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Modeling Environmental Susceptibility of Municipal Solid Waste Disposal Sites: A Case Study in São Paulo State, Brazil

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Abstract

The large excess of solid waste generated in cities is a result of population growth and economic development. Properly managing this municipal solid waste (MSW) is a challenge, mainly in underdeveloped and developing countries where financial concerns are an added problem. From the environmental point of view, a major issue is properly disposing MSW taking into consideration a wide range of factors, and working with different spatial data. In this study, we used geographic information system (GIS) to perform multi-criteria decision analysis (MCDA) conducted by analytical hierarchy process (AHP). The development of the environmental impact susceptibility model (EISM) for municipal solid waste disposal sites (MSWDS) applied to the state of São Paulo, Brazil considered factors such as geology, pedology, geomorphology, water resources, and climate represented by fifteen associated sub-factors. The results indicated that more than 82% of São Paulo's territory is situated in areas with very low, low, and medium environmental impact susceptibility categories. However, in the remaining 18% of the state land area, 85 landfills are located in areas with high and very high environmental impact susceptibility categories. These results are alarming because these 85 landfills receive approximately 17,886 tons of MSW on a daily basis, which corresponds to 46% of all municipal solid waste disposed in São Paulo state. Therefore, decision makers, urban planners and policymakers could use the findings of the EISM towards mitigating the environmental impacts caused by MSWDS.

Keywords

Modeling, Geographic Information System (GIS), Environmental Impact, Municipal Solid Waste, Landfills, Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP)

1. Introduction

The rapid world population growth and economic development are causing changes in terrestrial systems that can have serious and lasting consequences. The large amount of municipal solid waste (MSW) generated exceeds the capacity of the environment to decompose and recycle these wastes through natural processes [1]. The lack of proper waste management is a major environmental problem [2]. Sustainable management of MSW is required to achieve low environmental impact. One essential part in this process is to properly dispose waste, since disposal sites are permanent facilities that pose risks to the environment and population as they need to be monitored for extended periods of time [3].

Among many methods to dispose MSW in underdeveloped countries, the most common are open dumps and landfills. Open dumps are uncontrolled facilities where waste is directly disposed in the ground without any control causing several impacts. In contrast, sanitary landfills use techniques and methods to better control environmental impacts and are commonly used around the world, particularly in developed countries [4]. Although the number of sanitary landfills is increasing in the last decades in Brazil [5], the nation is through an inadequate MSW disposal scenario, with more than 60% of its cities still disposing MSW in open dumps [6] [7].

It is important take into consideration the environmental impact caused by municipal solid waste disposal (MSWD) in São Paulo, Brazil due to several factors. First, São Paulo is the most populous state in America and Western Hemisphere. Second, São Paulo is the biggest producer of MSW among all Brazilian states. Third, the per capita waste generation rate in São Paulo state is the biggest rate in Brazil with 1.4 kg/habitant/day with a growing trend over the years [8]. Finally, various São Paulo cities still dispose MSW improperly [9]. Therefore, all these factors together lead to the occurrence of negative environmental impacts.

Among diverse kinds of environmental impacts caused by humans, the MSWD is one of the most impactful, because solid wastes are retained in the same place where they are deposited even though they may undergo chemical and physical transformations over the years [10] [11] [12].

The improper MSWD locally cause environmental impacts, such as contamination of soil [13] [14] [15] [16], water sources [13] [17] [18] [19] and health public impacts [20] [21] and also globally cause environmental impacts, such as increase of greenhouse gases due to methane emissions [22] [23]. Consequently, the improper MSWD causes global and local impacts on the environment on different scales.

For this reason, assessing the environmental impact caused by MSWD sites must consider different parameters, to avoid potential negative effects. Developing a model for assessing environmental impact susceptibility must take into consideration multiple issues, values, scales and degrees of uncertainty, as well as assist stakeholder engagement. In this process, the models are usually built to satisfy one or more of five main purposes: 1) prediction, 2) forecasting, 3) management and decision-making under uncertainty, 4) social learning, and 5) developing system understanding and experimentation [24].

In this study to develop an environmental impact susceptibility model (EISM) for municipal solid waste disposal sites (MSWDS), we used a multi criteria decision analysis (MCDA) approach via an analytic hierarchic process (AHP) coupled with geographic information system (GIS). This paper is organized as follows: Section 2 discusses the literature review of GIS, MCDA and AHP applied to environmental studies. Section 3 describes the methods used to develop the EISM and describes the study area. Section 4 presents the model results for the state of São Paulo and the MSWDS assessment. Finally, the conclusions are presented in Section 5.

2. Background Literature Review

In this section, the literature review is divided into four parts: Section 2.1 includes the advantages of GIS in environmental studies, Section 2.2 demonstrates the importance of MCDA applied to municipal solid waste issues, and Section 2.3 explains the use of AHP.

2.1. Geographic Information System (GIS)

The use of geographic information system is one of the most promising approaches to investigate complex spatial phenomena, because GIS has the advantage of storing, retrieving and analyzing a considerable amount of disaggregated data from various sources and displaying the results spatially, which helps decision makers solve several problems [25] [26].

GIS has been used for several purposes [27], including environmental applications. Examples include estimating groundwater recharge [28], assessing water pollution [29], identifying forest fire susceptibility [30], mapping landslide susceptibility [31] and flood susceptibility [32], modeling erosion [33], and evaluating ecological vulnerability of sites [34].

GIS has also been used in numerous studies to improve municipal solid waste management (MSWM). Examples include predicting generation and composition patterns of MSW [35] [36], improving MSW collection and transport [25] [37] [38] [39] [40], selecting locations for MSW transfer stations [41] [42], assessing groundwater vulnerability [43] [44] and impact [45] near a MSWDS, and identifying areas for siting landfills [46]-[60].

2.2. Multi Criteria Decision Analysis (MCDA)

Multi criteria decision analysis is a method to structure a problem through the action concepts and intelligible criterion group to facilitate the communication in decision process, forming a conviction rather than determining an optimum [61]. Combining MCDA with spatial decision problems usually contains a large set of feasible alternatives and conflicts with an incommensurate evaluation criteria [62].

The MCDA applied to environmental studies had a significant growth over the last decade [63] [64]. The integration of spatial analysis using GIS to MCDA has been used in different environmental studies. Examples include, analyzing the possibility to convert pastures to croplands in Brazil [65], mapping the landslide susceptibility [31], and identifying geotechnical land suitability [66].

Spatial analyses associated with MCDA is considered one of the main application for GIS [67], and have also been used in several studies related to municipal solid waste issues [26] [41] [46] [49]-[54] [57] [60] [68]-[75]. Because MSWM involves multiple factors such as environmental, economic, political and social [37], combining MCDA with GIS increases the analysis effectiveness and accuracy [50] helping to understand the complexity of the problem, ensuring the robustness and reliability of the final decision.

2.3. Analytical Hierarchy Process (AHP)

In this study, we use the Analytical Hierarchy Process (AHP), which is a component of the Multi Criteria Decision Analysis method. The AHP was developed by Saaty in the 1970s [76] and consists of an assessment theory through pairwise comparison to help decision makers set priorities and choose the best decision [37] [59]. The AHP in combination with GIS has been widely used in the field of natural resources and environmental management [77], first because the combined approaches are easy to implement using map algebra operations and cartographic models, and second because the approaches are intuitively appealing to decision makers [62]. The comparisons are made using a scale of absolute judgments ranging from one to nine, where one represents equal importance and nine represents the highest importance from one element to another (**Table 1**). In addition, a reciprocal value is used to express the inverse comparison [78].

The process of AHP determination involves these subsequent steps: 1) compute sum of values in each column of pairwise matrix, 2) normalize the matrix by dividing each element by its column total and, 3) compute the mean of the elements in each row of the normalized matrix [60].

Afterwards to determinate the consistency of the AHP judgment, a consistency index (CI) (Equation (1)) is determined [76].

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{1}$$

In this equation, $\lambda_{\max}$ is the principal judgement matrix value [76] [78]. Subsequent the determination of CI, a consistency ratio (CR) needs to be calculated (Equation (2)) [76].

Table 1. The comparison scale in AHP.

Definition	Intensity of Importance
1	Equal importance
3	Weak importance
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent judgments

$$CR = \frac{CI}{RI} \tag{2}$$

In this equation, random index (*RI*) depends on the number of elements being compared [76] [78]. The *CR* is acceptable if its value is less than 10%. However, if this number is higher than 10%, the judgments may be inconsistent and should be re-evaluated [53].

3. Methods

To develop the environmental impact susceptibility model for municipal solid waste disposal sites, we considered six major steps: 1) selection of environmental decision factors and sub-factors; 2) data acquisition and integration into a GIS database; 3) definition of classes and assignment of ratings; 4) data standardization to a common scale of measurement; 5) calculation of relative weights using the AHP technique; and 6) derivation of the final model map using weighted linear combination (WLC) aggregation method (**Figure 1**). Each step is described as follows.

3.1. Selection of Environmental Decision Factors and Sub-Factors

In this study, the selection of environmental factors and sub-factors was based on the literature that takes into account the environmental impact susceptibility associated with disposal of municipal solid waste e.g. [3] [26] [43] [44] [49] [50] [53] [54] [57] [58] [59] [60] [74] [75] [80] [81] [82] [83]. We also took into consideration guidelines, relevant legislation and regulations, experts' opinions, and available data. Overall, a total of five factors including geology, pedology, geomorphology, water resources, and climate, with fifteen associated sub-factors were used in the model (**Figure 2**). This list is not exhaustive; we only considered what the literature included as the most important criteria to develop the environmental impact susceptibility model for municipal solid waste sites.

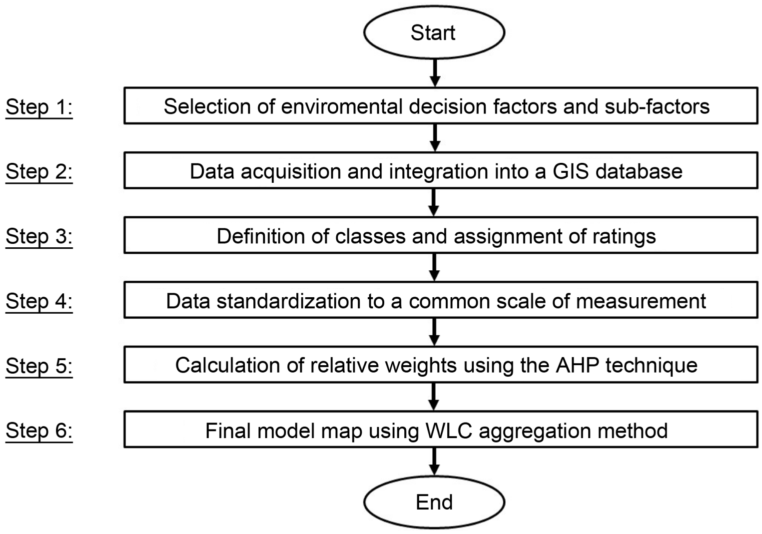


Figure 1. Flowchart of proposed methodology to develop the environmental impact susceptibility model.

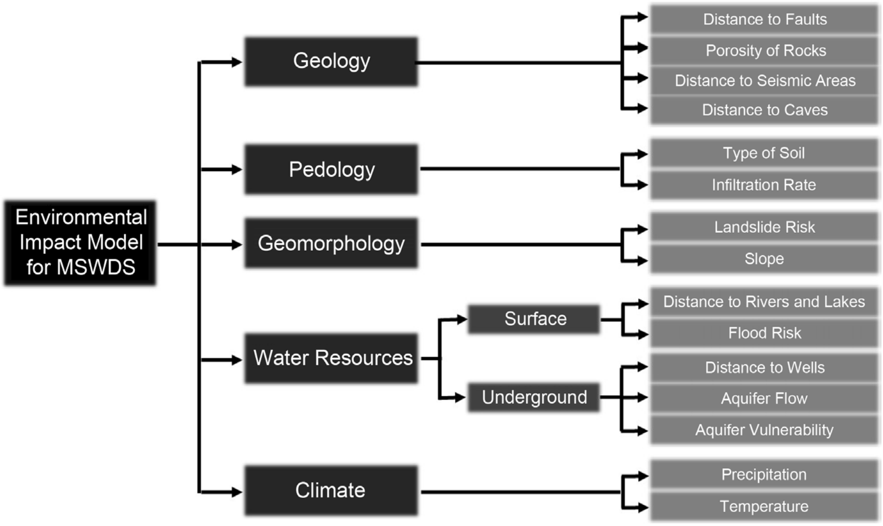


Figure 2. Factors and sub-factors used to develop the environmental impact susceptibility model for MSWDS.

3.1.1. Geology

Geological features influence the environmental susceptibility of municipal solid waste disposal sites because they can cause land instability in an earthquake region [66]. They can also, influence water infiltration if the rock formations are porous or have faults [84]. For this reason, when municipal solid waste is disposed above susceptible rocks, the process of waste landslide and water contamination may occur. Some geological aspects are considered in previous studies, including [43] [53] [54] [83] [85]. However, these studies did not consider simultaneously the four geological sub-factors used in this model, which are 1) distance to faults, 2) porosity of rocks, 3) distance to seismic areas, and 4) distance to caves.

3.1.2. Pedology

Soil parameters, such as depth and physical characteristics, could interfere in environmental susceptibility related to siting municipal solid waste facilities, mainly for two reasons. First, strength characteristics of the soil are important to support the overlying load from the waste mass. Second, the soil permeability can interfere in infiltration process, which in turn can cause contamination of water bodies. Multiple studies in MSWDS issues included pedologic aspects in their assessments, e.g., [3] [46] [82] [83]. In particular, we used the pedology sub-factors of 1) type of soil and 2) infiltration rate.

3.1.3. Geomorphology

Geomorphology is mainly related to terrain features and the influence of these characteristics on the topography and runoff process. For example, flat areas influence leachate infiltration, while steep areas influence terrain instability. Therefore, both can cause environmental impacts. Many studies took into consideration topographical aspects, e.g., [26] [59] [60] [83]. In particular, we used the geomorphological sub-factors of 1) landslide risk and 2) slope.

3.1.4. Water Resources

Another aspect that affects environmental susceptibility is associated with surface and underground water resources. It is not appropriate to have MSWDS close to surface water sources or in areas where the water table level is shallow due to the higher contamination risk. Several studies took into consideration these aspects, e.g., [26] [43] [49] [53] [54] [58] [60] [74] [82]. In this study, we used surface water resources sub-factors of 1) distance to rivers and lakes and 2) flood risk, while, for underground water resources, we used the sub-factors of 1) distance to wells, 2) aquifer flow, and 3) aquifer vulnerability to pollution.

3.1.5. Climate

Climate factors need to be used in modeling the environmental impact susceptibility for municipal solid waste disposal, mainly because they can interfere in the decomposition process of solid waste and in the volume of leachate generated, due to the water balance as well as the amount of landfill gas generated. Climate aspects also were considered in previous investigations, e.g., [44] [57] [59] [82]. In this study, we used the climatic sub-factors of 1) precipitation and 2) temperature.

3.2. Study Area

São Paulo state, in Southeastern Brazil, is located between 19˚ and 25˚ South latitude and 44˚ and 53˚ West longitude. It borders the Minas Gerais state to the north, Rio de Janeiro state to the northeast, the Atlantic Ocean to the east, Paraná state to the south, and Mato Grosso do Sul state to the west (**Figure 3**). São Paulo is the most populous Brazilian state, with approximately 44.4 million inhabitants in 2015 living in 645 municipalities with a total area around of 248.2 million·km^2 [79]. São Paulo is also the biggest producer of municipal solid waste in Brazil, generating about 39 thousand tons per day, which are disposed in 420 official municipal solid waste disposal sites [9].

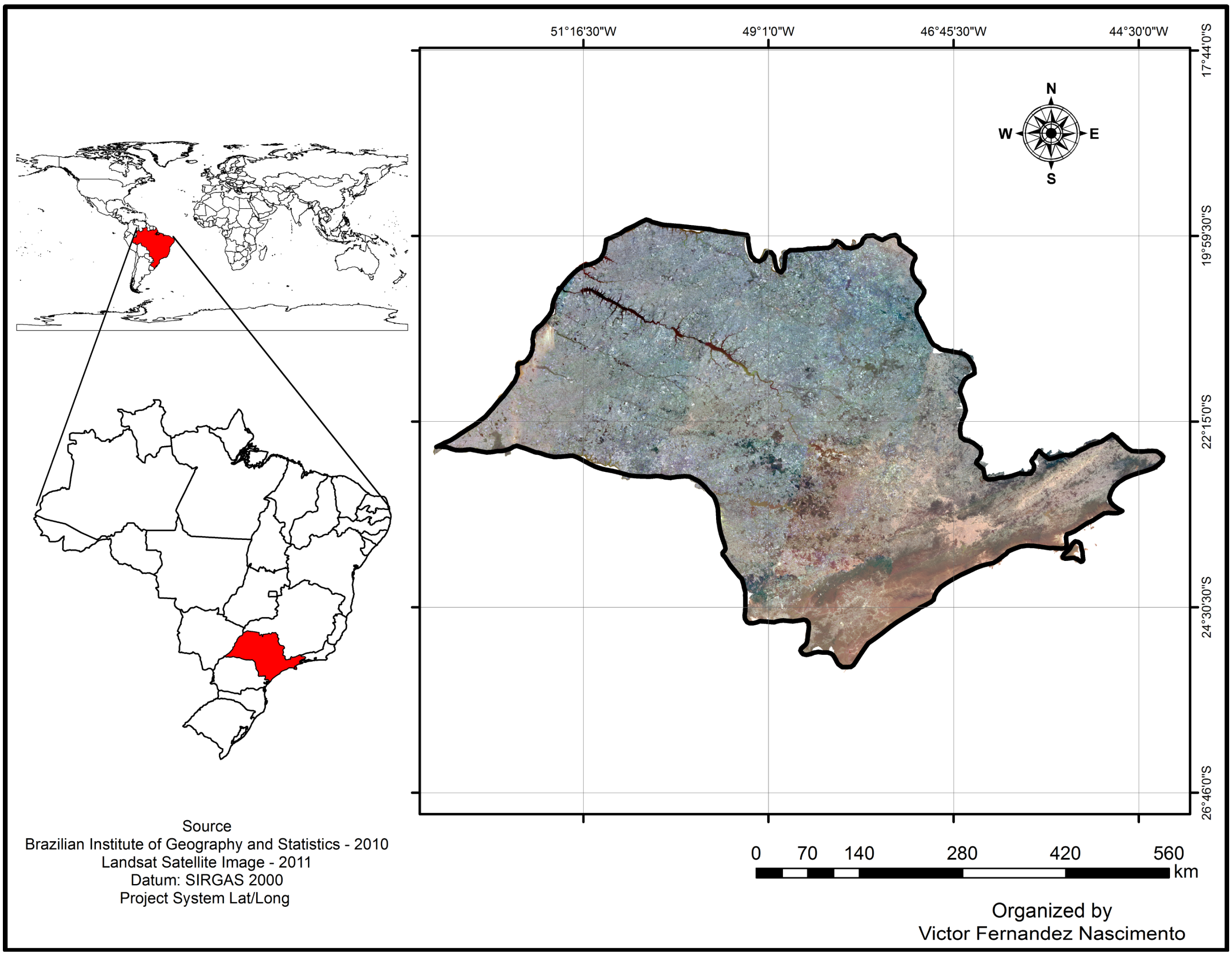
3.3. Data Acquisition and Integration into a GIS Database

The spatial database used in the environmental impact susceptibility model for municipal solid waste disposal sites applied to the São Paulo state was created using a variety of sources including geologic, pedologic, geomorphologic, hydrologic and, climatologic data of different scales (**Table 2**). The successful use of GIS depends on the accessibility of data, as well as its quality, representing the real world conditions through diverse layers [56].

In this study, all data layers were stored, manipulated, analyzed, and visualized using ArcGIS version 10.2 ModelBuilder as a starting point for a multi-criteria decision analysis. ModelBuilder is a GIS extension that encodes complex sequences of GIS operations into a simple graphic model from which the steps can be executed [86]. The data layers were georeferenced using the UTM System Datum SIRGAS 2000 (Zone 22 and 23 South).

3.4. Definition of Classes and Rating

Each of the fifteen sub-factors used in the environmental impact susceptibility



Source
Brazilian Institute of Geography and Statistics - 2010
Landsat Satellite Image - 2011
Datum: SIRGAS 2000
Project System Lat/Long

Figure 3. Map of the state of São Paulo, Brazil.

model for municipal solid waste disposal sites was divided into classes. Each class was rated on a scale from one to ten, where one represents the lowest level of susceptibility and ten represents the highest level of susceptibility for environmental impact.

The rating intervals from one to ten was selected based on similar scales used by [43] [55] [87] [88], as well as based on the experience and judgment of the authors. Furthermore, the importance for each class could vary based on the region of interest and characteristics of the specific area [56]. In this study the classes were assigned considering the relevant conditions in the state of São Paulo (**Table 3**).

3.5. Data Standardization to a Common Scale of Measurement

In order to overlay the spatial information to calculate the environmental impact susceptibility, it is necessary to standardize the data into a common measurement scale. Therefore, the fifteen sub-factors were converted into raster grid format consisting of 50 m × 50 m cells resulting in an image of 18,790 columns and 12,744 rows.

Table 2. Spatial data used in the environmental susceptibility impact model for MSWDS in São Paulo state.

Factors	Sub-factors	Sources	Information used to create layers	Format	Scale or Resolution	Date
Geology	Distance to Faults	Geology Report: [92]	Structures	Digital	1:700,000	2009
	Porosity of Rocks	Geology Report: [92]	Primary porosity	Digital	1:700,000	2009
	Distance to Seismic Areas	Geology Report: [92]	Geological/ Geotechnical Risks and Earthquakes	Digital	1:700,000	2009
	Distance to Caves	Permanent Cave Protection Areas in the São Paulo State: [93]	Caves	Digital	1:50,000	2015
Pedology	Type of Soil	Pedology Report: [94]	Type of Soil	Digital	1:500,000	1999
	Infiltration Rate	Pedology Report: [94]	Factor K	Digital	1:500,000	1999
Geomorphology	Landslide Risk	Landslide Hazard Index [95]	Landslide Hazard Classes	Digital	1:75,000	2014
	Slope	Digital Elevation Model-DEM [96]	Calculated using DEM	Digital	1:50,000	2013
Water Resources-Surface	Distance to Rivers and Lakes	Hydrology Report: [92]	Hydrography Unifilar and Bifilar	Digital	1:700,000	2009
	Flood Risk	Flood Hazard Index [95]	Flood Hazard Classes	Digital	1:75,000	2014
Water Resources-Underground	Distance to Wells	Hydrology Report: [92]	Representative Wells	Digital	1:700,000	2009
	Aquifer Flow	Hydrology Report: [92]	Aquifer Flow Classes	Digital	1:700,000	2009
	Aquifer Vulnerability	Natural vulnerability of aquifer to pollution [97]	Aquifer Vulnerability Classes	Digital	1:1,000,000	2013
Climate	Precipitation	Zoning bioenergy crops in São Paulo state report: [98]	Isohyet Lines	Digital	1:500,000	2008
	Temperature	Zoning bioenergy crops in São Paulo state report: [98]	Isotherm	Digital	1:500,000	2008

3.6. Weight Assignment Using AHP

The construction of a comparison matrix and the derivation of weights in our study uses the analytical hierarchic process web-based tool developed by [89]. First, the AHP methodology was applied to the factors (Table 4) and sub-factors (Table 5). Then, by multiplying these two results, the global weighting for each sub-factors was obtained (Table 6).

3.7. Weight Linear Combination (WLC) Method

After checking the reliability of the pairwise comparisons for factors and sub-factors, the environmental impact susceptibility model for municipal solid waste disposal sites in the São Paulo state was built using a weighted linear combination method, following (Equation (3)).

$$S = \sum_{i=1}^{n} w_i x_i \tag{3}$$

In this equation, S is the EISM final score, W_i is the sub-factor weight, and X_i is the standardized class rating of factor i. As the sum of weight for factor i is a multiplication of W_i and X_i for each sub-factor, the W_i is constrained to one, while X_i varies from zero to ten, and the final combined estimate is presented on this scale.

Therefore, the EISM final score was obtained for each raster cell as a sum of

Table 3. Rating classes.

Factors	Sub-factors	Class	Rating
Geology	Distance to Faults	<500 m	10
		500 - 1000 m	9
		1000 - 1500 m	8
		1500 - 2000 m	7
		2000 - 2500 m	6
		2500 - 3000 m	5
		3000 - 3500 m	4
		3500 - 4000 m	3
		4000 - 4500 m	2
		>4500 m	1
	Porosity of Rocks	High (>30%)	10
		Uncertain (0% > 30%)	9
		Moderate (15% - 30%)	8
		Low (0% - 15%)	3
	Distance to Seismic Areas	<10,000 m	10
		10,000 - 20,000 m	9
		20,000 - 30,000 m	8
		30,000 - 40,000 m	7
		40,000 - 50,000 m	6
		50,000 - 60,000 m	5
		60,000 - 70,000 m	4
		70,000 - 80,000 m	3
		80,000 - 90,000 m	2
		>90,000 m	1
	Distance to Caves	<500 m	10
		500 - 1000 m	9
		1000 - 1500 m	8
		1500 - 2000 m	7
		2000 - 2500 m	6
		2500 - 3000 m	5
		3000 - 3500 m	4
		3500 - 4000 m	3
		4000 - 4500 m	2
		>4500 m	1
Pedology	Type of Soil	Histosols	10
		Gleysols	9
		Spodosols	8
		Chernosols	7
		Neosols	6
		Nitosols	5
		Cambisols	4
		Planosols	3
		Latosols	2
		Argisols	1
	Infiltration Rate (Factor K)	0.0549 - 0.0610	10
		0.0488 - 0.0549	9
		0.0427 - 0.0488	8
		0.0366 - 0.0427	7
		0.0305 - 0.0366	6
		0.0244 - 0.0305	5
		0.0183 - 0.0244	4
		0.0122 - 0.0183	3
		0.0061 - 0.0122	2
		<0.0061	1

Continued

Geomorphology	Landslide Risk	P5	10
		P4	8
		P3	6
		P2	4
		P1	2
		P0	1
	Slope	>45%	10
		45% - 30%	9
		30% - 25%	8
		25% - 20%	7
		20% - 15%	6
		15% - 10%	5
		10% - 8%	4
		8% - 6%	3
		6% - 4%	2
		4% - 2%	1
		<2%	10
Water Resources-Surface	Distance to Rivers and Lakes	<500 m	10
		500 - 1000 m	9
		1000 - 1500 m	8
		1500 - 2000 m	7
		2000 - 2500 m	6
		2500 - 3000 m	5
		3000 - 3500 m	4
		3500 - 4000 m	3
		4000 - 4500 m	2
		>4500 m	1
	Flood Risk	P5	10
		P4	8
		P3	6
		P2	4
		P1	2
		P0	1
Water Resources-Underground	Distance to Wells	<500 m	10
		500 - 1000 m	9
		1000 - 1500 m	8
		1500 - 2000 m	7
		2000 - 2500 m	6
		2500 - 3000 m	5
		3000 - 3500 m	4
		3500 - 4000 m	3
		4000 - 4500 m	2
		>4500 m	1
	Aquifer Flow	120 - 80 m^3	10
		100 - 7 m^3	9
		80 - 40 m^3	8
		40 - 20 m^3	6
		23 - 3 m^3	5
		20 - 10 m^3	4
		12 - 1 m^3	3
		10 - 0 m^3	2
		6 - 1 m^3	1
	Aquifer Vulnerability	High	10
		Medium	6
		Low	2

Continued

Climate	Precipitation	>2000 mm	10
		2000 - 1600 mm	9
		1600 - 1500 mm	8
		1500 - 1400 mm	7
		1400 - 1300 mm	6
		1300 - 1200 mm	5
		<1200 mm	4
	Temperature	>24˚C	10
		24˚C - 23˚C	9
		23˚C - 22˚C	8
		22˚C - 21˚C	7
		21˚C - 20˚C	6
		20˚C - 19˚C	5
		19˚C - 18˚C	4
		18˚C - 16˚C	3
		>16˚C	2

Table 4. Pairwise comparison matrix, ranking, and weights for factors.

Factors (CR 2.1%)	[1]	[2]	[3]	[4]	[5]	[6]	Rank	Weight (%)
Geology	1						5	5.6
Pedology	3	1					2	17.9
Geomorphology	2	1/2	1				4	10.4
Surface Water Resources	4	2	2	1			1	26.0
Underground Water Resources	4	2	2	1	1		1	26.0
Climate	3	1/2	2	1/2	1/2	1	3	14.1

Table 5. Pairwise comparison matrix, ranking, and weights for factors and sub-factors.

Factors (CR %)	Sub-factors	[1]	[2]	[3]	[4]	Rank	Weight (%)
Geology CR (5.6%)	Distance to Faults	1				2	20.6
	Porosity of Rocks	5	1			1	64.0
	Distance to Seismic Areas	1/4	1/7	1		4	6.0
	Distance to Caves	1/3	1/6	2	1	3	9.4
Pedology CR (0.0%)	Type of Soil	1				2	33.3
	Infiltration Rate	2	1			1	66.7
Geomorphology CR (0.0%)	Landslide Risk	1				2	20.0
	Slope	4	1			1	80.0
Water Resources Surface CR (0.0%)	Distance to Rivers/Lakes	1				1	85.7
	Flood Risk	1/6	1			2	14.3
Underground CR (1.0%)	Distance to Wells	1				3	16.3
	Aquifer Flow	2	1			2	29.7
	Aquifer Vulnerability	3	2	1		1	54.0
Climate CR (0.0%)	Precipitation	1				1	66.7
	Temperature	1/2	1			2	33.3

the products of ratings assigned for each class (Table 3) and global weights obtained by AHP (Table 6) (Figure 4). The results were grouped into five categories

Table 6. Global weighting for sub-factors.

Factors		Sub-factors	Global Rank	Global Weight (%)
Geology		Distance to Faults	13	1.2
		Porosity of Rocks	11	3.6
		Distance to Seismic Areas	15	0.3
		Distance to Caves	14	0.5
Pedology		Type of Soil	7	6.0
		Infiltration Rate	3	11.9
Geomorphology		Landslide Risk	12	2.1
		Slope	5	8.3
Water Resources	Surface	Distance to Rivers/Lakes	1	22.3
		Flood Risk	10	3.7
	Underground	Distance to Wells	9	4.2
		Aquifer Flow	6	7.7
		Aquifer Vulnerability	2	14.0
Climate		Precipitation	4	9.4
		Temperature	8	4.7

of environmental impact susceptibility for municipal solid waste disposal sites: Very Low (S1), Low (S2), Medium (S3), High (S4) and Very High (S5) (Table 7).

4. Results and Discussion

4.1. Environmental Impact Susceptibility Model for Municipal Solid Waste Disposal Sites

The results of the environmental impact susceptibility model for municipal solid waste disposal sites in the state of São Paulo are presented in (Figure 5). The area for each susceptibility category indicate that most part of São Paulo state, 77.3% have medium environmental impact susceptibility category (S3), 16.8% has high category (S4), 4.8% has low category (S2), 1.1% has very high category (S5) and there is no representative areas for the very low category (S1) (Table 8).

The high and very high categories (S4 and S5, respectively) in the state of São Paulo extend are located near the surface water resources, which is correlated to the EISM global weights that has the sub-factor distance to rivers and lakes as the most important contributor. There is also a concentration of the higher categories near the Atlantic Ocean mainly in the southeast of the state of São Paulo, which can be explained by a combination of geographical variables. For example, there is a mountain range in this area formed by the *Serra do Mar* and *Serra da Mantiqueira*, which has a concentration of steep areas. In addition, these mountain range stop the humidity that comes from the ocean to the continent, which makes the precipitation near the coast very high in comparison to the rest of the state of São Paulo.

The EISM for MSWDS in the state of São Paulo was progressed well due to availability and reliability of spatial data and the findings in this study provide

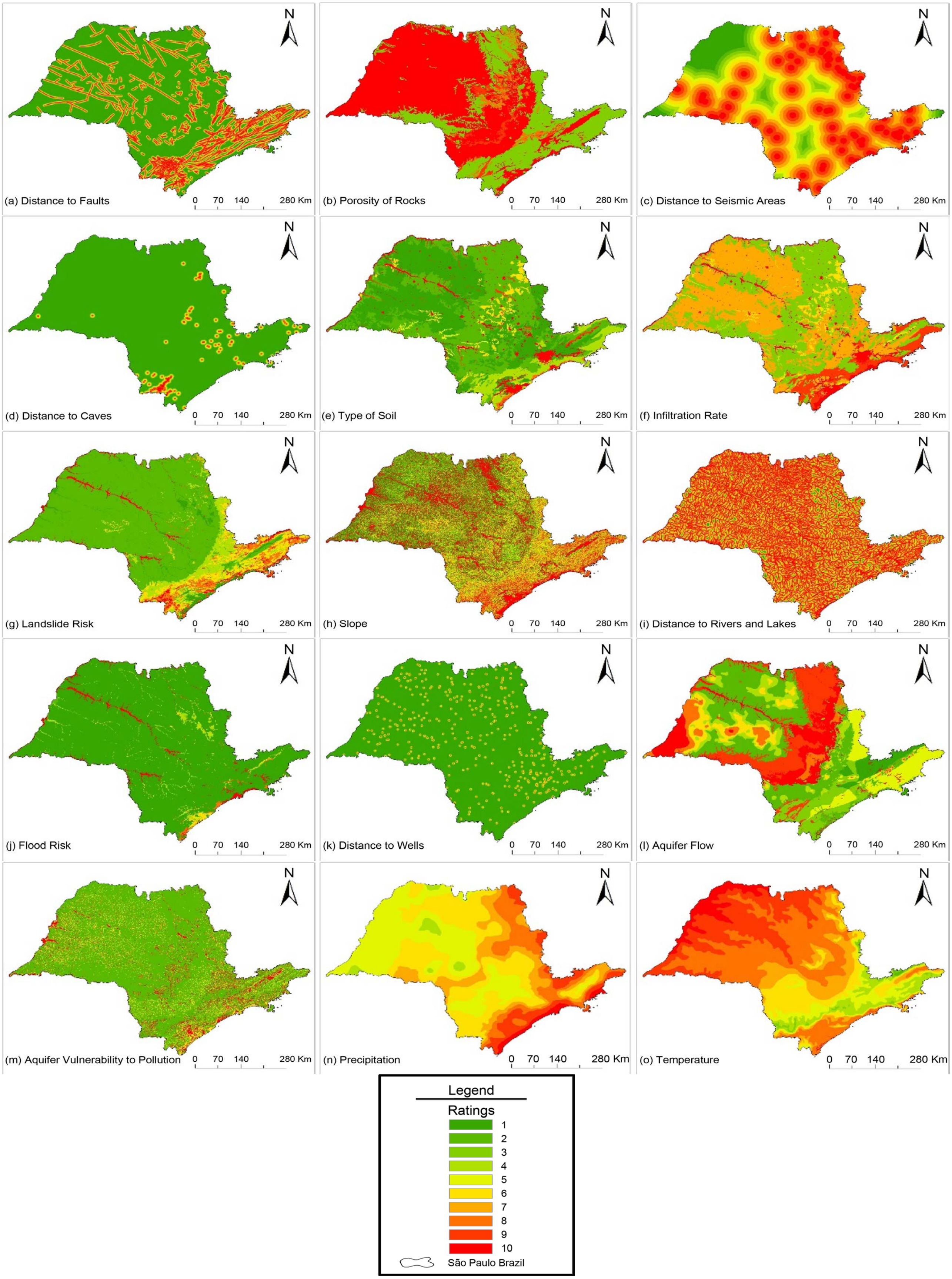


Figure 4. Maps for all selected sub-factors (color figure online).

Table 7. Environmental impact susceptibility model categories for municipal solid waste disposal sites.

Categories	Values
Very Low (S1)	0 - 2
Low (S2)	2 - 4
Medium (S3)	4 - 6
High (S4)	6 - 8
Very High (S5)	8 - 10

Table 8. Environmental susceptibility categorization for MSWDS in the São Paulo state.

Environmental impact susceptibility categorys	Area (km^2)	Area Percentage
Very Low (S1)	0	0%
Low (S2)	12,054	4.8%
Medium (S3)	192,631	77.3%
High (S4)	41,764	16.8%
Very High (S5)	2677	1.1%
Total	249,126	100%

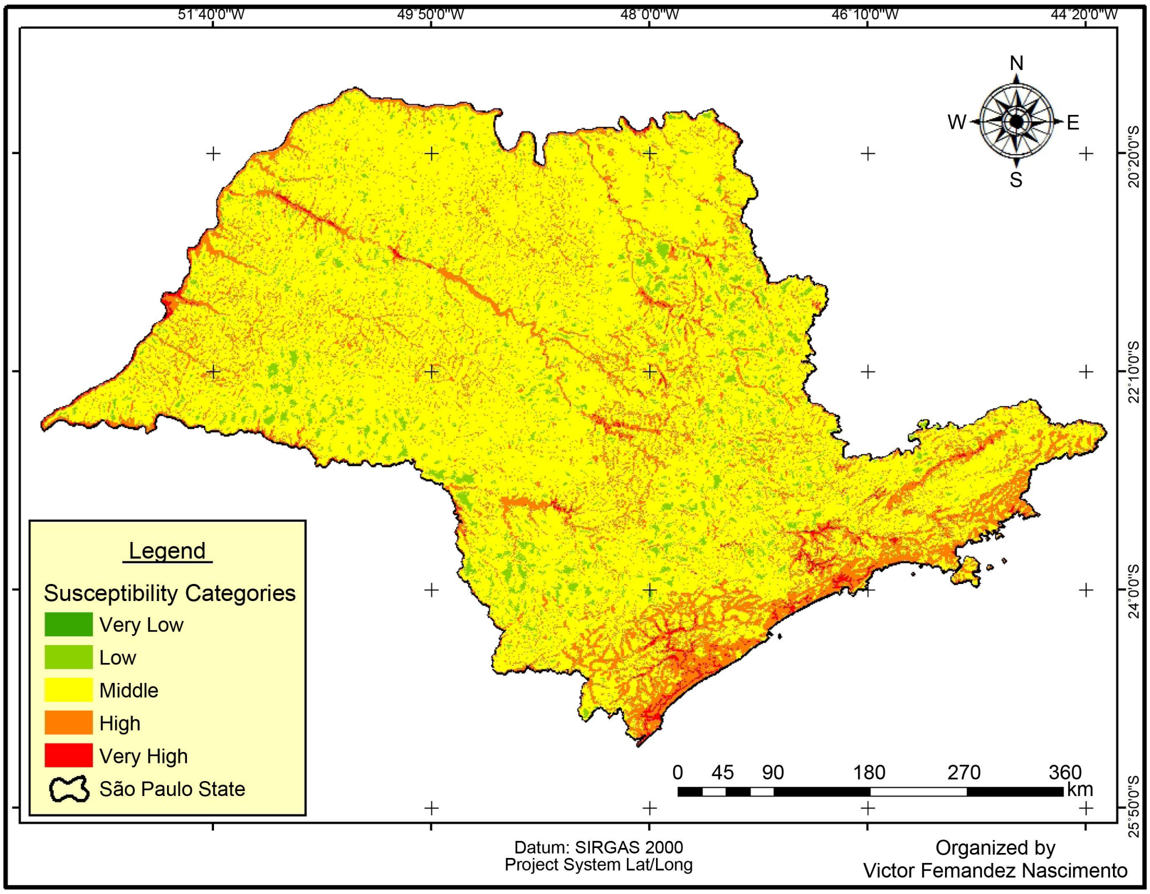


Figure 5. Environmental impact susceptibility for municipal solid waste disposal sites in São Paulo state (color figure online).

an advancement to previous models due to three main reasons: 1) a higher number of factors used, 2) a higher number of sub-factors used, and 3) a more extensive set of combined factors and sub-factors used. Therefore, the EISM results for MSWDS indicate a decent environmental impact susceptibility representation of the state of São Paulo.

4.2. Analysis of Susceptibility for MSW Disposal Sites in São Paulo State

In order to evaluate the environmental impact susceptibility for each municipal solid waste disposal site in São Paulo state we developed a spatial analysis (Figure 6) and statistical study (Table 9).

The geographical coordinates of municipal solid waste disposal sites for the 645 municipalities in São Paulo state were obtained from spreadsheets used to assess the waste quality index developed by the Environmental Company of São Paulo State (CETESB) [90]. Because some of São Paulo's cities use consortia to dispose solid waste, there are currently 420 municipal solid waste disposal sites

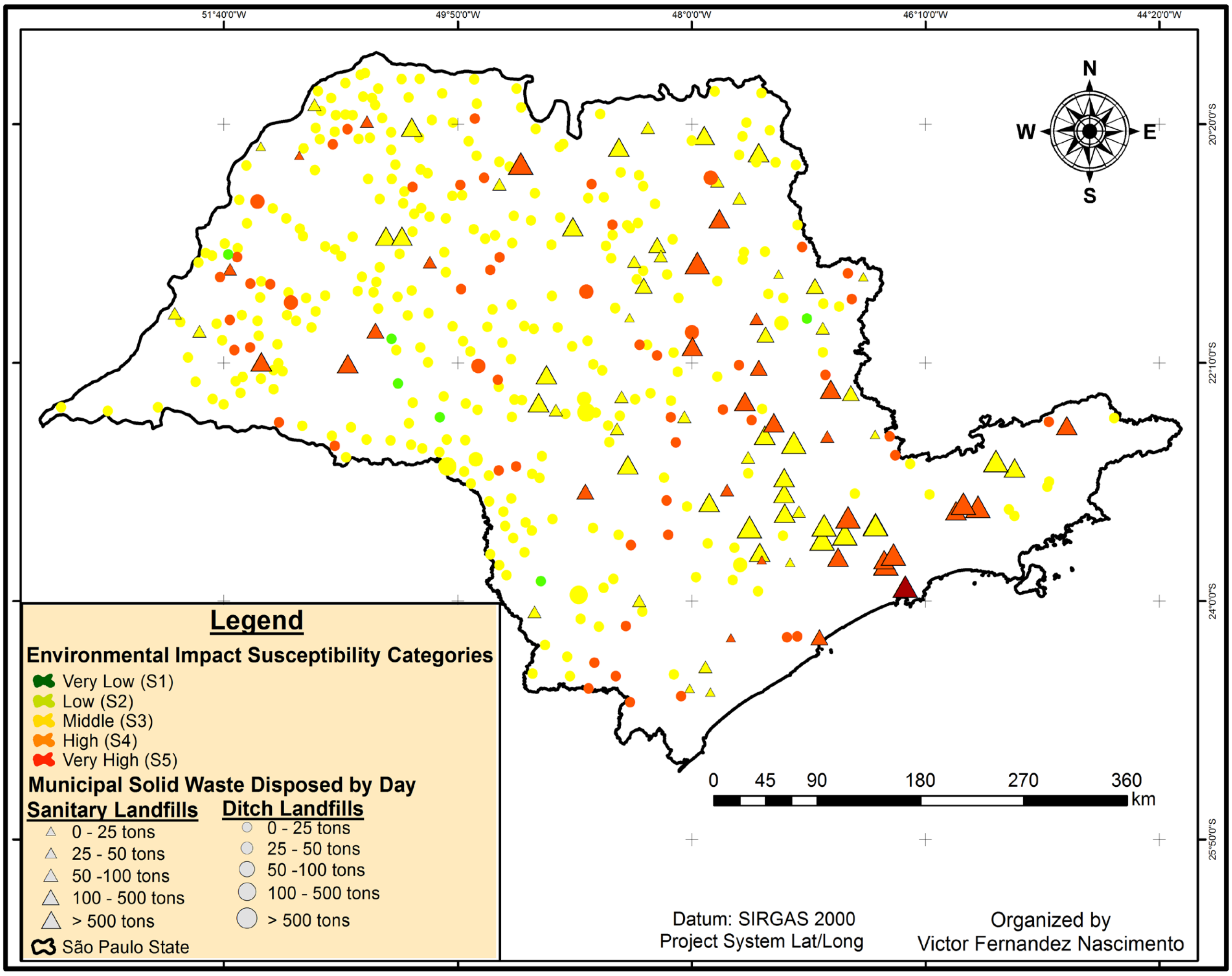


Figure 6. Environmental impact susceptibility categorization of municipal solid waste disposal sites in São Paulo state (color figure online).

Table 9. Municipal solid waste disposal sites in the state of São Paulo according to environmental susceptibility category.

Environmental impact susceptibility category	Number of Ditch Landfills	Number of Sanitary Landfills	Ton of MSW/disposed per day
S1 + S2	6	0	38.57
S3	271	57	20,957.56
S4	54	31	16,430.81
S5	0	1	1454.82
Total	331	89	38,880.76

cataloged and evaluated in the annual Inventory of Solid Waste [9]. Furthermore, after visual assessment through RapidEye satellite images for the years of 2013 and 2014, provided by the Ministry of Environment (MMA), it was determined that some of the municipal solid waste disposal sites were mislocated in the spreadsheets, for that reason, the locations were corrected and additionally the MSWDS areas were defined.

Afterwards, a spatial analysis was performed by overlaying the results of the EISM and the locations of municipal solid waste disposal sites in the state of São Paulo. Thus, it was possible to identify the specific MSWDS and the amount of municipal solid waste disposed of in each environmental impact susceptibility categories. For cases where the MSWDS had more than one susceptibility category, the highest category was assigned.

In São Paulo state, two different kinds of municipal solid waste disposal approach are used: ditch landfills (331 units) and sanitary landfills (89 units). Ditch landfills are a disposal technique for municipal solid waste on the ground without compaction and consequently with fewer requirements for implementation than a sanitary landfill. This procedure allows small towns, with population under to 25,000 inhabitants and daily generation of MSW less than ten tons to have their waste disposed without the necessity to construct a sanitary landfill [91]. Even though the quantity of MSW disposed in ditch landfills are smaller than the quantity disposed in sanitary landfills, usually ditch landfills pose more environmental risks and cause environmental impacts.

São Paulo is one of the states in Brazil where almost all cities use landfills instead of open dumps, which represent an improvement to avoid negative environmental impacts caused by MSWDS. Nevertheless, disposal of MSW in sanitary landfills instead of ditch landfills does not eliminate all possible environmental impacts but reduces the probability of their occurrence.

In addition, the increasing population and MSW generation in the São Paulo state has caused pressure in the old MSWDS that are almost filled. This problem added to the lack of suitable areas for new sanitary landfills are some of the most critical problems faced by municipalities, especially near the metropolitan areas of *São Paulo*, *Campinas*, *Baixada Santista* and *Vale do Paraíba*, where there is a high concentration of population and consequently production of MSW.

The assessment for MSWDS in the state of São Paulo, indicates that the number of landfills located in each environmental impact susceptibility category has a positive correlation with the extent of each category in the state area. If sanitary and ditch landfills are added in the assessment, approximately, 1.6% of them are placed in very low, low and very high environmental impact susceptibility categories (S1, S2 and S5 respectively). Approximately 20.4% of the landfill sites are located in high category (S4) and, the great majority, approximately 78% are situated in medium susceptibility category (S3).

When a separate analysis was performed for sanitary and ditch landfills, a total of six ditch landfills were in the lower susceptibility categories (S1 and S2) and just one sanitary landfill was in the very high susceptibility category (S5) (**Table 9**). Even though only 54 ditch landfills and 32 sanitary landfills are in the (S4 and S5) categories, a large amount of municipal solid waste (17,886 tons) is disposed of at these MSWDS daily, which corresponds to approximately 46% of the total MSW disposed in the state of São Paulo.

Based on the total amount of municipal solid waste classified under the highest susceptibility categories (S4 and S5), 97.5% is disposed in sanitary landfills, and only 2.5% is disposed in ditch landfills. This is a positive finding, since if properly operated and monitored, sanitary landfills provide better environmental protection than ditch landfills. The list of municipalities and the quantity of municipal solid waste disposed in sanitary and ditch landfills located in the high susceptibility categories are provided in (**Table 10**).

5. Conclusions

Through the development of the environmental impact susceptibility model for municipal solid waste disposal sites using multi criteria decision analysis and analytical hierarchic processes coupled with geographic information system, it was possible to identify the most and least environmentally susceptible areas using five environmental factors associated with fifteen sub-factors. With the application of the EISM, it was also possible to assess the current susceptibility of municipal solid waste disposal sites in São Paulo state, Brazil.

In this study, the results of the environmental impact susceptibility model indicated that even though more than 82% of the land area in São Paulo state is situated in very low, low, and medium susceptibility categories, 85 of 420 landfills, were located in the high and very high susceptibility categories. In these landfills, approximately 17,886 tons of municipal solid waste are disposed on a daily basis, which indicated that 46% of all MSW of the state of São Paulo is disposed in environmentally susceptible areas. For that reason, municipal solid waste disposal sites in São Paulo state require more attention and control to prevent the occurrence of negative environmental impacts and reduce the economic as well as social consequences.

The development of this model took three main modeling purposes into consideration, including prediction, management decision-making under uncertainty, and developing system understanding and experimentation. This type of spatial analysis can help stakeholders promote the mitigation of environmental

Table 10. Municipal solid waste disposed of in landfills in high and very high categories.

Categories	Sanitary Landfills	MSW/day (tons)	Ditch Landfills	MSW/day (tons)
S5	Santos	1454.82	0	0
S4			Adamantina	26.47
			Alvarez Machado	15.49
			Americo de Campos	3.48
			Andradina	42.71
			Anhembi	3.29
			Apiaí	12.82
			Bálsamo	5.58
			Barra do Turvo	2.26
			Bernardino de Campos	6.99
			Bõa Esperança do Sul	9.03
			Cajati	14.83
	Avaré	70.6	Campina do Monte Alegre	3.48
	Cachoeira Paulista	327.37	Cassia dos Coqueiros	1.26
	Caieiras	1629.74	Charqueada	10.33
	Cerquilho	33.62	Corumbataí	1.52
	Dracena	33.69	Divinolândia	5.41
	Embu	233.15	Dourado	5.69
	Guatapará	1301.61	Estiva Gerbi	6.01
	Jacareí	199.55	Gália	3.63
	Jales	36.76	Garça	32.36
	Jambeiro	507.92	Gastão Vidigal	2.84
	Jardinópolis	150.79	Guiaçara	7.32
	Juquia	8.59	Guapiara	5.06
	Leme	79.17	Guareí	6.68
	Limeira	256.82	Ibaté	25.48
	Mauá	2585.55	Iporanga	1.70
	Mogi-Guaçu	124.84	Iracemopolis	15.21
	Onda Verde	539.96	Itaoca	1.27
	Pedreira	35.74	Itápolis	30.57
	Penópolis	6.90	Itariri	7.42
	Pereira Barreto	8.80	Junqueirópolis	11.47
	Peruíbe	7.90	Marinópolis	1.19
	Piedade	7.60	Nantes	1.85
	Porto Ferreira	42.75	Óleo	1.22
	Presidente Prudente	194.49	Ouro Verde	5.33
	Quatá	293.96	Pacaembú	7.17
	Rio Claro	174.23	Pedra Bela	1.05
	Santo André	205.70	Pedrinhas Paulista	1.81
	São Carlos	317.80	Pedro de Toledo	5.25
	São José dos Campos	733.90	Piquete	9.31
	São Paulo*	5676.56	Pirangi	7.01
	Tupã	50.37	Poloni	3.60
			Presidente Bernardes	7.39
			Ribeirão dos Indios	1.33
			Sabino	8.10
			Sales	8.60
			Sales de Oliveira	8.20
			Santa Maria da Serra	7.70
			São Francisco	1.55
			Severinia	11.11
			Tapiratiba	7.55
			Torre de Pedra	1.08
			Tupi Paulista	8.28
			Vargem	3.41

Source: [9]; *Landfill located at Av. Sapopemba, n˚ 22,254-CTL.

impacts and assist in the process of identifying areas for new landfills.

This model can be applied to different areas, especially in developing countries, where most of the municipal solid waste is disposed directly in the ground, without control, resulting in adverse environmental impacts. Although the EISM was developed focusing in MSWDS, the authors consider that the model can also be used with some adaptations for other point source of environmental impact, such as, fuel stations, mines, and any type of solid waste disposal facilities such as industrial or hazardous wastes.

The main limitation in the development of the EISM is the accessibility of spatial data, as well as its quality. In addition, there is the subjectivity of class and rating definition of the sub-factors and the weight assignment using AHP, where variation in these values can cause a different result in the analysis. Furthermore, the importance for each class could vary based on the region of interest and characteristics of the specific area.

For future studies, to improve the environmental impact susceptibility assessment for MSWDS the authors suggest adding 1) forecasting, using different climate scenarios that influence leachate generation and emission of greenhouse gases, and 2) social learning, coupling a social model with the EISM, which could result in a greater understanding of global susceptibility.

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