs of landfill construction and operation are targeted toward minimizing economic costs and can fully trade off with each other. In that way, a high construction cost due to steep slopes of the land surface, can easily trade off with low operational costs due to minimized haul distances, in case a location closer to the waste production centers is selected. On the contrary, when environmental factors are analyzed, it is not that clear to which extent they can trade off, as, for example, locating a landfill as far as possible from surface water bodies does not compensate for a polluted aquifer. This was the main reason to decide to divide all factors involved to two distinct factor groups and treat each group separately in terms of levels of trade off, according to the methodology proposed by Eastman (2003).

In order to apply the above-described methodology all factors were introduced as map layers in the GIS program MapInfo Professional ver. 7.8. Raster data were processed with Vertical Mapper ver. 3.1, whereas fuzzy factor standardization and the multicriteria evaluation have been performed using the GIS program Idrisi Kilimanjaro (Eastman 2003).

Criteria group description and application

Constraints

As mentioned, nine constraining criteria are evaluated in the present study: (1) residential areas (RA); (2) land uses (LU); (3) highways and railways (HR); (4) environmentally protected areas (EPA); (5) important aquifers (IA); (6) surface water bodies (SWB); (7) springs and wells (SW); (8) exceptional geological conditions (GEO); and (9) distance from country borders and the coastline (DCB).

Constraints limit the alternatives under consideration and are expressed in the form of a Boolean (logical) map. Areas which are excluded from consideration are assigned a value of 0, while those open for further consideration are assigned a value of 1 (Fig. 2).

Residential areas According to Greek law (Greek Governmental Ministry Decision 114218/97 1997), a sanitary landfill cannot be located within 500 m of residential areas. Therefore, a 500-m buffer zone was applied to existing urban areas and industrial areas. For safety, a 3-km buffer zone was applied around airports (Bagchi 1990; Kontos et al. 2003).

Land uses In the study area agricultural land uses prevail. In the mountainous areas forests of various types

are present, which were excluded from further consideration. In order to detect suitable areas for MSW landfill siting, forest inventory and census data from the GIS database “Gr Survey—Digital Data for Greece” (Geoinfo Co. 1998) were combined to Landsat ETM satellite images from June 2000. The normalized difference vegetation index (NDVI) image has been created, which expresses the contrast between red and near-infrared reflectances of vegetation and is indicative of the abundance of pigments such as chlorophyll, or simply leaf area. The NDVI is expressed on a scale between -1 and +1, ranges between -0.2 and 0.1 for snow, inland water bodies, deserts, and exposed soils, and increases from about 0.1 to 0.7 for increasing amounts of vegetation. In the case of dense leaf canopies, e.g., the humid tropical forests, the NDVI saturates (Nemani et al. 2003). Finally, negative values represent non-vegetated surfaces (Eastman 2003).

Combining these sources of information offered the possibility to distinguish two discrete types of land uses: unsuitable for landfill siting, i.e., those comprising dense and sparse forests, which received a suitability index of 0, and suitable for further consideration, i.e., those

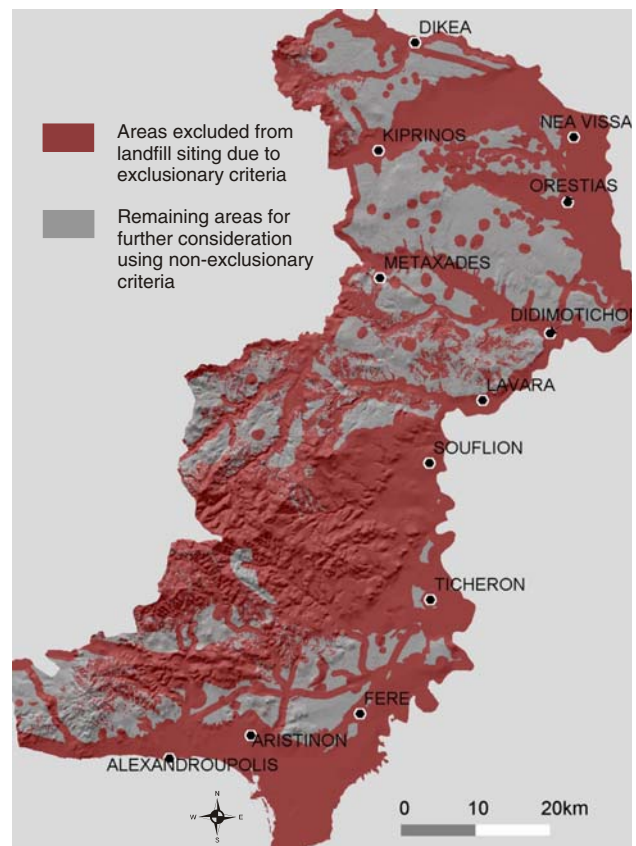


Fig. 2 Areas excluded from landfill siting due to exclusionary criteria

comprising mainly agricultural and uncultivated land which received a value of 1. Agricultural land uses were not excluded from consideration, although they were assigned a low suitability score while analyzing the factor type of land use. This way the probability of interfering landfill operation with agricultural activities was minimized, in case a better alternative existed, i.e., siting sanitary landfills in non-cultivated areas.

Highways and railways A 500-m buffer zone was maintained on each side of highways and railways. Roads other than highways were not treated as constraining features, since the selected landfill sites should have access.

Environmentally protected areas The study area contains wetlands of international interest, such as the Delta of River Evros and Dadia National forest. Several areas belong to the European network Natura 2000 (Dafis et al. 1997) and should be protected according to Greek law, EU conservation policies, or international treaties, such as the Ramsar Convention of 1971. According to the Greek law 114218/97 (1997), landfill siting within areas of monumental or recreational value is forbidden. In addition, a buffer zone of 500 m was maintained around protected areas, designating them as unsuitable for landfill siting.

Important aquifers A landfill site should be located in an area with low groundwater pollution risk. In order to assess groundwater vulnerability to pollution, the methodology presented by Gemitzi et al. (2006) has been applied. According to this study, five discrete groundwater vulnerability classes are designated, based on intrinsic aquifer parameters and on external to the aquifer system parameters. In the present study only intrinsic aquifer parameters are examined. External parameters, such as land uses or surface runoff accumulation, are also incorporated as individual criteria within the multicriteria process presented herein. The intrinsic aquifer parameters are: type of aquifer (i.e., confined, unconfined, fractured, karstic), depth to the water table, and hydraulic conductivity. Based on these parameters a groundwater vulnerability to pollution map is created (Fig. 3a), with values ranging from 0 (least vulnerable areas) to 255 (most vulnerable areas), and it was categorized into five discrete classes. Areas belonging to the fourth (high groundwater vulnerability to pollution) and fifth groundwater vulnerability class (very high groundwater vulnerability to pollution), i.e., vulnerability index greater than 150 were considered as unsuitable for landfill siting.

Surface water bodies According to the EU directives, a 500-m buffer zone should be maintained around significant surface water bodies. In the study area such a zone has been created around lakes, marshes, and rivers of perennial flow.

Springs and wells According to the EU directives, landfills must not be close to any source of water, due to pollution risk. Kontos et al. (2003) suggests a 500-m buffer zone, which corresponds to a 50–60-day groundwater travel time required for pathogen die-off, considering an average groundwater velocity of 10 m/d. The same buffer zone is maintained in the present study around sources of drinking or irrigation water, i.e., springs and wells.

Exceptional geological conditions Presence of active faults, geothermal fields, and saltwater intrusion zones are prohibitive geological conditions for siting a sanitary landfill. With regards to seismic activity, the study area shows only minor seismic events, and most of it is classified in Zone 1 of the new seismic hazard map of Greece (OASP 2004). According to this classification, Zone 1 has a value of active soil acceleration of 0.16 g (where g is the acceleration of gravity). This is the minimum value for Greece. Despite the low seismic activity of the study area, there are active faults in the southern part of the study area, as shown by the location of recent seismic epicenters, which caused earthquakes of small to medium magnitude. For this reason, buffer zones of 1,000 m along both sides of active faults were assigned, so as to prevent the siting of the proposed facility to be on or too close to known active faults.

Geothermal fields are also present in the study area. Known geothermal fields were delineated, whereas a zone of influence of 500 m around each known geothermal borehole or spring has been created, so as to exclude these areas from the siting process. In the same way, saltwater intrusion areas near the coast were excluded from further consideration, as they already present environmental quality problems.

Distance from country borders and the coastline The study area borders to the east with Turkey and to the north and northwest with Bulgaria. A buffer zone of 1,000 m was maintained from the Greek borders. A protective buffer zone of 3,000 m from the coastline was created, to protect not only the coastline but also all the tourist activities taking place in the coastal area.

Factors relevant to environmental concerns

Three factors, i.e., non-exclusionary criteria, related to environmental issues were analyzed: (1) hydrogeology (HDG); (2) hydrology (HDR); and (3) distance from water bodies (DWB).

Hydrogeology A landfill site should not be located in areas with high groundwater pollution risk. Although the Greek law (Greek Governmental Ministry Decision 114218/97 1997) does not provide specific guidelines, the groundwater pollution risk has been assessed using the methodology for groundwater vulnerability to pollution

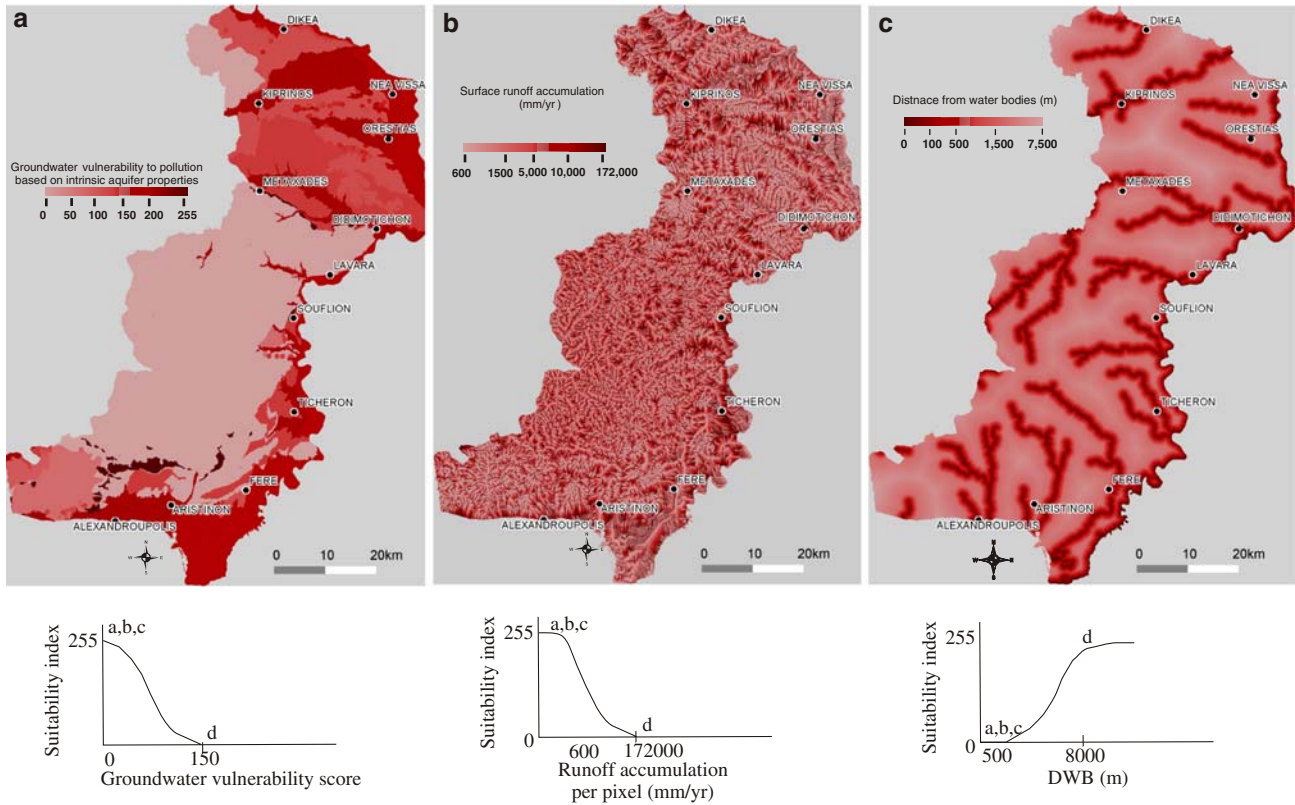


Fig. 3 **a** Groundwater vulnerability to pollution; **b** surface runoff accumulation; and **c** distance from water bodies

assessment discussed in the constraining criterion of important aquifers (Gemtzi et al. 2006), categorizing the study area into five groundwater vulnerability classes (Fig. 3a). In the examination of exclusionary criteria all pixels with groundwater vulnerability value greater than 150 (very high groundwater vulnerability to pollution) were considered unsuitable for landfill siting. The rest of the areas, i.e., pixels with vulnerability value less or equal to 150, were assigned a suitability score, transforming the values from 0 to 150 scale, to a continuous set of values, ranging from 0 to 255. Thus, a monotonically decreasing sigmoidal fuzzy membership function was applied (Fig. 3a).

Hydrology Surface runoff is a factor that is related both to environmental concerns, as the pollution potential increases in case of storm surges, as well as to economic costs, as it involves the construction costs for an efficient drainage system. Relevant studies examine the area of the upstream hydrologic basin (Kontos et al. 2003), or the floodplain of a specified return period (Siddiqui et al. 1996), in order to account for this factor. In the present study a different approach is adopted; each pixel in the study area receives an amount of rain and the specially developed routine, RUNOFF, incorporated in the raster

GIS Idrisi Kilimanjaro (Eastman 2003), calculates the accumulation of rainfall units per pixel based on an elevation image (DEM) (Jenson and Domingue 1988) (Fig. 3b). The higher the accumulation of runoff in a pixel the highest the flooding risk and the related costs for drainage network construction. A simple RUNOFF analysis accumulates rainfall on a per pixel basis as if one unit of rainfall was dropped on every location. In our case, mean annual precipitation data from 13 gaging stations scattered all over the study area, for the time period 1966–2001, was incorporated in the routine. Besides providing a DEM, the routine has been enhanced with a permeability image, in order to account for soil permeability and to adjust the accumulated rainfall accordingly (Eastman 2003).

A monotonically decreasing sigmoidal fuzzy membership function was applied to transform runoff accumulation to a 0–255 scale (Fig. 3b). Control point (a) was set to 600 mm/year where function membership becomes 1 and control point (d) was set to 172,000 mm/year where function membership becomes 0. The value of 172,000 mm/year after multiplication by the pixel size, i.e., 900 m², corresponds to an average discharge of 425 m³/d. Control points (a) and (d) were selected after imposing a quantiles classification scheme, placing an equal number of pixels of the study area into each class. The first point corresponds to the end of the first class, i.e., 600 mm/year (approximately 5% of the study area) and

the second point corresponds to the starting point of the last class, i.e., 172,000 mm/year (basin outlets) (upper 5% of the study area) defined as control points (a) and (d), respectively, for the sigmoidal fuzzy function. Pixels with accumulated runoff values lower than 600 mm/year and higher than 172,000 mm/year were considered equally suitable to the first and second control points, and received a function membership value of 1 (highest suitability) and 0 (lowest suitability), respectively.

Distance from water bodies Besides excluding landfill siting in areas within 500 m around significant surface water bodies, i.e., lakes, marshes, and rivers of perennial flow, it is preferable to locate such activities as far as possible from surface water bodies. A location profile has been created, representing the average distance to a series of features from anywhere within a map area (Northwood Technologies Inc. and Malconi Mobile Ltd 2001). The algorithm generates a grid, where at each cell a value is calculated that represents the average distance to all feature locations, i.e., surface water bodies, surrounding that cell (Fig. 3c). The greater the average distance from surface water bodies, the more suitable the pixel is considered to be for landfill siting.

A monotonically increasing sigmoidal fuzzy membership function was applied in order to transform the calculated distances to a continuous set of values ranging from 0 to 255 (Fig. 3c). Control point (a) was set to 500 m (lowest suitability) where function membership becomes 0, and control point (d) was set to 8,000 m (the most distant pixel to water bodies) where function membership becomes 1 (highest suitability).

Factors relevant to socioeconomic and design parameters

Six factors relevant to socioeconomic and design parameters are examined: (1) proximity to residential areas (PRA); (2) site access (SA); (3) type of land use (TLU); (4) proximity to waste production centers (PWPC); (5) site orientation (SO); and (6) slope of the land surface (SLS).

Proximity to residential areas Landfill siting is excluded within 500 m from residential areas. It is desirable, though, to locate a sanitary landfill as far as possible from existing towns, villages, or settlements. A location profile was generated, as in the case of the factor distance from water bodies (Fig. 4a). This time, however, the weighted average distance of each grid cell of the study area to the five nearest residential areas was calculated. The weighting factor was the population of each residential area according to the 2001 census data, provided by the Greek Statistical Service. The greater the weighted average distance from residential areas, the more suitable the pixel is considered to be for siting a MSW landfill.

A monotonically increasing sigmoidal fuzzy membership function was applied in order to transform the calculated distances to a 0–255 scale (Fig. 4a). Control point (a) was set to 500 m (lowest suitability) where function membership becomes 0, and control point (d) was set to 20 km (the most distant pixel to residential areas) where function membership becomes 1 (highest suitability).

Site access The proposed construction of sanitary landfill would be economically more feasible if it is located close to existing roads. Additional costs for road construction, in areas distant to roads, would make their selection less attractive. A very low suitability value, however, was assigned for pixels within a distance of 100 m from existing roads, in order for landfill vehicles not to interfere with the rest of the traffic. A location profile was created, calculating the distance of each grid cell in the study area to the closest existing road (Fig. 4b).

In this case a symmetric sigmoidal fuzzy membership function was applied to transform the computed distances to a 0–255 scale (Fig. 4b). Control point (a) was located at 99 m (inflection point where function membership increases from 0 to 1), control point (b) was set to 100 m where function membership becomes 1 (highest suitability), control point (c) was set to 250 m (inflection point where function membership starts to decrease), and control point (d) was set to 5 km (the most distant pixel from any road in the study area) where function membership becomes 0.

Type of land use As mentioned in the constraining criterion land uses, all types of forests were excluded from the siting process. Agricultural areas were assigned suitability values according to the NDVI value, which increases from 0.1 to 0.7 for increasing amounts of vegetation, and becomes >0.7 in the case of dense leaf canopies (Nemani et al. 2003). A monotonically decreasing sigmoidal fuzzy membership function was applied to transform the NDVI values to a 0–255 scale (Fig. 4c). Pixels with lower than 0.1 NDVI values were considered as equally suitable as those with 0.1 NDVI values, whereas pixels with higher than 0.5 NDVI values were assigned a value of 0 suitability, even though they were excluded while examining the land uses constraining criterion.

Proximity to waste production centers The proximity to waste production sources represents one aspect of the economic feasibility of a candidate landfill site, decreasing hauling costs by locating landfills near population centers. Taking into account that the present study aims at locating one landfill site for the whole study area, the average distance of each pixel from all the residential centers in the study area was calculated, weighted by the number of inhabitants of each population

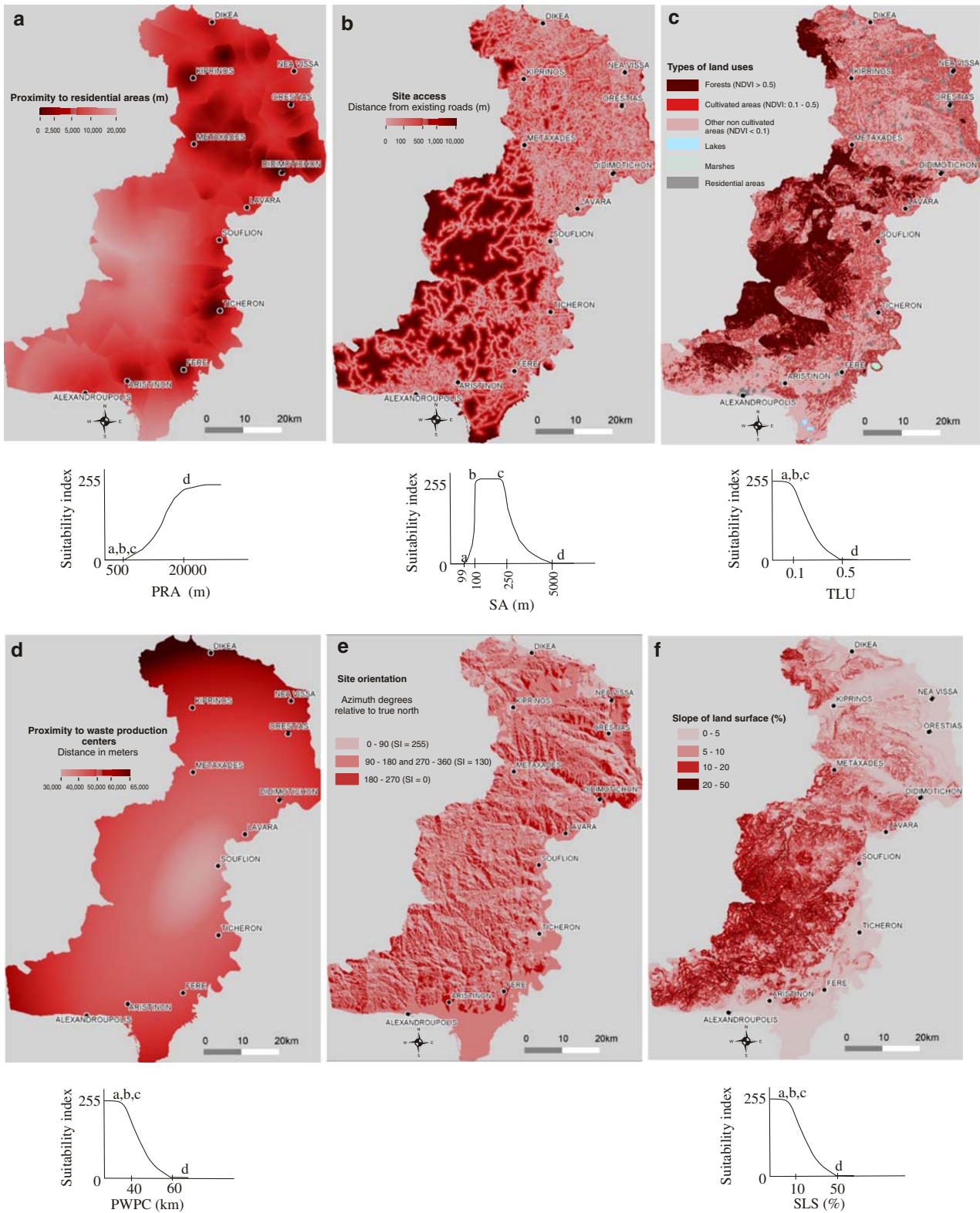


Fig. 4 a Proximity to residential areas; b site access; c types of land uses; d proximity to waste production centers; e site orientation; and f slope of the land surface

center (Fig. 4d). This factor is quite different from the proximity to residential areas, as the former targets at reducing hauling costs, whereas the latter aims at

minimizing public dissatisfaction. It should be pointed out herein, that in the case of proximity to residential areas criterion, the weighted average distance from the five nearest population centers has been calculated, as these are expected to be the most dissatisfied ones in case a landfill site is located in their vicinity. On the contrary, in the case of the proximity to waste production centers, the weighted average distance from all residential areas was calculated, as all of them will contribute to waste generation proportionally to their population.

A monotonically decreasing sigmoidal fuzzy membership function was applied to transform the computed distances to a 0–255 scale (Fig. 4d). Control point (a) was set to 40 km where function membership becomes 1 (highest suitability), and control point (d) was set to 60 km where function membership becomes 0 (lowest suitability). Pixels with values lower than 40 and greater than 60 received values of 1 and 0, respectively.

Site orientation The dominant wind orientation in the study area is north to northeast. Aspect measures the direction that each grid cell faces in three-dimensional space, i.e., perpendicular to the strike of a surface, and is recorded in azimuth degrees relative to true north.

Four discrete aspect classes were defined and assigned suitability values ranging from 0 to 255, according to whether they favor odor and particle transport or not. In that way the orientation class from 0° to 90° was assigned a value of 255 (best), the classes from 90° to 180° and from 270° to 360° received a value of 130 (moderate suitability), and the class from 180° to 270° received a value of 0 (unsuitable) (Fig. 4e).

Slope of the land surface The slope of the land surface is a crucial factor as far as construction costs are involved, as very steep slopes will lead to higher excavation costs. The slope of the land surface was calculated on a pixel basis, as a percentage, ranging from 0 to 50%, using the DEM of the study area (Fig. 4f). A monotonically decreasing sigmoidal fuzzy membership function has been applied to transform the above values to 0–255 scale (Fig. 4f). Control point (a) was set to 10% where function membership becomes 1 (highest suitability), and control point (d) was set to 50% where function membership becomes 0 and the associated suitability is diminished. Pixels with value lower than 10% were considered equally suitable for landfill siting as those with slope value of 10%.

Aggregation procedure

After standardizing all factors to a common 0–255 scale using fuzzy membership functions, factor weights were given to all factors in each group. The weights indicate a factor's importance relative to all other factors and

control how factors compensate for each other in each factor group.

Factor weights sum to 1 for each factor group that the project has been divided into. Several techniques exist for assigning factor weights. The simplest one could be the division of 1 into the number of factors in each factor group. However, weights produced with this procedure are not often realistic. A more efficient way of producing factor weights is the AHP (Saaty 1977; Pavlikakis and Tsihrantzis 2003), which was first introduced into GIS by Rao et al. (1991). In the present study the AHP has been implemented applying the module WEIGHT, incorporated in the raster GIS program Id-risi Kilimanjaro (Eastman 2003). In this module, each pair of factors in a particular factor group is examined at a time, in terms of their relative importance (Table 1). After all possible combinations of two factors, the module calculates a set of weights that sum to 1 and a CR. This ratio indicates any inconsistencies that may have been made during the pairwise comparison process, i.e., the probability that factor weights have been assigned quite randomly (Eastman 2003). A CR greater than 0.10 indicates that factor weights should be re-evaluated (Saaty 1977).

A weighted linear combination (Voogd 1983) is applied in order to combine information from various factors in each factor group. This aggregation technique multiplies factor scores by their factor weight and then sums the products to yield the suitability score as described by Eq. 3.

Nevertheless, when analyzing a siting problem that involves both economic and environmental criteria, it is easy to determine how factors related to economic costs trade off, as they can be converted to monetary value. On the other hand, it is very difficult to decide if and to which extent environmental factors trade off, as there is no way, for example, to convert the pollution of a water body to monetary cost. Control over risk and trade off is made possible through a second set of weights, order weights, applied to factors on a pixel-by-pixel basis, for the different rank-order positions of factors at every location (pixel). The order weights will first modify the degree to which factor weights will have influence in the aggregation procedure, thus they will govern the overall level of trade off (Eastman and Jiang 1996; Yager 1988). After factor weights are applied to the original factors, the results are ranked from low to high suitability for each location. The factor with the lowest suitability score is then given the first-order weight, the factor with the next higher suitability score is given the second-order weight, and so on. This has the effect of weighting factors based on their rank from minimum (lowest suitability) to maximum (highest suitability) value for each location. The relative skew toward either minimum or maximum of the order weights controls the level of risk in the evaluation (Eastman 2003) (Table 2). Addition-

ally, the degree to which the order weights are evenly distributed across all positions controls the degree to which factor weights have influence.

The procedure is repeated once for each group of factors, resulting in two intermediate suitability landfill siting maps. The final suitability map is produced by aggregating, using the same procedure, the intermediate results.

In the following paragraphs the factor and order weights in each one of the two factor groups are presented. In both cases skewing order weights toward the less suitable factor, offers a more conservative solution and stresses pixels in the study area to lower suitability values.

Weighting and aggregating factor group 2 The pairwise comparison matrix and the calculated factor weights for factor group 2 are shown in Table 3.

The assigned order weights (Table 3) show a low level of risk and minimized trade off, as environmental factors are not expected to trade off. Skew toward the factor with the lowest suitability score, shows a very strict decision. The intermediate landfill siting suitability map is presented in Fig. 5a.

Weighting and aggregating factor group 3 The pairwise comparison matrix and the calculated factor weights for factor group 3 are shown in Table 1.

The assigned order weights (Table 1) are distributed evenly among all factors regardless of their rank-order position. Only a minor skew toward factors with the lowest suitability scores makes the decision moderately risk averse, while trade off is maximized, allowing the factor weights to be employed. Figure 5b presents the suitability map for landfill siting based on factor group 3.

Weighting and aggregating intermediate results

Intermediate results were aggregated in order to produce the composite MSW landfill siting suitability map. Constraints always remain as Boolean masks and they are not involved in any weight assignment process. The intermediate suitability maps, which resulted from the

Table 3 Pairwise comparison matrix for factor group 2

	HGD	HDR	DWB	Calculated factor weights
HGD	1	1	3	0.4286
HDR	1	1	3	0.4286
DWB	1/3	1/3	1	0.1429
Consistency ratio =	0.0			
Order weights	0.7	0.2	0.1	
Rank	1st	2nd	3rd	

two previously examined groups, were used as equally weighted factors in the final aggregation process:

Factor group 1: 0.5; factor group 2: 0.5.

The following order weights were assigned:

Order weights	0.6	0.4
Rank	1st	2nd

The assigned order weights show a low level of risk. Aggregation is skewed toward the factor with the lowest suitability score.

Sizing procedure

In order to estimate the required landfill area for Evros prefecture, the methodology described by Aivaliotis et al. (2004) was adopted. The following assumptions were made: symmetrical combination of landfill and landraise, with base surface area of size A (in 10^3 m^2) and of two shapes, square and orthogonal. The average per capita solid waste production in Greece for the year 2004 has been reported at 1.1 kg/capita/day (European Compost Network 2004) and the average density in the landfill after compaction is between 500 and 800 kg/m³ (Aivaliotis et al. 2004). For the study area, the estimated solid waste quantity M is then 1,309,411 tons for a 20-year operation period, assuming a 0.5% population increase per year and a constant average waste production per capita per year. According to Aivaliotis et al. (2004), the size A of the required surface area of the landfill, for waste quantity M (in tons) to be placed, will be within the range of $A = (M/1.76)^{0.725}$ to $A = (M/2.55)^{0.725}$. Thus the required landfill area ranges from 120,000 to 160,000 m², for the two mentioned shapes. For a more conservative approach the higher value, i.e., 16 ha, has been used in the siting calculations.

Results

The final suitability results were divided into five discrete categories from low to high suitability, i.e., 0–50 (very low suitability), 50–100 (low suitability), 100–150 (moderate suitability), 150–200 (high suitability), 200–255 (very high suitability), as shown in Fig. 5c. Table 4 presents the areas of these classes and the percentages of the total study area. Figure 5d shows the areas of very high suitability.

According to the estimated required area of 160,000 m², a post aggregation constraint should be introduced requiring that suitable sites must be at least 160,000 m² in size, if only one landfill is to serve the entire study area. This is achieved by selecting a fixed quantity of top-ranked locations, i.e., those that belong to the fifth suitability category (200–255), equivalent to the required

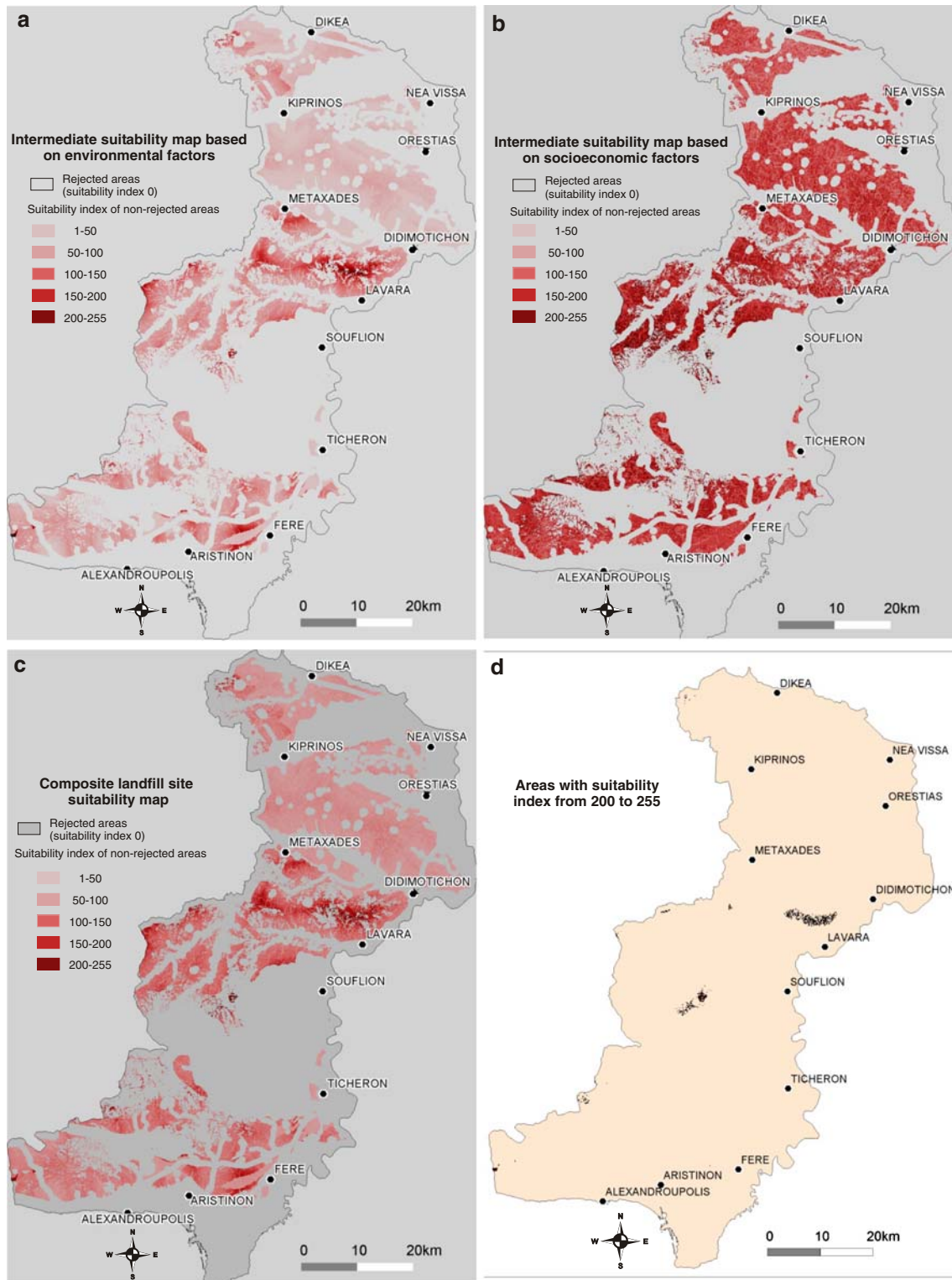


Fig. 5 **a** Intermediate suitability map based on environmental factors; **b** intermediate suitability map based on socioeconomic factors; **c** composite landfill site suitability map; and **d** areas with very high suitability index

area. The result is a Boolean map, where exact amounts of land are allocated for MSW landfill (Fig. 6a). Three sites are identified, while their size and average suitability

index, i.e., average suitability value of all pixels within the selected site, are presented in Fig. 6a.

Moreover, due to the fact that such constructions require permission from military and archeology services, the selected areas should be examined for absence of such features. It is noted that military facility and archaeological data are not available, and therefore cannot be used in the GIS analysis.

A different scenario is also presented in Fig. 6b, c, where the alternative choice of two sites for landfill construction, i.e., one for the north and one for the southern part of the study area was examined. As each one of these two parts of the prefecture holds almost half of the entire prefecture population, the required area for either of them will be approximately half the predefined required area calculated for the whole prefecture. It should be noted herein that all factors and constraints remained the same, as in the previous aggregation procedure. Only the factor of proximity to waste production centers changed, as this time only residential areas of either the north or the south part of the study area participated in the calculations. According to this alternative, five areas are designated as suitable, i.e., suitability index ≥ 200 , in the north Evros region and one in the south Evros region, as shown in Fig. 6b, c. It should be mentioned that in this work all suitable areas are presented, and not the two most suitable ones. The choice of either scenario and either of the identified sites should also be based on detailed cost-benefit studies as well as on public opinion, and is beyond the scope of this study.

Discussion

In the present study a methodology for assessing location suitability for MSW landfill was developed that takes into account both exclusionary and non-exclusionary criteria, and coupling GIS with multicriteria evaluation techniques and fuzzy logic.

Several approaches have been presented for landfill siting using GIS and multicriteria evaluation (e.g., Kao and Lin 1996; Siddiqui et al. 1996; Kontos et al. 2003; Sener et al. 2006). The coupling of the above methodologies with fuzzy logic has been presented in recent

studies (e.g., Charnpratheep et al. 1997; Gupta et al. 2003; Al-Jarrah and Abu-Qdais 2005). In the present study, however, besides offering all the advantages of the above-mentioned techniques, an important contribution has been achieved through the application of the order weights, on a pixel-by-pixel basis, which offers the full control over the level of risk and trade off desired. Moreover, the distinction of the parameters involved in the siting process into three groups, i.e., constraints which are not included in the weighting process, environmental factors that generally do not trade off and socioeconomic parameters that usually trade off, offers a noticeable flexibility in the aggregation procedure. It is thus quite simple to explore different siting scenarios, as far as a cost-sensitive approach is desired, or a more sensitive environmental alternative is aimed.

Furthermore, the choice of the fuzzy membership function control points at which set membership becomes either 0 or 1, was a critical issue in the factor standardization process of the present study. It is important to consider the physical meaning of each variable, before choosing the inflection points of the fuzzy membership function. As far as distances are concerned, inflection points are located at distances specified by the law, or by common sense. In case of factors of broad value range, such as proximity to waste production centers, a quantiles classification scheme was applied, placing an equal number of pixels into each class, and control points were located at the end of the first class and the starting point of the last class (approximately upper and lower 5% of the study area). On the other hand, when analyzing the site access factor, it was merely a choice of common sense the assignment of very low suitability to all areas within a distance of 100 m from any road, for the landfill vehicles not to interfere with other traffic. At that point suitability raises at 100 m, remains very high within distances up to 250 m from roads, where it starts decreasing, while function membership becomes 0 (lowest suitability) at 5 km (the most distant pixel from any road in the study area). This is achieved through the application of a symmetric membership function.

Factor weights were assigned to the nine non-exclusionary criteria (factors) involved in the calculation process. It is clear that assignment of factor weights is based on previous knowledge of the factor characteristics and the particularities of the study area, as well as on the experience of the scientists involved in the weight assignment process. It was attempted, however, to develop a weight assigning process as objective as possible, by applying techniques like the AHP. Moreover, applying order weights provided full control over the level of risk and trade off in produced results. In the case of factor group 2, the same factor weight was assigned to hydrology and hydrogeology factors, while most of the

Table 4 Landfill siting suitability results

Suitability class	Suitability index	Area (km ²)	Percentage of the study area
Very low	0–50	2,720	68
Low	50–100	400	10
Moderate	100–150	680	17
High	150–200	160	4
Very high	200–255	40	1

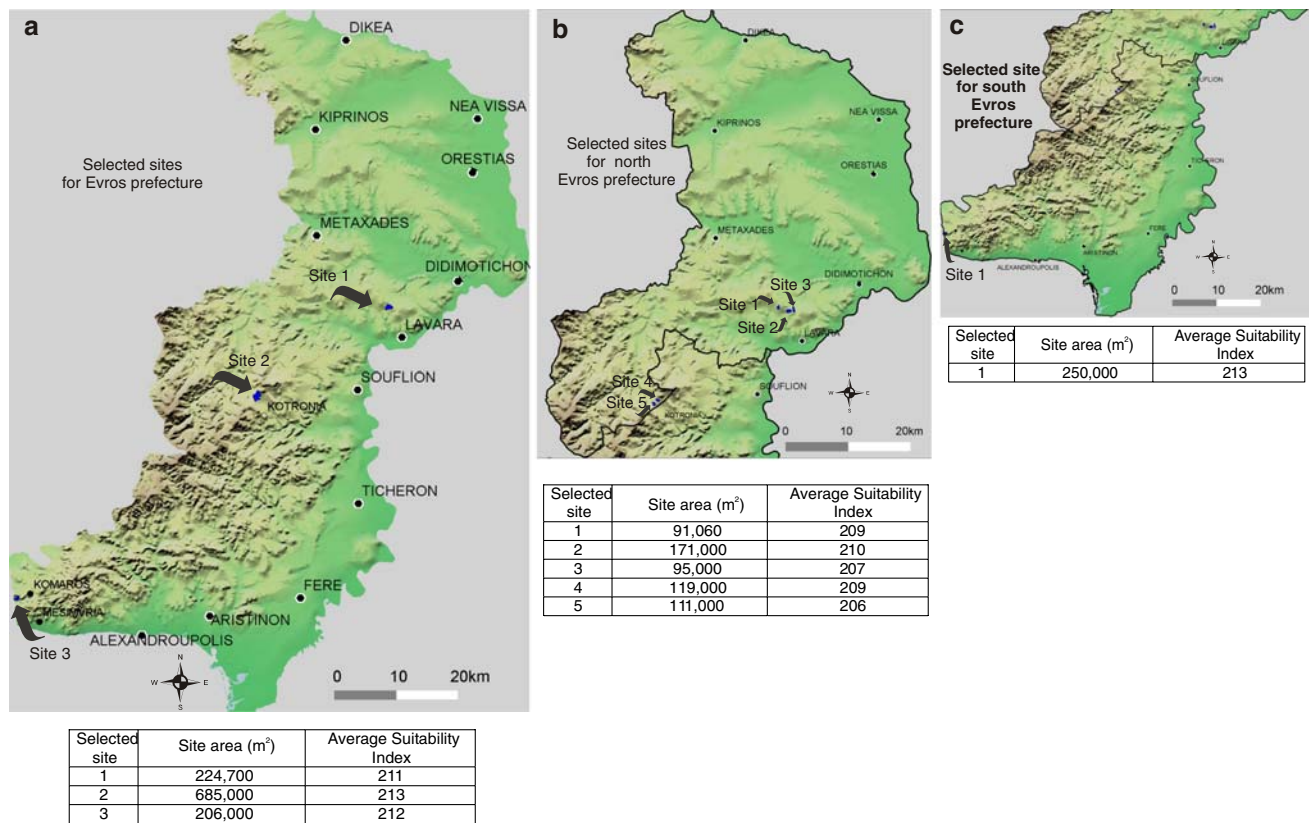


Fig. 6 a Selected suitable sites for Evros prefecture; b selected suitable sites for the north part of Evros prefecture; and c selected suitable sites for the south part of Evros prefecture

order weight was assigned to the least suitable factor, allowing only a minor level of trade off between factors and producing an environmentally risk averse result. In that way, a very strict decision is made, as far as environmental issues are concerned. In the case of factor group 3, order weights are dispersed to all six factors, leading to a high level of trade off, as socioeconomic factors impose. There is, however, a minor skew toward the least suitability factors, making thus the decision moderately risk averse.

In the final aggregation process, factor weights are evenly dispersed to both factors, i.e., environmental and socioeconomic, as they both play an important role while siting a MSW landfill. Order weights are skewed again toward the factor with the least suitability score, making the choice quite risk averse.

The prolonged shape of the study area leads to high haul distances, in case a single site is selected for the whole prefecture of Evros. An alternative solution could be the selection of two candidate sites, i.e., one for the north and a different one for the south part of the study area as presented in Fig. 6b, c. The choice of either solution, however, should be based on detailed cost-benefit study, which is beyond the scope of the present

work. Furthermore, transfer stations can be used to minimize transportation cost.

Conclusions

The presented study shows an integration of GIS, fuzzy logic, and multicriteria evaluation techniques in the assignment of site suitability for MSW landfill. Nine exclusionary criteria and nine non-exclusionary criteria were examined in the computation process, categorized in three groups. Two intermediate suitability maps were produced, which were combined to create the composite suitability map. The AHP was used and offered a quite objective weights assignment process. Furthermore, the use of the second set of weights, order weights, as applied in the present work, provides great flexibility in the aggregation procedure, offering full control over the risk and trade off in the produced results.

It should be mentioned herein that the presented work offers a siting methodology and not a decision itself. The final decision, most of the times, is dictated by the public opposition and the political costs, while the present study emphasizes on the scientific evidence provided for the study area. Furthermore, economic factors should be considered for solid waste transportation. However, the siting process, with the methodology

outlined in the present study, could be very useful for future siting of human activities related to solid waste management and disposal.

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