ELSEVIER

Journal of Hazardous Materials 58 (1998) 3–14

JOURNAL OF HAZARDOUS MATERIALS

A vector-based spatial model for landfill siting

Hung-Yueh Lin, Jehng-Jung Kao *

Institute of Environmental Engineering, National Chiao-Tung University, 75 Po-Ai street, Hsinchu, 30039, Taiwan

Abstract

An inappropriate landfill site may have negative environmental, economic or ecological impacts. Therefore, landfill siting should carefully consider various factors and regulations and evaluate a significant amount of spatial data. However, processing of spatial information for various siting factors is tedious. Digitized data is thus frequently used for improving data processing and analysis efficiency. Vector-based data are composed of points, lines and polygons, which express geo-referenced attributes of the real world. Compared to raster-based data, although describing real world spatial information more precisely, the lack of uniformity makes vector-based data difficult to use with a mathematical optimization model. In this study, a mixed-integer spatial optimization model is developed based on vector-based data to assist decision makers in finding a suitable site from a siting area. Major factors considered in the model include impacts on the environment, economic efficiency, and site compactness. A sample case is provided to demonstrate the effectiveness of the model. © 1998 Elsevier Science B.V.

Keywords: Landfill siting; Spatial model; Vector-based data; Geographical information systems

1. Introduction

The annual volume of municipal solid waste (MSW) in Taiwan, as reported [1], is continuously increasing. Up to now, sanitary landfill is still an economic final disposal route for solid waste. Wingerter [2] indicated that landfilling was unavoidable; even if waste was incinerated, ash produced from an incinerator has to be landfilled. Prior to the construction of a landfill, an appropriate site should be located. The limited availability of land in this populated country, the lack of enough experts in local government, the environmental impact awareness among the general public, and the increase of MSW make the siting process extremely difficult. Furthermore, landfill siting generally must

* Corresponding author. Fax: +886 3 5728251; e-mail: jjkao@green.ev.nctu.edu.tw

PII S0304-3894(97)00116-7

consider various criteria, factors, and regulations. Consideration of twenty or more factors is quite common in a landfill siting analysis [3]. Consequently, from initiating a siting process until obtaining an operation license may take several years. Without careful consideration of various siting factors, an inappropriate landfill site may be improperly selected. Such an unsuitable site may lead to significant negative impacts on the environment and require costly remediation. For example, on May 16, 1996, the China Times reported that the government had granted NT$260 million for removing the waste previously landfilled in an inappropriate site in Toufen. This fund is almost equivalent to the annual budget for environmental protection for the entire Miaoli County [4]. However, landfill siting, although its importance has been widely recognized, is difficult to implement by the local government in Taiwan because of the lack of funds and experts to process, analyze, and evaluate related information. This study was therefore initiated to explore tools to facilitate landfill siting analysis.

The development of modern computers has allowed the successful application of a geographical information system (GIS) to a number of fields including landfill siting [5], resource management [6], land use management, transportation planning, etc. [7]. With the map layer analysis functions provided by GIS, spatial information can be processed effectively to facilitate decision making. GIS data can be categorized into two types: raster-based and vector-based data. The former divides the spatial area into grids of the same size. Each grid is assigned with a different category value, representing different geo-referenced attributes. Vector-based data uses points, lines and polygons, with each being assigned with a different category value, to represent different spatial attributes in the real world. A general GIS, although capable of processing spatial information effectively, lacks the ability to implement an optimization model. Without the capability to analyze optimality, GIS can offer only limited assistance when the siting area is large. The development of the proposed model in this work is intended to overcome this difficulty. The model is an enhancement of the previously developed raster-based model [8]. The current model can be used for vector-based data with irregularly shaped spatial information.

In a review of previous literature, spatial models were generally constructed into a mixed-integer [9,10] or non-linear programming models [11,12]. These models involve analysis of suitability of land parcels within an area, specification of objective functions by the analyst, and determination of candidate locations which satisfy the constraints for continuity or compactness and other factors. Diamond and Wright [11] defined compactness as the square of the longest distance between any two points within the selected zone divided by the area of the zone. Non-linear and integer multiobjective programming models were then applied to solve a land use problem. The non-linear property of the model makes it difficult to solve by a computer. Wright et al. [9] defined compactness as the length of the perimeter of the selected zone divided by the area. Benabdallah and Wright [12] used the same definition of compactness and a mixed-integer programming model to analyze a multiple subregion allocation problem with raster-based data. However, the large number of variables and constraints used in their model make it difficult to solve. Although the model is changed into a non-linear model to reduce the number of variables and constrains, the solution obtained by the non-linear model may not be the global optimum. Minor and Jacobs [10] proposed an improved mix-integer model to find the landfill site with best compactness and least cost from a set of irregularly shaped land parcels. Kao and Lin [8] developed a mixed-integer multifactor model for siting a landfill. Compared to previous models for raster-based data, this model used less variables and constraints. In this study, the raster-based model is modified further to make it applicable to vector-based data.

The model allows the use of digital data for the assessment of candidate sites, thereby helping the user to select the most appropriate site. The development of the vector-based spatial model, together with the previously developed raster-based model makes the models completely compatible with most GIS data. With the models and a GIS, digitized spatial information can be effectively processed for evaluating various regulations and criteria. Map layer analysis functions provided by the GIS facilitate the manipulation, analysis and presentation of massive spatial information. In the following sections, the methodology proposed for establishing the vector-based landfill siting model is described. A hypothetical case is then followed to demonstrate the effectiveness of applying the developed model. Results obtained for the case study are also discussed.

2. Methodology

As shown in Fig. 1, the general procedure for applying a GIS to landfill siting includes (1) collection of spatial and related data for a study area, including digital map layers, regulations, and criteria, and so on; (2) specification of appropriate selection criteria based on local characteristics of the siting area; (3) preliminary screening based on siting restrictions with GIS map layer analysis functions to screen out inappropriate

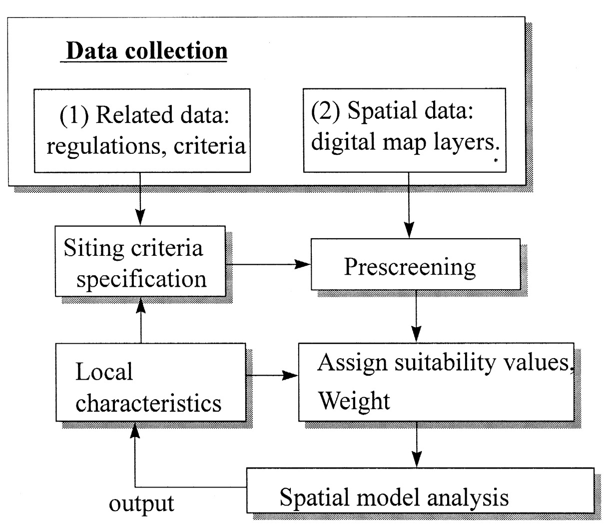


Fig. 1. Research flowchart.

areas; and (4) assigning different suitability values depending on the attributes of a candidate site for considered siting factors. These suitability values are then added together, multiplied by weights which express their relative importance. This gives the final suitability of a candidate site for construction of a landfill. The areas remaining after the preliminary screening in step (3) may still be vast, making it difficult to assess a suitable site from the remaining candidates. Step (4) gives only the total suitability value of each independent land parcel within the remaining area. However, a desirable site is generally consists of several land parcels instead of a single parcel. With the above procedure, a combined measure of several adjacent land parcels is not available and it is therefore not easy to make the final siting decision. The spatial model derived in this paper is capable of obtaining the optimal site with multiple land parcels based on the objective function and constraints set by the user.

The model developed in this study is detailed below. In Eq. (1), I_i is a 0–1 integer variable which indicates whether land parcel i is being included in a candidate site. W_1^k is the relative weight of kth siting factor and W_2 is the weight for compactness. Siting factors include groundwater, geology, restricted zones, transportation efficiency, slope, population density and land ownership. C_i^k is the suitability score of siting factor k for land parcel i:

$$\min \sum_{i=l}^{i=n} I_i \cdot A_i \left(\sum_{k=l}^{k=m} W_l^k \cdot C_i^k \right) + W_2 \cdot \sum_{i=l}^{i=n} V_i \tag{1}$$

subject to

$$S_i \cdot I_i - \sum_{j \epsilon F} S_{i,j} \cdot I_j + V_i \geq 0 \tag{2}$$

$$\sum_{i=l}^{i=n} I_i \cdot A_i \geq A_r \tag{3}$$

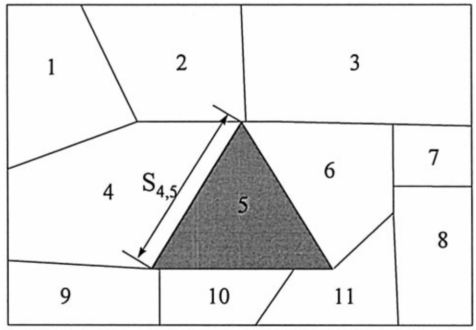
$$\left(C_i^k - G^k \right) \cdot I_i \geq 0$$

$$\text{for } k = l \ldots m$$

In Eq. (2), V_i is used to record the length of the site perimeter. S_i represents the total perimeter of land parcel i. E_i represents the set of parcels adjacent to parcel i. S_{ij} represents the length of the shared border between parcel i and parcel j.

In Eq. (3), A_i represents the area of land parcel i. A_f is the minimal land area required. Eq. (4) indicates restrictions for considered landfill siting factors. G^k is the basic requirement of kth factor. The relationship among S_i, S_{ij}, and E_i is illustrated in Fig. 2. In the figure, S_5 represents the total perimeter of parcel 5 and S_{45} represents the common border between parcel 4 and parcel 5. E_5 represents the set of parcels adjacent to parcel 5.

The model is applied to the remaining area left after the preliminary screening by a GIS and a set of siting criteria. This preliminary screening is important because a large number of inappropriate land parcels will be eliminated, so saving the computational time in solving the model. With an objective function and various desired constraints



$$S_5 = S_{4,5} + S_{5,6} + S_{5,9} + S_{5,10} + S_{5,11}$$

$$E_5 = [4,6,9,10,11]$$

Fig. 2. Illustration of perimeters and borders.

specified by the user, the model can locate the most suitable site. In Section 3, a hypothetical case is described to demonstrate the application of the model, followed by discussion of the results obtained by the model.

3. Case Study

The hypothetical case used in this study is made from the sample map layers provided by the GRASS GIS software [13]. Map layers for the following siting factors are used.

- ground water protection areas: to avoid a landfill polluting important ground resources;
- soil and geology: to select a proper site with poor permeability and stable geographical characteristics;
- restricted zones (ecological preservation zones, wetlands, national parks, etc.): to avoid a landfill being placed close to an environmentally sensitive areas;
- existing road network: to assess transportation and collection efficiency;
- land slope: to evaluate construction, operation, and maintenance difficulty;
- population density: to reduce the possible health hazardous risk to the public;
- land ownership: to evaluate the difficulty for obtaining the land.

Fig. 3 shows the map layers used for the case. These map layers must be processed before further analysis can be performed. Analysis of the suitability of each land parcel for landfill is done first. Obviously unsuitable areas are screened out to reduce the siting area. Suitability scores are then assigned to all remaining land parcels. As indicated in Eq. (4) of the model, the suitability scores of candidate parcels must exceed a certain level for some considered factors. For example, a landfill site should be kept as far as possible away from any important water bodies, for reducing pollution impact to the water body. On the other hand, a landfill site should be placed as close as possible to existing roads, for saving road development, transportation, and collection costs. Furthermore, land parcels with land slope either too steep or too flat are not appropriate for

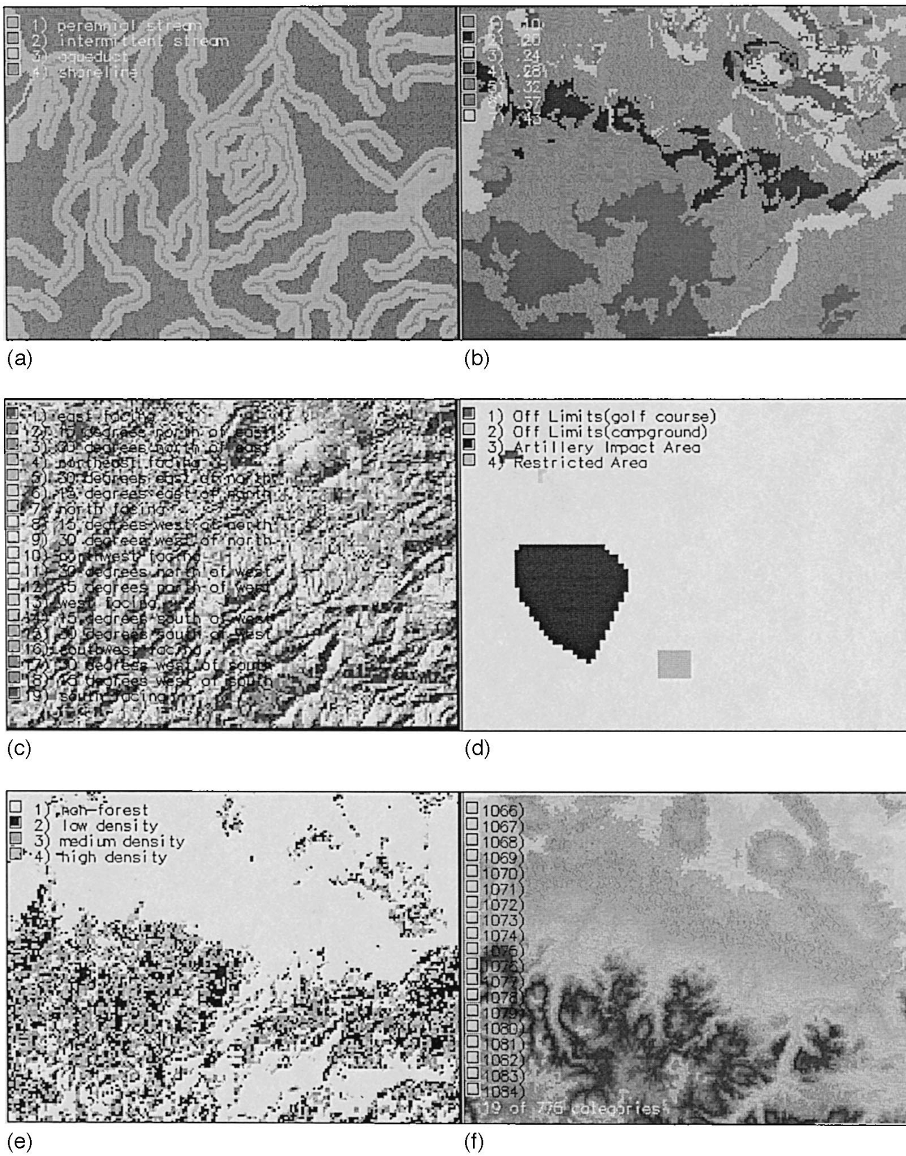


Fig. 3. Raw map layers of study case (Source; sample map layers provided by GRASS [13]). (a) Rivers and buffer zones (b) Hydraulic transmission coefficient (c) Slope aspect (d) Restricted zones (e) Forest density (f) Elevation (g) Landuse (h) Roads (i) Vegetation cover (j) Photographs from sattelite

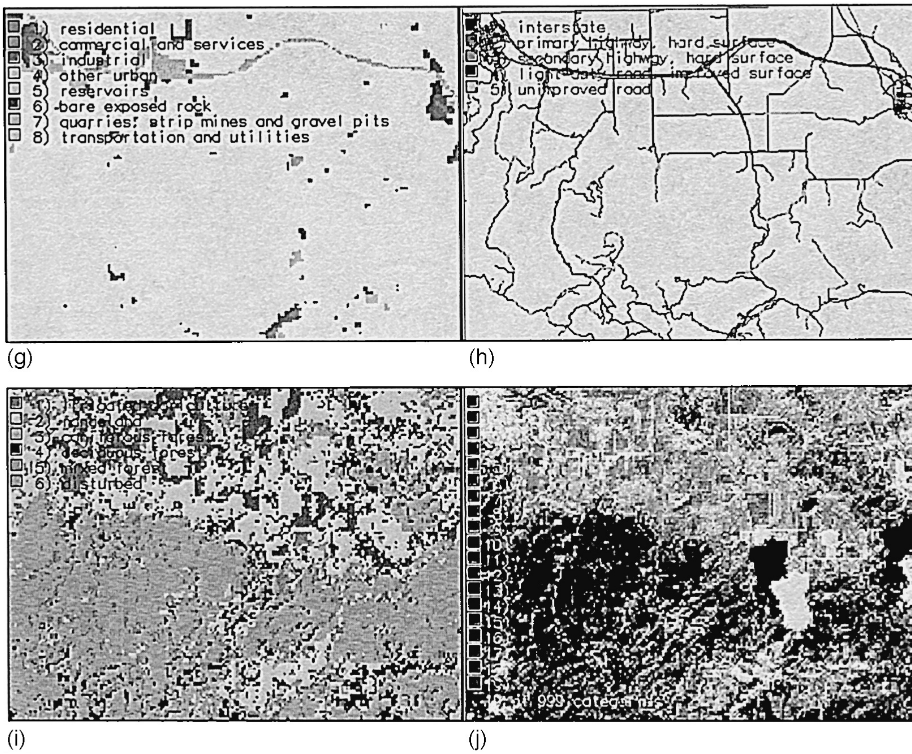


Fig. 3 (continued).

building a landfill. With similar assessments, the suitability of each designated parcel for each siting factor can be assessed based on its different condition. After having decided on the score of suitability for a factor, a relative weight is assigned in accordance with the importance of the factor relative to other factors. The weights may be determined based on experts' opinions or the result of a questionnaire survey. The relative weights adopted in our work are extracted from Lin et al. [14]. By accumulating the suitability scores of all considered siting factors for all land parcels in a selected site, the summed suitability score can be computed as the first part shown in Eq. (1) of the model. Upon determining all suitability scores of factors, optimization can be carried out with the proposed mixed-integer programming model.

Table 1 shows land parcels remaining after the aforementioned preliminary stage screens out those areas which are too close to rivers, groundwater resources areas, environmentally sensitive lands, land with steep slope (in excess of 40%), and areas close to populated zones. For the detailed definitions of the suitability scores for siting factors can be found in our former work [8]. The area, perimeter, and the summed suitability score of each remaining parcel are listed in the table. Using the information detailed in Table 1, we can proceed the optimization analysis with the established

Table 1
Data for parcels used in case study

Parcel number	Perimeter (M)	Area (ha)	Suitability value
01	3939	66.1	28.58
02	4023	70.5	44.41
03	2389	33.8	7.37
04	7906	305.2	32.56
05	3360	55.2	22.25
06	4100	99.8	21.1
07	3983	74.5	46.66
08	2506	21.4	6.49
09	3283	47.9	9.58
10	8719	292	48.04
11	2680	44.8	5.36
12	3109	56.8	40.97
13	7976	262.5	28.96
14	2768	46	14.19
15	2581	33.1	27.67
16	1917	14.4	5.99
17	2146	26.2	32.26
18	2997	55.7	19.33
19	1506	9	32.61
20	2273	31.3	33.18
21	4028	97.1	14.62
22	2365	30.5	27.45
23	2392	31.6	26.45
24	7627	262.5	42.56
25	6758	196.8	29.21
26	9475	503.4	37.71
27	1587	12.9	15.23
28	7051	173.1	11.77
29	3114	60.4	17.09
30	2463	31.2	5.21
31	1690	16.7	41.83
32	3251	62.2	10.18
33	2166	28.3	24.69
34	2370	30.9	11.84
35	6472	195.1	21.68
36	5552	107.4	46.26
37	3231	65.3	15.48
38	6346	194.6	34.76
39	2709	42.3	35.41
40	4660	88.7	29.87
41	7100	230.2	34.91
42	1501	14.3	29.09
43	7151	153.1	17.91
44	1875	22.3	26.61
45	1912	18.2	14.88
46	3155	61.5	38.76
47	2187	28.1	13.42
48	3086	44.2	28.42
49	1786	18.5	22.47

Table 1 (continued)

Parcel number	Perimeter (M)	Area (ha)	Suitability value
50	3451	60.2	14.48
51	1986	22	7.66
52	6442	194.8	34.03
53	7567	282.2	34.37
54	2334	31.8	32.78
55	2339	30.5	40.2
56	3169	46.9	33.69
57	3239	65.5	38.49
58	2431	33.2	21.59
59	3200	64	12.11
60	2341	29.6	25.88

The lower of the suitability value of a parcel means the more suitable the parcel for constructing a landfill facility.

model. XMP/ZOOM [15], a mixed-integer programming package, is used to solve the model. The result is illustrated in Fig. 4. There are a total of 60 land parcels in this case. The site with dark parcels in the diagram is the solution obtained when the weight for compactness is equal to the total weights for the other siting factors. A different solution may be obtained if different weights or required size are specified. This issue is discussed in more detail in Section 4.

Fig. 4. Final result and study area.

4. Results and discussion

After the weights of considered factors, the objective function, and constraints are set by the user, the developed model can be applied to find the optimal site. The weights, objective function, or constraints can be altered if siting criteria or considerations change.

For the specification of a weight set, the results of this study shows that reducing the importance (weight) of the compactness factor leads to the increase of suitability scores obtained in the optimal site from this model. However, the compactness of the optimal site decreases. The relative importance of the compactness factor to other siting factors is not fixed. It may vary depending on the characteristics of the siting problem under consideration. If the weights of other siting factors are significantly larger than that for the compactness factor, then it is easy to end up obtaining a site with land parcels that are not continuous and consequently cannot constitute a valid site. On the contrary, if the compactness factor is weighted too heavily, although a site with the most compactness is obtained, factors of environmental, economic, or social condition for the site may not be great.

A similar situation applies to the relative importance (weight) of various site selection factors. For different problems or areas, weights for different factors may be set differently. Sometimes the determination of the weights is subjective. Different decision makers may assign different weights. Careful consideration should be given to environmental, economic and social factors and to ensure that the result meets siting goals. Assessment of the relative importance among factors can be done by using a decision making method such as a questionnaire survey, the Delphi method [16], or AHP(analytic hierarchy process) [17].

Because the objective function is to be minimized, the finally selected site will be the one with smallest size among all feasible candidate sites. Even if a larger suitable site exists, it will not be identified. One way to deal with this problem is to gradually alter the size required. Alternatively, as proposed by Minor and Jacobs [10], the objective equation could be slightly amended by adding an additional term as shown below.

$$\min \sum_{i=l}^{i=n} I_i \cdot A_i \left(\sum_{k=l}^{k=m} W_l^k C_i^k \right) + W_2 \left(\sum_{i=l}^{i=n} V_i - \lambda \sum_{i=l}^{i=n} I_i \cdot A_i \right) \tag{5}$$

In this new equation, the total value of V_i represents the total perimeter length of the site. If the second term of the above function is equal to zero, λ represents the ratio of the perimeter over the area of a site. The above formulation will result in finding a site with compactness approximates to λ. The minimum value of λ is $2/$radius for a circle.

To guarantee the obtained site satisfies some minimal requirements for some individual factors, frequently the analyst likes to set limits on factors for the desired candidate site. Eq. (4) serves just such a function. Actually, instead of being implemented by a mixed-integer programming model, the simple overlaying function provided by a GIS can easily screen out unsuitable zones, as in the preliminary screening step. However, sometimes the limit is set on the combined measure of attribute values of parcels which constitute a site. For example, limits for factors such as land price and capacity are generally set on the total value for all parcels in a site, rather than on the value of each individual parcel. The total land cost must be smaller than the available budget and landfilling capacity must be enough for satisfying the desired life of the site. For setting such a limit on a combined measure, Eq. (4) can be revised as follows.

$$\sum_{i=l}^{n} I_i \cdot C_i^k \geq G^k \tag{6}$$

Eq. (6) can be used to set the restriction of a combined measure. However, Eq. (6) cannot be used for all factors. For other example, the distance of a site to a river must be determined by the actual minimal distance to a river of all land parcels within the site. A combined measure such as average site distance or total site distance to a river is not appropriate to use. For other examples such as distance to the road network and soil type, their limits are better set by the Eq. (4).

5. Conclusion

The model developed in this study is applicable for vector-based data. Combined with the previously developed raster-based model, it can be applied to general GIS data. Integrated with a GIS, the model is capable of processing digital spatial data efficiently to facilitate landfill siting analysis. The case discussed in this article demonstrates the use of the model for siting analysis. The spatial model can locate the most suitable site based on the objective function, considered siting factors, weights for relative importance of factors, and other requirements set by the analyst or decision maker. The magnitudes of the relative weights for siting factors may significantly affect the final decision. However, the determination of the weights is frequently rather political than scientific and generally involve an iterative decision making process.

The current model is so far not physically integrated with a GIS and the previously developed raster-based model. The integration, the application of the model for real cases and other enhancement of a network user interface are under development. The enhanced integrated model is expected to serve as an efficient tool to help the local solid waste authority in Taiwan improve landfill siting analysis.

References

[1] EPA of Executive Yuan, ROC, The local environmental information in Taiwan, ROC, 1993, pp. 421–422.
[2] E.I. Wingerter, Are landfills and incinerators part of the answers? Three viewpoints, EPA J. 15 (2) (1989) 22–26.
[3] R. Zyma, R.E.A. siting considerations for resource recovery facilities public works, 1990, pp. 84–86.
[4] EPA of Executive Yuan, ROC, The local environmental information in Taiwan, ROC, 1993, p. 172.
[5] R.C. Lindquist, Illinois cleans up: using GIS for landfill siting geo info systems, February 1992, pp. 30–35.
[6] K. Fedra, Decision support for natural resources management: Models, GIS and expert systems, AI Applications 9 (3) (1995) 3–19.

[7] M.F. Goodchild, B.O. Parks, L.T. Steyaert, Environmental modeling with GIS, Oxford Univ. Press, 1993.
[8] J.J. Kao, H.Y. Lin, Multifactor spatial analysis for landfill siting, J. Environ. Eng., ASCE 122 (10) (1996) 902–908.
[9] J. Wright, C. Revelle, J. Cohon, A multiobjective integer programming model for the land acquisition problem, Regional Sci. Urban Econ. 13 (1983) 31–53.
[10] S.D. Minor, T.L. Jacobs, Optimal land allocation for solid- and hazardous-waste landfill siting, J. Environ. Eng., ASCE 120 (5) (1994) 1095–1108.
[11] J.T. Diamond, J.R. Wright, Efficient land allocation, J. Urban Planning Dev., ASCE 115 (2) (1989) 81–96.
[12] S. Benabdallah, J.R. Wright, Multiple subregion allocation models, J. Urban Planning Dev., ASCE 118 (1) (1992) 24–40.
[13] US Army Corps of Engineers, GRASS4.1 users reference manual, US Army Corps of Eng. Construction Engineering Research Lab., Champaign, IL, 1993.
[14] S.J. Lin, et al., The analysis of criteria of waste processing facilities and landfill siting. Economics and construction committee of Taiwan provincial government, 1985.
[15] R. Marsten, XMP users' guide, Dept. of Manage. information systems, Univ. of Arizona at Tucson, Tucson, AZ, 1987.
[16] A.I. Batavia, G.S. Hammer, Toward the development of consumer-based criteria for the evaluation of assistive devices, J. Rehab. Res. Dev. 27 (4) (1978) 425–436.
[17] M.Z. Siddiqui, J.W. Everett, B.E. Vieux, Landfill siting using geographic information systems: a demonstration, J. Environ. Eng., ASCE 122 (6) (1996) 515–523.