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Uma nova estratégia para definir áreas para aterros sanitários consorciados baseados em análise multicritério

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RESUMO

O processo de seleção de área para aterros sanitários pode ser realizado com uma Análise Multicritério de Decisão (MCDA) em um ambiente SIG. No entanto, as variáveis ambientais precisam ser modeladas adequadamente antes que qualquer MCDA seja realizada. Uma maneira de fazer isso é integrar o MCDA com a Inferência Fuzzy. Ainda assim, até onde sabemos, essa estratégia não foi avaliada na seleção de áreas para aterros do consórcio. Aqui, propomos uma nova estrutura para selecionar áreas de aterro sanitário de consórcio, integrando MCDA e lógica Fuzzy com características ambientais e socioeconômicas em ambiente GIS. Para isso, consideramos múltiplos níveis de adequação socioambiental para atender um grande e pequeno número de cidades em um período de 20 anos. Uma região do interior de São Paulo, Brasil, com 32 municípios foi selecionada como área de estudo e o método da Combinação Linear Ponderada (WLC) foi aplicado para combinar variáveis ambientais e socioeconômicas. Os pesos foram determinados utilizando o Analytical Hierarchy Process (AHP) e a lógica Fuzzy foi aplicada para modelar as variáveis. Nossa abordagem foi capaz de identificar áreas com níveis satisfatórios de adequação a aterros sanitários, atendendo a um grande e pequeno número de municípios, minimizando os impactos socioambientais. Essa abordagem é importante porque pode ajudar a direcionar as entidades governamentais para uma seleção apropriada de uma área dentro de suas fronteiras regionais. Também recomendamos o método proposto para outras regiões e locais.

Palavras-chave: Processo de Hierarquia Analítica, Impacto Ambiental, Lógica Fuzzy, Resíduos Sólidos.

A new strategy to define consortium sanitary landfill siting location based on multicriteria analysis

ABSTRACT

The area selection process for sanitary landfills can be performed with a Multicriteria Decision Analysis (MCDA) in a GIS-environment. However, environmental variables need to be properly model before any MCDA is performed. One manner to perform this is to integrate MCDA with Fuzzy Inference. Still, to the best of our knowledge, this strategy was not evaluated in the selection of areas for consortium landfills. Here, we propose a new framework to select consortium landfill areas by integrating MCDA and Fuzzy logic with environmental and socioeconomic features in GIS environment. For this, we considered multiple levels of social-environmental suitability to attend a large and a small number of cities in a 20-years period. A region in the interior of São Paulo, Brazil, with 32 municipalities was selected as study area and the Weighted Linear Combination (WLC) method was applied to combine environmental and socioeconomic variables. Weights were determined using the Analytical Hierarchy Process (AHP) and Fuzzy logic was applied to model the variables. Our approach was able to identify areas with satisfactory suitability levels for landfills, both serving a large and a small number of municipalities while minimizing social-environmental impacts. This

approach is important as it may help directs governmental entities to a appropriate selection of an area within their regional boundaries. We also recommend the proposed method for other regions and locations.

Keywords: Analytical Hierarchy Process, Environmental Impact, Fuzzy Logic, Solid Waste.

Introduction

Human activities, including industrial, domestic, commercial and construction, produce solid waste in different forms. Part of this waste is regarded as hazardous for the environment and natural resources (Al-Anbari et al., 2018). With continuous population growth and accelerating industrial development, solid waste is increasing at a tremendous rate (Singh, 2019). This is a problem faced by many countries but is more critical in developing countries, which account for 80% of the world's population (Alanbari et al., 2014; Bosompem et al., 2016; Ferronato et al., 2017; Al-Anbari et al. 2018; Goulart Coelho et al. 2018).

In Brazil, a Federal Law (n°12,305/2010) states that solid waste must be disposed of in landfills while attending specific operational norms. These norms are essential to avoid risks to public health and safety while minimizing environmental impacts. The process of landfill area selection is a complex decision-making task related to solid waste management. It is subject to government regulation, municipal funding, public health concerns and increasing density of population (Al-Anbari et al., 2018). Additionally, this task must take into account several environmental and socioeconomic criteria, like physical characteristics of the environment, distance from population cores, and transport logistics for solid waste disposal.

To overcome these challenges, the selection of landfill areas should be taken by a Multicriteria Decision Analysis (MCDA) approach. The MCDA is used to solve problems with a geographic inference, like landfill area selection, and it is easier when performed in a Geographic Information System (GIS) environment. Several steps are needed to execute an MCDA and one of them is the weighting of variables selected for the inference model. For this, the weight assessment has traditionally carried out by the Analytical Hierarchy Process (AHP), originally proposed by Saaty (1990).

Selecting a suitable landfill area using MCDA in a GIS-based environment is the traditional approach and was applied in different countries, such as USA (Chang et al., 2008), China (Wang et al., 2009), Sierra Leone (Gbanie et al., 2012), Italy (De Feo and De Gisi, 2014), Ghana (Bosompem et al., 2016), India (Kumar

and Hassan, 2013; Kolekar et al., 2017), Canada (Khan et al., 2018), Turkey (Yesilnacarar et al., 2012; Yildirim and Guler, 2016; Yildirim et al., 2018), Iran (Eskandari et al., 2012; Alanbari et al., 2014; Motlagh and Sayadi, 2015; Rahmat et al., 2016; Torabi-Kaveh et al., 2016; Khodaparast et al., 2018; Khoshand et al., 2018; Karimi et al., 2018) and Brazil (Nascimento and Silva, 2014; Nascimento et al., 2017; Colvero et al., 2018; Pavani et al., 2019). To construct the inference models, the aforementioned studies adopted criteria divided into three basic contexts: environment, social, and economic.

Recent studies in Brazil (Felicori and Marques, 2017; Spigolon et al., 2018; Pavani et al., 2019) applied the MCDA approach to select suitable areas for consortium landfills. This kind of landfill receives solid waste from more than one municipality. Selected areas should represent a solution to solid waste management shared by the municipalities. Consortium landfills is a practice encouraged by Federal Law (n°12,305/2010) in Brazil, but it is under-explored in other countries. The advantages of adopting a consortium area are: (i) improvement of operational practices at the landfill; (ii) a lower number of areas required, reducing the number locations susceptible to contamination; (iii) sharing of the administrative and operational costs of the landfill; and (iv) greater environmental control (Pavani et al., 2019). Furthermore, municipalities that adopt consortium solutions receive priority from the Brazilian government in obtaining financial support (Brasil, 2010). Three works were conducted in Brazil about consortium landfill area selection. The first, developed by Felicori and Marques (2017), considered the region of Zona da Mata in Minas Gerais. These authors used a Weighted Linear Combination (WLC) method, associated with the AHP technique to determine the weights of variables, and the Fuzzy logic to normalize them. Still, this work did not include all the environmental variables (criteria) established by the Brazilian Norm (NBR n°13.896/1997). Criteria like pedology, geology, and water depth are directly linked to contamination chances of natural resources and were not included in the model proposed by Felicori and Marques (2017). This

inclusion may reduce the negative environmental impact associated with landfill installation.

The other two studies were developed by Spigolon et al. (2018) and Pavani et al. (2019). They also did not consider all environmental criteria established in the Brazilian Norm (NBR n°13.896/1997). And none of them applied Fuzzy logic to normalize the variables which compose the inference model. Fuzzy logic is suitable to model uncertainties, which is a characteristic of the environmental variables (Kolekar et al., 2017). Physical environment variables like pedology, geomorphology, geology have a continuous spatial distribution, thus applying Fuzzy logic can model more accurately how these variables are distributed in the environment.

Although MCDA is already used for landfill area selection, up to date, no study considered the MCDA with both AHP and Fuzzy Logic to select areas for consortium landfill using the environmental and socioeconomic variables presented in-law and regulations. Here we propose an approach to the consortium landfill area selection with a high level of social-environmental suitability to attend both large and small numbers of cities for a period of 20 years. The contribution of this study is twofold. Firstly, we identified social-environmental suitable areas to dispose of solid waste from multiple cities, for a period of 20 years. Secondly, we proposed a model that can be applied in other regions and is

able to minimize the adverse environmental impacts of a landfill installation. The rest of this article is organized as follows. Section 2 details the materials and method adopted in this study. Section 3 presents and discusses the results and, finally, Section 4 concludes the paper.

Materials and Method

Study area

The study area (Figure 1) named Pontal do Paranapanema has approximately 2 million hectares and is located in the western region of São Paulo State, Brazil. Its population is estimated in 585,713 inhabitants distributed across 32 municipalities (IBGE, 2010), equating a density of 29.3 people per km². The generation of solid waste is 224,548 tons per year (SNIS, 2016; CETESB, 2016). Presidente Prudente, with more than 200,000 inhabitants, is the municipality responsible for the generation of 43% of total solid waste produced in the region (IBGE, 2010). The region is located in a sub-tropical climate, composed by the climatic units: Iepê (BIII_m), Presidente Prudente (BIV_m) and Pontal do Paranapanema (BIV_m) (Boin, 2000). The predominant geology is the Vale do Rio do Peixe formation, followed by Rio Paraná formation, and the predominant soil is Argisol followed by Red Latosol (IBGE, 2017).

Figure 1. Location of the Pontal do Paranapanema region – São Paulo State, Brazil.

Method

We adopted the environmental and socioeconomic variables required or recommended by Brazilian law for landfill area

selection (Table 1). The law-imposed variables were denominated as restrictive and, the other variables recommended by these laws or suggested in the literature were denominated as ponderable. All spatial data representing each

variable (restrictive and ponderable) were organized in a GIS geodatabase. Six synthesis maps were produced with the map-algebra process. In Brazil, the reference system required is SIRGAS 2000 (Geocentric Reference System for the Americas), and UTM (Universal Transverse Mercator) was adopted as the projection system.

Synthesis Map 1 represents all the areas restricted for installing a landfill in Pontal do Paranapanema according to Brazilian law. This map was obtained based on Boolean logic. Synthesis Map 2 highlights all areas available, with different environmental and socioeconomic suitability levels for installing a landfill. This map was made applying the WLC method, with the AHP technique and Fuzzy logic. Four classes of suitability were defined for the areas: low, medium, high and very high. The Natural Breaks method (Dent et al., 2009) was applied to create the intervals of those classes. After that, all areas with dimensions less than the minimum required for the disposal of the solid waste produced by all 32 municipalities were removed. This map was named Synthesis Map 3. Buffers of 20, 40 and 100 km were applied to identify the spatial distribution of the available areas around the municipality with the largest solid waste generation. We obtained the Synthesis Map 4 with this operation. Later, groups from three-to-five municipalities were created based upon their proximity, and their available areas were identified for the installation of a consortium landfill. This map was named Synthesis Map 5. Each group was denominated as a Regional Pole and areas were classified according to their environmental and socioeconomic suitability levels. Areas with a size less than the minimum required for consortium landfill within each regional pole were removed to obtain the Synthesis Map 6.

Determination of minimum area size for the construction of a consortium landfill

The selected area for the consortium landfill should receive the solid waste produced by the 32 municipalities of Pontal do Paranapanema over a period of 20 years. To that end, the population projection from 2019 to 2039 was estimated using Equation (1) (Nascimento and Silva, 2014). Population data from the last national census (2010) and the average annual rate of increase between 2000 (previous census) and 2010 (IBGE, 2010; SEADE, 2017) were used.

$$N = (N_0 \left(1 + \frac{T_x}{100}\right))^t \quad (1)$$

where N is the number of inhabitants; N_0 is the initial number of inhabitants; T_x is the annual percentage increase, and t is the time in years.

The total of solid waste generated per year by the population is calculated as shown in Equation (2). The generation of solid waste per capita of the population (kg/inhabitant.day) was determined using data from the National Sanitation Information System (SNIS, 2016) and the Environmental Company of the State of São Paulo (CETESB, 2016).

$$R_i = P_i \times G_{PC} \times \frac{365}{1000} \quad (2)$$

where R_i is the solid waste mass-generated in the year "i" (t/year); P_i is the population in the year "i"; and G_{PC} is the solid waste generation per capita of the population (kg/inhabitant.day).

Equation (3) was applied to estimate the total volume of solid waste. The R_i value ranges from 0.35 to 0.90 t/m³ (Obladen et al., 2009). The value of 0.70 t/m³ was adopted (Vilhena, 2018).

$$V_t = \frac{R_i}{M_{RC}} + V_R \quad (3)$$

where V_t is the total volume of solid waste (m³/year); M_{RC} is the specific mass of the solid waste after being compacted (t/m³); and V_R is the volume to cover the landfill cell, which corresponds to 20% of the compacted solid waste volume (ReCESA, 2008).

The minimum area size for the consortium landfill is calculated as shown in Equation (4). A landfill of height (h) of up to 5 meters is recommended to facilitate the entrance and exit of vehicles and the compacting of the solid waste (ReCESA, 2008). This height was adopted in Equation (4).

$$A_t = \frac{V_t}{h} + A_{Inf} \quad (4)$$

where A_{Inf} is the infrastructure area added at 10%.

Environmental and socioeconomic variables and data normalization

Several laws and regulations were analyzed to determine the variables that must be taken into account when selecting a landfill area in Brazil. Brazilian law requires a group of environmental and socioeconomic variables

(Table 1) and also recommends another group of variables (Table 2) for landfill area selection. Three restrictive variables exist in the environmental context (Table 1): Drainage distance; Conservation Unit (CU) areas and Groundwater depth.

To reclassify the attribute values of each of the restrictive variables to zero or one, we

Table 1. Restrictive variables for landfill area selection according to Brazilian law.

Context	Variables (criteria)	Brazilian Law	Cartographic data source	Attribute	Value
Environ- men- tal	Drainage distance	NBR (Brazilian technical standard) 13.896/97 (ABNT 1997)	IBGE (Brazilian Institute of Geographic and Statistics) (2017) 1:250.000	≤ 200 m	0
			DataGEO (Infrastructure of environmental spatial data of the State of São Paulo) (2013) 1:50.000	> 200 m	1
		Law n° 12.651/2012 (Brazil, 2012)	IBGE 1:250.000	≤ 500 m	0
				> 500 m	1
	Conservation Units	Law n° 9.985/2000	ICMBIO (Chico Mendes Institute for Biodiversity Conservation)	Inside of Conservation Unit area	0
	Groundwater Depth	NBR 13.896/97	CPRM (Mineral Resources Research Company)	≤ 1.5 m	0
Geological Survey of Brazil (2018)			> 1.5 m	1	
Socio economic	Airport distance	Law n° 12.725/2012	ANAC (National Civil Aviation Agency) (2018)	≤ 20 km	0
				> 20 km	1

Two attributes were considered for the "drainage distance" variable: any area closer than 200 meters from all rivers (NBR 13.896/97) or any area up to 500 meters from large rivers (Federal Law n° 12.651/2012). Several studies like Gbanie et al., (2013), Motlagh and Sayadi (2015), Bahrani et al. (2016), Chonattu et al., (2016), Yildirim and Guler (2016), have used this variable because a landfill has a high potential to contaminate proximal water resources. To the "conservation units" variable, a "not allowed" restriction was assumed within any conservation unit area. Federal Law (N° 9.985/2000) states that the government can order interim administrative limitations on the exercise of activities that potentially cause environmental degradation in the Conservation Units areas. To "groundwater depth", the minimum height required between a

applied the Boolean logic because of the deterministic characteristics of the restrictive variables, i.e. "allowed" and "not allowed". The "0" value was assigned to represent "restricted" areas and the "1" value to represent "not restricted" areas for landfill implementation (Table 1).

landfill cell and the groundwater depth is 1.5 meters (NBR 13.896/97). Although the available data of our study area did not present groundwater below 1.5 meters (CPRM, 2018), it is important that geological tests be performed before landfill installing. This is because the study area has dense drainage and may favor groundwater outcropping in less than 1.5 m. "Airport distance" is the only socioeconomic variable required by Brazilian law, being the minimum radius of 20 km (Table 1).

We combined all restrictive variables using the Boolean logic, obtaining the Synthesis Map 1 (Figure 3) which represents all restricted areas inside the region to install a landfill. The "AND" operator was used in the Boolean combination. Figure 2 illustrates the stages of making Synthesis Map 1.

Figure 2. Stages of Synthesis Map 1 preparation (restricted areas for landfill installation).

Brazilian law and literature recommended 10 variables (Table 2) to conduct a landfill area selection task. Fuzzy logic was applied to normalize the attribute values of these variables on a range of 0 to 1. This was used to return the variable values in a common scale measurement. A proper fuzzy membership function was determined and the respective control points for all ponderable variables were defined (Table 2).

The "drainage distance" is a restrictive variable (Table 1). However, it was also included in the inference model as a ponderable variable (Table 2). We assumed that the greater the distance from a river, above the 200 m limit, the lower are the chances of negative environmental impacts. The same idea was applied to the "Conservation Unit" and "groundwater depth" variables. Thus, to "Conservation Unit" areas, 3 km was adopted as a control point of the fuzzy membership function, following the CONAMA document (n°428/2010) (Table 2). To "groundwater depth", we assumed that the farther from the groundwater depth a landfill cell is located, the less is the risk of water contamination. Using 681 well-distributed points in the study area, we interpolate a surface representing the spatial groundwater depth distribution. These points represent the static level of rural and urban wells (CPRM, 2018). We used the Inverse Distance Weighting (IDW) method, and a Root Mean-Squared Error (RMSE) of 10.97 meters was obtained. The groundwater depth map was then normalized using a crescent linear fuzzy membership function with control points "a = 2" (lowest depth value sampled) and "b = 112" (highest depth value sampled). A crescent linear fuzzy membership function (Table 2) was applied to normalize the data of the "geology", "pedology", "geomorphology", "Conservation Unit", "Land Use and Land Cover" (LULC) and "built-up area distance" variables. This implies that the farther away from the minimum function value, the more appropriate it is for the landfill area. It should be highlighted that the "geology" and "geomorphology" variables were not considered by other related studies like Spigolon et al. (2018) and Pavani et al. (2019). These variables provide essential information regarding the morphostructure and the morphosculpture of a region. Geology is related to the possibility of contamination by the leaching of solid waste, which, when finding a porous layer, will infiltrate at a greater velocity. Geomorphology refers to the shape of the relief and influences the velocity and

direction of the superficial flow of particles. Therefore, the weights for these variables were defined taking these aspects into account. The Gaussian function was used for "road distance" and "slope variation" variables. The control point "b" (Table 2) consists of the midpoint of the graph and corresponds to the value most suitable for each variable.

The slope map was produced using a DEM (Digital Elevation Model) with 30 m of spatial resolution from the SRTM (Shuttle Radar Topography Mission) mission. The LULC map was obtained from a supervised satellite image classification. For this, we acquired images from the Landsat 8 satellite, OLI sensor, with 30 meters of spatial resolution. The images were from July 2017 and obtained at the surface reflectance level from the United States Geological Survey (<https://espa.cr.usgs.gov/ordering/new/>). The Maximum Likelihood pixel-to-pixel classifier was applied in the open-source software SPRING 5.5.2, adopting an RGB (6,5,4) composition. We trained the algorithm with representative samples of the 5 classes identified in the study area, with a minimum of 20 pixels per sample and 5 samples per class. The thematic classes were: water body, arboreous vegetation, crop field, pasture, and bare soil. "Built-up areas" (IBGE, 2017) and "rural settlement" (ITESP, 2018) classes were added later to the LULC map since they were already mapped by governmental bodies. Our study area has many rural settlements due to a strong land reform problem and we assumed that these data influence their socioeconomic characteristics. To validate the LULC map, we randomly distributed 100 points across the area and used it as reference Planet Scope images with 3 meters of spatial resolution. We obtained an overall accuracy of 87% and a Kappa index of 0.82, which represents a "very good" classification, according to Landis and Koch (1977).

Analytical Hierarchy Process to weight assignment

We adopted the Weighted Linear Combination method to combine the environmental and socioeconomic variables. The weights of these variables were determined using the AHP technique. AHP was also applied to determine the weights of variable's subclasses such as geology, geomorphology, pedology, and LULC. The AHP performs a pairwise comparison and adopts a scale from 1 to 9, where 1 indicates identical importance between the compared variables and 9 implies higher importance of one

variable over the other (Saaty, 1990). With the help of specialists and values from recent literature (Pavani et al., 2019), a relative importance matrix (Table 3) was constructed for the variables and their subclasses. The normalized

matrix was calculated and the weight (i.e. the eigenvector) of each variable determined (Table 4). A similar process was executed for the variables' subclasses (Table 5).

Table 2. Recommended variables for landfill area selection according to Brazilian law and normalization of these variables based on Fuzzy logic.

Criteria	Variable	Source of restriction	Cartographic data source	Fuzzy membership function	Function Control Points
Environmental	Drainage distance	NBR 13.896/97	IBGE (2017) 1:250.000 DataGEO (2013) 1:50.000	Increasing linear	a = 200 b = 5,413
	Slope variation	NBR 13.896/97	DEM (Digital Elevation Model) of the mission SRTM (Shuttle Radar Topography Mission) spatial resolution 30 meters	Gaussian	a = 1 b = 5 c = 10
	Geology	NBR 13.896/97	IBGE (2017) 1:250.000	Increasing linear	a = 0 b = 1
	Pedology	NBR 13.896/97	DataGEO (2017) 1:250.000	Increasing linear	a = 0 b = 1
	Geomorphology	Samizava et al. (2008)	IBGE (2017) 1:250.000	Increasing linear	a = 0 b = 1
	Groundwater depth	NBR 13.896/97	CPRM (2018)	Increasing linear	a = 2 b = 112
	Conservation Units area	CONAMA 428/2010	IBGE 1:250.000 ICMBIO	Increasing linear	a = 3000 b = 91532
Socio-economic	Land use and land cover (LULC)	Pavani et al. (2019)	Image classification Landsat 8 (2017) 1:50.000	Increasing linear	a = 0 b = 1
	Built-up area distance	NBR 13.896/97	IBGE (2017) 1:250.000	Increasing linear	a = 500 b = 33,673
	Road distance	NBR 13.896/97 Samizava et al. (2008) Eskandari et al. (2012)	IBGE (2017) 1:250.000	Gaussian	a = 200 b = 600 c = 1,000

Table 3. Matrix of relative importance among the ponderable variables in the landfill area selection.

Variable (factor)	A	B	C	D	E	F	G	H	I	J
Drainage distance (A)	1									
Slope variation (B)	3	1								
Geology (C)	1/3	1/5	1							
Pedology (D)	1/3	1/5	1	1						
Geomorphology (E)	1/2	1/2	3	3	1					
Groundwater depth (F)	1	1	3	3	2	1				
Conservation Units area (G)	1/2	1/3	1	1	1/3	1/3	1			
Built-up area distance (H)	1	1/3	3	3	1/2	1/2	1	1		
Road distance (I)	1	1/3	3	3	1/4	1/4	1/3	1	1	
Land use and land cover (J)	1/2	1/4	3	3	1/3	1/3	1	1/2	1/2	1

Table 4. Normalized matrix and weights of the ponderable variables.

Factor	A	B	C	D	E	F	G	H	I	J	Eigenvector (weight)
*A	0.109	0.074	0.115	0.115	0.22	0.179	0.122	0.082	0.055	0.107	0.118
B	0.327	0.223	0.192	0.192	0.22	0.179	0.184	0.247	0.165	0.214	0.214
C	0.036	0.045	0.038	0.038	0.037	0.06	0.061	0.027	0.018	0.018	0.038
D	0.036	0.045	0.038	0.038	0.037	0.06	0.061	0.027	0.018	0.018	0.038
E	0.055	0.112	0.115	0.115	0.11	0.09	0.184	0.164	0.22	0.161	0.133
F	0.109	0.223	0.115	0.115	0.22	0.179	0.184	0.164	0.22	0.161	0.169
G	0.055	0.074	0.038	0.038	0.037	0.06	0.061	0.082	0.165	0.054	0.066
H	0.109	0.074	0.115	0.115	0.055	0.09	0.061	0.082	0.055	0.107	0.086
I	0.109	0.074	0.115	0.115	0.028	0.045	0.02	0.082	0.055	0.107	0.075
J	0.055	0.056	0.115	0.115	0.037	0.06	0.061	0.041	0.028	0.054	0.062

* (A) Drainage distance; (B) Slope variation; (C) Geology; (D) Pedology; (E) Geomorphology; (F) Groundwater depth; (G) Conservation Units area; (H) Built-up area distance; (I) Road distance (J) Land use and land cover.

Table 5. Variables, their subclasses, and the weights determined by the AHP.

Variables	Subclass	Weights
Geology	Holocene Mudslides	0.029
	Continental Body of Water	0.029
	Formation Candoi	0.390
	Formation Presidente Prudente	0.211
	Formation Rio Paraná	0.120
	Formation Santo Anastácio	0.072
	Formation Vale do Rio do Peixe	0.120
	Group Serra Geral	0.293
Pedology	Not Soil	0.034
	Haplic Gleisol (GX)	0.034
	Red Latosol (LV)	0.243
	Red Nitosol (NV)	0.370
	Argisol (P)	0.155
	Litholic Neosol (RL)	0.034
	Quartzarenic Neosol (RQ6)	0.062
	Fluvic Neosol (RY1)	0.034
	Haplic Planosol (SX)	0.034
Geomorphology	Water	0.035
	Fluvial Plain (Apf)	0.035
	Plain and River Terrace (Aptf)	0.035
	River Terrace (Atf)	0.035
	Round tops (Convex) (Dc)	0.157
	Structural Dissecting - Convex tops (DEc)	0.063
	Tabular Interflux (Dt)	0.252
	Pediaplano Degradado Inumado (Pgi)	0.390
Land use and land cover (LULC)	Water	0.037
	Vegetation	0.097
	Pasture	0.251
	Growth	0.251
	Exposed Soil	0.326
	Built-up Area	0.037

The weights defined by specialists focused on the capacity of support from the environment into retaining or reducing solid waste contamination. For the geology variable, Formation Candoi and Serra Geral Group received the highest weights since they are composed of metamorphic rocks (Serra Geral)

and are less suitable to water infiltration. Other Formations and areas are formed by sedimentary rocks, presenting pores between its layers and being more susceptible to leaching contamination. The pedology variable followed a similar analysis as the geology variable, and soils more susceptible to contamination and erosion

problems, like Gleisoil and Neosol were select as less suitable for a landfill implementation. Argisol and Latosol are more commons soils, and their location and granulometric characteristics reduce the risk of contamination. The geomorphology variable weights prioritized areas composed by Tabular Interflux and Pediplano as these are interfluvial reliefs with plain structures and fewer drainage areas. Finally, for the LULC variable, pasture and agricultural areas receive higher weights since most of the region is composed of them.

The Consistency Index (CI) and the Consistency Ratio (RC) were calculated to evaluate the pairwise comparison matrix. This matrix is consistent with RC values between 0% and 10% (Saaty, 1990). A CI of 0.085% and a CR of 0.057% were obtained for the matrix of variables. For the geology, geomorphology, pedology, and LULC subclasses of variables, the values obtained for CI were 0.005%, 0.011%, 0.0005%, and 0.039%, and the values for CR were 0.004%, 0.008%, 0.0003%, and 0.031% respectively, indicating how feasible the weighting process was.

The inference model was constructed using the WLC method (Equation (5)). In this method, each cell of the resultant map represents the sum of the products between the variable of interest (Table 2) and the weight assigned with, that were obtained by AHP (Table 4). The results were grouped into four classes of environmental and socioeconomic suitability levels: low, medium, high and very high.

$$\text{synthesis map} = \sum_{i=1}^n w_i x_i \quad (5)$$

where n is the number of variables used to construct the inference model; w is the weight assigned to variable i; X is the normalized values of variable i. Both weight and variable values vary from 0 to 1. The estimated synthesis map is presented on this scale.

Results and discussion

Identification of restricted areas

Synthesis Map 1 (Figure 3) shows all the restricted areas to the installation of a landfill in the study region. These areas represent 49.6% (912,289 ha) of the total region (1,838,294 ha). "drainage distance" was the variable that most contributed to this percentage. This variable represents 63.3% of the total restricted areas and is followed by the "airport distance" (27%) and "Conservation Unit area" (9.7%) variables. The study area has a high drainage density and the decision to adopt two attributes for the "drainage distance" variable (at 200 and 500 m distance) influenced the results. Felicori and Marques (2017) indicated that 93.5% of the restricted areas in their study were composed of the "drainage network density" variable in their inference model. We found that the "airport distance" is another variable that highly affecting the restricted area values. It required a 20 km radius stretched restricted area beyond the municipality in which the airports are located.

Figure 3. Restricted areas for the installation of a landfill in the study area.

41% of the 32 landfills in the study area are located in restricted areas (Figure 3). The lifetime of some of these landfills is nearing the end (CETESB, 2017), implying the requirement of new areas or its expansion. Colvero et al. (2018) showed similar results and found that 78% of the current landfills and dumps in their area are located in restricted sites according to Brazilian law. Our results and those obtained by Colvero et al. (2018) demonstrate noncompliance with federal law regarding landfill area selection in our country.

Identification of areas with different levels of environmental and socioeconomic suitability

Synthesis Map 2 (Figure 4) shows available areas with different environmental and socioeconomic suitability levels for landfill installation. Approximately half (50.4%) of the

study area is suitable for a landfill. 53.1% of these areas are concentrated in high (36.6%) and very high (16.5%) suitability levels. Areas with very high levels are predominantly distributed in the eastern portion of the region. These results are probably associated with soil and relief characteristics. The relief in this portion of the region is the Pediplano Degradado Inumado (Pgi), and the predominant soil is Red Latosol (LV), which has a clayey texture, being more appropriate (in relation to the other geophysical characteristics of the area) to receive a landfill (IBGE, 2007). Areas with high and very high suitability levels are the farthest from drainage and built-up heavily populated areas. They present less permeable soils (Nitosols), more resistant rocky substratum (Candói Formation) and a flattened relief (Pediplano Degradado Inumado).

Figure 4. Available areas with environmental and socioeconomic suitability levels for the landfill Installation.

Using the population and the solid waste projection data (Section 3.1), we verified that the dimension of the area required for a consortium landfill, to attend the 32 municipalities for a period of 20 years, is 192 hectares. These areas were subtracted from Synthesis Map 2, and the inference model showed that only 7% (120,610 ha) of the available area is suitable for installing a consortium landfill (Figure 5). However, 84.7% of these areas are characterized by high and very

high suitability levels. The greater the suitability level of the area, the higher the chances of reducing the negative impacts on both the population and the environment. The proportion of available areas was quantified according to its suitability level (Table 6). Other studies (Pavani et al., 2019; Felicori and Marques, 2017) also applied this approach to identify the minimum size required for a consortium landfill area and also obtained good results.

Figure 5. Areas available for a consortium landfill to serve the 32 municipalities for a period of 20 years.

Table 6. The proportion of areas with environmental and socioeconomic suitability levels for the landfill.

Environmental and socioeconomic suitability level	The proportion of area (Synthesis Map 3)	
	Hectares (ha)	Percentage
Low	9,210.19	7.6%
Medium	9,258.43	7.7%
High	36,275.51	30.1%
Very High	65,865.55	54.6%
Total	120,609.69	100%

The study area is composed of 32 municipalities, and Presidente Prudente is the municipality with the largest solid waste generation rate (SNIS, 2016). The cost of transporting solid waste to a landfill is high for the municipal government. Transportation can also result in soil contamination if improperly performed. To minimize transport costs, logistic

issues should be considered at the consortium landfill area selection (Spigolon et al. 2018). We applied buffers of 20, 40 and 100 km to identify the spatial distribution of the available areas around the largest solid waste generation municipality (Figure 6). The proportion of these areas was quantified according to their suitability levels (Table 7).

Figure 6. Spatial distribution of the available areas around the largest solid waste generating municipality.

Table 7. Area suitability levels according to distance from the largest solid waste generating municipality.

Environmental and socioeconomic suitability level	Proportion of available areas					
	20 km radius		40 km radius		100 km radius	
	Area		Area		Area	
	ha	%	ha	%	ha	%
Low	191.14	100%	1,748.58	11.7%	5,831.26	6.3%
Medium	0.00	0%	0.00	0%	3,473.83	3.8%
High	0.00	0%	1,438.84	9.6%	24,971.71	27.0%
Very High	0.00	0%	11,767.26	78.7%	58,282.83	63.0%
Total	191.14	100%	14,954.68	100%	92,559.63	100%

Areas included in the 40 km to 100 km radius from the largest solid waste generation pole (Presidente Prudente) presented a better overall scenario for the landfill consortium. We noted that 88.1% (Table 7) of the areas with high and very high suitability levels are at least 40 km away from the Presidente Prudente center, while the 20 km radius concentrated areas with low suitability levels (Table 7). Areas of low suitability can result in negative impacts on both environmental and socioeconomic resources as they have permeable soils (Gleysols and Neosols), flooded reliefs (Plain and River Terrace) and built-up areas.

Identification of regional poles for consortium landfill installation

The 32 municipalities in the Pontal do Paranapanema region occupy a longitudinal extension of approximately 200 km, but most of the municipalities have a low number of inhabitants. Felicori and Marques (2017) point out that a minimum distance between urban centers of small municipalities should be considered to create a consortium landfill. Groups of three-to-five municipalities were created based upon their proximity (Figure 7). In this case, each group was denominated a regional pole (Figure 8) and these areas were classified according to their environmental and socioeconomic suitability

levels. A radius of 100 km (50% of the longitudinal extension of the studied area) was adopted between the center of a municipality and its neighbors. For each regional pole, the minimum area required to install a consortium

landfill with a 20-year life-span was obtained (Table 8). The distribution of the available areas was analyzed according to their suitability level by regional pole (Figure 9).

Figure 7. Regional poles for consortium landfill installation.

Figure 8. Spatial distribution of available areas by regional poles according to their suitability level.

It was verified that, except for regional pole number 4, the minimum size required for a

consortium landfill corresponds to approximately 30% of the total area of each regional pole (Table

8). More available areas were found when the regional poles approach was compared with the single consortium approach among the 32

municipalities. Hence, the area required for a consortium landfill installation directly influences the amount of area available.

Table 8. Distribution of the available areas by regional poles.

Regional Pole number	Number of Municipalities/ Number of Inhabitants (2010 Census)	Available Areas (ha)*	Minimum size required for the area	
			Hectares (ha)	Percentage (%)
1	3 / 50,662	159.521,22	61.198,65	38.4
2	3 / 84.267	74.004,51	18.128,62	24.5
3	5 / 32.022	64.105,05	18.428,58	28.7
4	4 / 248.584	60.266,23	4.576,00	7.6
5	5 / 66.070	219.310,28	75.124,28	34.3
6	3 / 25.570	173.994,23	68.977,04	39.6
7	4 / 38.247	68.871,04	22.181,36	32.2
8	5 / 38.281	105.958,83	38.083,61	35.9

*Area was calculated using synthesis map 2.

Figure 9. Distribution of available areas by regional pole according to their suitability level.

The spatial distribution of regional poles 2 and 4 was analyzed with the synthesis map 1 (Figure 3). As such, the largest solid waste generating municipality (Presidente Prudente), requiring a larger area for a consortium landfill installation, is located within regional pole number 4. Most (75%) of the regional poles presented areas with high or very high suitability levels (Figure 9). This revealed that the restricted areas are responsible for a decrease in the percentage of the available areas, mostly because of the airport's location.

In short, this study presented a new approach to identify candidate areas for a landfill installation. We observed that, by creating regional poles, our model was advantageous to

both environmental and socio-economic perspectives. Future research may focus on the installation stage, which requires additional research like the Environmental Impact Study (EIA) and the Environmental Impact Report (RIMA) (CONAMA n°01/1986). EIA/RIMA involves field campaigns and geotechnical analysis to better evaluate the proposed area for the final stages of a landfill installation. Regardless, in our study, we also contributed to the indication of prohibited areas under law, regulations, and resolutions to install a landfill. After evaluating the proposed regions, we recommend integrating economic indicators associated with the specificities of each municipality, such as the cost of waste

transportation and the cost of the installation itself.

Conclusion

This study presented a new framework to select consortium landfill areas by integrating MCDA and Fuzzy logic associated with regional characteristics in a GIS environment. With this approach, we were able to locate areas suitable for a consortium landfill installation in the Pontal do Paranapanema region using a macro analysis supported by national law and regulations. This approach was able to identify areas with high or very high suitability levels for consortium landfill installation, both serving a large number of municipalities (32) and a small number (from three to five municipalities). The study showed that, when considering a small number of municipalities, more areas with high and very high suitability are available.

The Fuzzy logic made it possible to model uncertainties related to environmental and socioeconomic variables used to construct the inference model. Additionally, the MCDA and AHP applications were essential for minimizing uncertainties related to the landfill area selection task. We also demonstrated that identifying available areas around the largest solid waste generation pole is an important decision that may favor logistic issues related to the installation. Geotechnical studies are recommended for the candidate areas indicated here. Additionally, future research could include other variables in the inference model and verify its improvement according to their own regional characteristics.

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