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Adapting EVIAVE methodology as a planning and decision-making tool in Venezuela

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ABSTRACT

Landfills in Venezuela have serious problems regarding their location, design and operation. In fact, basic waste disposal is one of the main weaknesses of the municipal waste management in this country. The Venezuelan Ministry of Environment and Renewable Resources has studied and identified the negative impacts of operating landfills, but no program has been implemented to determine the cause–effect relation of these impacts or to design strategies to counteract with the serious environmental and health risks generated. This paper describes how EVIAVE methodology can be successfully used for landfill diagnosis, and shows how this type of landfill diagnosis was applied in Venezuela. For our research study, we carried out both a quantitative and qualitative evaluation of the environmental problems generated by 22 landfills in Venezuela. Our study was based on the following environmental indexes: Landfill Environment, Environmental Risk, Environmental Value, and Probability of Contamination. For the purposes of our study, it was first necessary to adapt EVIAVE to the legal system and social context in Venezuela. The results obtained confirmed the applicability of this methodology to Venezuelan landfills. EVIAVE was found to be an effective planning tool that provided crucial information for the development of action plans, which would improve landfill operation, and help make decisions pertaining to their closure, sealing and eventual recovery.

1. Introduction

Municipal waste management is currently a critical concern in South American and Caribbean countries. However, until now, the solutions proposed for the negative impacts produced by municipal waste have not been implemented. Current practices still include the landfilling of untreated, unsorted waste as the main waste disposal method. Not surprisingly, this has led to severe public health problems as well as environmental pollution [1]. Consequently, waste disposal has become an extremely serious issue in South American and Caribbean countries, especially in urban areas [2–5]. Even though some of these countries have a legal framework for waste control, very few possess the infrastructure and human resources to enforce regulations. As a result, this has produced an extremely paradoxical situation. The percentage of waste collection in these countries is often as high as 81%, but there is no final disposal for 43% of the waste collected [6].

Waste management in Venezuela is not very different from the rest of South American and Caribbean countries. It is based on a simplified sequence of generation, collection and disposal under uncontrolled conditions. There are no provisions for the search and implementation of systems for recovery, recycling, treatment and waste disposal in sanitary landfill sites, which would prevent further environmental damage and reduce health risks to the population [7–9].

In 1999 the Venezuelan Ministry of Environment and Renewable Resources [10] made an inventory of landfills in the country, and identified a total of 215 sites. Further studies of municipal waste

Abbreviations: CRI, Contamination Risk Index; Pbc, Probability of Contamination Index; A_1, environmental descriptor: water use; A_2, environmental descriptor: type of surface water mass; A_3, environmental descriptor: water quality; B_1, environmental descriptor: water use; B_2, environmental descriptor: water quality; C_1, environmental descriptor: air quality; D_1, environmental descriptor: soil use; D_2, environmental descriptor: vegetation type; D_3, environmental descriptor: vegetation covering; eV, Environmental Value Index; ERI, Environmental Risk Index; LSI, Landfill Suitability Index; OAL, open-air landfill; PCL, partially controlled landfill; CL, controlled landfill; MARNR, Venezuelan Ministry of the Environment and Natural and Renewable Resources.

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landfilling increased the number of sites to 234 [7–9]. Most of these sites were found to be deficient for the following reasons: (i) inadequate or non-existent compaction and sealing; (ii) absence of gas and leachate control; (iii) no monitoring of the installations; (iv) waste scavenging in infrahuman conditions; (v) presence of animals at the landfill; (vi) total lack of compliance with Venezuelan laws regarding urban waste disposal.

Despite this alarming situation, no action program has as yet been established to deal with the serious environmental problems in Venezuela. Nevertheless, in 2004, the Venezuelan government passed the Law of Waste [11], which provided a legal framework for improving landfill conditions. The enactment of this law pointed to the need to make an inventory of the number of landfills operating in poor conditions with a view to designing and implementing plans to close and seal them. However, thus far, very few efforts have been made to diagnose landfill sites. The only measures taken thus far have been to target specific emergencies on a one-off basis. However, such measures are not part of a coherent framework of strategic actions that would be conducive to a global solution. Not surprisingly, no methods have been implemented as decision-making tools for cleaning up landfill sites.

A number of authors have developed methods for evaluating environmental impacts [12,13], some of which can be specifically applied to the siting and design of new landfills [14–16]. Nonetheless, these studies are of limited relevance to our research since many only target very specific areas. Furthermore, we are concerned with landfills which are currently in operation. To solve this problem, the University of Granada has developed a landfill diagnosis method, known as EVIAVE, which is capable of providing sufficient data to determine the environmental problems generated by landfills and to control their operation. This method can be applied to landfills with non-hazardous waste, as defined by EU Directive 31/99/EU [17], or to landfills with municipal waste including some mixed hazardous waste, regarding the elimination of solid waste in landfills in the European Union or in countries with similar or less restrictive laws. EVIAVE methodology has been successfully applied in Spain [18] and Chile [19] though it first had to be adapted to the legal and socioeconomic characteristics of each country.

Our research study applied EVIAVE to landfills in Venezuela in order to define the real dimensions of the landfilling problem and to establish a decision-making process that would specify needs and priorities for effective waste management in municipal landfills. This paper describes how the results of our study were validated by contrasting them with available information about landfill sites in Venezuela. Section 2 provides a summary of EVIAVE methodology. Section 3 describes the area where this methodology was applied. Section 4 explains how EVIAVE was adapted to the legal and social context of Venezuela. Section 5 analyzes and discusses the results obtained. Finally the conclusions of this research study are summarized in Section 6.

2. Description of EVIAVE methodology

EVIAVE methodology for the environmental diagnosis of landfills is based on the use of a series of environmental indexes that quantify the impact of landfills on the surrounding environment [18–21]. According to EVIAVE, the degree to which a landfill affects the environment is caused by its level of exploitation as well as the environmental characteristics of its location, as represented by the following five environmental elements: surface water, ground water, atmosphere, soil, and human health and society.

Fig. 1 shows the hierarchical structure and sequence of operations performed to obtain the indexes. At the first level, landfill variables are classified, which correspond to those at the site. Environmental descriptors are also specified at this level. These descriptors reflect the environmental elements present at the landfill.

At the second level each variable is quantified by the Contamination Risk Index (CRI). The Probability of Contamination (Pbc) is also calculated for each environmental element in the neighborhood of the landfill. The Pbc depends on the scale of operation, as well as the waste characteristics and scope of waste disposal at the landfill. The Environmental Value (eV), also specified at this level, identifies and quantifies the environmental assessment of each environmental element at the landfill site. This index takes into account the relationship between the environmental, social and political characteristics of the site, the emissions at the release-point, and the environmental importance of each element in the immediate context of the landfill. It also provides information concerning the suitability of the landfill location.

The third level specifies the Environmental Risk Index (ERI) that determines the potential negative impacts for each environmental element. It reflects the interaction between the release-point and the environment. At the fourth and final level, the Environment Landfill Index (ELI) is determined. This index represents the overall environmental state of the landfill, and quantifies the interaction between the landfill and the environment where it is located. A full description of EVIAVE is available at http://www.eiadifusa.ugr.es [21].

3. Description of the area

The Bolivarian Republic of Venezuela is located on the northern coast of South America, and has an area of 916,445 km^2. The country has a 2813-km coastline and is bounded on the north by the Caribbean Sea and the Atlantic Ocean, on the east by Guyana, on the south by Brazil, and on the west by Colombia. Geopolitically speaking, Venezuela is divided into 23 states, a district capital, and federal dependencies, formed by a group of approximately 311 offshore islands. Venezuela is further subdivided into 335 municipalities.

To identify the landfills in the country, we analyzed previous studies [7,10,22–34] and the results are summarized in Table 1. Based on criteria established by the Venezuelan Ministry of Environment and Renewable Resources, these sites were classified

Table 1
Classification of landfills operating in Venezuela [7,10,22–34].

State	Numbers of sites	Landfill classification			
		LS	CL	PCL	OAL
Amazona	7				7
Anzoátegui	17		2	4	11
Aragua	8			8	
Apure	7			3	4
Barinas	9		1	1	7
Bolívar	7		2	1	4
Carabobo	8		1	5	2
Cojedes	9		1	4	4
Delta Amacuro	5				5
Falcón	28				28
Guarico	12				12
Lara	7		1		6
Mérida	4			2	2
Miranda	10		1	1	8
Monagas	14	1	1	4	8
Nueva Esparta	3		1		2
Portuguesa	14			3	11
Sucre	12				12
Táchira	17			1	16
Trujillo	11			1	10
Yaracuy	6			4	2
Vargas	1		1		
Zulia	18		2		16
Total	234	1	14	42	177

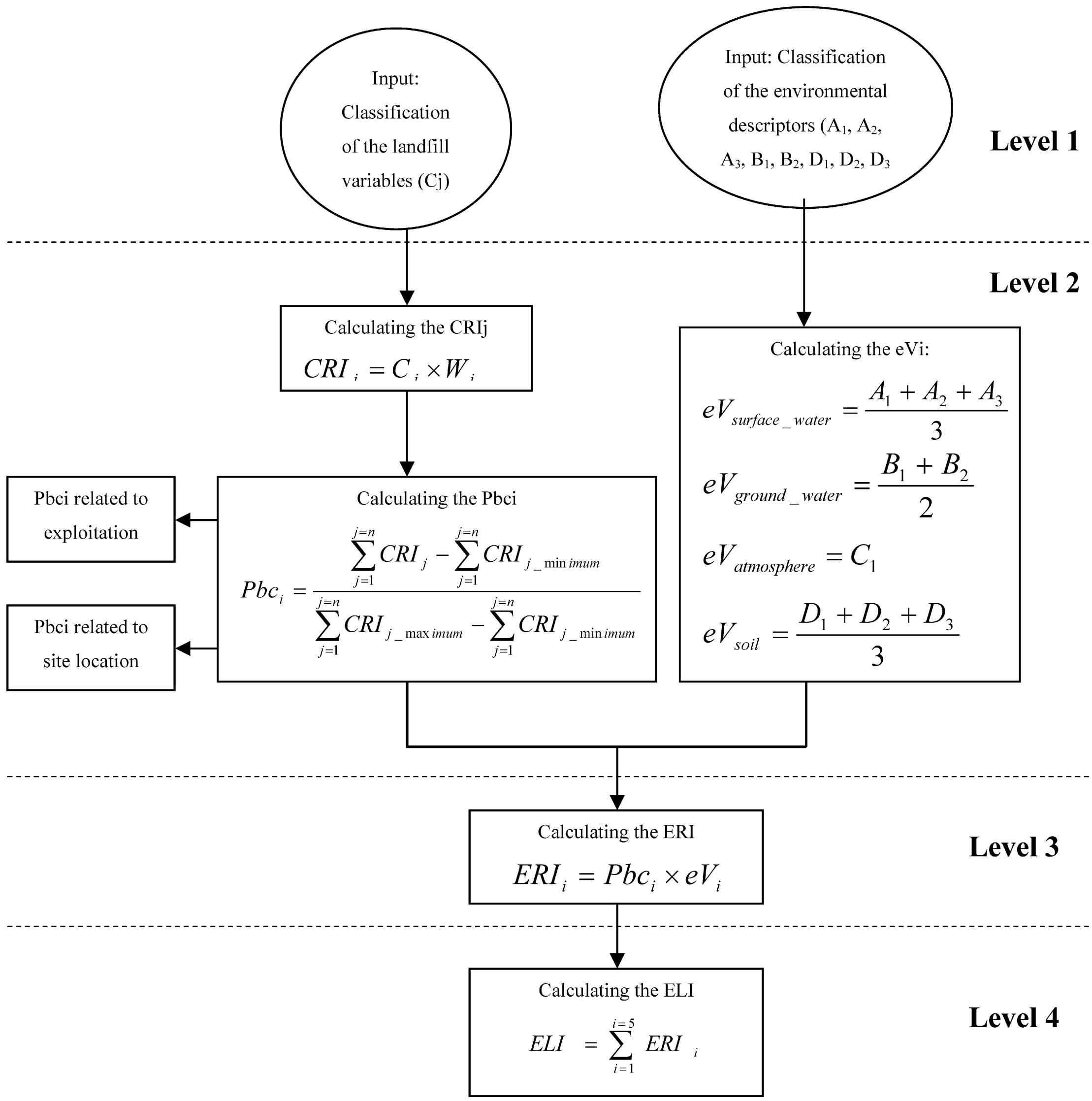


Fig. 1. EVIAVE methodology.

as follows [10]: (i) open-air landfills (OAL) of variable size with no restrictions on waste disposal and no environmental control; (ii) partially controlled landfills (PCL), originally planned as sanitary landfills although, their chaotic operation makes them, for all practical purposes, open-air landfills; (iii) controlled landfills (CL), subject to some waste management though in need of stricter monitoring and regulation; (iv) sanitary landfills in which waste dumping and disposal is strictly monitored. Based on this classification, we found that in the entire country there was only one site that could be regarded as a controlled landfill, and that most of the landfills studied were open-air landfills.

Because of budget restrictions as well as the scarcity of data concerning landfill sites, we selected a total of 22 landfills in the states of Lara, Yaracuy, and Cojedes in the central-western region, and Trujillo and Mérida in the Andean region (Fig. 2). All of these sites were nearby or located in the state of Lara, residence of the author in charge of data collection. An added advantage was the existence of information about the characteristics of these sites. Based on the criteria established by the Ministry of Environment and Renewable Resources [10], 14 of the sites were defined as open-air landfills; 4 as partially controlled landfills; and finally 8 as controlled landfills (Table 2). In this case, no sanitary landfill category was included because there was only one in the entire country, which was too far away from the state of Lara to be able to visit.

4. Adapting EVIAVE methodology

EVIAVE defines landfill variables as those aspects or characteristics which, because of their sensitivity to biochemical and physical processes, have a direct or indirect influence on environmental elements (Table 3). These variables permit the quantification of environmental effects because they are characteristic of the landfill site. In addition, they also measure the landfill exploitation level. EVIAVE defines the environmental descriptors for each environmental element (Table 4). These descriptors give information about the environmental importance of specific elements at the site [18–20]. In this respect, they identify and quantify the relation of each environmental element in the area in regards to its environmental and/or socio-political characteristics and the emissions at the landfill.

In EVIAVE, the selection of variables and environmental descriptors is based on the results of research studies pertaining to how landfills can affect the environment, as well as on the criteria specified in current regulations and guidelines in Europe and

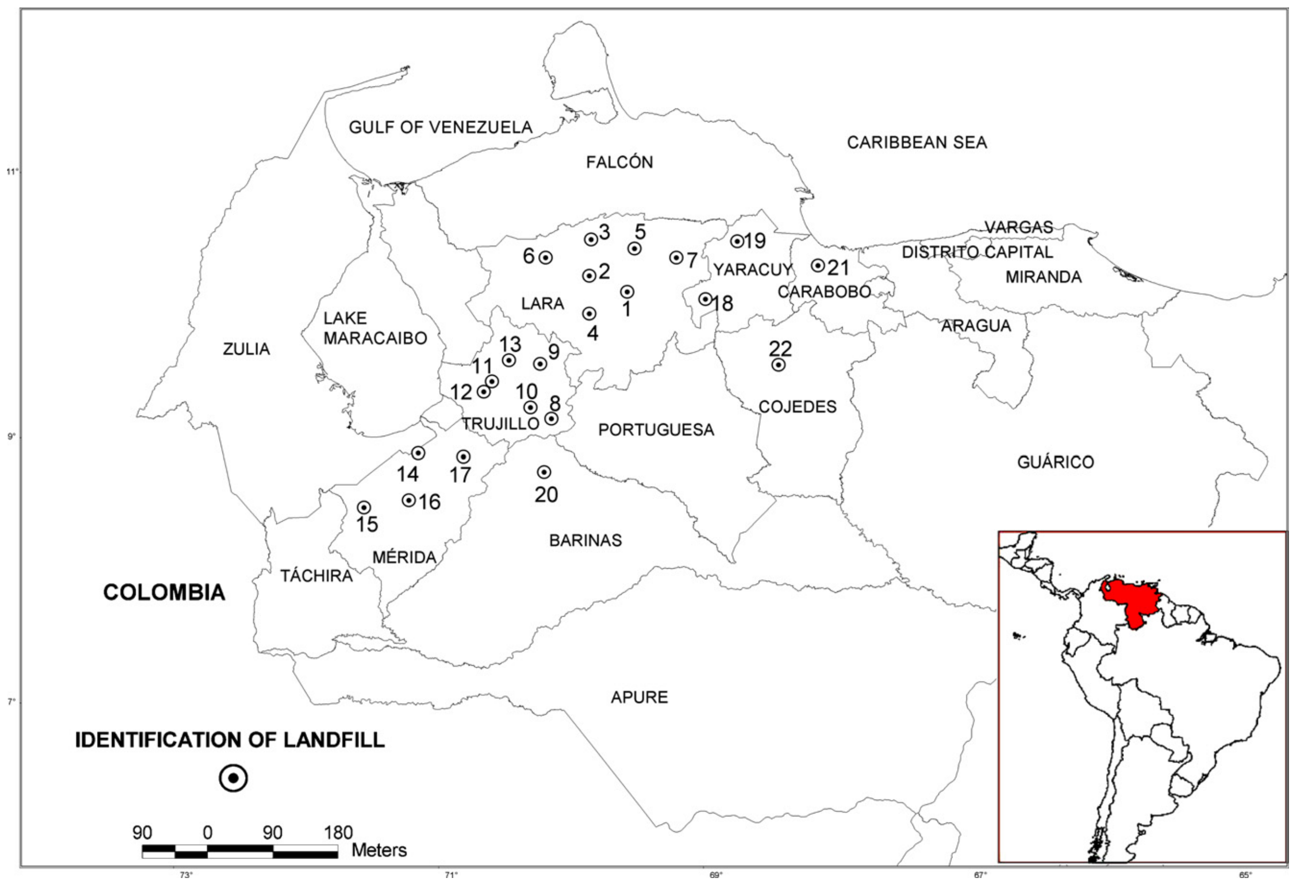


Fig. 2. Map of situation of studied landfills.

Spain [18–20]. Examples of EU legislation include EU Directive 31/99/EU on the landfill of waste and Water Framework Directive 2000/60/EC. Examples of Spanish legislation include Royal Decree 927/88, enacting the national Water Management and Supply Law and Royal Decree 2414/1961, enacting regulations governing hazardous, unsanitary, harmful and dangerous activities. The first step in the application of this methodology thus entails the adaptation of variables and environmental descriptors to the legal framework and socio-economic characteristics of the country where the landfills are located.

Table 2
Landfill sites classification (CL: controlled landfill; PCL: partially controlled landfill; OAL: open-air landfill) [10].

State	Landfills site		Classification
Lara	1	Pavía	CL
	2	Los Jebes	OAL
	3	Los Palmares	OAL
	4	Curva del viento	OAL
	5	Guanarito	OAL
	6	Chirico	OAL
	7	La Pica	OAL
Trujillo	8	Bocono	OAL
	9	Lomas de Bonilla	OAL
	10	Jiménez	CL
	11	Quebrada del Toro	OAL
	12	Sucre	OAL
	13	Andrés Bello	OAL
Mérida	14	La Jabonera	PCL
	15	Onía	OAL
	16	San Felipe	OAL
	17	El Balcón	PCL
Yaracuy	18	Tapa La Lucha	PCL
	19	Jaime	PCL
Barinas	20	Barinas	CL
Carabobo	21	La Paraguita	CL
Cojedes	22	Chaparalito	OAL

Accordingly, the first phase in our research study was the analysis of the variables and environmental descriptors, and their subsequent adaptation to the legal system, social characteristics and the specificity of Venezuelan ecosystems. When there were no Venezuelan legal references or studies to justify the modification of variables or environmental descriptors of EVIAVE, the original classification was used. These modifications did not affect the structure, indexes, and objectives of the methodology, but only the conditions of certain variables and environmental descriptors. Of the 26 variables, 10 were substantially modified, whereas 7 of the 9 environmental descriptors suffered some degree of modification.

For example, EVIAVE originally classified the *Seismic Risk* variable on the basis of the relations between the modified Mercalli Intensity Scale and the M.S.K scale, according to Spanish legislation concerning earthquake-resistant construction. However, a study of the seismic spectrum in South American countries shows that seismicity in this area is different due to different seismic generation mechanisms. In fact, each region has its own ground motion attenuation law, and the effects of directivity are not the same [35]. In Venezuela, the COVENIN Standard 1756-1 [36] identifies eight seismic areas in the country. Each seismic area is classified from 0, where there is no seismic risk, to 7, where the seismic acceleration coefficient (A_0) is 0.40. This classification is based on over 100 years of seismic maps (1898–1998) and more than seven studies on seismic risk published in the last 15 years. The new criteria for the *Seismic Risk* variable are shown in Table 5.

Table 3
EVIAVE variables affecting different environmental elements.

Variable	Classification of the variable		Environmental element				
	Location	Design and operation	Surface water	Ground water	Atmosphere	Soil	Human health and society
Aquifer characteristics	•			•			
Compaction		•	•	•	•	•	•
Control of gas		•		•	•	•	•
Control of liquid leachate		•	•	•		•	•
Covering material		•	•	•	•	•	•
Distance from infrastructure	•						•
Distance from population points	•						•
Distance from surface water mass	•		•				
Erosion	•					•	
Fault	•			•			
Final covering		•	•	•	•	•	•
Landfill age		•	•	•	•	•	•
Morphology	•		•				
Number of inhabitants		•	•	•	•	•	•
Pluviometry	•		•	•	•	•	•
Release-point localization in flood-water storage volume	•		•	•		•	
Safety		•					•
Seismic risk	•		•	•	•	•	•
Settling of waste		•	•	•	•	•	•
Slopes of waste		•	•	•	•	•	•
State of roads in the landfill		•			•		
Surface drainage systems		•	•	•			
Visibility	•						•
Waste and organic matter types		•	•	•	•	•	•
Waterproofing of release vessel		•	•	•		•	
Wind	•					•	•

Table 4
EVIAVE impact indicators for environmental components.

Environmental components[a]	Impact indicators
Surface water	A_1: Type of surface water mass A_2: Water use A_3: Water quality
Ground water	B_1: Water use B_2: Water quality
Atmosphere	C_1: Air quality
Soil	D_1: Soil use D_2: Vegetation type D_3: Vegetal covering

[a] Environmental value in the case of "Human health and society" always has maximum value 5, so environmental components have not been defined in the methodology.

In addition, EVIAVE originally defined the environmental descriptor *Type of water mass* (A_2) in consonance with Spanish and European legislation. Water bodies were classified as follows: (i) artificial water courses, such as navigation channels, irrigation canals, and ponds; (ii) 3rd level rivers and seasonal water courses, such as rivers and streams; (iii) seasonal water bodies, such as lagoons and reservoirs; (iv) 1st and 2nd level rivers and saltwater bodies; (v) permanent water bodies, such as marshlands, intertidal areas, saltmarshes, estuaries, tidal inlets, and other vulnerable areas. In Venezuela, the Water Law [37] deals with protected water bodies and their surrounding territory (ABRAES). This includes water masses with special characteristics or with pollution and degradation problems. Examples of such areas are the following: (i) protected river basins and water bodies; (ii) national hydraulic resources; (iii) areas surrounding reservoirs; (iv) swamps and protected wetlands. Group (iv) was adapted to Venezuelan legislation (see Table 6).

Other landfill variables and environmental descriptors were similarly adapted. Tables 7 and 8 summarize the variables and environmental descriptors that had to be modified including justification and legislation considered [11,36–39]. This new classification by Paolini [40] is available at http://www.eiadifusa.ugr.es.

5. Application of the EVIAVE methodology: results and discussion

A prerequisite for the applying EVIAVE is necessarily the identification of the environmental, socio-political, and operational characteristics of landfills. To facilitate this process, two kinds of data tables were used. The first table contained data related to the environmental characteristics of the landfill sites. These characteristics included topography, distance from surface water bodies, distance from population centers, and hydrogeological features of

Table 5
Classification of variable *Seismic Risk*.

Classification (C_j)	Condition			References
	Seismic area		Seismic acceleration coefficient (A_0)	
Very low	1	0	–	[35,36]
Low	2	1	0.10	
		2	0.15	
Average	3	3	0.20	
		4	0.25	
High	4	5	0.30	
		6	0.35	
Very high	5	7	0.40	

Table 6
Quantification of the impact indicator *Type of surface water mass* (A_2) for the environmental component surface water.

Classification (A_2)	Conditions	References
1	Artificial water courses: channels, irrigation channels and ponds	
2	3rd level rivers and seasonal water courses: rivers and streams	
3	Seasonal mass of water: lagoons and reservoirs	[37]
4	1st and 2nd level rivers and seawater	
5	Permanent water mass: marsh and intertidal areas, albuferas, salines, estuarios and tides branches; protected river basin and protected water mass; hydraulic national resources; areas preserved to reservoirs; waterlogged areas and protected wetland	

Table 7
Modification of variables of landfill.

Variable	Modification	Justification
Distance from population centers	All criteria used to classified this variable were changed	Resolution 230 of Venezuela about project and operation of sanitary landfill [11]
Waterproofing of release-point	Criteria classified as *regular* was changed	
Daily covering	Criteria classified as *satisfactory* was changed	
Daily covering	Criteria classified as *satisfactory* was changed	
Daily covering	Criteria classified as *satisfactory* was changed	
Security	Criteria classified as *very high* was changed	
Final covering		
	Criteria classified as *very appropriate* was changed	
Seismic risk	All criteria used to classified this variable were changed	Venezuelan Norm on Seismic zoning (COVENIN) [36]
Landfill size	All criteria used to classified this variable were changed	Waste rate generation and average size of landfills in Venezuela
Wind	All criteria used to classified this variable were changed	Direction and frequency of winds in Venezuela
Vulnerability of ground water	Methods for aquifer vulnerability assessment used: GOD	In Venezuela hydrogeological information covering is uncertain and little, so the method which is easier to apply to quantify vulnerability of ground water is GOD, which is used in this country
Release-point localization in surface runoff	We considered the conditions of the variable according to the historical memory of the inhabitants of the area	In Venezuela, there are only studies of flood risks very timely so it was necessary to describe the classification of the variable considering only historical memory of the inhabitants of the areas.

Table 8
Modification of environmental descriptors.

Environmental descriptor		Modification	Justification
Surface water	Water use (A_1)	It was necessary to adapt denominations of uses, according to the types of water identified in the Venezuelan legislation	Law of Water [37] and Decree 883 on classification and control of water body and waste water emissions [38]
	Type of surface water mass (A_2)	Only criterion that considers areas declared sensitive and vulnerable was changed	Law of Water [37]
	Water quality (A_3)	All criteria used to classified this descriptor were changed	In Venezuela there is not enough information about the characteristics of water bodies, nor has a classification according to the type and quantity of microorganisms present or as biotic indices. In consequence criteria to classify this environmental descriptive are only based on organoleptic characteristics of the water
Ground water	Water use (B_1)	All criteria used to classified this descriptor were changed	Decree 883 on classification and control of water body and waste water emissions [38]
	Water quality (B_2)	Criteria classified *water in very good condition* and *water in good condition* were modified	
Atmosphere	Air quality (C_1)	Only criterion classified *very bad* was modified	Decree 638 on air quality and air pollution control [39]
Soil	Vegetation type (D_2)	All criteria used to classified this descriptor were changed	Venezuela is located in a neotropical area, so wide variety of landscapes, including vegetation types, determine a rich biological diversity

the area. The second table contained data related to landfill operation. Relevant characteristics were the existence of a cover system, leachate and biogas control, and waste settlement. After data collection, we applied the modified version of EVIAVE. Table 9 shows the indexes obtained for the 22 landfills studied.

The results were statistically analyzed with the software application SPSS®.[4] Each data set was analyzed with the following statistical descriptors: number of cases, mean, standard deviation, standard error of the mean, and minimum and maximum values.

The analysis of variance (ANOVA) (level of significance, 0.05) was used to analyze descriptive statistical data with the purpose of generating a variance analysis of one factor for various dependent variables (i.e. the environmental indexes generated by the methodology) in reference to one independent variable. This is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components, due to different explanatory variables. In its simplest form ANOVA gives a statistical test of whether the means of several groups are all equal, and therefore generalizes Student's two-sample *t*-test to more than two

[4] Copyright SPSS. Inc., 1089-2005, Version 14.0.1 for Windows, license purchased by the University of Granada.

Table 9
Environment Landfill Indices.

Landfill	Environmental element	Pbc	Pbc_o	Pbc_u	eV	ERI	ELI		Order of priority
							Value	Classification	
Onía	Surface water	0.85	0.88	0.80	4.67	3.97	18.00	High	1
	Ground water	0.79	0.88	0.59	5.00	3.95			
	Atmosphere	0.80	0.84	0.65	4.00	3.20			
	Soil	0.82	0.88	0.69	4.00	3.28			
	Health and society	0.72	0.87	0.45	5.00	3.60			
Chaparralito	Surface water	0.82	0.85	0.75	3.33	2.73	15.99	High	2
	Ground water	0.82	0.85	0.75	4.50	3.69			
	Atmosphere	0.81	0.84	0.70	4.00	3.24			
	Soil	0.82	0.85	0.75	3.33	2.73			
	Health and society	0.72	0.84	0.50	5.00	3.60			
La Pica	Surface water	0.75	0.89	0.48	3.33	2.50	15.61	High	3
	Ground water	0.71	0.89	0.28	5.00	3.55			
	Atmosphere	0.79	0.86	0.55	4.00	3.16			
	Soil	0.75	0.89	0.41	3.33	2.50			
	Health and society	0.78	0.88	0.58	5.00	3.90			
Los Palmares	Surface water	0.82	0.88	0.70	2.33	1.91	15.60	High	4
	Ground water	0.72	0.88	0.34	4.00	2.88			
	Atmosphere	0.80	0.84	0.65	4.00	3.20			
	Soil	0.80	0.88	0.63	4.33	3.46			
	Health and society	0.83	0.87	0.75	5.00	4.15			
Sucre	Surface water	0.78	0.85	0.63	3.33	2.60	15.29	High	5
	Ground water	0.74	0.85	0.47	5.00	3.70			
	Atmosphere	0.74	0.81	0.50	4.00	2.96			
	Soil	0.76	0.85	0.53	3.00	2.28			
	Health and society	0.75	0.84	0.58	5.00	3.75			
Quebrada del Toro	Surface water	0.78	0.85	0.63	3.33	2.60	15.16	High	6
	Ground water	0.74	0.85	0.47	5.00	3.70			
	Atmosphere	0.74	0.81	0.50	4.00	2.96			
	Soil	0.75	0.84	0.53	3.00	2.25			
	Health and society	0.73	0.84	0.53	5.00	3.65			
Jaime	Surface water	0.72	0.85	0.45	4.00	2.88	14.89	Medium	7
	Ground water	0.74	0.85	0.47	4.50	3.33			
	Atmosphere	0.77	0.81	0.65	4.00	3.08			
	Soil	0.73	0.85	0.44	2.33	1.70			
	Health and society	0.78	0.84	0.65	5.00	3.90			
Jiménez	Surface water	0.65	0.70	0.55	4.67	3.04	13.91	Medium	8
	Ground water	0.65	0.73	0.47	4.50	2.93			
	Atmosphere	0.65	0.66	0.65	4.00	2.60			
	Soil	0.63	0.66	0.56	3.00	1.89			
	Health and society	0.69	0.68	0.70	5.00	3.45			
Andrés Bello	Surface water	0.73	0.84	0.53	2.33	1.70	13.45	Medium	9
	Ground water	0.68	0.85	0.25	5.00	3.40			
	Atmosphere	0.73	0.80	0.50	4.00	2.92			
	Soil	0.71	0.84	0.41	3.00	2.13			
	Health and society	0.66	0.80	0.38	5.00	3.30			
San Felipe	Surface water	0.79	0.89	0.60	4.33	3.42	13.29	Medium	10
	Ground water	0.75	0.89	0.41	1.00	0.75			
	Atmosphere	0.79	0.86	0.55	4.00	3.16			
	Soil	0.77	0.88	0.50	3.33	2.56			
	Health and society	0.68	0.88	0.30	5.00	3.40			
Chirico	Surface water	0.75	0.90	0.45	2.33	1.75	12.84	Medium	11
	Ground water	0.71	0.90	0.25	5.00	3.55			
	Atmosphere	0.71	0.88	0.20	4.00	2.84			
	Soil	0.75	0.90	0.38	1.67	1.25			
	Health and society	0.69	0.89	0.30	5.00	3.45			
Lomas de Bonilla	Surface water	0.73	0.84	0.50	4.67	3.41	12.14	Medium	12
	Ground water	0.68	0.84	0.28	1.00	0.68			
	Atmosphere	0.71	0.80	0.45	4.00	2.84			
	Soil	0.72	0.84	0.44	3.00	2.16			
	Health and society	0.61	0.83	0.20	5.00	3.05			
Bocono	Surface water	0.68	0.76	0.50	3.33	2.26	12.10	Medium	13
	Ground water	0.64	0.76	0.34	1.00	0.64			
	Atmosphere	0.67	0.70	0.55	4.00	2.68			
	Soil	0.64	0.73	0.44	4.33	2.77			
	Health and society	0.75	0.75	0.75	5.00	3.75			
Barinas	Surface water	0.63	0.68	0.53	1.67	1.05	11.98	Medium	14
	Ground water	0.66	0.70	0.56	4.50	2.97			

Table 9 (*Continued*)

Landfill	Environmental element	Pbc	Pbc_o	Pbc_u	eV	ERI	ELI		Order of priority
							Value	Classification	
	Atmosphere	0.74	0.78	0.60	4.00	2.96			
	Soil	0.65	0.73	0.47	3.00	1.95			
	Health and society	0.61	0.74	0.38	5.00	3.05			
Los Jebes	Surface water	0.73	0.80	0.60	1.33	0.97	11.94	Medium	15
	Ground water	0.65	0.80	0.28	4.00	2.60			
	Atmosphere	0.70	0.75	0.55	5.00	3.50			
	Soil	0.71	0.78	0.56	2.00	1.42			
	Health and society	0.69	0.79	0.50	5.00	3.45			
Guanarito	Surface water	0.69	0.73	0.63	2.33	1.61	11.80	Medium	16
	Ground water	0.64	0.73	0.44	5.00	3.20			
	Atmosphere	0.55	0.66	0.20	5.00	2.75			
	Soil	0.67	0.73	0.53	2.00	1.34			
	Health and society	0.58	0.71	0.33	5.00	2.90			
Curva del Viento	Surface water	0.72	0.80	0.55	2.33	1.68	11.51	Medium	17
	Ground water	0.65	0.80	0.28	1.00	0.65			
	Atmosphere	0.70	0.75	0.55	5.00	3.50			
	Soil	0.71	0.80	0.50	3.00	2.13			
	Health and society	0.71	0.79	0.55	5.00	3.55			
El Balcón	Surface water	0.68	0.80	0.45	4.00	2.72	11.46	Medium	18
	Ground water	0.65	0.80	0.28	1.00	0.65			
	Atmosphere	0.68	0.75	0.45	4.00	2.72			
	Soil	0.64	0.75	0.38	3.00	1.92			
	Health and society	0.69	0.79	0.50	5.00	3.45			
La Jabonera	Surface water	0.72	0.74	0.68	3.33	2.40	10.99	Medium	19
	Ground water	0.64	0.75	0.38	1.00	0.64			
	Atmosphere	0.65	0.67	0.60	4.00	2.60			
	Soil	0.63	0.69	0.47	3.33	2.10			
	Health and society	0.65	0.71	0.53	5.00	3.25			
La Paraguita	Surface water	0.73	0.76	0.65	3.00	2.19	10.99	Medium	20
	Ground water	0.67	0.78	0.41	1.00	0.67			
	Atmosphere	0.81	0.80	0.85	3.00	2.43			
	Soil	0.71	0.78	0.56	2.67	1.90			
	Health and society	0.76	0.79	0.70	5.00	3.80			
Tapa La Lucha	Surface water	0.71	0.81	0.50	2.00	1.42	10.12	Medium	21
	Ground water	0.66	0.81	0.28	1.00	0.66			
	Atmosphere	0.74	0.80	0.55	4.00	2.96			
	Soil	0.68	0.83	0.31	2.33	1.58			
	Health and society	0.70	0.83	0.45	5.00	3.50			
Pavía	Surface water	0.61	0.69	0.45	1.67	1.02	8.36	Low	22
	Ground water	0.55	0.69	0.22	1.00	0.55			
	Atmosphere	0.62	0.61	0.65	4.00	2.48			
	Soil	0.54	0.64	0.31	2.33	1.26			
	Health and society	0.61	0.67	0.50	5.00	3.05			

groups. In practice, there are several types of ANOVA depending on the number of treatments and the way they are applied to the subjects in the experiment.

In this case, one-way ANOVA was used. It tested for differences in indexes calculated with the methodology, which considered the following independent variables or groups: (i) environmental elements (surface water, ground water, atmosphere, soil, and human health and society); (ii) state where the landfills were located (Lara, Trujillo, Mérida, Yaracuy, Barinas, Carabobo and Cojedes); (iii) landfill classification, depending on its operation type (open-air, partially controlled, or controlled landfill). In the application of the model, we assumed the independence of cases, as well as the normality and equality (or homogeneity) of variances.

5.1. Environmental quantification of the overall condition of landfills

The Environment Landfill Index (ELI) quantifies the overall state of the landfill environment. This helps to prioritize the actions that should be taken, and to facilitate strategic planning and decision-making. Logically, the landfills that should first receive attention are those that are in the worst shape. Landfills with a high ELI are most in need of urgent sanitary measures.

The last three columns of Table 9 show the ELI value of each landfill analyzed in this research study, the classification of the index, and finally the action priorities. At the time of our study, the Pavia Landfill had an ELI of 8.36, which signified that this landfill had the lowest environmental impact. In contrast, the Onia Landfill had a high environmental impact, which was in consonance with its ELI (18.00).

The results obtained with EVIAVE confirmed the results of previous studies. For example, other studies had described Pavia as a controlled landfill [10,27]. It was positively classified because specific areas of this landfill were designated for different types of waste, gas emissions were somewhat controlled, and there were infrastructures for the collection of surface water and the daily covering of waste. However, since this installation did not show optimal levels of exploitation and control, it could not be classified as a sanitary landfill since it had no infrastructures for leachate collection.

At the other end of the list, the Onia Landfill, defined in previous studies as an open-air landfill, had absolutely no monitoring and

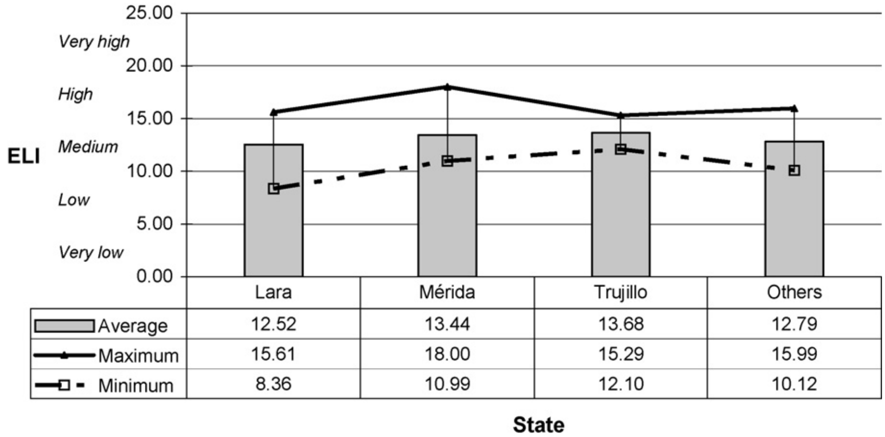


Fig. 3. Mean, minimum and maximum ELI values, related to landfill location.

control. Previous studies of this landfill had highlighted the presence of people and animals scavenging among the waste, and the frequent occurrence of uncontrolled fires [9,10].

Fig. 3 shows the mean, minimum and maximum ELI, depending on the state in Venezuela where the landfills are located. In order to discover if there were statistically significant differences, we first compared the null hypothesis of equal means with the alternative hypothesis that at least one of the means differed from the others. If this indicated that we should reject the null hypothesis, we then tried to discover which pair of means differed from each other. This was performed by a multiple comparison of the equality of all possible mean pairs. There are various methods that can be used for this type of simultaneous comparison. In our case, we applied the Fischer Method (F), also known as the Least Square Deviation (LSD).

The single factor ANOVA of the ELI resulted in a p-value associated with test F that was higher than the level of significance considered in the study (0.05). Consequently, we were able to conclude that there were no statistically significant differences in the ELI for each state (p-value = 0.921 > 0.05). This indicates that waste management problems are similar in all the states, and confirm that waste management practices are a serious problem in South American countries [1–5]. This is particularly true in Venezuela, where municipal waste treatment is based on disposal in uncontrolled or semi-uncontrolled conditions [7–9,27].

The ELI values of the landfills were also analyzed in relation to their exploitation level. In other words, they were classified as controlled landfills, partially controlled landfills and open-air landfills. Fig. 4 shows the mean, minimum, and maximum ELI in terms of this classification. A single factor ANOVA also showed statistically significant differences in the ELI for this classification (p-value = 0.049 > 0.05). This confirmed that if the exploitation and design of the landfills improved, the ELI would decrease. In our study, we carried out a multiple comparison of the ELI, and established two homogeneous subgroups. The first subgroup was made up of those landfills classified as controlled landfills, where some monitoring and regulation were observed. The second subgroup had higher ELI values, and was composed of partially controlled and open-air landfills with a somewhat chaotic operation [10].

5.2. The effect of landfills on the surrounding environment

The effect of landfills on different environmental elements varies, depending on the location of the landfill, as well as its type of operation [41–43]. The Environmental Risk Index (ERI) quantifies the degree to which a landfill affects each environmental element.

The seventh column of Table 9 shows the ERI value of each landfill at the time of study. Fig. 5 shows the mean, minimum, and maximum ERI for each environmental element. The highest average ERI value was for human health and environmental society, which was classified as high risk. These results confirmed the health problem generated by the landfills studied, and highlighted the totally inadequate operational structure, particularly regarding the sanitary conditions, of the vast majority of waste disposal sites in South America and the Caribbean [1,3]. This signifies that the health of people living in areas adjacent to the site is at a very high risk of being affected by emissions from the landfill. The population most exposed to direct risks generally belong to the lower classes, and

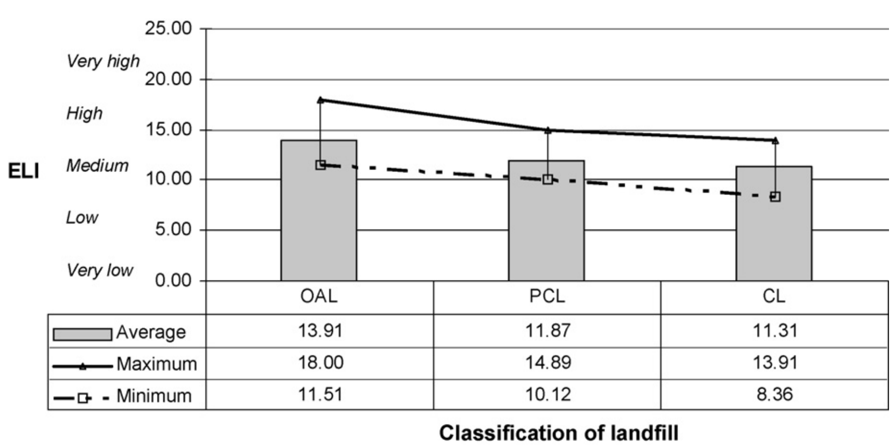
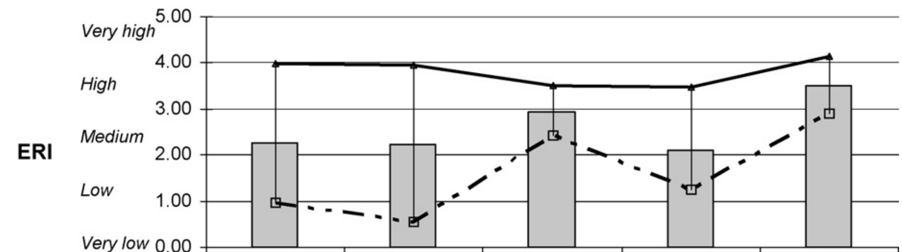


Fig. 4. Mean, minimum and maximum ELI values, related to landfill classification.



	Surface water	Ground water	Atmosphere	Soil	Health and society
Average	2.27	2.24	2.94	2.12	3.50
Maximum	3.97	3.95	3.50	3.46	4.15
Minimum	0.97	0.55	2.43	1.25	2.90

Environmental Element

Fig. 5. Mean, minimum and maximum ERI values, related to environmental elements.

have very little socioeconomic earning power. They are frequently in direct contact with the waste, and thus become agents of contagion, who spread disease to their family members and neighbors [44–46].

The maximum ERI value ($ERI_{human\ health\ and\ society}$ = 4.15), indicative of an extremely high-risk environment, corresponded to Los Palmares, which was an open-air landfill. This value was so high for a variety of reasons. First, the landfill had no trained staff responsible for its operation, and there were both people and animals scavenging among the garbage. Second, the landfill was located near power lines and treatment plants. There were also cities and housing developments nearby, which generated a high degree of social rejection as well as a significant human health risk.

Similarly, the Onia landfill also showed maximum ERI values for both surface water and ground water ($ERI_{surface\ water}$ = 3.97 and $ERI_{ground\ water}$ = 3.95). The waste disposal at this landfill was virtually uncontrolled, and it had no plans for controlled expansion or the implementation of a coating system. No provision had been made for the control of leachate and gas emissions. Furthermore, there was a total absence of drainage, which increased the risk of contamination of both surface and ground water. The MARMR [10] had previously classified Onia as an open-air landfill. It was located in an area where the rainfall, surface and underground water resources were abundant and of good quality [7,8,27,34]. Studies have confirmed that high rainfall increases leachate production, and consequently, the surface water and ground water are at higher risk of contamination [41]. The ERI value obtained in our research confirmed the results of previous studies.

Likewise the minimum ERI value, regarded as very low, corresponded to the ground water at the controlled landfill in Pavia ($ERI_{ground\ water}$ = 0.55). The Pavia landfill was located in an area where aquifers were local and discontinuous. Because of the very low yield of these aquifers, there was little risk of the ground water being affected by the landfill. In this case, the ERI values for the other environmental elements were found to be low for surface water and soil; medium for atmosphere; and high for human health and society.

In this case the result of the single factor ANOVA carried out for the ERIs showed the existence of statistically significant differences for environmental elements because the *p*-value was lower than the level of significance (p-value = 0.000 < 0.05). In this sense, we performed a multiple comparison of the ERI, which established two homogeneous subgroups: the first subgroup was composed of the environmental elements with the least risk of being affected by the landfill (i.e. surface water, ground water, and soil); the second subgroup was composed of the environmental elements most at risk of being affected by the landfill (i.e. atmosphere, and health and society).

5.3. Landfill site suitability

Waste deposited at a landfill is usually subject to a series of complex biochemical and physical processes, which generate environmental impacts. The significance of such impacts largely depends on the spatial distribution of the effects of the proposed action, the distribution of affected receivers, and a number of other factors, including climate as well as local geology and hydrogeology. These impacts vary from country to country, from region to region, and from site to site [47].

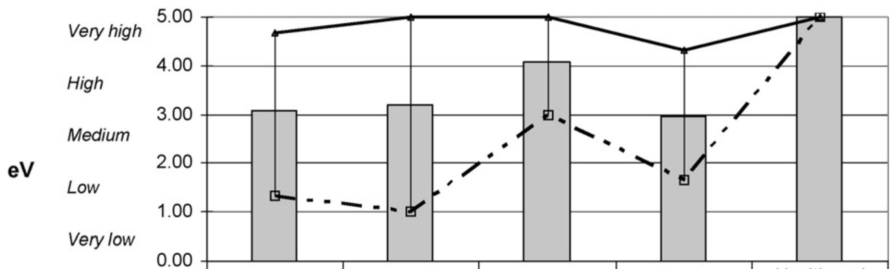
Although the prevention of negative environmental impacts can never be totally guaranteed at the landfill site, the selection of an appropriate site is crucial [14–16]. For example, by using artificial materials, such as landfill liners, it is possible to avoid biogas and leachate pollution of the ground and surface water near the landfills [47–49]. Nevertheless, such a measure is not foolproof. If the containment barrier fails, landfill gas and leachate may be released into the environment. This would evidently constitute a hazardous event [50]. Alternately, the existence of a natural clay barrier might provide sufficient containment to satisfy the requirements of a sustainable landfill. This would reduce the environmental risk by controlling the hazard migration pathway so that the receptor would not be affected [47,51,52].

In Venezuela, authorities rarely conduct studies to analyze the suitability of landfill sites. As a result, municipalities often choose sites for landfills, where the structure and relief are unsuitable, and where the environmental elements are susceptible to emissions from dumping sites [7,9].

EVIAVE methodology provides information about the suitability of landfill sites by analyzing the Probability of Contamination, based on the location (Pbc_u), and the Environmental Value (eV). When EVIAVE was applied to the selected landfills (Table 9), it showed that many of the sites had high eV values (see Fig. 6). This confirmed that the environment was affected by the landfill location.

For example, the Onia and Jimenez landfills had a very high eV index for surface water and ground water ($eV_{water\ surface}$ = 4.67 and $eV_{ground\ water}$ = 5.00). In both cases, the waste was deposited near the surface water. This surface water was regarded as an essential resource for the community since it was used as drinking water and for agricultural purposes. Nevertheless, it showed physical, chemical, and bacteriological parameters with higher values than the permissible limits specified in current legislation.

The Probability of Contamination Index also reflects the suitability of the landfill site because it considers variables that are related



	Surface water	Ground water	Atmosphere	Soil	Health and society
Average	3.07	3.18	4.09	2.97	5.00
Maximum	4.67	5.00	5.00	4.33	5.00
Minimum	1.33	1.00	3.00	1.67	5.00

Environmental Element

Fig. 6. Mean, minimum and maximum eV values, related to environmental elements.

to the characteristics of the area where landfills are located, and which significantly influence the degree to which the environmental elements are affected. Table 9 shows values for the Probability of Contamination stemming from the location of the landfill. Fig. 7 shows the mean, minimum, and maximum values for each environmental element.

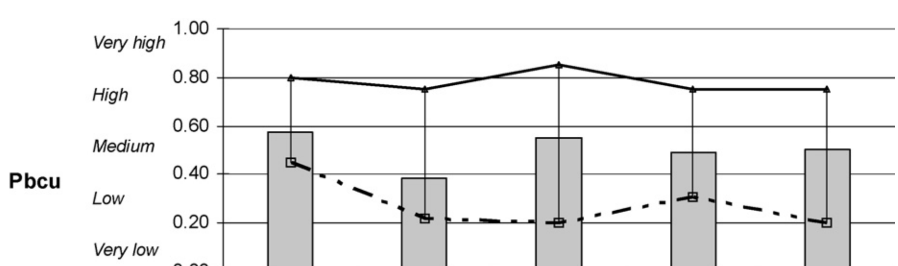
Some of the landfills were found to have a Pbc_u that was high or very high. The Onia landfill had a high value for this index ($Pbc_{u\ water\ surface} = 0.80$) because of its location near the surface water, where there was heavy rainfall, flooding, unfavorable morphology [53], and seismic risk [54]. In the Onia landfill there were also water courses running through the waste disposal site. This increased leachate generation and contaminated ground and surface water [55]. Some of the landfills studied were located in areas with unfavorable wind and abundant rainfall. This was the case of the Jaime landfill ($Pbc_{u\ atmosphere} = 0.65$). Other landfills were poorly located because they were close to essential infrastructure and to towns with high visibility. This was the case of Los Palmares ($Pbc_{u\ health\ and\ society} = 0.75$) and Bocono ($Pbc_{u\ health\ and\ society} = 0.75$). These findings were in consonance with the results of other studies, which indicated that landfill siting had been carried out without first assessing the variables, regulations, or technical criteria for identifying an appropriate location [8–10,27]. Because of the absence of proper planning and site selection, many landfill locations rapidly reached their capacity, and were found to be inadequate for long-term use. The result was the eventual depletion of the capacity of such sites and the reduction of their useful life.

In contrast, some of the landfills studied had a Probability of Contamination Index that was low or very low. This was the case of the landfill in Lomas de Bonilla, which was located far away from urban areas and critical infrastructure ($Pbc_{u\ health\ and\ society} = 0.20$) as well as from ground water ($Pbc_{ground\ water} = 0.28$). The Guanarito landfill was located in an area where weather conditions were such that they did not increase the risk of atmospheric contamination ($Pbc_{u\ atmosphere} = 0.20$) and far away from urban areas and critical infrastructures ($Pbc_{u\ health\ and\ society} = 0.33$).

The analysis of the eV and Pbc_u indexes classified landfill sites into three groups, based on their respective locations (Table 10): (i) suitable location (five landfills); (ii) unsuitable location (12 landfills); (iii) neither suitable nor unsuitable (five landfill sites in need of further study to decide whether they should be sealed).

5.4. Suitability of exploitation

A landfill requires design, engineering, and management. A high degree of control is required to prevent hazards associated with the waste disposal in the landfill [47,55]. Indeed, the significance of environmental impacts is also dependent on landfill operation and design. With a view to quantifying environmental impacts due to operation and design, EVIAVE calculated the Probability of Contamination Index related to exploitation (Pbc_o) for each landfill site. This index considered variables related to landfill operation as well as design characteristics, such as the control of gas emissions, the



	Surface water	Ground water	Atmosphere	Soil	Health and society
Average	0.57	0.39	0.55	0.49	0.51
Maximum	0.80	0.75	0.85	0.75	0.75
Minimum	0.45	0.22	0.20	0.31	0.20

Environmental Element

Fig. 7. Mean, minimum and maximum Pbc_u values, related to environmental elements.

Table 10
Suitability of locations of the landfills studied.

Landfill	Suitability of location		
	Suitable	It needs further study	Unsuitable
Pavía	X		
Los Jebes		X	
Los Palmares			X
Curva del viento		X	
Guanarito			X
Chirico			X
La Pica			X
Bocono			X
Lomas de Bonilla		X	
Jiménez		X	
Quebrada del Toro			X
Sucre			X
Andrés Bello			X
La Jabonera	X		
Onía			X
San Felipe			X
El Balcón		X	
Tapa La Lucha	X		
Jaime			X
Barinas	X		
La Paraguita	X		
Chaparralito			X

existence of a containment barrier, landfill cells, or the use of soil to cover waste.

Table 9 shows the values of this index for the 22 landfills analyzed. Fig. 8 shows the mean, minimum, and maximum values of the Pbc_o for environmental elements. The analysis of these results showed all environmental elements and landfill values that were classified as high or very high. The single factor ANOVA showed the absence of statistically significant differences between environmental elements, states, and classification of the landfills.

The results confirmed the fact that waste disposal in Venezuela is generally carried out without any type of operational plan [7–9,27]. There is no specification of the activities that should be carried out, the most appropriate operational method, the implementation time, or the resources required. Consequently, the results of our study underlined the existence of poor waste management as well as the lack of enforcement of basic regulations pertaining to waste disposal. The results of our study also highlighted the absence of the basic infrastructures necessary to minimize the negative effects of emissions generated by the landfills. Open-air landfills without any type of coherent waste management (e.g. Las Palmares, Onia, and Quebrada del Toro) had the highest Pbc_o.

As shown in Fig. 8, the minimum values of Probability of Contamination related to exploitation corresponded to the Pavia landfill (the Pbc_o value for all environmental elements was 0.6). The reason for this positive evaluation was that at the Pavia landfill, the waste deposited was covered and compacted on a daily basis. Gas emission control was carried out by means of ventilation shafts. Furthermore, the waste deposited on terraces and embankments did not show evidence of erosive processes. Nevertheless, the landfill was so old that there was some stabilization of the biochemical waste deposited in the landfill, which made the landfill soil richer when it was reinserted in the environment [56,57].

5.5. Action proposals

The application of EVIAVE methodology adapted to Venezuela quantified the extent to which the landfills affected the surrounding environment. The negative impacts were mainly due to deficient levels of exploitation and unsuitable location sites. In consequence, the Venezuelan administration responsible for environmental actions should define an effective planning tool, which facilitates the specification of action programs to improve the design and operation of landfills in order to minimize environmental risk.

The Environmental Landfill Index provided a comprehensive evaluation of the interaction between the landfills and their environment, and thus helps to establish a prioritization of actions. As a result, action programs should first be defined for landfills with a higher ELI.

In the case of landfills in the suitable location group, a Conditioning Plan should be designed in order to define better operation and design conditions that would reduce negative environmental impacts. In view of the unsuitability of the release-point location, a Closing Plan should also be defined to stop the disposal of waste at hazardous release-points and to design a sealing system to reduce the environmental impact as much as possible. To draw up the Closing and Conditioning Plan, the Contamination Risk Index for each variable and for each environmental element should be studied in order to determine the state of impact of each variable. This would help to plan direct actions for those variables in which it was possible to reduce the environmental impact. The application of EVIAVE indexes to define action plans is an extremely complex topic. Because of its scope, it will be analyzed and discussed in subsequent research work. Finally in the case of landfills that are neither suitable nor unsuitable, further study would be necessary in order to decide whether they should be sealed and or conditioned.

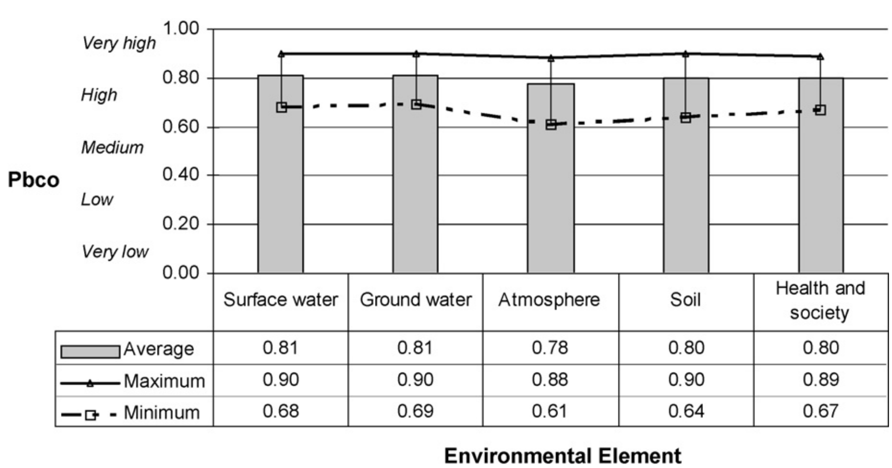


Fig. 8. Mean, minimum and maximum Pbc_o values, related to environmental elements.

6. Conclusions

EVIAVE methodology effectively defines and quantifies the negative environmental impacts of landfills, and evaluates waste management. In our research study, we used EVIAVE with a view to diagnosing and prioritizing remedial actions for landfills in Venezuela. However it was first necessary to adapt this method to the Venezuelan legal and social framework. The modifications made were not structural, but only affected the criteria for the classification of certain landfill variables and environmental descriptors.

The results obtained in our study were compared to the results of previous studies of landfill sites. The similarity in results demonstrated the validity of the modified version of EVIAVE. However, the indexes calculated with EVIAVE had the advantage of quantifying environmental impacts, and providing more information than had previously been available in studies carried out by the Venezuelan Ministry of the Environment and Renewable Resources and by regional governments in Venezuela.

The modified version of EVIAVE was applied to 22 landfills. The results obtained are also applicable to other landfills in Venezuela. The environmental indexes in our research quantified the extent to which the landfills affected the surrounding environment. Our results confirmed that most of the landfills had deficient levels of exploitation, and were located at unsuitable sites. This was found to be harmful to human health. The Environmental Landfill Index quantified the overall environmental problems caused by the landfills, and a list of strategic actions was drawn up and prioritized.

The results of our study showed that EVIAVE methodology is an effective planning tool, which facilitates the specification of action programs to improve the design and operation of landfills in Venezuela in order to minimize environmental risk.

Acknowledgements

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