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Evaluation of a municipal landfill site in Southern Spain with GIS-aided methodology

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ABSTRACT

Landfill siting should take into account a wide range of territorial and legal factors in order to reduce negative impacts on the environment. This article describes a landfill siting method, which is based on EVIAVE, a landfill diagnosis method developed at the University of Granada. Geographical Information Systems (GIS) technology is also used to generate spatial data for site assessment. Landfill site suitability is assessed on a scale based on territorial indices that measure the risk of contamination for the following five environmental components: surface water, groundwater, atmosphere, soil, and human health. The method described in this article has been used to evaluate an area in Granada (Spain) where there is a currently operating landfill. The results obtained show that suitable locations for the disposal of municipal waste were successfully identified. The low environmental index values reflect the suitability of this landfill site as well as its minimal negative impacts on the environment.

1. Introduction

Landfill siting is a complex process involving social, environmental and technical parameters as well as government regulations. As such, it evidently requires the processing of a massive amount of spatial data. Various landfill siting techniques have been developed for this purpose. Some of them use Geographic Information Systems (GIS) to find suitable locations for such installations [1–3]. For example, Lin and Kado [4] developed a mixed-integer spatial optimization model based on vector-based data to help decision makers find a suitable site within a certain geographic area. Other researchers propose the use of multiple criteria analysis by itself [5,6], or with GIS [7]. The use of artificial intelligence technology, such as expert systems, can also be very helpful in solid waste planning and management. Fuzzy inference systems have also been proposed [8,9].

EVIAVE is an environmental diagnosis method developed by researchers at the University of Granada. It provides information concerning potential environmental problems caused by currently operating landfills. It is basically a tool for assessing the suitability of landfill sites and for monitoring their operation. Its main objective is to develop a decision support system for integrated municipal waste management, more specifically for decisions related to renovating or closing landfill sites. EVIAVE has been validated with data from more than fifty landfills in Spain [10], Venezuela [11] and Chile [12].

2. Landfill siting using a GIS

Over the last three decades, advances in computer science have led to the creation of GIS, initially based on McHarg's [13] basic map layering concept. GIS combines spatial data (maps, aerial photographs, and satellite images) with quantitative, qualitative, and descriptive information databases, which can support a wide range of spatial queries. All of these factors have made GIS an indispensable tool for location studies [14], particularly for landfill siting.

Processing such data with conventional drawing and calculation tools is generally time-consuming. GIS, however, converts georeferenced data into computerized maps, while GIS map analysis tools also make it possible to efficiently manipulate maps with a computer. The advantages of using GIS for waste disposal and landfill site selection have been demonstrated by various researchers. Jensen and Christensen [15] demonstrate the use of GIS in the

Abbreviations: GIS, Geographical Information Systems; CRI, Contamination Risk Index; Pbc, Probability of Contamination Indicator; eV, Environmental Value; ERI, Environmental Risk Index; LSI, Landfill Suitability Index.

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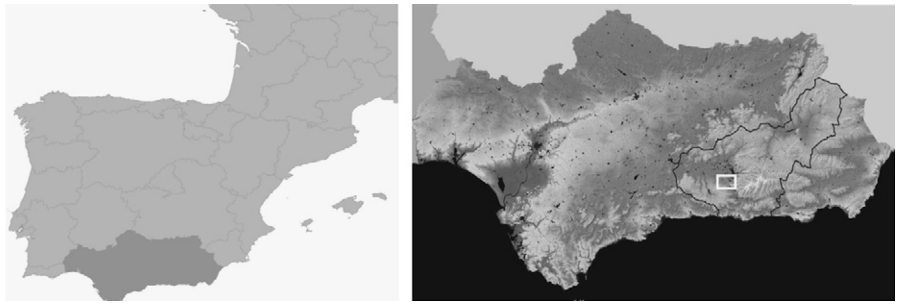

Fig. 1. Map of situation and localization of existing landfill site.

selection of solid and hazardous waste disposal sites. GIS was subsequently used by Fatta et al. [16] for the site selection of an industrial waste facility. Siddiqui [1] presents a method that identifies and ranks potential landfill areas for preliminary site assessment. This method combines GIS with a decision-making method based on the analytic hierarchy process (AHP). GIS technology has also been combined with AHP and fuzzy set theory [9]. Lin and Kado [4] developed a mixed-integer programming model to obtain a site with optimal compactness. The compactness model was further extended to include multiple siting factors with weights that were determined by the GIS map layer analysis function.

According to Michaels [17] a GIS can be used to combine various demographic, geological, land use and census tract maps to apply landfill criteria, and find suitable areas to place a landfill. Kao et al. [18] developed a prototype network GIS to increase the efficiency of complex solid waste landfill siting. Furthermore, this system makes site-related information available to the general public; assists local environmental protection agencies in maintaining a GIS; and helps the central environmental protection agency to manage, instruct, and evaluate the local siting process. Kontos et al. [7] describe a spatial method that integrates multiple criteria analysis, GIS, spatial analysis, and spatial statistics with a view to evaluating a region for landfill siting.

This article describes an EVIAVE-based method developed at the University of Granada for the assessment of landfill sites in accordance with European Union legislation. This method is innovative because it establishes general indices to quantify overall environmental impact as well as individual indices for specific environmental components (i.e. surface water, ground water, atmosphere, soil, and human health). Quantification variables and impact indicators represent indices more precisely as well as make the results more objective.

Since this method requires processing large quantities of spatial data, we used GIS and its spatial analysis tools to create the digital geodatabase. Commercial GIS software packages include analytical tools that perform spatial analysis processes. To automate the processes of establishing composite evaluation criteria, performing multiple criteria analysis, and carrying out spatial clustering, algorithms were developed in a Microsoft Visual Basic programming environment compatible with ESRI ArcGIS, a GIS software. Although POPSIS [19] and Compromise Programming [20] are multiple criteria analysis methods that have been proposed for the evaluation of the final suitability index, we decided to use simple additive weighting (SAW) to solve the multiple criteria problem.

The GIS-aided landfill siting method presented in this article combines GIS spatial analysis tools with MCA to evaluate an entire region. We describe how this method was applied to a region in Granada (Spain) to assess the suitability of a currently operating landfill site. The hydrogeological, environmental, social, and technical/economic evaluation criteria are the same as those used in EVIAVE.

3. Area of study

The area studied measures 300 km^2, and is located to the south of the metropolitan area of Granada on the western edge of the Sierra Nevada mountain range (Fig. 1). After Seville and Malaga, Granada has the third largest population in Andalusia, and two thirds of its inhabitants live in the metropolitan area of the city. 55% of the population of the province of Granada (817,000) is concentrated in a surface area of 830 km^2, i.e. less than 7% of the total area. The population density in the metropolitan area is thus 530 inhabitants per km^2 as compared to 32 inhabitants per km^2 in the rest of the province.

In this area there is a landfill of medium density and high density. This landfill is used to dispose and eliminate waste from a solid waste treatment plant located in the town of Alhendín at Loma de Manzanares. This plant handles the waste from 26 municipal districts, whose 677,505 inhabitants generate 300,000 t of waste per year.

4. Methodology

4.1. *Definition*

The presence of a landfill in this area evidently has an important effect on the environment. Its impact is largely dependent on the affected elements at the site as well as on the spatial distribution of the effects. The first step in the evaluation of the environmental impact of the landfill is the identification of any elements, which may be sensitive to this impact. In different Environmental Impact Assessment (EIA) processes [21], these elements are known as *environmental components*. The components in our study are ground water, surface water, soil, atmosphere, and human health [22–25] because of their interactions with the dynamics of the release point. This means that the landfill is regarded as an active installation that can produce emissions.

Our evaluation method is based on the use of environmental indices to provide a quantitative assessment of the possible environmental interactions between a landfill and potentially affected environmental components because of the siting of the landfill. Similarly to EVIAVE, this method evaluates municipal solid waste landfills classified as non-hazardous waste landfills by Directive 31/99 [26]. It is thus applicable in the European Union, and in any other country where similar legislation exists, or indeed, where there is no legislation or where the legislation is less prescriptive than this Directive.

Fig. 2 shows the hierarchical structure of the decision problem, which has four levels. The first level represents the criteria and subcriteria used. It takes into account spatial attributes for landfill siting, and the quantification of landfill variables and environmental impact indicators used to calculate different environmental indices. The second level represents the Probability of Contami-

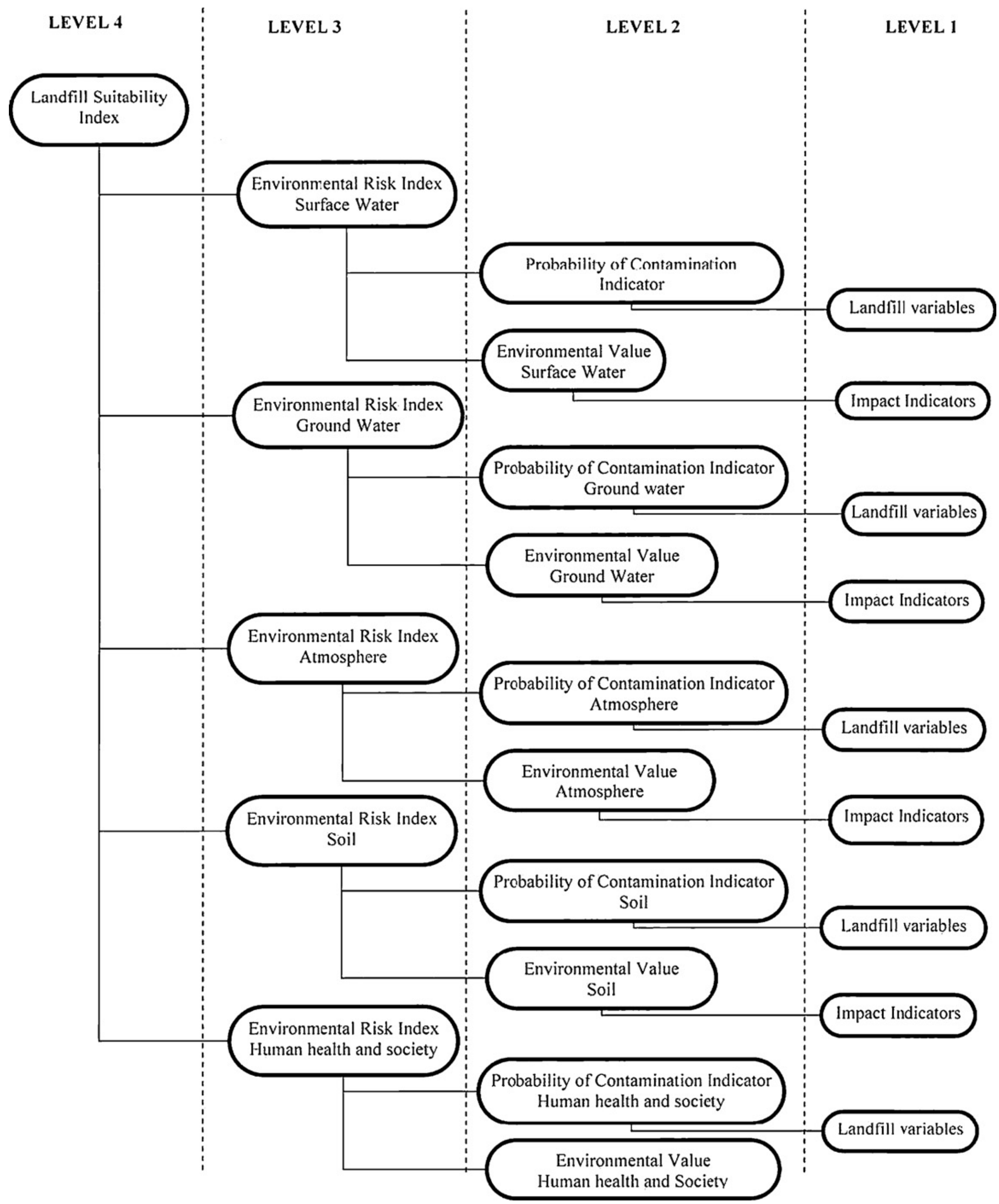

Fig. 2. Hierarchical structure of the methodology.

nation Indicator for each environmental component (Pbc_i) and the Environmental Value for each component (eV_i). The third level represents the Environmental Risk Index for each component (ERI_i) whereas the fourth and last level represents the ultimate goal of the decision hierarchy or Land Suitability for Landfill Siting Index (LSI).

4.1.1. Level 1: landfill variables and impact indicators

4.1.1.1. Definition of landfill variables. Any waste-facility siting framework must be capable of identifying important factors and interactions that contribute to the siting outcome. A theoretical framework is needed to structure these elements and cause–effect relationships [27]. In order to better assess contamination probability, the framework elements are known as *variables*, which represent each environmental component at the landfill. They are related to the biochemical and physical processes that directly or indirectly affect the environmental components. Such elements are associated either with the siting outcome or an essential component of the siting process.

The siting framework or variables were selected by taking into account previous research and reviews of relevant research. Also taken into account were European and Spanish legislation regarding the following:

- distances from the boundary of the site to residential and recreation areas, waterways, water bodies, and other agricultural or urban sites;

Table 1
Waste-facility siting framework

Variables	Environmental components affected	References
Aquifer characteristics	Ground water	[28–30]
Distance from infrastructure	Human health and society	[7,31,32]
Distance from surface water mass	Surface water	[7,33–35]
Distance from population centers	Human health and society	[7,36,37]
Erosion	Soil	[1,38]
Fault	Ground water	[1,38]
Slope to surface water	Surface water	[1,38]
Pluviometry	Ground water, surface water, atmosphere, soil, and human health and society	[39–42]
Release-point localization in flood-water storage volume	Ground water, surface water, and soil	[1,38]
Release-point localization in surface runoff	Ground water and surface water	[1,38]
Visibility	Human health and society	[7,43]
Seismic risk	Ground water, surface water, atmosphere, soil, and human health and society	[38]
Wind	Atmosphere and human health and society	[7,22,38]

- existence of groundwater, coastal water or nature protection zones in the area;
- geological and hydrogeological conditions in the area, more specifically, the existence of a geological barrier consisting of a mineral layer which satisfies permeability and thickness requirements established in Directive 31/99;
- risk of flooding, subsidence, landslides or avalanches on the site;
- protection of the nature or cultural patrimony in the area;
- climate conditions.

Table 1 shows a summary of the variables for each environmental component as well as various causal connections identified in other research studies.

Based on EVIAVE, the evaluation for each variable (j) can be obtained by the *Contamination Risk Index*, as expressed in Eq. (1). In this expression, C_j is the *Classification of the variable* and provides information concerning the interaction of disposal processes and environmental characteristics related to the variable, whereas W_j is the *weighting* of each variable [10,44]. The range of values of the index may be 1, 2, 3, 4 or 5.

$$\mathrm{CRI}_j = C_j \times W_j \tag{1}$$

EVIAVE defines the weighting of each variable, which can have values of 1 or 2, depending on the relationship between the variable and the concept of *structural elements* at the release point. The structural elements considered were organic matter, humidity, and waste density. These three concepts participate in the principal biochemical and physical processes that take place at the release point. They cause gas and leachate emissions, which affect all variables, and provide greater weighting of the different landfill variables [10,44]. W_j reaches a value of 2 when the variable is directly related to the structural elements, or when it affects environmental components. In this case the weighting of each variable turned out to be the same.

As an example, in the following sections we provide an explanation of the classification and weighting of the variable *Aquifer characteristics*. The same justification and quantification was applied to all the other variables and environmental components. This variable identifies the characteristics of aquifers located near possible landfill sites and quantifies their vulnerability by taking into account leachate emissions from the waste mass. Since it is a variable that directly affects groundwater environmental components, it has a weighting of 2.

The variables have been classified on the basis of the vulnerability index of the aquifer to pollution. Since many countries have experienced problems of ground water contamination, this has led to the development of methods to discover exactly how pollutants reach aquifers. Examples of aquifer vulnerability assessment methods are DRASTIC, SINTACS, GOD and EPIK. The first three are for the evaluation of free detritic aquifers, whereas the fourth targets karstic aquifers. They are all rather similar, and only differ in the number of variables. The choice of method depends on factors such as [45]: (i) knowledge of the methodology; (ii) available information; (iii) scope of the evaluation; (iv) validation of results. Of course, some of these methods are more widely used than others, and in many cases the choice of method depends on the country involved. For example, the USA and Canada prefer DRASTIC, while South America tends to use both GOD and DRASTIC. GOD is more prevalent in Spain and England, whereas the rest of Europe tends to use SINTACS. EPIK is generally preferred in regions along the Mediterranean coast, and is mostly used for the evaluation of karstic aquifers [45]. Table 2 shows the classification of this variable, based on all of these methods.

4.1.1.2. Definition of impact indicators. The description of environmental characteristics allows us to quantify the environmental components necessary to specify environmental indices. *Impact indicators* were defined in the Environmental Impact Assessment process to measure the impact of the landfill on each component. These are environmental characteristics that could be affected by projects [21]. They depend on the project type as well as on the specific characteristics of the affected area. Examples of such indicators are air quality, biological populations, communities and habitats, water quality, biota, etc. [21,48,49].

For our purposes, impact indicators were defined to quantify Environmental Value Indices for each environmental component.

Table 2
Classification of the variable *Aquifer characteristics*

Classification (C_j)		Condition		References
		Method	Vulnerability Index (VI)	
Very low	1	GOD	Iv < 0.1	[45–48]
		DRASTIC	Iv < 28	
		SINTACS	Iv ≤ 80	
		EPIK	Iv = 2 or 3	
Low	2	GOD	0.1 ≤ Iv < 0.3	
		DRASTIC	29 ≤ Iv ≤ 85	
		SINTACS	81 ≤ Iv ≤ 105	
		EPIK	Iv = 4 or 5	
Average	3	GOD	0.3 ≤ Iv < 0.5	
		DRASTIC	86 ≤ Iv ≤ 142	
		SINTACS	106 ≤ Iv ≤ 140	
		EPIK	Iv = 6 or 7	
High	4	GOD	0.5 ≤ Iv < 0.7	
		DRASTIC	143 ≤ Iv ≤ 196	
		SINTACS	141 ≤ Iv ≤ 186	
		EPIK	Iv = 8 or 9	
Very high	5	GOD	Iv ≥ 0.7	
		DRASTIC	Iv < 196	
		SINTACS	Iv ≥ 187	
		EPIK	Iv = 10	

Table 3
Impact indicators for environmental components

Environmental components	Impact indicators	References
Surface water	A_1: Type of surface water mass A_2: Water use A_3: Water quality	[50–54]
Ground water	B_1: Water use B_2: Water quality	[50,51,55,56]
Atmosphere	C_1: Air quality	[22,57]
Soil	D_1: Soil use D_2: Vegetation type D_3: Vegetal covering	[58,59]

These indicators were selected because of their relevance for impact assessment in the eyes of professionals, stakeholders, and the general public. Table 3 shows impact indicators for each environmental component in the case of municipal landfills, environmental calculation, and certain causal connections identified in relevant research. One or more impact indicators were defined for each environmental component except in the case of human health, which has a maximum environmental value index.

Each impact indicator may obtain values of 1, 2, 3, 4 or 5. For example, Table 4 shows the justification and quantification in the case of the impact indicator *use of water* for the surface water environmental component. The same justification and quantification was applied to the other characteristics and environmental elements.

4.1.2. Level 2: Probability of Contamination Indicator and Environmental Values

4.1.2.1. Definition of Probability of Contamination Indicator. According to EVIAVE, the definition of the Probability of Contamination for each environmental component must consider the scale of operation, waste characteristics and the spread of waste disposals in the landfill environment [10,44] because suitable siting, design and operation of the landfill are essential to eliminate or minimize potentially adverse environmental impacts [21,25]. It was thus possible to analyze two indices: *Probability of Contamination due to landfill operation*, and *Probability of Contamination because of landfill siting*.

In this case we have only considered the Probability of Contamination Indicators for each environmental component. These indicators are the same as those defined by EVIAVE, but only the variables related to landfill siting were taken into account. Probability of contamination is expressed by Eq. (2) where n is the number of variables affecting each environmental element; CRI_j is the Contamination Risk Index for each variable (j); $\mathrm{CRI}_{j\mathrm{minimum}}$ is the minimum value obtained by the CRI for each variable; and $\mathrm{CRI}_{j\mathrm{maximum}}$ is the maximum value obtained by the CRI for each variable. It may have values between 0 and 1 (see Table 5).

$$\mathrm{Pbc}_i = \frac{\sum_{j=1}^{j=n}\mathrm{CRI}_j - \sum_{j=1}^{j=n}\mathrm{CRI}_{j_{\mathrm{minimum}}}}{\sum_{j=1}^{j=n}\mathrm{CRI}_{j_{\mathrm{maximum}}} - \sum_{j=1}^{j=n}\mathrm{CRI}_{j_{\mathrm{minimum}}}} \quad (2)$$

Table 4
Justification and quantification of the impact indicator *Water use* for the environmental component *ground water*

A_2	Water use	5	Human drinking water, aquaculture and recreational uses, including beaches suitable for bathing
		4	Agriculture
		3	Industrial
		2	Other human uses not previously considered
		1	Not for human use

4.1.2.2. Environmental Value. The concept *Environmental Value* identifies and quantifies the environmental assessment of each environmental component in the area of the landfill. It is regarded as a relative environmental value since it takes into account the relationship between the landfill's environmental characteristics and/or social and political characteristics, the possible emissions at the release point [10,44], as well as the environmental importance of each element in the immediate surroundings of the landfill.

Environmental Values for surface water, ground water, atmosphere, and soil are expressed by Eqs. (3)–(6), respectively. As previously mentioned, human health always has a maximum value. In these expressions A_i, B_i, C_i and D_i are classifications of the impact indicators shown in Table 3.

$$\mathrm{eV}_{\mathrm{surfacewater}} = \frac{A_1 + A_2 + A_3}{3} \quad (3)$$

$$\mathrm{eV}_{\mathrm{groundwater}} = \frac{B_1 + B_2}{2} \quad (4)$$

$$\mathrm{eV}_{\mathrm{atmosphere}} = C_1 \quad (5)$$

$$\mathrm{eV}_{\mathrm{soil}} = \frac{D_1 + D_2 + D_3}{3} \quad (6)$$

Values range from 1 to 5 for each environmental element as shown in Table 5. If an environmental element obtains high or very high values, this means that the landfill is located in an area of greater environmental sensitivity for the element in question [10,44].

4.1.3. Level 3: Environmental Risk Index

The *Environmental Risk Index* definition is similar to the EVIAVE index of the same name. It determines the environmental impact potential for each environmental component, and reflects whether or not any interaction exists between the release point or landfill and the characteristics of the environment [10,44]. For each landfill, the ERI indicates which environmental element or elements would be or are most affected by the presence of wastes. This makes it possible to determine the extent of possible deterioration at each landfill site. This index is expressed by Eq. (7), where Pbi_i is the Probability Indicator, and where eV_i is the Environmental Value for each environmental component (i). The index has values between 0 and 5. Table 7 shows values for the index and its classification, based on the Pbc_i and eV_i values.

$$\mathrm{ERI}_i = \mathrm{Pbc}_i \times \mathrm{eV}_i \quad (7)$$

4.1.4. Level 4: Landfill Suitability Index

The global suitability of landfill sites is quantified by a general index called the Landfill Suitability Index (LSI). In EVIAVE the Environmental Landfill Impact Index (ELI) characterizes the overall environmental stage of operating landfills [10,44]. In this case the index characterizes the overall environmental suitability of the possible landfill sites. The grading scale used for the Landfill Site Suitability Index is 0–25, ranging from the least suitable to the most suitable area. This index is represented by Eq. (8) where ERI_i is the Environmental Risk Index for each environmental component (i). Table 8 shows the classification of the index.

$$\mathrm{LSI} = \sum_{i=1}^{i=5}\mathrm{ERI}_i \quad (8)$$

Unlike other methodologies [1–3], these indices do not initially exclude areas from further examination. Therefore, the legally unsuitable areas will have a low initial suitability index, which in all likelihood will ultimately exclude them from further examination during the final steps of the siting process.

Table 5
Classification of environmental indicators

Indicators	Classification				
Pbc_i	Improbable $0 \le Pbc_i < 0.2$	Not very probable $0.2 \le Pbc_i < 0.4$	Seldom probable $0.4 \le Pbc_i < 0.6$	Probable $0.6 \le Pbc_i < 0.8$	Very probable $0.8 \le Pbc_i \le 1$
eV_i	Very low $1 \le eV_i < 1.8$	Low $1.8 \le eV_i < 2.6$	Average $2.6 \le eV_i < 3.4$	High $3.4 \le eV_i < 4.2$	Very high $4.2 \le eV_i \le 5$
ER_i	Very low $0 \le ER_i < 1$	Low $1 \le ER_i < 2$	Average $2 \le ER_i < 3$	High $3 \le ER_i < 4$	Very high $4 \le ER_i \le 5$
LSI	Unsuitabililty $20 \le LSI \le 25$	Low suitability $15 \le LSI < 20$	Average suitability $10 \le LSI < 15$	High suitability $5 \le LSI < 10$	Very high suitability $0 \le LSI < 5$

4.2. Modeling the landfill variables

There are two basic approaches to the question of how to model space in GIS. Depending on whether the focus is on properties or localization, two different data models may be generated: the vector model or the raster model.

The choice of one model or the other depends on what the GIS is going to be used for [59,60]. We chose the raster model for our research because of its speed and efficiency at superpositioning maps. The vector model was used only to generate the basic cartography, and initially model variables.

An optimal resolution of 10 m was adopted for base cartography at a scale of 1: 10,000. The following techniques and operations were applied: local analysis (reclassification and map superposition), immediate vicinity analysis (filtrates and slope calculation), and extended vicinity analysis (Euclidean distances and proximity or 'buffer' analysis).

4.3. Model implementation

Cartographic modeling is a more general term than the set of steps described above. The method involves the arrangement of a series of data layers in logical sequence, including topological and thematic operations, information external to GIS, and value judgments in order to find solutions to specific spatial problems [61]. Tomlin [62] describes cartographic modeling as a general methodology for the analysis and synthesis of geographical data, and defines it as the use of the basic GIS operations in a logical sequence to resolve complex spatial problems. The phases of our model correspond to the levels defined in the hierarchical structure of the decision problem:

1. *Cartographs of the Contamination Risk Index* (CRI_j). Each localization variable is modeled and reclassified, and subsequently, each W_j is measured using map calculator algorithms [62] and the product operator. Each landfill localization variable generates a cartograph for each impact on the environmental components. The value for the Contamination Risk Index is indicated on each pixel.
2. *Cartographs of the Impact Indicators (A_i, B_i, C_i, D_i)*. Each Impact Indicator is modeled to generate a cartograph for each one.
3. *Cartographs of the Probability of Contamination Indicators* (Pbc_i). Results are grouped by using arithmetic superposition to obtain cartographs of the Probability of Contamination Indicators, with one image for each environmental component.
4. *Cartographs of Environmental Values* (eV_i). The values obtained to quantify the Impact Indicators are used to calculate the Environmental Value (eV) for each environmental component by means of arithmetic superposition of the Impact Indicators. A cartograph for each environmental element is then generated.
5. *Cartographs of the Environmental Risk Index* (ERI_i). The product of the values of the Probability of Contamination Indicators and the Environmental Values determines and cartographs the Environmental Risk Index (ERI_i) for each environmental component.
6. *Cartographs of the Landfill Suitability Index* (LSI). Finally, the cartograph of the LSI is obtained by means of multi-criteria analysis (MCA). The factors used are the different Environmental Risk Indices for each environmental component (surface water, ground water, atmosphere, soil and human health). The value associated with each pixel of the map gives a final indication of the suitability of the site.

4.4. Analysis of model sensitivity

Sensitivity analyses are directly related to modeling in any scientific field. A model is always a simplified version of reality which enables us to describe a specific problem, and thus reach a better understanding of it through the representation of essential elements and mechanisms of real world systems, whether physical, social, economic or environmental. In order to demonstrate that a model is a reliable representation of such a real system, it is necessary to carry out certain validation processes to lend sufficient credibility to the model. In this research, we verify the method used, and also carry out a results validation test as well as a model stability analysis.

5. Application of the methodology: results and discussion

At the first level Impact Indicators and Contamination Risk Indices for variables were identified, classified and quantified. Each variable and Impact Indicator were modeled, and a cartograph for each one was generated. Fig. 3 shows an example of Impact Indicators D_1 (Soil use) and D_2 (Vegetation type) for the environmental component *soil* in the area studied. Both have values between 1 and 5, and at the landfill site, their respective values are low.

Fig. 3 shows too an example of the cartograph of the Contamination Risk Index in the case of the variables *erosion* and *distance to population points* in the area. Both have values between 2 and 10, and at the landfill site their respective values are low. A similar cartograph was generated for the rest of the Impact Indicators and variables.

At the second level Environmental Values and Probability of Contamination Indicators for each environmental component were calculated, taking into account results from level 1. Some maps were obtained for the other environmental components. In this case Environmental Values in the area studied obtained values between 1–3, 1–4, 4–5 and 1–4 for surface water, ground water, atmosphere and soil, respectively. Human health always has a maximum Environmental Value. The landfill site shows very low values for surface water, groundwater and soil (eV = 1), whereas it has very high values for atmosphere and human health (eV = 5). *Atmosphere* has a

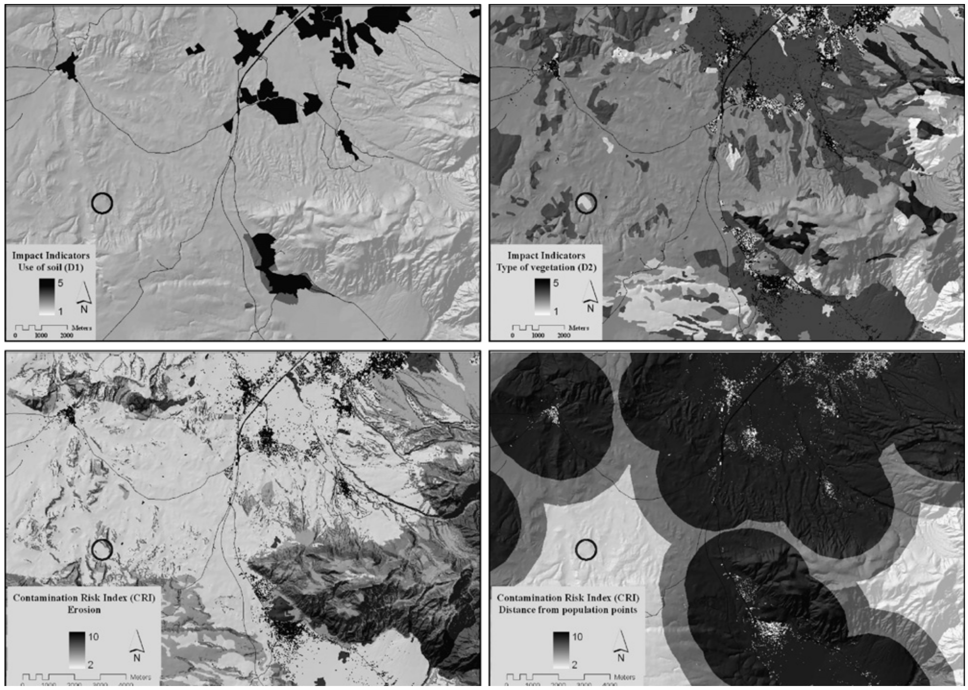

Fig. 3. Cartograph of impact indicators D_1 (Soil use) and D_2 (Vegetation type) and Contamination Risk Index for variables erosion and distance to population centers in the studied area. Circles indicates landfill site.

maximum value because the landfill is located far away from cities and industrial areas. As a result, the air quality at the site before the existence of a landfill was very high. Low values for this index indicate environmental characteristics of lesser importance at the location that should be protected from the negative impact of landfill emissions.

The Probability of Contamination Indicator for the environmental components reflects the greater or lesser possibility of environmental impact, and takes into account a wide range of factors, not only those that contribute to interactions between the landfill and environmental components. Fig. 4 shows the Probability of Contamination for the environmental components *surface water* and *ground water* in the area. A similar cartograph was obtained for the rest of the components. In this case the Probability of Contamination Indicator in the area obtained values between 0.13–0.68, 0.16–0.41, 0.6, 0.2–0.6 and 0.35–0.85 for surface water, ground water, atmosphere, soil, and human health, respectively. The landfill site has an index of *Improbable* for ground water (Pbc = 0.19) and *Seldom probable* for surface water (Pbc = 0.32), soil (Pbc = 0.2) and human health (Pbc = 0.35). The environmental

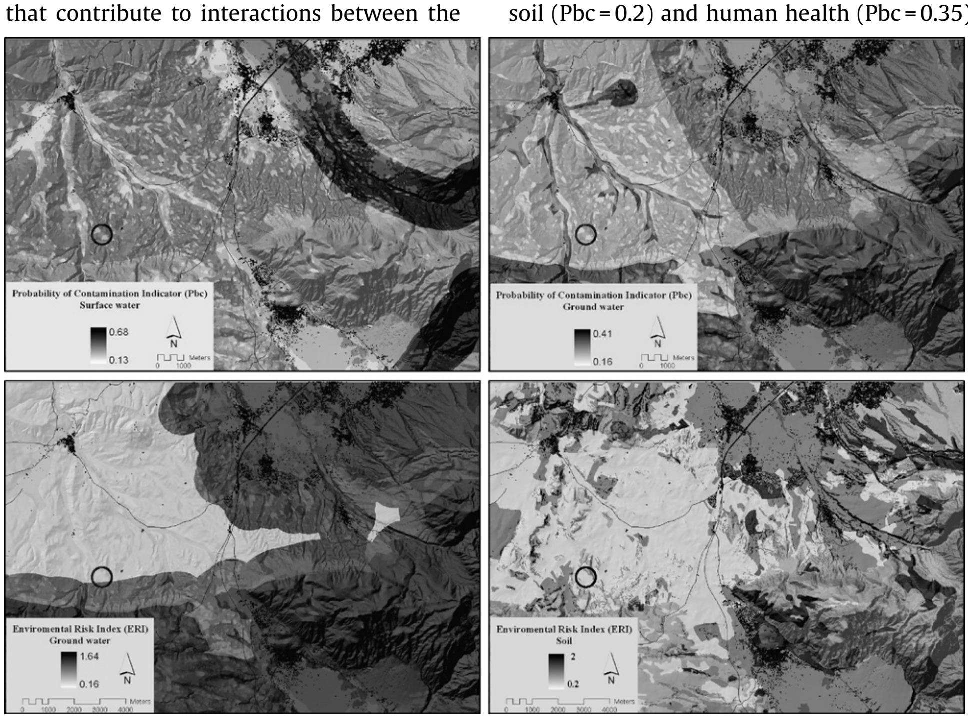

Fig. 4. Cartograph of Probability of Contamination Indicator for surface water and ground water and Environmental Risk Index for ground water and soil in the studied area. Circles indicates landfill site.

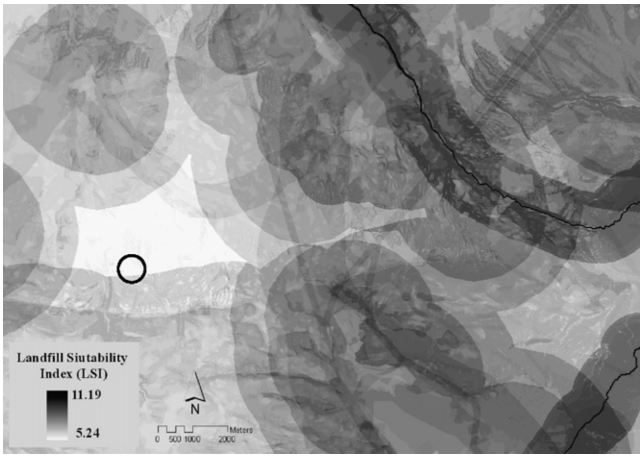

Fig. 5. Cartograph of Landfill Suitability Index in the area. Circle indicates landfill site.

component *atmosphere* shows a rather higher value, and is thus classified as Probable (Pbc = 0.6). These results indicate that the landfill site does not have characteristics which might contribute to the contamination of the different environmental components, except in reference to *atmosphere*. In this case, the landfill could have an impact, influenced by high rainfall, seismic risk in the area, and wind characteristics.

The third level generates the Environmental Risk Index for each environmental component with a view to discovering which was most affected by the presence of the landfill. Fig. 4 shows too a cartograph of the index for the environmental components, *ground water* and *soil*. Similar maps were obtained for the rest of the environmental components. The index values for the area are 0.13–2.04, 0.16–1.64, 2.40–3, 0.2–2 and 1.75–4.25 for surface water, ground water, atmosphere, soil, and human health, respectively. The landfill at the site obtained values, which are very low for surface water (ERI = 0.32), groundwater (ERI = 0.19) and soil (ERI = 0.2). The index is also low for human health (ERI = 1.5), whereas it is very high for atmosphere (ERI = 3). The Environmental Risk Index for the landfill site indicates that the environmental risk for all the components, except *atmosphere*, is not important. This signifies that the landfill site is suitable except for this environmental component. In this case the high quality of the air and the high Probability of Contamination Indicators because of rainfall, wind and seismic risk contribute to a higher risk of contamination for this specific component.

Finally, the application of this methodology resulted in a Landfill Suitability Index, which reflects the overall environmental impact of a landfill. Fig. 5 shows the index values obtained for the area studied. For example, locations that were far away from surface and ground water, infrastructures or population centers obtained a lower index. Consequently, they are regarded as suitable locations for municipal waste landfills. The values of this index in the area were between 11.2 and 5.2. The landfill at the site is in a place with an Index of 5.21, which is considered *high* to *very high* on the previously described scale.

6. Conclusions

The method described in this article has been shown to be valid for the analysis of landfill sites. It generates indices that give information regarding site suitability, and which take into account only the environmental characteristics of the location. The final suitability index not only provides information about the optimality of the location, but also about potential problems that can affect one or more environmental components. This data is fundamental for any decision about whether or not to locate a landfill at a particular site.

Based on the results obtained in our study as well as the sensitivity analysis carried out, we can conclude that Geographical Information Systems are a useful tool for the optimal siting of landfills. Our study shows that this instrument has the potential to assist planners, decision-makers and other agents involved in the process of selecting suitable sites for municipal landfills since it increases their knowledge of the physical terrain, thus facilitating the analysis and implementation of action plans.

Although *atmosphere* was the environmental component that was most affected, the results obtained show that the landfill evaluated in our study is operating at a site with low index values, and thus is a generally suitable location for this purpose.

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