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A methodology for landfill location using geographic information systems: a Colombian regional case

Metodología para la localización de rellenos sanitarios mediante sistemas de información geográfica. Un caso regional colombiano

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RESUMEN

El crecimiento económico y el acelerado desarrollo de las regiones han generado elevadas tasas de producción de residuos sólidos, desechos que en numerosas localidades son dispuestos en lugares sin ningún tipo de medida técnica ni ambiental. En este artículo se presenta un desarrollo metodológico para la localización de rellenos sanitarios mediante la combinación de sistemas de información geográfica (SIG), con el proceso analítico jerárquico (PAJ) y el método de ponderación aditiva simple (MPAS). La metodología desarrollada fue aplicada a un caso regional colombiano: Tame, Arauca. Se desarrolló un escenario de comparación entre la legislación colombiana y la metodología propuesta. Los resultados muestran que existen diferencias significativas en la estimación de la disponibilidad de área. Con respecto al 95% de la ponderación máxima (1.000 puntos), la metodología propuesta fue un 81% más restrictiva que la legislación colombiana.

Palabras clave: relleno sanitario, localización, metodología, sistema de información geográfica.

ABSTRACT

The regions' economic growth and accelerated development have created high solid waste production rates; such waste is disposed of in many localities in places without any technical and/or environmental measures having been taken. This paper presents guidelines for locating landfills by combining geographic information systems (GIS) with analytic hierarchy process (AHP) and simple additive weighting (SAW). The methodology so developed was applied to the regional case of Tame in the Arauca department in Colombia; a scenario involving Colombian legislation was compared to the proposed methodology. The results showed that there were significant differences in estimating area availability. Regarding 95% of maximum weighting (1,000 points), the proposed methodology was 81% more restrictive than the Colombian legislation.

Keywords: landfill, selection site, methodology, geographic information system.

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Introduction

Regional economic growth and accelerated development leads to high solid waste production rates thereby making final disposal one of the main problems facing municipalities as waste in many localities has been deposited in locations without any kind of technical or environmental measure having been taken.

Although difficulty in selecting an appropriate location for final solid waste disposal has been identified for several decades, the solutions which have been proposed so far have not covered all the intermediate and smaller towns in Latin-American countries (Turiago and Arrieta, 2010). The problem has not only focused on the search for suitable locations but has also focused on the increase in open-air solid waste dumps which has resulted in an increase in cases of damage to water resources and ecological and socioeconomic systems. Our regions have thus demanded their closure during recent years. Such action has been implemented in Colombia through Ministry of Environment resolution 1390/2005 (MAVDT, 2005).

Although Colombia has legislation regarding locating these facilities (i.e. decree 838/2005) (MAVDT, 2005), it lacks a unified methodology for assessing and selecting potential areas for locating a landfill using geographic information systems (GIS). Inappropriate selection can contribute towards a poor image and reputation, thereby affecting future operation and public health. Selecting a location thus becomes a step by step process involving environmental, engineering and economic criteria (Frantzis, 1993).

A GIS combines spatial data (i.e. maps, aerial photographs and satellite images) with quantitative, qualitative and descriptive information from databases supporting a wide range of spatial queries (Zamorano *et al*., 2008) making GIS an indispensable tool

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in location studies (Church, 2002), particularly for landfill placement (Sumathi *et al*., 2008).

Many researchers have demonstrated the advantages of using GIS for selecting a final disposal location; Jensen and Christensen (1986) have demonstrated the use of GIS in location selection for the final disposal of hazardous waste. Fatta *et al*., (1998) have used GIS for selecting industrial waste landfill location. Siddiqui (1996) has presented a method for identifying and classifying potential areas as a tool for the preliminary evaluation of final disposal sites; this method combined GIS with a decision-making method based on analytic hierarchy process (AHP). GIS technology has also been combined with AHP and fuzzy sets theory (FST) (Charnpratheep *et al*., 1997). Lin and Kado (1998) have developed a mixed-integer programming model for obtaining a site having optimal compactness; the model has been expanded to include multiple location factors with weighting determined by GIS map layer analysis function. Sener *et al*., (2006) and Zamorano *et al*., (2008) have developed an assessment model combining GIS with multi-criteria decision analysis (MDA), AHP and simple additive weighting (SAW).

The idea of combining MDA with AHP and SAW seeks decision-makers' opinion to order and establish priorities for evaluating selection criteria. MDA and AHP are based on three basic principles: constructing hierarchies, prioritising and evaluating inconsistent judgment. These techniques are mostly used in analysing environmental problems created by a particular landfill's location (e.g. Lootsma, 2000; Chuang, 2001; Sener *et al*., 2006; Guiqin *et al*., 2009; Geneletti, 2010). The present research thus involved an international literature review of methodologies using MDA and AHP to identify the criteria used, their evaluation order and importance.

Location methods based on geomorphological units' (GU) characteristics are often used because of better evidence regarding characteristics intrinsic to the territory (e.g. Pividal, 1999; Sener *et al*., 2006; Yesilnacar and Cetin, 2007; Mondelli *et al*., 2007). A geomorphological characteristics-based definition of deductible homogeneous units allows better assessment of the variables used as indicators in decision-making. Its strength lies in managing three factors: landscape vulnerability, surface water and underground water (Pividal, 1999). This type of method was considered when developing and analysing the methodology proposed in the present research.

Its main objective was to develop methodology in line with Colombian legislation for identifying potential areas for landfill locations by combining GIS with AHP and SAW by studying international methodologies using multi-criteria decision-making analysis (MDA) and that based on GU.

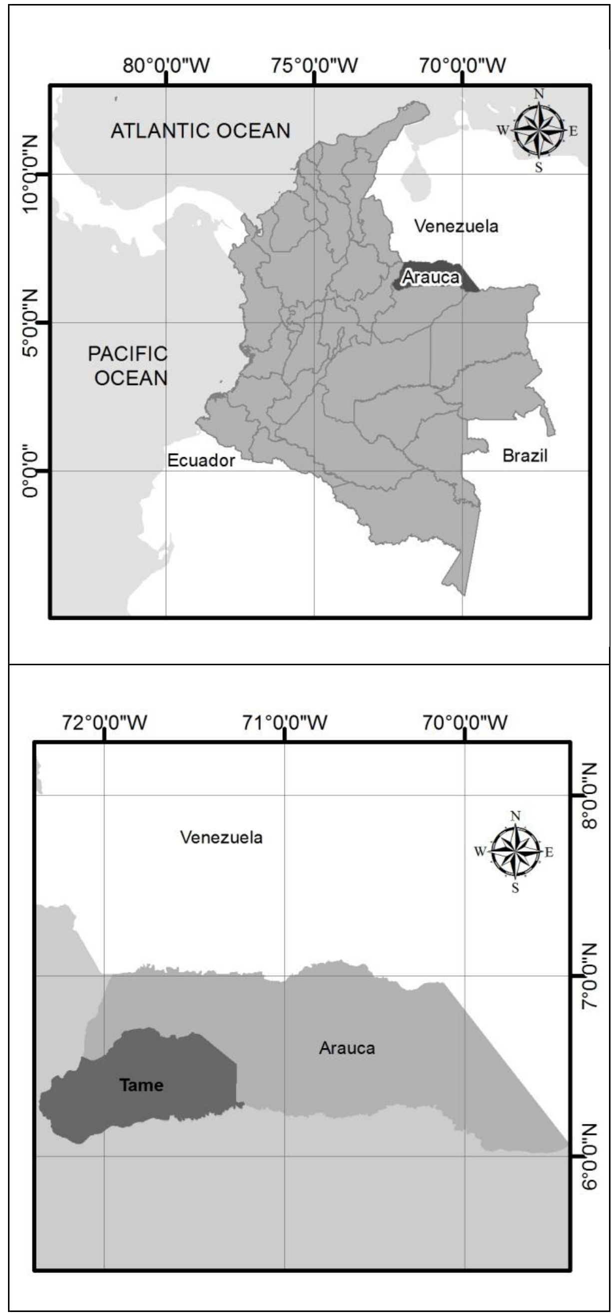

Figure 1. Study area location

Materials and Methods

Description of the study area

The research was undertaken in the municipality of Tame, Arauca department, Colombia. The municipality is located at 6°27´ N and 71°46´ W (Figure 1); it lies at 350 masl, having a rural population of 28,442, 19,134 urban inhabitants and 5,365 km^2 surface area. Average annual temperature is 26°C, 2,200 mm average annual rainfall and predominant northeast wind direction. There are three main river systems (i.e. river basins): the Casanare River, the Cravo Norte River and the Ele River. The research area is home to the Sierra Nevada del Cocuy National Park located to the southwest of the municipality (see Figure 2).

Methodological proposal

The hierarchical evaluation structure proposed by the current methodology led to identifying and the proper assessment of each criteria by using GIS (see Figure 3). The weighting scale proposed for the different municipal lands had a 0-1,000 point range; areas scoring close to the upper weighting limit had greater compatibility

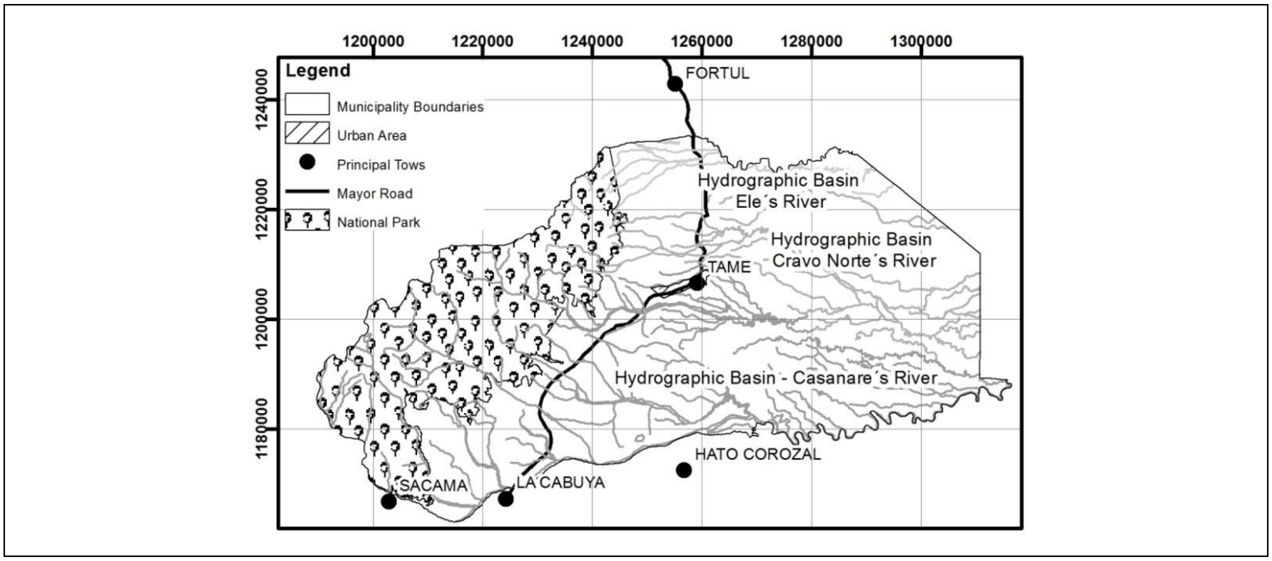

Figure 2. The study area's physical characteristics

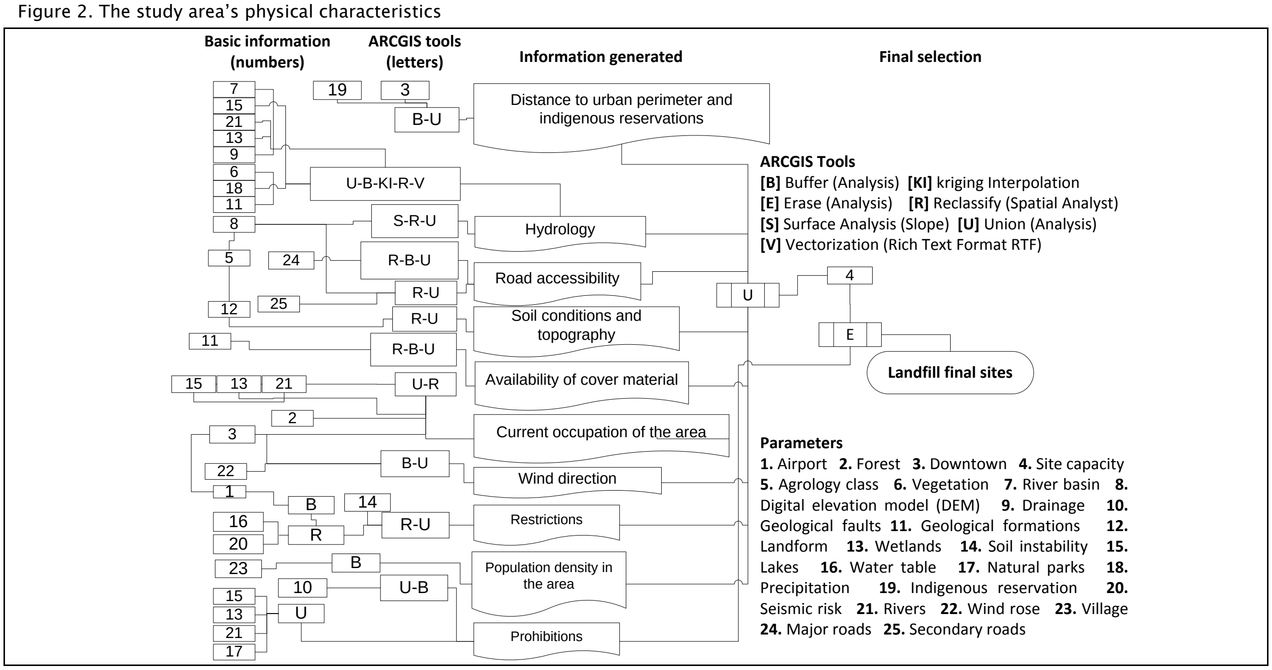

Figure 3. Functional model for the proposed methodology

for positioning a solid waste disposal installation. The evaluation criteria are given below with their respective weighting ranges.

1. *Hydrology*: The surface water bodies connecting areas of life and their involvement can lead to damaging large areas regarding the survival of flora, fauna and communities located in areas of direct and indirect influence. The possibility of contaminant in surface water bodies thus requires evaluation (e.g. leachate) (Lee and Jones, 1991; Pividal, 1999; Abu-Rukah and Al-Kofahi, 2001). The evaluation included surface runoff and drainage index assessing the impact on the ease or difficulty offered by the territory so that leachate drainage could be integrated into permanent water bodies (Pividal, 1999) (Table 1).

Table 1. Assessing hydrology criteria (US.SCS, 1972; Pividal, 1999; MAVDT, 2005)

Distance to water bodies	Weighting	Drainage index, D[a]	Weighting	Surface runoff[b]	Weighting
> 2,000 m	50	< 1,0	50	< 50 mm	50
1,000-2,000 m	30	1.0-3.0	40	50-200 mm	40
500-999 m	15	3.0-6.0	20	200-350 mm	20
50-499 m	7	6.0-12.0	10	350-500 mm	10
< 50 m	0	> 12	0	> 500 mm	0

[a]*: relationship between the density of drainage from a watershed (km/km2) and distance to permanent water bodies (km) (Pividal, 1999); b: estimated by the runoff curve number method (US.SCS, 1972).*

2. *Road accessibility*: This criterion assessed the ease and economics involved in collecting and transporting solid waste to the particular area in which final disposition would take place. Landfills must be located in places having alternative routes according to weather conditions. Alternatively, they should be located near highway networks to reduce construction costs involved in connecting roads and should not interfere with current and future traffic (TSWCR, 1991; MAVDT, 2005; Guiqin *et al*., 2009) (Table 2).

Table 2. Assessing road accessibility criteria (MAVDT, 2005)

Main road conditions	Weighting	Main road slope	Weighting	Access road distance	Weighting	Access road slope	Weighting
Paved	20	0-3%	20	0-5 km	20	0-3%	20
Unpaved	8	3.1-5%	12	5.1-10 km	12	3.1-5%	12
		5.1-7%	8	10.1-15 km	4	5.1-7%	8
		> 7.1%	0	> 15 km	0	> 7.1%	0
Number of access roads	**Weighting**	**Access road conditions**	**Weighting**	**Impact on traffic**	**Weighting**		
Two or more	20	Paved	20	None	40		
One	8	Affirmed	12	Moderate	20		
No	0	Passable	8	High	0		
		Absence	0				

3. *Distance to urban perimeters and indigenous reservations*: The transportation costs involved in moving waste from a settlement to a final disposal area were considered (MAVDT, 2005; Sener *et al*., 2006; Geneletti, 2010). Collection and transport costs continue to be localities' largest budget items, even when the costs associated with solid waste disposal are rapidly growing (Ronen *et al*., 1983) (see Table 4).

Table 4. Assessing the criteria: distance to urban perimeters and indigenous reservations (MAVDT, 2005)

Distance	Weight
2-5 km	100
5.1-10 km	50
10.1-25 km	20
25.1-50 km	10
> 50 km	0

4. *Availability of cover material*: The transportation costs involved in moving cover material to comply with technical and environmental specifications in daily operation and landfill closure were considered (MAVDT, 2005; Sumathi *et al*., 2008) (Table 5).

Table 5. Assessing cover material availability criteria (MAVDT, 2005)

Material quality	Weighting	Distance to material	Weighting
Granular	40	0-2 km	50
Sandy clay	32	2.1-4 km	30
Sandy silt	20	4.1-6 km	20
Clay	16	6.1-10 km	10
Clayey silt	8	> 10 km	0
Silt and rocks	0		

5. *Soil conditions and topography*: The slope, ease of soil movement, land use capacity and geomorphology are basic parameters in assessing a landfill's construction and operating costs (Pividal, 1999; Kontos *et al*., 2005; MAVDT, 2005). Landscape assessment was proposed with this criterion, as were the fragility of the environment from a visual standpoint and relief modification (Table 3).

Table 3. Assessing the criteria: soil conditions and topography (adapted from INCORA, 1995; MAVDT, 2005)

Slope	Weighting	Soil movement	Weighting	Agrology class[a]	Weighting	Landform	Weighting
0.1-3%	40	Very easy	40	4-5	40	Broken-encased	40
3.1-7%	30	Easy	32	1-3	10	Hillside- partially encased	32
7.1-12%	20	Regular	20	6-8	0	Hillside-open	20
12.1-25%	10	Difficult	12			Flat-open	12
> 25%	0	Impossible	0				

[a]: *Agrological classification according to Colombian regulations (INCORA, 1995)*

6. *Current occupation of area*: Landfills located close to human settlements have a large environmental impact, mainly associated with noise, smells and health vectors (Karagiannidis *et al*., 2004; Kontos *et al*., 2005; Christine *et al*., 2007). This work was thus aimed at predicting impacts on the community and natural resources (MAVDT, 2005) (Table 6); soil protection regarding natural parks' perimeter buffer strips (i.e. transition zones) was included.

Table 6. Assessing the criteria: current occupation of area (adapted from MAVDT, 2005)

Area occupation	Weighting
Rural	80
Suburban	40
Urban	20
Other protective soil	0

7. *Population density*: The possible involvement of the population located in the area of direct influence where final waste disposal was to be made was evaluated (MAVDT, 2005; Christine *et al*., 2007) (Table 7).

Table 7. Assessing population density criteria (MAVDT, 2005)

Population density	Weighting
0-2 inhabitants/ha (low)	40
2.1-5 inhabitants/ha (medium)	20
> 5 inhabitants/ha (high)	0

8. *Wind direction:* This criterion assessed the impact of landfill odour and particles (i.e. which might be carried by the wind towards populated settlements during disposal due to their weight) (US.EPA, 2000; Sarkar *et al*., 2003; Kontos *et al*., 2005) (Table 8).

9. *Restrictions*: These involved areas where even though a landfill could be located, built and operated there, it had to comply with certain specifications and particular requirements without which its location, construction and operation was not possible. Restrictions: distance to urban land, proximity to airports, groundwater sources,

unstable areas and high seismic risk areas (MAVDT, 2005) (Table 9).

Table 8. Assessing wind direction criterion (adapted from US.EPA, 2000; Sarkar et al., 2003; Kontos et al., 2005; MAVDT, 2005)

Direction	Distance to the urban perimeter (km)		
	0-15	15-30	> 30
	Weighting		
Regarding the nearest town	0	20	40
In the opposite direction to the nearest town	5	25	40

Table 9. Assessing restriction criterion (MAVDT, 2005)

Restrictions	Weighting
0	50
1	30
2	15
> 2	0

10. Capacity: The area required for the final disposition was obtained from solid waste production projections within an area of influence (i.e. 60 km radius regarding an urban perimeter) in relation to the projected horizon (i.e. 30 years). Areas equal to or greater than the required area obtained a 130 point weighting which descended linearly according to the available area (MAVDT, 2005).

11. Prohibitions: These concerned areas where landfill location, construction and operation was prohibited. Such prohibitions would include surface water sources, groundwater sources, critical natural habitats, national parks system areas and buffer zones and areas having geological faults (MAVDT, 2005). No weighting was allocated when rated within exclusionary criterion.

Results and Discussion

Applying the methodology

ArcGIS was used for processing basic information to identify and properly assess each criteria proposed by the methodology. The following were taken into account (i.e. base information) (Figure 3): airports, forests, downtown areas, site capacity, agrology class, vegetation, river basins, digital elevation model (DEM), drainage, geological faults, geological formation, landforms, wetlands, soil instability, lakes, water table, natural parks, rainfall, Indian reservations, seismic risk, rivers, prevailing wind direction, villages, major roads, and secondary roads. The models involved in assessing landfill capacity criteria gave an estimated 280,324 inhabitant population (i.e. within a 60 km radius of influence) for a projected 30 year horizon (2038). Estimated waste production was 323.2 tons per day for the required landfill area involving 176,965 m^3 per year annual volume to be managed (i.e. solid waste plus intermediate and final coverage). The calculation estimated 16 hectares for final disposition installation (trench or ditch excavated technology).

Table 10 shows the main results from applying the proposed methodology; the maximum weighting for each criterion is presented with its corresponding area. Once methodological criteria had been evaluated, the mapping overlap method was used to link the weighting in the same information layer; areas having prohibitions were then discarded. The resulting map is shown in Figure 4. It was decided to use weighting ranges from an established evaluation scale (i.e., between 0-1,000 points) for viewing the results (Table 11).

Table 10. Results for assessment criteria in the study area. Maximum weighting

Criteria	Weighting	Area (%)	Observation
Hydrology			
Distance to water bodies	50	12.7	> 2 km
Drainage to permanent water bodies	50	38.2	Drainage index, D < 1.0
Surface runoff	20	3.2	200-350 mm
Road accessibility			
Conditions (major road)	20	29.9	Paved
Average slope (major road)	20	33.0	0-3%
Distance (access road)	20	31.5	0-5 km
Average slope (access road)	20	33.0	0-3%
Number (access road)	20	100.0	One road
Conditions (access road)	20	29.9	Paved
Impact on traffic congestion (major road)	40	100.0	None
Distance to urban perimeter and Indian reservations	100	15.6	2-5 km
Availability of cover material			
Quality of the material (texture)	40	6.4	Granular material
Distance to source site	50	33.9	0-2 km
Soil conditions and topography			
Average slope	40	54.8	0.1-3%
Ease of soil movement	40	54.8	Very easy
Agrology class	40	25.2	4-5
Landform	40	29.0	Broken-encased
Current occupation of the area	80	61.1	Rural
Population density in the area	40	89.7	0-2 inhabitants/ha
Prevailing wind direction	40	53.2	Contrary-urban centre (> 30 km)
Restrictions	50	0.44	-
Capacity	130		12 ha
Prohibitions	Not applicable	45.8	-

Table 11 shows that the proposed methodology estimated areas having the greatest potential for landfill location; 0.3% of the municipal surface (16.1 km^2) had 95%-100% maximum score weighting and such area was located to the north of the urban centre of the municipality in the study (see Figure 4).

Table 11. Weighting ranges and percentage of area associated with the methodological proposal

Weighting ranges (%)[a]	Area (%)
95-100	0.3
90-95	2.3
85-90	10.3
80-85	16.7
60-80	68.7
< 60	1.7

a: Weighting scale: 0–1,000 points

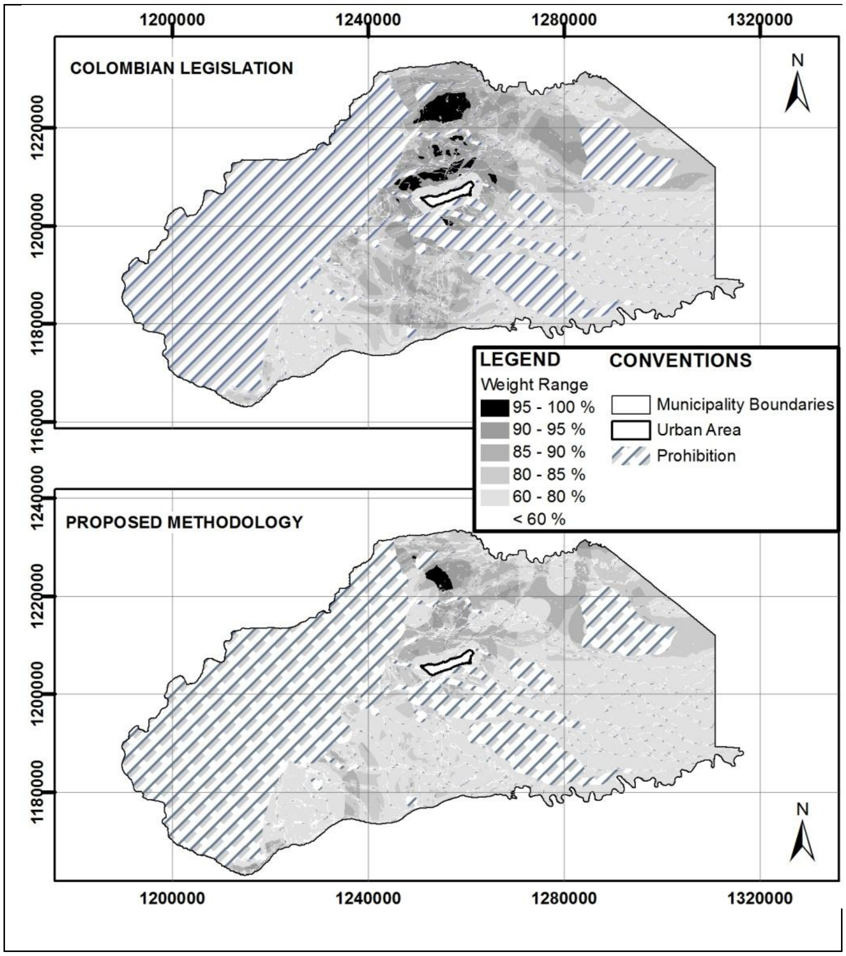

Figure 4. Map of potential areas for the landfill location. Colombian legislation and proposed methodology

The criteria which led to differences between Colombian law and the proposed methodology are discussed below. Based on the literature concerning international reference methodologies reviewed, it was observed that criteria used by such researchers had been considered by Colombian legislation; however, such legislation is deficient regarding hydrological component evaluation, the main production factor and leachate impact evaluation which is why the proposed methodology criterion "1. Hydrology" was included.

The special treatment given to natural parks did not limit these areas' protection by means of prohibitions in their area of direct influence but linked areas of indirect influence having ecological, landscape and relief-type transitions such as buffer perimeter strips (see Criterion 6. Current occupation of area).

Agrological classes were discriminated by taking into account major land potential compared to a municipality's production dynamics (see Criterion 5. Soil conditions and topography). For example, it was determined that areas having high agricultural potential were not suitable for landfill location because they represented an opportunity for local and regional economies' growth and development. Consequently, the methodological proposal defined these areas as being environmentally sensitive and, therefore, that they be assigned zero weighting by virtue of their protected nature.

The distance effect on final installation concerning the spread of odours, dust and noise regarding the urban area of municipality was included in criterion "8. Wind direction".

Methodological proposal compared to Colombian legislation

Colombian legislation (i.e. Decree 838) (MAVDT, 2005) was compared to the proposed methodology to assess differences in determining potential areas for landfill location. Paired Student t-tests revealed significant differences in potential area estimates. Figure 4 shows the maps obtained according to Colombian legislation guidelines and the methodological proposal. Regarding 95% maximum weighting (i.e. 1,000 points), the proposed methodology was 81% more restrictive than Colombian legislation in estimating area availability. As weighting increased, differences in area availability became greater (Table 12).

Table 12. Differences in estimated availability of area. Methodological proposal compared to Colombian legislation

Weighting (%)	Area (ha). Colombian legislation	Area (ha). methodological proposal	Differences (%)
> 95	8,579	1,620	81.1
> 90	36,788	7,701	79.1
> 85	90,052	38,813	56.9
> 80	163,015	99,905	38.7
> 75	301,901	186,751	38.1
> 70	407,497	319,790	21.5
> 65	487,025	421,347	13.5
> 60	523,273	496,681	5.1

Conclusions

The results showed that the methodological proposal regarding potential areas for identifying landfill location synthesised allows the criteria determining their construction, operation and closure. The evaluation criteria included environmental, economic, social and technical characteristics for determining the best territorial options for the municipalities being studied. It also showed that analysis and coordinated and systematic modelling using AHP, SAW and GIS led to obtaining accurate results.

The data showed that the proposed methodology was 81% more restrictive than Colombian legislation in estimating the area available for landfill location regarding the weighting range between 95%-100% of maximum score (i.e. 1,000 points), mainly due to incorporating hydrology criterion including drainage index and surface runoff (i.e. absent in Colombian legislation). This assessed impact according to the ease or difficulty that the territory offered so that leachate drainage could be integrated into permanent water bodies.

The results led to increasing knowledge about development methodologies for landfill location in Colombian municipalities. This is useful for improving methodologies using GIS as a territorial analysis tool for locating waste disposal facilities.

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