MULTIFACTOR SPATIAL ANALYSIS FOR LANDFILL SITING

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ABSTRACT: Siting a landfill typically requires processing a significant amount of spatial data with respect to various siting rules, regulations, factors, and constraints. Manually performing such a spatial analysis with drawing tools is generally tedious. A modern geographical information system (GIS), although capable of manipulating spatial data to facilitate the analysis, lacks the ability to locate an optimal site when compactness and other factors are simultaneously considered. An appropriate siting model was therefore explored for use with a raster-based GIS. A mixed-integer programming model was developed to obtain a site with optimal compactness. A comparison was made between the model and two other previously proposed models in terms of their applicability and simplicity for raster-based data. The compactness model was further extended to include multiple siting factors with weights determined using map layer analysis functions provided by a GIS. This multifactor model was applied to analyze the effects of varied weights and factors on making a siting decision.

INTRODUCTION

Sanitary landfilling is the conventional method of disposing of municipal solid waste (MSW). Even with an incinerator, the ash produced must be transported to a landfill for final disposal. Recently, constructing landfills in environmentally sensitive areas has been strictly prohibited. On the other hand, the general consensus of "Not in My Back Yard" (Lindquist 1991) further restrains the local MSW authorities from placing landfills near residential areas, thereby increasing the difficulty of finding appropriate landfill sites in Taiwan, a highly populated island. Thus, selecting areas suitable for placing a landfill has become an increasingly urgent concern in local governments. Lowrance (1989) pointed out the imminence of a solid waste crisis: an increase in demand for landfill sites at the same time as there is a decreasing supply of land for such purposes.

Numerous factors must be evaluated when siting a landfill. An appropriate landfill site should have minimum impact on environment, society, and economy, comply with regulations, and be generally acceptable to the public (Zyma 1990). Without thoroughly considering all prevailing regulations and environmental, sociocultural, engineering, and economic factors, or being unable to fully grasp the background information of a candidate site, the decision maker might reach an inappropriate conclusion. Detailed spatial data should be collected for above factors to assess associated impacts. A landfill siting analysis is generally multidisciplinary and requires extensive effort to evaluate considered factors.

A map-layer–based screening approach has been proposed (McHarg 1960; Lane and McDonald 1983) to perform such a multifactor land suitability analysis. However, implementing such a complicated procedure in a conventional information processing approach would be expensive and tedious. A modern geographic information system (GIS) is capable of processing a large amount of spatial data, thereby potentially saving time that would normally be spent in selecting an appropriate site. Michaels (1988) demonstrated that, by using a GIS, the State of Illinois in the United States employed map layers for six factors to conduct initial screening of potential sites. Lindquist (1991) found that using a GIS for site selection not only increased objectivity and flexibility, but also ensured that a large amount of spatial data can be processed in a short time. Relatively easy presentations of GIS siting results are also one of its advantages.

The GIS used herein is GRASS (U.S. 1993), a public-domain GIS. GRASS is a raster-based GIS operated on a UNIX platform, although limited vector-type functions are also available. In the raster mode, spatial data are divided into cellular georeferenced objects. Factors involving the attributes of a geographical object are expressed with numbers and linked to the GIS cell that represents the object. A map layer consists of a collection of GIS cells; each map layer stores an attribute of an area. The primary advantage of applying such a raster-based GIS is the simplicity of its data storage and processing that makes it easily combined with other tools.

For a general GIS, although useful in aforementioned siting experiences, the algorithm for obtaining the optimal site, with simultaneous consideration of site compactness and other factors, is generally unavailable. A site obtained by a raster-based GIS is generally expressed by a set of aggregated land cells. However, the shape of such a set of aggregated cells may not be compact (Minor and Jacobs 1994). Compactness represents the integrity of the site and the extent to which it can be regarded as tightly integrated. The lower the level of compactness implies the less likely it is to satisfy siting requirements, subsequently making general land planning much more difficult. On the other hand, the more compact the selected site implies the better the site's integrity, thereby making the site likely to be arranged properly for landfilling.

Compactness can be defined by a variety of methods (Wright et al. 1983; Gilbert et al. 1985; Diamond and Wright 1989). For instance, Wright et al. (1983) used the ratio of the perimeter to the area of a site as a measure for compactness. According to this definition, the shorter the perimeter of a site, the higher its degree of compactness. Diamond and Wright (1989) applied the ratio of the square of the largest diameter to the area of a selected site as the other measure. The largest diameter refers to the longest distance between any two points within the selected site. However, calculating the longest distance is based on a nonlinear function which can not be included in a linear programming model. Minor and Jacobs (1994) and Benabdallah and Wright (1992) adopted the former definition for a waste landfill siting problem and a land allocation problem, respectively. Spatial compactness models, although having proven useful for solving a siting problem, were not integrated into a raster-based GIS, despite the fact that Diamond and Wright (1989) indicated that such an integration would provide an intelligent decision making tool for land-use problems. One of the major difficulties encountered in integration was that a significant amount of integer variables and constraints were required to construct a compactness model

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for raster-based GIS map layers, thereby making the model difficult to solve by a general mix-integer programming solver. The present work was therefore initiated to explore an appropriate compactness model to overcome the above difficulty.

An improved compactness model was proposed and integrated with a raster-based GIS for implementing spatial-siting analysis to perform a search for an appropriate MSW landfill site. However, as aforementioned, a landfill-siting decision is hardly based on a single criterion or factor. A single factor decision model such as the proposed compactness model is unsatisfactory for analyzing a landfill siting problem. The compactness model was therefore extended to include multiple siting factors. This multifactor model is capable of analyzing a complex landfill-siting problem while simultaneously considering various environmental, sociocultural, engineering, and economic factors.

In the following description, the proposed compactness model is first described. The proposed model and the two previous models are compared on the basis of their applicability and simplicity for raster-based data. Next, the model is extended to include multiple weighted factors for a MSW landfill siting problem for Yuanli County in central Taiwan. Various alternative solutions obtained based on varied factors and levels of compactness are also presented and evaluated.

COMPACTNESS MODEL

Compactness

No direct relationship arises between compactness and other landfill siting factors. However, compactness influences the final siting decision to determine whether the selected cell areas can be an appropriate landfill site. For instance, unconnected land cells are inappropriate to serve as a landfill site. Moreover, even if the land cells are continuous but have a poor shape, they are again inappropriate to be a candidate site. Therefore, a compactness model is applied to ensure the compactness of the selected site.

Perimeter Calculation

In the present work, as used by Wright et al. (1983), the compactness of a site is defined as the ratio of its perimeter to its area. This study focuses primarily on raster-based data. A site is comprised of adjacent square GIS cells of which the side length of square borders is uniform. Based on this framework, $I_{i,j}$ (0, 1) integer variable is defined to represent whether cell i, j belongs to a considered site. When the value of the variable is 1, the cell is part of the site; if the value is 0, the cell is not part of the site. Each cell side length is positively or negatively directed according to the value of $I_{i,j}$. Fig. 1 illustrates how the directed sides are defined. When a cell is part of the site, $I_{i,j}$ equal to 1, the directions of cell sides are clockwisely defined. On the other hand, if a cell is not part of the site, $I_{i,j}$ equal to 0, then its cell side directions are counterclockwisely defined. For computational convenience, each side length is designated to be 0.5 units, and the directed length pointed upward or leftward is negative. With this concept of directed sides, each side length of a cell can be defined by the following equations:

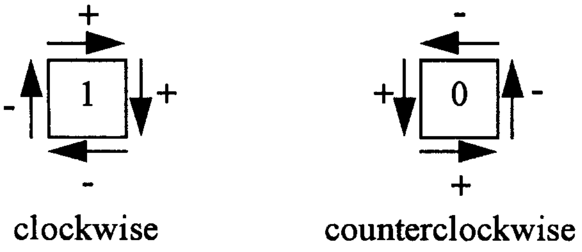

FIG. 1. Directed Cell Sides

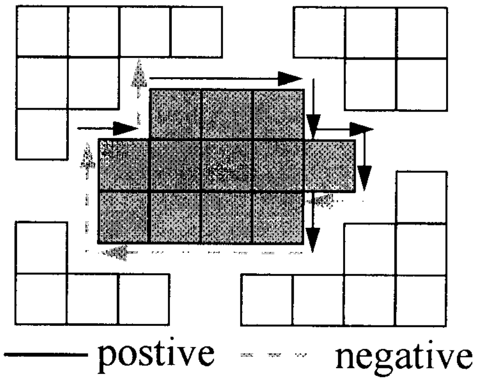

FIG. 2. Directed Perimeter

$$LT_{i,j} = -0.5 + I_{i,j}; \quad LR_{i,j} = -0.5 + I_{i,j}; \quad LB_{i,j} = 0.5 - I_{i,j};$$

$$LL_{i,j} = 0.5 - I_{i,j} \qquad (1a\text{–}d)$$

where $LT_{i,j}$, $LR_{i,j}$, $LB_{i,j}$, and $LE_{i,j}$ = top, right, bottom, and left side lengths of cell i, j, respectively.

Any side of a cell must be adjacent to one side of another cell. According to Fig. 1, when the values of $I_{i,j}$'s for any two adjacent cells are the same, i.e., both equal to 1 or 0, the sum of the directed lengths of the common side of both cells will be zero that expresses the side is not part of the perimeter. On the other hand, where the values of $I_{i,j}$'s for two adjacent cells are different, the sum of the two directed lengths of the common side will be +1 or −1 that expresses the side is part of the perimeter. In calculating the perimeter of a site, the contributing perimeter of a cell side is the sum of its directed side lengths of two adjacent cells that share the same side.

For a closed curve, the vectors of the pieces on the curve should be summed up to be zero. Therefore, the total length of the "top" plus "right" contributing perimeters of a site should be equivalent to the total length of "bottom" plus "left" ones; in addition, both total lengths have an opposite sign. Fig. 2 shows a sample site of twelve cells. As indicated in this figure, the sum of all negative side lengths is equal to the sum of all positive side lengths for cells sides on the boundary of the site. As such, the perimeter of a site can be determined by merely calculating the "top" and "right" contributing perimeter lengths.

The contributing perimeters of the top and right side of a cell, i, j, can be computed by the following formula:

$$\text{Top side: } SLT_{i,j} = LT_{i,j} + LB_{i,j-1} \qquad (2a)$$

$$\text{Right side: } SLR_{i,j} = LR_{i,j} + LL_{i+1,j} \qquad (2b)$$

The contributing perimeter of a cell, SL, can therefore be defined by the following equation:

$$SL_{i,j} = SLT_{i,j} + SLR_{i,j} = 2I_{i,j} - I_{i+1,j} - I_{i,j-1} \qquad (3)$$

Possible values of $SL_{i,j}$ are 0, 1, −1, 2, and −2. When the value is other than 0, its absolute value expresses the number of sides of the cell that contribute part of the perimeter of the considered site. A linear programming model cannot directly calculate the absolute value; thus, a new nonnegative variable, $V_{i,j}$, is introduced. This yields the following constraint, i.e.

$$2I_{i,j} - I_{i+1,j} - I_{i,j-1} + V_{i,j} \geq 0 \text{ for all } i, j \qquad (4)$$

When $SL_{i,j}$ is less than 0, $V_{i,j}$ is equal to its absolute value. When $SL_{i,j}$ is larger than 0, $V_{i,j}$ is equal to 0. Thus, the total of all $V_{i,j}$ values represents the sum of all negative $SL_{i,j}$ values. As mentioned for vectorial balance of a closed curve, the sum of all positive values should be equal to the sum of all negative values. The total of all $V_{i,j}$ values is therefore equal to half of the perimeter of a site.

Model

According to the perimeter calculation described above, the spatial compactness model proposed in the present study is listed

$$\text{Min} \sum_{i=0}^{i=m} \sum_{j=1}^{j=n+1} V_{i,j} \qquad (5a)$$

subject to $2I_{i,j} - I_{i,j-1} - I_{i+1,j} + V_{i,j} \geq 0 \; \forall \; i \in \{0, \ldots, m\};$

$\forall \; j \in \{1, \ldots, n + 1\}$ (5b)

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} I_{i,j} \geq A \; \forall \; i \in \{1, \ldots, m\}; \forall \; j \in \{1, \ldots, n\} \qquad (5c)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} C_{i,j}^{k} \cdot I_{i,j} \geq G^{k} \; \forall \; k \in \{1, \ldots, p\} \qquad (5d)$$

$I_{i,j}$ is (0, 1) integer   other constrains or bounds (5e)

where m and n = number of columns and rows of cells that represent entire siting area; A = required size (in numbers of cells) of desired site; $C_{i,j}^{k}$ = value of siting factor k for cell i, j; p = number of considered factors; G^{k} = lower bound of sum of factor values of cells in site for siting factor k. Notably, ensuring that each cell in the siting area has an adjacent cell requires adding a pseudo column of cells (for $j = n + 1$) on the right-hand side of the siting area; a pseudo-row (for $i = 0$) of cells is also added on the top of the siting area. The continuity of the selected cells of the solution to the above model is guaranteed because the model seeks the smallest perimeter.

Comparison with Previous Models

Comparisons of the proposed model and those developed by Minor and Jacobs (1994) and Wright et al. (1983) or Benabdallah and Wright (1992) are provided below, as based on their applicability and complexity for raster-based data. Both models are briefly described in this section for comparison. A detailed description of the development and demonstration of the models can be found in Minor and Jacobs (1994), Wright et al. (1983), and Benabdallah and Wright (1992). The Minor and Jacobs model is a linear mixed-integer programming model for siting a hazardous-waste landfill within an area that is partitioned into 66 parcels with irregular sizes and shapes. Their model is formulated in the following.

$$\text{Min} \sum_{i=1}^{N} c_i x_i \qquad (6a)$$

subject to $x_i - x_j \leq B_{ij} \; \forall \; i, j \in \{i + 1, \ldots, N\}$ (6b)

$$x_j - x_i \leq B_{ij} \; \forall \; i, j \in \{i + 1, \ldots, N\} \qquad (6c)$$

$$x_i + x_j + B_{ij} \leq 2 \; \forall \; i, j \in \{i + 1, \ldots, N\} \qquad (6d)$$

B_{ij} [illegible] $x_i - x_j \leq 1 \; \forall \; i, j \in \{i + 1, \ldots, N\}$ (6e)

$$\left(\sum_{i=1}^{N} \sum_{j=i+1}^{N} S_{ij}(B_{ij}) + \sum_{i=1}^{N} S_{ei} x_i \right) \leq \lambda \left(\sum_{i=1}^{N} a_i x_i \right) \forall \; i, j$$

$\in \{i + 1, \ldots, N\}$ other constrains or bounds (6f)

where N = number of parcels in siting area; c_i = cost of parcels $_i$; x_i and x_j = (0, 1) integers that determine whether parcel i and parcel j are selected; B_{ij} = (0, 1) integer, which determines whether common boundary of parcel i and parcel j is included in perimeter or not; S_{ij} represents length of common boundary of parcel i and parcel j; S_{ei} = boundary length of parcel i that resides on border of siting area; λ = upper bound of compactness; and a_i = area of parcel i.

Benabdallah and Wright (1992) used a raster-based linear mix-integer model to solve a multiple site land-use planning problem. In seeking a multiple site solution with the model, an increase in the number of planned sites increases the number of required integer variables, thereby making the model difficult to solve. Although they proposed a nonlinear model to reduce the number of variables, the solution to the nonlinear model might not be the global optimum. If only one site is desired, their linear model is the same as that proposed by Wright et al. (1983). The formulation of their linear model is listed below.

$$\text{Min} \sum_{i=1}^{n} \sum_{j \in T_i} S_{ij}(P_{ij} + N_{ij}) \qquad (7a)$$

subject to $x_i - x_j - P_{ij} + N_{ij} = 0 \; \forall \; i, j$

$\in T_i$ other constrains or bounds (7b)

where x_i and x_j = (0, 1) integers that determine whether cell i and cell j is part of site; T_i = set of cell numbers of cells adjacent to cell i; $S_{i,j}$ = length of side shared by cell i and cell j; and $P_{i,j}$, $N_{i,j}$ = (0, 1) integers that determine whether associated $S_{i,j}$ is part of perimeter.

Table 1 lists, for each cell, the number of required varibles and constraints for each model for raster-based data. The required number of variables and constraints are counted only for two of the four sides of each cell, because each side is shared by two cells. The Minor and Jacobs model uses four constraints for each cell side to determine whether each side is part of the perimeter. The Wright model uses one constraint for each cell side. If each side is not repeatedly computed, the Wright model requires two constraints for each cell. For the proposed model, however, only one constraint is required for each cell. For the number of required variables, the proposed model requires only one integer and one non-integer variable, but the Minor and Jacobs model requires three integer variables and the Wright model requires five integer variables. As for a mixed-integer linear programming model, an increase in the number of integer variables rapidly increases the computational time required to solve the model. However, an increase in the number of noninteger variables does not have such a significant effect. The decrease in the required number of integer variables of the proposed model is therefore particularly useful in reducing the computational time. Furthermore, the proposed model requires only one constraint per cell. It is less complex than the other two models. The proposed model is more appropriate for a raster-based siting problem.

The models of Minor and Jacobs (1994) and Wright et al. (1983) can also be applied for cells or blocks in irregular size and shape and for selection of multiple sites. Although an improvement has been made in the proposed model for irregular cells, related computer programs, case studies, and comparison with previous models are still under development.

TABLE 1. Comparison of Spatial Compactness Models for Required Numbers of Variables and Constraints for Each Cell

Model (1)	Number of integer/noninteger variables (2)	Number of constraints (3)
Minor and Jacobs (1994)	3/0	8
Wright et al. (1983)	5/0	2
Current model	1/1	1

SPATIAL ANALYSIS FOR LANDFILL SITING

By using the proposed compactness model, a case study of Yuanli County in central Taiwan was implemented to exemplify the proposed procedure integrating the GIS and a spatial analysis model. The procedure, as shown in Fig. 3, can be divided into three major parts: siting criteria and factors, suitability scores of factors and spatial multifactor analysis. Each part is described below, along with a discussion of results obtained for the studied area.

Siting Criteria and Factors

Before the spatial analysis is performed to site a landfill, siting criteria and factors should be evaluated for their applicability for the siting area from related legislation, restrictions, rules, experiences, and expertise in various aspects. Criteria are rules that prohibit a landfill from being placed within a specific area; factors are important attributes that should be used to evaluate the suitability of a site. Other than assessing and comparing the suitability of a candidate site, the foregoing criteria and factors are used to screen out unsuitable areas and define a model objective for implementing the spatial analysis model described later in this section. A siting area is generally large in a number of GIS cells, thereby making the spatial model impossible to solve within an acceptable computational time. It would become solvable if the siting area is reduced after screening out clearly unsuitable areas. In general, related environmental, sociocultural, and engineering-economic issues are evaluated to form the criteria and factors. Typical samples of each type of issue are provided below with the associated criteria used in the present work.

Environmental Issues

- Water resources: a landfill should not be placed within ground water or water resource protection areas

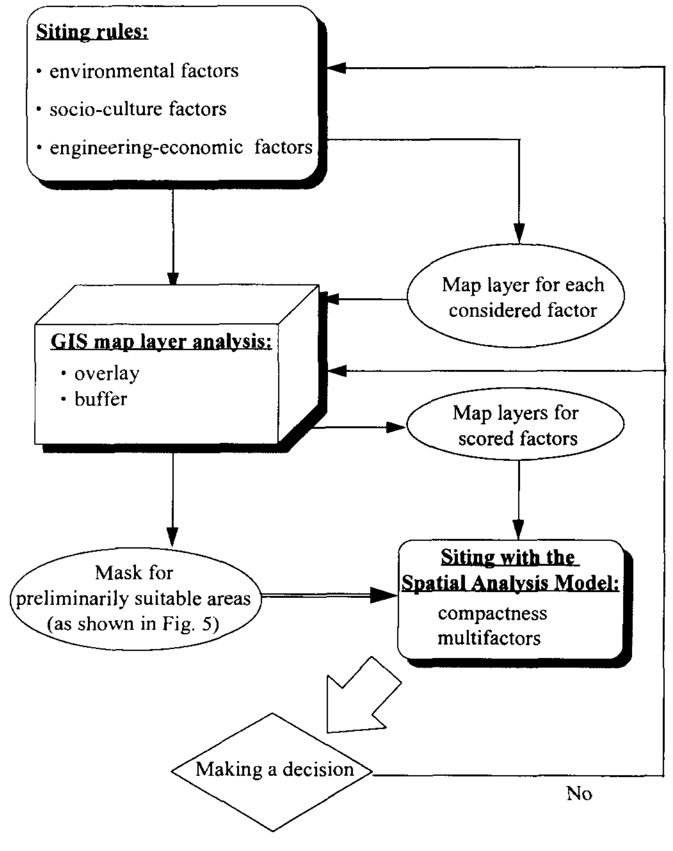

FIG. 3. Procedure for Spatial Landfill Siting Analysis

- Surface water: a landfill should be placed at an appropriate distance away from a surface water body to prevent the water body from being polluted by the possible leachate of the landfill. In this work, 180 m is used for the distance
- Floodplain: a landfill should not be placed within the floodplain to reduce the possibility of overland drainage pollution

Sociocultural Issues

- Urban development: a landfill should not be placed on a site close to a residential or an urban area to avoid deterioration of the land value and development
- Historical or cultural sites: a landfill should not be placed on a site close to a historical or cultural site

Engineering-Economic Issues

- Fault zones: fault zones can lead to instability in engineering structures, that increases the possibility of damage. A landfill should therefore be some distance away from such a zone. In this work, 80 m is used for the distance
- Land slope: an area with a large land slope may be unstable, thereby making construction and maintenance difficult. An area with a land slope in excess of 40% is generally inappropriate to place a landfill
- Land cost: land with little economic value is generally considered as a good place to construct a landfill. In this work, land costing more than 50% of the highest price is ruled out
- Road network accessibility: a landfill should not be placed too far away from the transportation system so that MSW collection and transportation costs can be reduced. In this work, a landfill should be placed within 1 km of existing roads

For the studied area, various GIS map layers are collected for the above described issues. Unsuitable areas are screened out with GIS map analysis functions based on the criteria used for aforementioned issues. A typical implementation of the GIS map layer analysis functions is shown in Fig. 4. Information for each factor is stored in a map layer to allow unsuitable areas to be screened out. The area studied in this work is about 69 km^2 that is divided into 10,806 cells in a cell size of 80 m × 80 m. After the screening analysis, as the map layer shown in Fig. 5, the possible area that may be used for further analyses to obtain an appropriate landfill site is reduced to 11.62 km^2, 1799 GIS cells. This map layer functions as the mask of preliminary suitable areas to be used in follow-up analyses. This preliminary screening step is particularly important in site selection with a spatial-analysis model. Without the reduction in possible areas, the model would be difficult to solve. Eliminating the clearly unsuitable areas would also significantly reduce the effort required to collect and process additional information to implement further analyses. Also included in this figure are the locations of the selected sites for all tested cases, as described later (the subsection Spatial Siting Analysis) in the present paper.

Scores of Individual Factors for Suitability of GIS Cell

After developing the preliminary mask map layer, as shown in Fig. 5, scores are assigned to considered factors to develop map layers for the levels of suitability of each GIS cell. These suitability map layers are used in the spatial multifactor analysis described in the next section. Landfill site selection is affected by a variety of different factors. For instance, pro-

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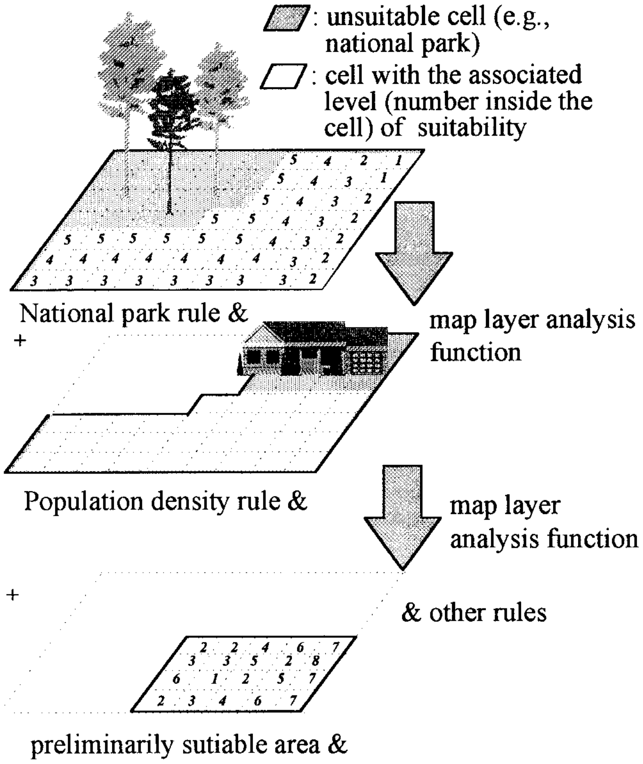

FIG. 4. Typical Implementation of Map Layer Analysis Functions

spective sites farther from a river imply the less the likelihood of water pollution. Alternatively, sites closer to existing roads incur a smaller transportation-related cost. The degrees of suitability of varied cells for a specific factor may be different. A scoring system is commonly applied to express the varied degrees. Table 2 lists the scores assigned for seven factors: ground-water resources (E1), surface water (E2), land cost (C1), road network accessibility (C2), land slope (C3), urban development (S1), and sensitive or critical areas (S2). For easy integration into the spatial model, of which the objective is to be minimized, high suitability is expressed with a low score. The smaller the score implies the better the suitability of a cell. The scores for groundwater resources are defined on the basis of a geological investigation by the Agricultural Commission, Taiwan, R.O.C. Results of their investigation divide the area into seven types: (1) recent alluvium with rich aquifers; (2) terrace deposits, most parts with rich aquifers; (3) lateritic terrace deposits, parts with rich aquifers; (4) conglomerate and pyroclastics, some with aquifers; (5) medium to coarse-grained white sandstone, limited aquifers in several narrow belts only; (6) sandstone with poor aquifers; and (7) shale and argillite with poor or without aquifers. Scores for surface water are determined by the distance between the cell to a river bank. Scores of land cost are determined by the percentage of land price of the cell to the highest land cell price within the siting area. Scores for road network accessibility are determined by the distance between the cell to the nearest road network. Scores for land slope are price of the cell to the highest land cell price within the siting area. Scores for road network accessibility are determined by the distance between the cell to the nearest road network. Scores for land slope are determined by the land slope of the cell. Scores for urban development derive from a combined measure of population density and distance from the nearest road network. Scores for sensitive and critical areas are determined according to the distance between the cell to a floodplain, natural conservation district, or an historical site.

Spatial Siting Analysis with Multiple Factors

Weights for Factors

Balancing the relative importance of varied factors can be difficult for a problem in which multiple factors are considered. Weights are generally assigned to these factors to express the relative importance. Determining the weights is, however, quite controversial and occasionally subjective. Table 3 lists two sets of weights used in this work for the aforementioned seven factors and the compactness for eight studied cases. The weights are heuristically assigned without applying any decision making procedure. The design of the eight cases is primarily intended to explore the effect of different weights for the compactness and different sets of considered factors on the

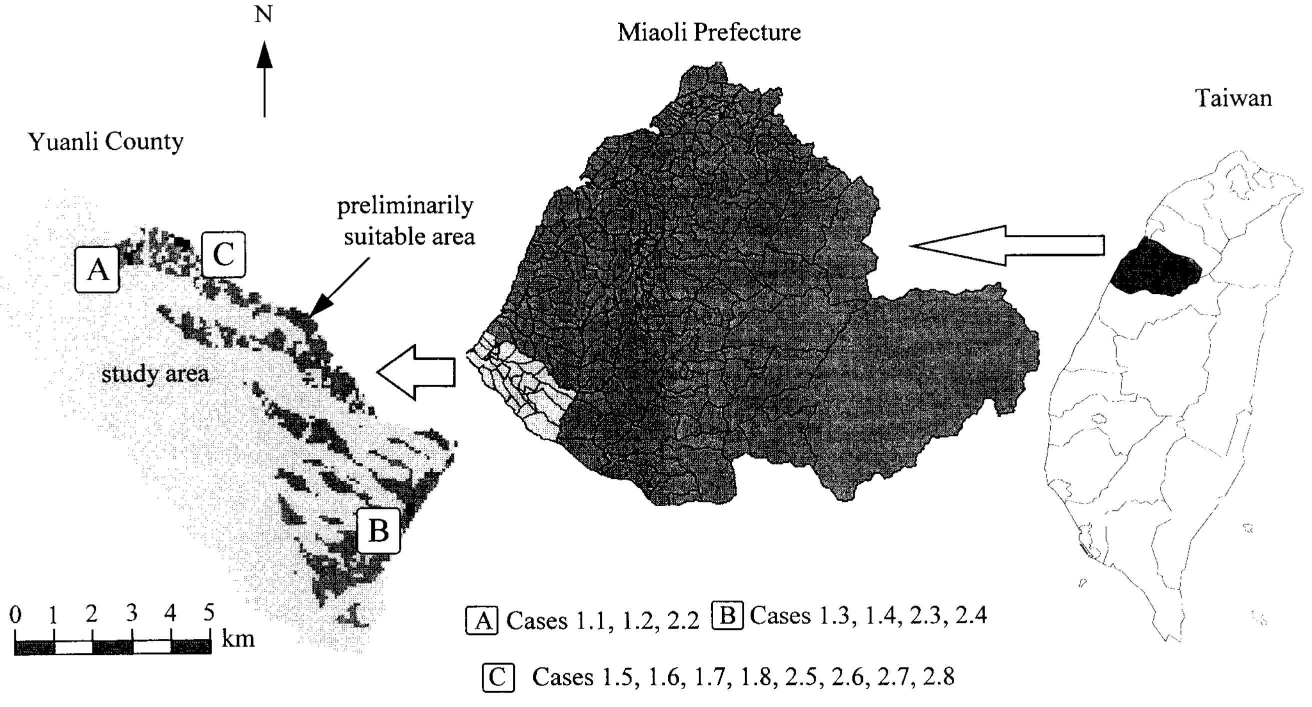

FIG. 5. Study Area, Preliminarily Suitable Area, Location of Selected Site in Each Case

TABLE 2. Suitability Scores for Siting Factors

Factor (1)	Suitability Score Assignment High 0–20 (2)	Medium-high 20–40 (3)	Medium 40–60 (4)	Medium-low 60–80 (5)	Low 80–100 (6)
Surface water (E2)	>600 m	>400 m	>320 m	>240 m	>180 m
	—	<600 m	<400 m	<320 m	<240 m
Land cost (C1)	<10%	>10%	>20%	>30%	>40%
	—	<20%	<30%	<40%	<50%
Road network accessibility (C2)	<80 m	>80 m	>120 m	>200 m	>400 m
	—	<120 m	<200 m	<400 m	<1,000 m
Slope (C3)	4–14%	3–4%	2–3%	0.5–2%	<0.5%
	—	14–16%	16–19%	19–23%	23–40%
Sensitive or critical area (S2)	>3,000 m	>2,000 m	>1,300 m	>700 m	<700 m
	—	<3,000 m	<2,000 m	<1,300 m	—

Note: Ground water (E1) Type 7:10, 6:20, 5:40, 3:60, 2:70, 1:80; Urban development (S1) determined by a combined measure of population density and distance to road.

TABLE 3. Considered Factors with Associated Weights for Each Case

Identification (1)	Compactness (2)	Environmental Factors E1 (3)	E2 (4)	Engineering Economic Factors C1 (5)	C2 (6)	C3 (7)	Sociocultural Factors S1 (8)	S2 (9)
[Weight set 1]	35	5.3	5.2	3.2	4.4	3.8	4.1	4.3
[Weight set 2]	150	5.3	5.2	3.2	4.4	3.8	4.1	4.3
Case 1	—	—	—	X	X	X	—	—
Case 2	X[a]	—	—	X	X	X	—	—
Case 3	X	—	—	X	—	—	X	X
Case 4	X	X	—	X	—	—	—	—
Case 5	X	X	X	X	X	—	—	—
Case 6	X	X	X	X	—	—	—	—
Case 7	X	—	X	—	X	—	X	—
Case 8	X	X	X	X	X	X	X	X

[a] X's indicate considered factors in each case.

TABLE 4. Summed Factor Scores of Cells within Selected Site in Each Case (Weight of Compactness is 35)

Identification (1)	Compactness (2)	Environmental Factors E1 (3)	E2 (4)	Engineering Economic Factors C1 (5)	C2 (6)	C3 (7)	Sociocultural Factors S1 (8)	S2 (9)
[Weight]	35	5.3	5.2	3.2	4.4	3.8	4.1	4.3
Case 1.1	(13)[a]	(925)	(740)	90	172	120	(358)	(1,194)
Case 1.2	13	(925)	(740)	90	172	120	(358)	(1,194)
Case 1.3	7	(578)	(879)	12	(960)	(1,191)	78	232
Case 1.4	7	578	(879)	12	(960)	(1,191)	(78)	(232)
Case 1.5	9	726	471	101	172	(414)	(172)	(895)
Case 1.6	9	726	471	(101)	172	(414)	(172)	(895)
Case 1.7	11	(751)	480	(107)	136	(380)	172	(913)
Case 1.8	12	758	471	109	166	164	180	891

[a] Numbers in parentheses are summed scores for factors not included in the objective function for each case.

TABLE 5. Summed Factor Scores of Cells within Selected Site in Each Case (Weight of Compactness is 150)

Identification (1)	Compactness (2)	Environmental Factors E1 (3)	E2 (4)	Engineering Economic Factors C1 (5)	C2 (6)	C3 (7)	Sociocultural Factors S1 (8)	S2 (9)
[Weight]	150	5.3	5.2	3.2	4.4	3.8	4.1	4.3
Case 2.2	9	(874)	(770)	88	222	140	(365)	(1,200)
Case 2.3	7	(578)	(734)	12	(960)	(1,191)	78	232
Case 2.4	7	578	(734)	12	(960)	(1,191)	(78)	(232)
Case 2.5	8	734	471	105	180	(324)	(173)	(891)
Case 2.6	8	734	471	(105)	180	(324)	(173)	(891)
Case 2.7	8	(734)	471	(105)	180	(324)	173	(981)
Case 2.8	8	751	480	105	180	278	174	895

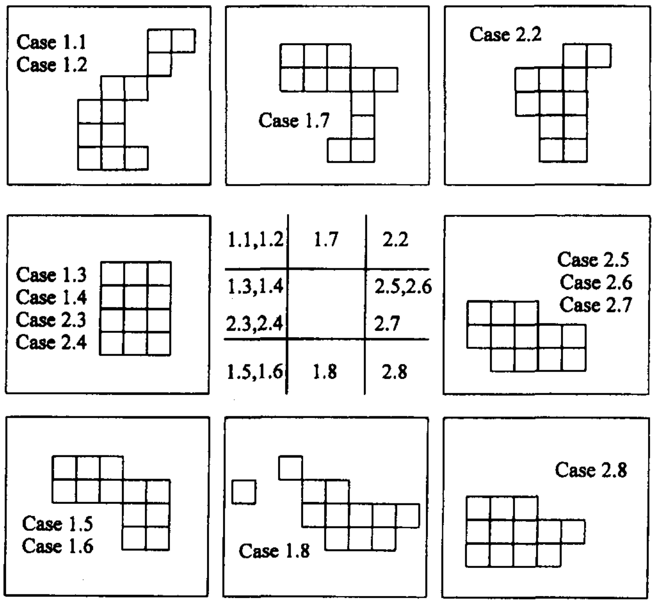

FIG. 6. Shapes of Sites Selected in Each Case with Model

final siting solution. Although the appropriateness and sensitivity of the weights and other information such as utility functions can be systematically evaluated by some decision making methods described by Cohon (1978) and Zeleny (1982), they are beyond the scope of the present study.

Spatial Model with Multiple Factors

For applying a problem with multiple factors, the objective function of the formulation (5) should be modified as follows.

$$\text{Min} \sum_{i=0}^{i=m} \sum_{j=1}^{j=n+1} \left(w_v V_{i,j} + \sum_{k=1}^{p} w_k C_{i,j}^{k} \right) \qquad (8)$$

where w_v = weight for compactness; and w_k = weight for factor k. The minimal size of a site, A in the formulation (5), is set to be 7.68 hectares, 12 GIS cells. This model is formulated based on the weighting method described by Cohon (1978). The model is solved with XMP/Zoom (Marsten 1987), a Fortran library for solving a mixed-integer programming model.

Spatial-Siting Analysis

Tables 4 and 5 list the solutions for applying the model to the eight cases listed in Table 3. The two sets of weights listed in Table 3 are the same except the weight for compactness: 35 for Set 1 and 150 for Set 2. For ease of discussion, 'Case n.m' in the following description indicates case m with weight set n, e.g., Case 1.3 indicates Case 3 with weight set 1. Fig. 6 displays the shapes of selected cells for all cases, and their locations in the siting area are marked in Fig. 5. Fig. 6 clearly indicates that the compactness of solutions for Set 2 is better than those for Set 1 because the weight of compactness in Set 2 is set higher than that in Set 1. Therefore, with a higher weight for compactness, a more compact solution is likely to be obtained. Nine different solutions were obtained for the eight cases with two sets of weights. The selected cells of all solutions are continuous with the exception of Case 1.8. The reason for the discrete solution of Case 1.8 is that all seven factors in addition to the compactness are considered in the case, and the weight assigned to the compactness is insufficiently large to dominate the accumulated effect of all seven factors. This problem does not occur again for Case 2.8 because a larger weight is set for compactness. The larger the weight of the compactness implies the more compact the obtained solution. Tables 4 and 5 reveal that, unless the weight is set high, an increase in the number of considered factors subsequently decreases the possibility in finding a compact solution. Therefore, a less compact solution may be obtained.

In summary of compactness weighting, the compactness factor must be considered to ensure that the cells selected can be sufficiently compact to construct a landfill. Using a small weight for compactness would not be sensitive enough to force the model to obtain a compact site. On the other hand, if the compactness weighting is set too high, although able to select a site with best compactness, sites with good suitability for environmental, sociocultural, and engineering-economic factors with a little poorer compactness may be missed. Weighting should therefore be gradually adjusted as necessary. The appropriate value of the compactness weight with varied sets of factors may differ. For instance, in Cases 1.3 and 1.4, the compactness weight is 35 and sufficient to find a compact site. In Case 1.8, however, this value is insufficient to find an appropriate compact site.

The final solution may also differ when a different set of factors is included in the model. For instance, the difference between solutions for Cases 1.2 and 1.3 or Cases 2.4 and 2.5 is obvious. An additional factor added to the model may significantly change the final solution. For instance, solutions for Cases 1.8 and 2.8 are quite different from the others. Determining an appropriate set of siting factors with appropriate weights requires evaluating the relative importance of factors by close interaction with decision makers, usually more than one for a landfill-siting problem. Decision makers may assign a different set of factors with different weights after they have evaluated the solutions similar to those shown in Table 4, Table 5, Fig. 5, and Fig. 6. The model may be applied iteratively several times until the decision makers identify a final solution.

CONCLUSIONS

In the present work, a spatial siting analysis model that considers compactness has been developed for use with a raster-based GIS for siting a landfill. The compactness is important in terms of whether selected cells are sufficiently compact to serve as a landfill site. The developed compactness model requires less variables and constraints than the previous models. This feature significantly reduces the model complexity and makes it suitable for integration with a raster-based GIS.

When other factors are simultaneously considered to establish the model, an appropriate weight should be set for compactness to ensure a good solution. The higher the weight of the compactness implies the more compact the solution. However, some solutions with good suitability for other factors (but with a compactness level close to the optimal one) may be neglected if the weight of compactness is set too high. Furthermore, varied sets of considered factors with varied weights lead to different solutions. Close interaction with decision makers should be encouraged to derive an appropriate set of factors with appropriate weights. Although developed primarily for landfill siting, the proposed model can be applied also to other site selection problems such as land application of sludges, transfer stations, incinerators, and recycling facilities.

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