A methodology for the optimal siting of municipal waste landfills aided by Geographical Information Systems

M. Zamorano[1], A. Grindlay[2], A. Hurtado[1,2], E. Molero[2] & A. Ramos[1]
[1]*Department of Civil Engineering, University of Granada, Campus de Fuentenueva s/n, 18071 Granada, Spain*
[2]*Area of Urban and Regional Planning, University of Granada Campus de Fuentenueva s/n, 18071 Granada, Spain*

Abstract

An inappropriate landfill site may have negative environmental, economic or ecological impacts. Landfill siting should therefore consider a wide range of territorial and legal factors to reduce such negative impacts as far as possible. This paper describes the application of an integrated system of landfill siting methodology. The methodology incorporates techniques from various scientific fields as well as GIS (Geographical Information Systems) to generate spatial data for the evaluation of the suitability of an area for optimal landfill siting. The resulting land suitability is reflected on a graded scale with several territorial indexes indicating the risk and probability of contamination for five environmental components: surface water, groundwater, atmosphere, soil and human health. The methodology has been applied to a site in Granada (Southern Spain).
Keywords: landfill siting, municipal waste landfill, Geographical Information Systems, territorial siting criteria, waste management.

1 Introduction

Although authorities are attempting to reduce waste generation and disposal by implementing recycling programs and new facilities, the sanitary landfill remains a necessary part of the municipal waste management system [1, 2, 3].

WIT Transactions on Ecology and the Environment, Vol 92, © 2006 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WM060371

Waste disposal in landfills involves a series of complex biochemical and physical processes which lead to the generation of various emissions and environmental hazards. These include ground and surface water contamination, landfill settlement, fires and explosions, vegetation damage, unpleasant odours, air pollution and global warming [4–9].

Siting a landfill is a complex process involving a combination of social, environmental and technical parameters as well as observance of government regulations [2, 10]. Various techniques for landfill siting are described in the literature, including Geographical Information Systems (GIS) [11, 12], a mixed-integer spatial optimization model based on vector-based data [13], multiple criteria analysis [13, 14] and artificial intelligence technology based on fuzzy inference [2, 15].

In recent years a research team from the University of Granada has developed an environmental diagnosis methodology known as EVIAVE. The methodology is designed to facilitate environmental diagnoses of urban waste landfills, providing sufficient information to determine and quantify the set of environmental problems posed by each landfill [16]. This paper presents a new municipal landfill siting methodology based on a combination of EVIAVE and GIS, and describes its application to a landfill in Granada (Southern Spain). Evaluation criteria are based on international landfill siting practice, a review of the relevant literature and Spanish and European Union legislation.

2 Methodology description

The methodology is based on the use of environmental indexes designed to provide quantitative assessment of the possible environmental interaction between a landfill and potentially affected *environmental components* [17]. The original EVIAVE methodology was intended for application to municipal solid waste landfills in countries in the European Union and any other country where similar legislation exists [16].

The decision-making process is conceived as a hierarchical structure consisting of four stages. The first stage concerns the criteria and subcriteria for taking into account spatial aspects of the proposed site. These are used to quantify specific landfill variables and impact indicators, which are in turn used to calculate the different environmental indexes. The second stage represents the Probability of Contamination Indicator for each environmental component (Pbc_i), along with the corresponding Environmental Value (eV_i). The third stage involves the calculation of the Environmental Risk Index (ERI_i) for each environmental component, while the fourth or final stage represents the ultimate objective of the decision-making hierarchy: i.e. the Landfill Suitability Index (LSI). In the following sections we shall analyse each of these stages in turn.

2.1 Stage 1: Landfill variables and impact indicators

2.1.1 Landfill variables

In order to assess contamination probability, *variables* for each environmental component have been identified. These are based on characteristics of the landfill related to biochemical and physical processes which directly or indirectly affect the environmental components [16, 18]. The variables were established taking into account relevant theoretical and practical studies regarding the siting of landfills, as well as guidelines established in European and Spanish legislation. Examples of landfill variables are: aquifer characteristics, distance from infrastructure, distance from surface water mass, distance from population points, fault lines and rainfall.

Under the EVIAVE methodology, evaluation for each variable (j) may be obtained by means of the *Contamination Risk Index*, whose expression is shown in eqn (1). In this expression, C_j is the *classification of the variable* and provides information about the interaction between disposal processes and environmental characteristics related to the variable, while W_j is the *weighting* of each variable [16]. The range of values of the index may be 1, 2, 3, 4 or 5.

$$CRI_j = C_j \times W_j \tag{1}$$

The weighting of each variable has a value of 1 or 2, determined on the basis of the relationship between the variable and the concept of *structural elements* at the landfill. The *structural elements* considered in the EVIAVE methodology are the existence of organic matter, humidity and density of wastes. These three elements participate in the main biochemical and physical processes produced in the landfill and cause production of gas and leachate, affecting all the variables and providing greater weighting to some of them [16, 18]. W_j reaches a value of 2 when the variable is directly related to the structural elements, or when it affects the environmental components.

Table 1: Classification of the variable 'Aquifer characteristics'.

Method		GOD	DRASTIC
Classification (Iv=Vulnerability Index)	Very low (C_j=1)	Iv < 0.1	Iv < 28
	Low (C_j=2)	0.1 ≤ Iv < 0.3	29 ≤ Iv ≤ 85
	Average (C_j=3)	0.3 ≤ Iv < 0.5	86 ≤ Iv ≤ 142
	High (C_j=4)	0.5 ≤ Iv < 0.7	143 ≤ Iv ≤ 196
	Very high (C_j=5)	Iv ≥ 0.7	Iv ≥ 196

Table 2: Classification of the variable 'Aquifer characteristics'.

Method		SINTACS	EPIK
Classification (Iv=Vulnerability Index)	Very low (C_j=1)	Iv ≤ 80	Iv = 2 or 3
	Low (C_j=2)	81 ≤ Iv ≤ 105	Iv = 4 or 5
	Average (C_j=3)	106 ≤ Iv ≤ 140	Iv = 6 or 7
	High (C_j=4)	141 ≤ Iv ≤ 186	Iv = 8 or 9
	Very high (C_j=5)	Iv ≥ 187	Iv = 10

By way of example, the variable 'Aquifer characteristics' attempts to identify the characteristics of aquifers located near the proposed landfill site and to quantify their vulnerability, taking into account leachate emissions from the waste mass. This variable directly affects the environmental component ‘groundwater’, and therefore obtains a weighting of 2. Classification of the variable (Tables 1 and 2) is made on the basis of different indexes of vulnerability of the aquifer to pollution, which vary according to its characteristics [19]. Similar justification and quantification are applied to the other variables and environmental components.

2.1.2 Impact indicators

Impact indicators were defined in the ‘Environmental Impact Assessment’ process in order to measure impact on each environmental component. In the present methodology the indicators are environmental features which could be affected by the landfill project [17]. The features are subsequently used to quantify Environmental Value Indexes for each environmental component. Indicators were selected on the basis of their relevance for impact assessment as viewed by professionals, stakeholders, and the general public. In the case of surface water, for example, impact indicators are: type of surface water mass, use of water and water quality. Each impact indicator may obtain a value of 1, 2, 3, 4 or 5. Table 3 shows justification and quantification in the case of the impact indicator ‘Use of water’ for the environmental component ‘surface water’, taking into account Spanish and European Union legislation [20, 21]. Similar justification and quantification are applied to the other characteristics and environmental components.

Table 3: Impact indicator ‘Use of water’ for ‘surface water’.

A_2	Classification
1	Not for use by humans
2	Hydroelectric, navigation and other uses
3	Industrial
4	Agriculture
5	Human drinking water, aquaculture and recreational uses including beaches suitable for bathing

2.2 Stage 2: Probability Of Contamination Indicator and environmental values

2.2.1 Probability of Contamination Indicator

The *Probability of Contamination Indicator* (Pbc_i) for each environmental component considers possible contamination due to the characteristics of the landfill site. It is expressed by eqn (2), where *n* is the number of variables affecting each environmental component, CRI_j is the Contamination Risk Index for each variable (j), $CRI_{jminimum}$ is the minimum value obtained by the CRI for each variable in stage 1 and $CRI_{jmaximum}$ is the maximum value obtained by the CRI for each variable in stage 1. The indicator may obtain values between 0 and 1 and generates classifications of ‘Improbable’ ($0 \leq Pbc_i < 0.2$), ‘Seldom probable’

($0.2 \leq Pbc_i < 0.4$), 'Relatively probable' ($0.4 \leq Pbc_i < 0.6$), 'Probable' ($0.6 \leq Pbc_i < 0.8$) and 'Very probable' ($0.8 \leq Pbc_i \leq 1$).

$$Pbc_i = \frac{\sum_{j=1}^{j=n} CRI_j - \sum_{j=1}^{j=n} CRI_{j_{\min imo}}}{\sum_{j=1}^{j=n} CRI_{j_{\max imo}} - \sum_{j=1}^{j=n} CRI_{j_{\min imo}}} \tag{2}$$

2.2.2 Environmental Value

The concept *Environmental Value* (eV_i) is designed to identify and quantify the environmental assessment of each environmental component in the area of the landfill. It is considered as a relative environmental value, since it takes into account the relationship between the landfill environmental and/or social and political characteristics and the *possible* emissions in the landfill [18], as well as the environmental importance for each element in the surroundings of the landfill. Environmental Values for surface water, groundwater, atmosphere and soil are expressed by the mean values for the different impact indicators for each environmental component; for human health Environmental Value is always has maximum value. Values range between 1 and 5 for each environmental component, with classifications of 'Very low' ($1 \leq eV_i < 1.8$), 'Low' ($1.8 \leq eV_i < 2.6$), 'Average' ($2.6 \leq eV_i < 3.4$), 'High' ($3.4 \leq eV_i < 4.2$) and 'Very high' ($4.2 \leq eV_i \leq 5$). If an environmental element obtains high or very high values, this indicates that the landfill is located in an area of greater environmental sensitivity for the element in question [16, 18].

2.3 Stage 3: Environmental Risk Index

The *Environmental Risk Index* (ERI_i) determines the environmental impact potential for each environmental component, reflecting whether or not interaction exists between the landfill and the characteristics of the environment [16]. For each landfill, the ERI indicates which components are or would be most affected by the presence of wastes, making it possible to determine the extent of possible deterioration in each landfill site.

$$ERI_i = \sum_{i=1}^{i=5} (Pbc_i \times eV_i) \tag{3}$$

The index is expressed by eqn (3), where Pbi_i is the Probability Indicator and eV_i is the Environmental Value, both for each environmental component (i). The index obtains values between 0 and 5 and is classified as 'Very low' ($0 \leq ERI_i < 1$), 'Low' ($1 \leq ERI_i < 2$), 'Average' ($2 \leq ERI_i < 3$), 'High' ($3 \leq ERI_i < 4$) and 'Very high' ($4 \leq ERI_i \leq 5$).

2.4 Stage 4: Landfill Suitability Index

Finally, overall suitability of the landfill site is quantified by a general index known as the *Landfill Suitability Index* (LSI). In the EVIAVE methodology the Environmental Landfill Impact Index (ELI) characterized the overall environmental state of operating landfills [16]. By contrast, the LSI characterizes the overall environmental suitability of the landfill siting. The graded scale used for the Index is from 0 to 25, ranging from the least suitable to the most suitable area. The mathematical expression used to obtain the LSI is eqn (4), where ERI_i is the Environmental Risk Index for each environmental component (i). Classifications generated are 'Unsuitable' (20= LSI = 25), 'Low suitability' (15= LSI <20), 'Average suitability' (10= LSI <15), 'High suitability' (5= LSI <10) and 'Very high suitability' (0= LSI <5).

$$LSI = \sum_{i=1}^{i=5} ERI_i \tag{4}$$

3 Evaluation of land suitability: an example

This study has described the development of a new methodology to evaluate the process of siting a waste facility. Application of the methodology involves processing a variety of spatial data. In the present case GIS was used to create the digital geodatabase, using the spatial analysis tools provided by GIS. Several algorithms were used to automate the process of determining composite evaluation criteria, perform the multiple criteria analysis (MCA) and perform the spatial clustering process. These algorithms were developed in the Microsoft Visual Basic programming environment, which is compatible with the GIS software ESRI ArcGIS [22]. Various MCA methods have been recommended for the evaluation of the final suitability index, including POPSIS [23] and Compromise Programming [24]. However, in the present study the simple additive weighting (SAW) method was selected as the most appropriate way of solving the multiple criteria problem. The GIS-aided landfill siting methodology presented here combines the spatial analysis tools provided by GIS with MCA to evaluate the entire region, based on specific evaluation criteria (hydrological-hydrogeological, environmental, social, technical/economic).

3.1 Area of study

The area selected has an extension of 300 km² and is situated to the south of the conurbation of Granada (Southern Spain) on the western edge of the Sierra Nevada (fig.1). After Sevilla and Málaga, Granada has the third largest population of the Autonomous Community of Andalusia, with approximately 440,000 inhabitants, of whom two thirds live in the metropolitan area of the city. This figure represents 55% of the total population of the province of Granada

(817,000), concentrated in a surface area of 830 km², i.e. less than 7% of the total surface area. Population density in the area is thus 530 inhabitants per km², as against 32 inhabitants per km² in the rest of the province.

With regard to the treatment, disposal and elimination of solid wastes, there is an urban solid waste treatment plant in the municipal district of Alhendín. This plant handles the waste from the 30 municipal districts which make up the conurbation of Granada, as well as from 36 districts outside the conurbation.

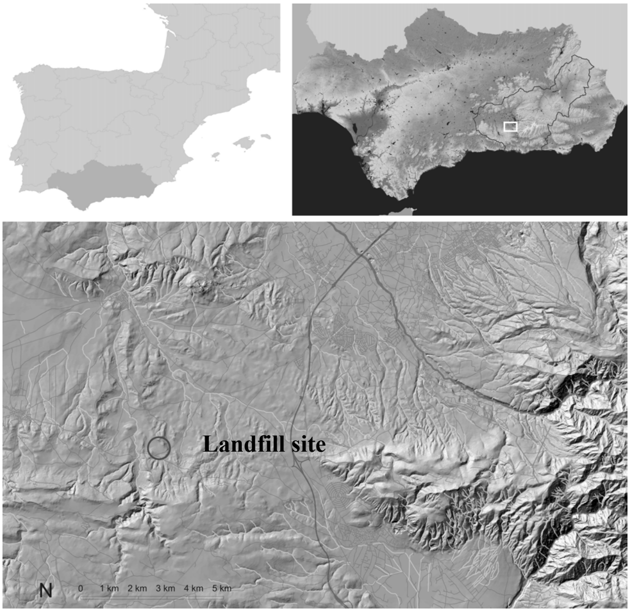

Figure 1: Map of situation and localization of existing landfill site.

3.2 Modelling the landfill variables

In the field of Geographical Information Systems there are two basic approaches to the question of how to model space. Depending on whether attention is given to properties or localization [24], two different data models may be generated: the vector model and the raster model.

The two models present a series of advantages and disadvantages according to the use for which GIS is intended [25, 26]. However, in the present study the raster model was finally selected due to its speed and efficiency at superpositioning maps, while the vector model was used only to generate the basic cartography and for the initial variable modelling.

An optimal resolution of 10 m was adopted for base cartography at a scale of 1: 10,000 and 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).

3.3 Model implementation

'Cartographic modelling' is a more ample 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 judgements, with an aim to finding solutions to specific spatial problems [27]. Tomlin [28] describes cartographic modelling as a 'general methodology for the analysis and synthesis of geographical data', and defines it as 'the use of the basic operations of a GIS in a logical sequence to resolve complex spatial problems'. These are the phases of the applied model:

1. Cartographs of the Contamination Risk Index (CRI_j). Each localization variable is modelled and reclassified and subsequently each W_j is measured using map calculator algorithms [22] and the product operator. Each localization variable landfill generates a cartograph for each impact on the environmental components, and the value for the Contamination Risk Index is indicated on each pixel.
2. Cartographs of the Probability of Contamination Indicators (Pbc_i). In a subsequent step results are grouped using arithmetic superposition in order to obtain cartographs of the Probability of Contaminations Indicators, with one image corresponding to each environmental component.
3. Calculation of Environmental Values (eV_i) and cartographs of the Environmental Risk Index (ERI_i). The values obtained are used to determine the Environmental Risk Index (ERI_i), by means of arithmetic superposition of the Environmental Value (eV) for each environmental component.
4. Cartographs of the Landfill Suitability Index (LSI). To conclude the model, the cartograph of the LSI is obtained by means of multi-criteria analysis techniques (MCA), taking as factors the different Environmental Risk Indexes 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.

Results obtained in the application of the methodology gave a Landfill Suitability Index of 6.48 for the siting of the landfill, equivalent to 'high' according to the classification described above. Figure 2 shows results for the model applied with GIS.

The Probability of Contamination Indicator for the environmental components obtained classifications of 'Improbable' for ground water and 'Seldom probable' for surface water, soil and human health. The component 'atmosphere' obtained a rather higher value of 'Probable'. These results indicate that the siting of the landfill does not present general characteristics which might contribute to the contamination of the different environmental components, except in the case of atmosphere. In this case, the landfill could present an impact influenced by high rainfall, seismic risk in the area and wind characteristics.

Results for the Environmental Risk Index (ERI_i) show final contamination risk values for each environmental component. In this case the Environmental

Value for each component is also taken into account, with classifications of 'very high' for health and atmosphere, 'high' for groundwater, 'low' for soil and 'very low' for surface water. With the addition of these data, results for ERI_i are finally 'very low' for surface water, groundwater and soil; 'low' for human health and 'high' for atmosphere. Again, atmosphere presents a higher risk of being affected, due not only to the higher probability value but also to the very high Environmental Value.

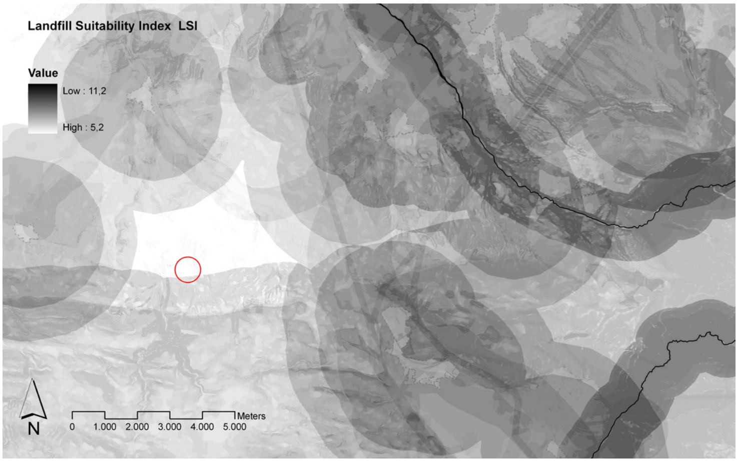

Figure 2: LSI for the area under study.

3.4 Analysis of model sensitivity

Sensitivity analyses are directly related to modelling in any scientific field. A model is always a simplified version of reality which enables us to describe a specific problem and reach a better understanding of it, through the representation of essential elements and mechanisms of systems in the real world, 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 the present study a verification of the methodology was undertaken, together with a results validation test and model stability analysis.

4 Conclusions

The methodology has been shown to be applicable to analysing the suitability of a site for landfill localization, due chiefly to the generation of a final suitability index. However, analysis of results for the other indexes may also facilitate the study of potential problems related to the different environmental components, thus contributing to the decision of whether or not to locate the landfill in a particular setting. On the basis of the results of the practical application of the model in Granada as well as the sensitivity analysis, we may conclude that Geographical Information Systems may be usefully applied to the optimal siting of facilities with such exceptional characteristics as landfills. It seems reasonable, moreover, to predict 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, by extending their knowledge of the physical terrain and facilitating the analysis and execution of plans of action.

Acknowledgement

This research is part of an R+D Project funded by the Spanish Ministry of Science and Technology entitled "Design and implementation of methodologies for the environmental diagnosis of urban waste landfills and waste dumps".

References

[1] Komilis, D.P., Ham, R.K. & Stegmann, R., The effect of municipal solid waste pretreatment on landfill behavior: a literature review. *Waste Management and Research*, **17**, pp. 10-19, 1999.
[2] Al-Jarrah, O. & Abu-Qdais, H., Municipal solid waste landfill siting using intelligent system. *Waste Management*, **26(3)**, pp. 299-306, 2005.
[3] Vaillancourt, K. & Waaub, J-P. Environmental site evaluation of waste management facilities embedded into EUGÈNE model: A multicriteria approach. *European Journal of Operation Research*, **139**, pp. 436-448, 2002.
[4] Abu-Rukah, Y. & Al-Kofahi, O., The assessment of the effect of landfill leachate on ground-water quality – a case study: El-Akader landfill site, North Jordan. *Journal of Arid Environments*, **49**, pp. 615-630, 2001.
[5] Edgers, L., Noble, J.J. & Williams, E., A biologic model for long-term settlement in landfills. *Proceedings of the Mediterranean Conference on Environmental Geotechnology,* (M.A. Usmen and Y.B. Acat., eds), Cesme, Turkey, pp. 177-184, 1992.
[6] El-Fadel, M., Findikakis, A.N. & Leckie, J.O., Environmental impacts of solid waste landfilling. *Journal of Environmental Management*, **50**, pp. 1-25, 1997.
[7] Raybould, J.G. & Anderson, D.J., Migration of landfill gas and its control – a case history. *Journal of Engineering Geology,* **20**, pp. 75-83, 1987.
[8] Gilman, E.F., Flower, F.B. & Leone, I.A., Standardized procedures for planting vegetation on completed sanitary landfills. *Waste Management & Research*, **3**, pp. 65-80, 1985.
[9] Sarkar, U., Hobbs, S.E. & Longhurst, P., Dispersion of odour: a case study with a municipal solid waste landfill site in North London, United Kingdom. *Journal of Environmental Management*, **68**, pp. 153-160, 2003.
[10] McBean, E., Rovers, F. & Farquhar, G., *Solid Waste Landfill Engineering and Design*. Prentice-Hall PTR, Englewood Cliffs, New Jersey, USA, 1995.

[11] Siddiqui, M.Z., Landfill siting using Geographical Information Systems: a demonstration. *Journal of Environmental Engineering*, **122(6)**, pp. 515-523, 1996.
[12] Kontos, Th.D., Komilis, D.P. & Halvadakis, C.P., Siting MSW landfills in Lesvos Island with a GIS-based methodology. *Waste Management and Research*, **21(3)**, pp. 262-27, 2003.
[13] Lin H-Y, & Kado, J-J., A vector-based spatial model for landfill siting. *Journal of Hazardous Materials*, **58**, pp. 3-14, 1998.
[14] Kao, J-J., Multifactor spatial analysis for landfill siting. *Journal of Environmental Engineering*, **122(10)**, pp. 902-908, 1996.
[15] Gupta, R., Kewalramani, M.A. & Ralegaonkar, R.V., Environmental impact analysis using Fuzzy Relation for landfill siting. *Journal of Urban Planning and Development*, **129(3),** pp. 121-139, 2003.
[16] Zamorano, M., Garrido, E., Moreno, B., Paolini, A. & Ramos, A., Environmental diagnosis methodology for municipal waste landfills as tool for planning and decision-making process. *Sustainable Development and Planning*, Wessex Institute of Technology, 1, pp. 545-554, 2005.
[17] Antunes, P., Santos, R. & Jordao, L. The application of Geographical Information Systems to determine environmental impact significance. *Environmental Impact Assessment Review*, **21**, pp. 511-535, 2001.
[18] Calvo, F., Moreno, B., Zamorano, M. & Szanto, M., Environmental diagnosis methodology for municipal waste landfills. *Waste Management*, **25**, pp. 68-79, 2005.
[19] Foster, S. & Hirata, R. Determinación del riesgo de contaminación de aguas subterráneas. Una metodología basada en datos existentes. [Determining the risk of contamination in groundwater. A methodology based on existing data.] *CEPIS,* pp.1-81, 1991.
[20] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.
[21] Real Decreto 927/1988, de 29 de julio, por el que se aprueba el Reglamento de la Administración Pública del Agua y de la Planificación Hidrológica, en desarrollo de los Títulos II y III de la Ley de Aguas. [Royal Decree 927/1988 of 29 July, approving the Regulation proposed by the Public Administration for Water and Hydrological Planning, in application of Chapters II and III of the Water Act.]
[22] McCoy, J. & Johnston, K., Using *ArcGis Spatial Analyst*. Environmental Systems Research Institute. Redlands, California, 2002.
[23] Yoon, K. & Hwang, C.L., *Multiple Attribute Decision Making: an Introduction*. Sage Publications Inc., London, UK, 1995.
[24] Zaleny, M., Fuzzy Sets. *Information and control*, **8**, pp. 338-353, 1982.
[25] Bosque, J. *Sistemas de información geográfica*. [Geographical Information Systems.] Madrid, Rialp, 1997.
[26] Bosque, J., Díaz, M.A., Gómez, M., Rodríguez, V.M., Rodríguez, A.E. & Vela, A., Un procedimiento, basado en un SIG, para localizar centros de tratamiento de residuos. [A GIS-based procedure for siting waste

treatment centres.] *Anales de Geografía de la Universidad Complutense*, **19**, pp. 295-323, 1999.

[27] Barredo, J.I. & Gómez, M., *Sistemas de Información Geográfica y Evaluación Multicriterio en la Ordenación del Territorio*. [Geographical Information systems and multicriteria evaluation in the organization of territory] Ed. Ra-Ma. Madrid, 2005.

[28] Tomlin, D., *Cartographic modelling*. Maguire, D., Goodchild, M. and Rhind, D. (eds). Geographical Information Systems. Volume. 1, New York, Longman, 1991.