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CARACTERIZAÇÃO DOS RESÍDUOS SÓLIDOS URBANOS DOS MUNICÍPIOS PAULISTAS POR SETOR CENSITÁRIO

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RESUMO

O aterro sanitário tem sido uma alternativa frequentemente praticada para destinação de resíduos municipais, constituindo uma maneira conveniente de lidar com a questão em desenvolvimento. Entretanto, a seleção de áreas para aterros sanitários é uma decisão complexa, pois envolve questões sociais, econômicas e ambientais. O presente estudo teve como objetivo a análise multicritério, com uso de processo analítico hierárquico em ambiente de modelagem computacional de um SIG, para classificar áreas do estado de São Paulo, quanto ao seu grau de adequação enquanto alternativa locacional para aterro sanitário. Para tanto, foram considerados 15 critérios, selecionados com base em uma revisão sistemática e meta-análise, sendo os quais: declividade do solo, distância das águas superficiais, distância das áreas protegidas, distância das fontes subterrâneas, distância das falhas, distância das estradas, distância das linhas de energia, distância das indústrias, distância dos aeroportos, distância de áreas residenciais urbanas, distância de áreas agrícolas, distância do patrimônio cultural, distância de gasodutos e oleodutos, além do uso do solo. A partir desses critérios, foram elaborados três cenários (ambiental, social e econômico), posteriormente, analisados de forma integrada, considerando as seguintes alternativas: (i) cenários com pesos iguais; (ii) cenário ambiental com 60% de importância, social e o econômico com 20%; (iii) cenário social com 60% de importância, ambiental e o econômico com 20%; e (iv) cenário econômico com 60% de importância, ambiental e o social com 20%. Então, os aterros do estado de São Paulo foram espacializados a fim de verificar quantos se encontram em áreas adequadas. Espera-se que a classificação realizada neste estudo possa apoiar as autoridades competentes na gestão de resíduos municipais, particularmente, na seleção de alternativas locacionais adequadas para implantação de aterros sanitários.

Palavras-chave: Sistemas de informações geográficas (SIG), Processo Hierarquico Analítico, Aterro sanitário.

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LISTA DE ABREVIATURAS E SIGLAS

AHP – Processo Hierárquico Analítico

CI - Consistency Index

CR – Consistency Ratio

GIS - Geographic information system

MCDM - Multi-criteria decision making

MCDP - Multi-criteria decision processes

MSW – Municipal Solid Waste

NIMBY – Not in my backyard

RSU - Resíduos Sólidos Urbanos

SIG - Sistema de Informações Geográficas

SUMÁRIO

1. INTRODUÇÃO

Encontrar áreas para aterros sanitários está entre as questões-chave com maior demanda na atualidade e, ao mesmo tempo, enfrenta desafios associados as diversas restrições locacionais. O crescimento da população urbana, com respectivo aumento na geração de resíduos, concomitante à diminuição da disponibilidade de terras, progressivamente ocupadas pela expansão das áreas edificadas, em conjunto com às restrições sociais, econômicas e ambientais, torna a identificação de alternativas locacionais um dos maiores desafios da sociedade contemporânea.

Em meados da década passada, a população mundial gerava cerca de sete a dez bilhões de toneladas de resíduos sólidos (resíduos domésticos, comerciais, industriais e de construção civil) por ano (UNEP ISWA, 2015). Deste montante, dois bilhões de toneladas por ano correspondem a resíduos urbanos e esta taxa aumenta de acordo com o crescimento da população (FRACALANZA; BESEN, 2016).

Apesar da demanda crescente, encontrar um local para aterro não é trivial; diferentes regulamentos e restrições locais dificultam a busca por um local adequado. A localização do aterro também está se tornando cada vez mais restritiva devido à crescente consciência ambiental (NASCIMENTO et al., 2019), diminuição do financiamento governamental, e extrema oposição política e social (SENER; SÜZEN; DOYURAN, 2005).

Embora necessário, aterros sanitários não são bem vistos pela população e sua distância das áreas urbanas estão aumentando ao longo do tempo (ALVARENGA DE MORAIS et al., 2019). Além disso, áreas próximas a um aterro, muitas vezes, podem acarretar na diminuição dos valores das propriedades (SIMSEK et al., 2014a), o que aumenta a oposição da comunidade local, conhecida como "*not in my backyard*" (NIMBY). Assim, projetos de aterro sanitário, que são benéficos para os habitantes da cidade ou região como um todo, encontram grande resistência por parte dos habitantes que vivem nas localidades próximas. Contudo, é importante garantir um bom equilíbrio entre distância, custos e emissões ao selecionar a alternativa locacional para um novo aterro.

Considerando a reconhecida eficiência dos Sistemas de Informação Geográficas (SIGs) para análise de dados espaciais, bem como os múltiplos critérios envolvidos na seleção de alternativas locacionais, a combinação de SIG com o Processo Hierárquico Analítico (AHP), pode constituir uma abordagem adequada, para classificar o grau de adequação de áreas disponíveis para implantação de aterro sanitário.

O AHP, técnica estruturada para organizar e analisar decisões complexas, baseadas em matemática e psicologia, tem sido utilizada como uma ferramenta poderosa nos processos de seleção de aterros sanitários. Por exemplo, Kara e Doratli (2012) usaram GIS e AHP para encontrar áreas adequadas no norte de Chipre, e Al-Ruzouq et al. (2018) usaram essas ferramentas para encontrar áreas adequadas na região de Polog, localizada na República da Macedônia, enquanto Khodaparast et al. (2018) as usaram para encontrar áreas adequadas na cidade de Qom, Irã.

Nesse contexto, o presente estudo teve como objetivo a análise multicritério, com uso de processo analítico hierárquico em ambiente de modelagem computacional de um SIG, para classificar áreas do estado de São Paulo, quanto ao seu grau de adequação enquanto alternativa locacional para aterro sanitário. A inovação proposta está no uso de 15 critérios de análise, selecionados com base em uma revisão sistemática e meta-análise de 57 artigos, que analisaram alternativas locacionais para implantação de aterros sanitários.

2. ARTIGO

2.1 Spatial analysis for landfill site selection in São Paulo State

Abstract

The sanitary landfill has been a frequently practiced alternative for municipal waste disposal, constituting a convenient way to deal with the developing issue. However, the selection of areas for sanitary landfills is a complex decision, as it involves social, economic and environmental issues. The present study aimed at multi-criteria analysis, using a hierarchical analytical process in a GIS computational modeling environment, to classify areas in the state of São Paulo, in terms of their degree of suitability as a locational alternative for a sanitary landfill. For that, 15 criteria were considered, selected based on a systematic review and meta-analysis, which are: soil slope, distance from surface water, distance from protected areas, distance from underground sources, distance from faults, distance from roads , distance from power lines, distance from industries, distance from airports, distance from urban residential areas, distance from agricultural areas, distance from cultural heritage, distance from gas and oil pipelines, in addition to land use. Based on these criteria, three scenarios were created (environmental, social and economic), later analyzed in an integrated manner, considering the following alternatives: (i) scenarios with equal weights; (ii) environmental scenario with 60% importance, social and economic with 20%; (iii) social scenario with 60% importance, environmental and economic with 20%; and (iv) economic scenario with 60% importance, environmental and social with 20%. Then, the landfills in the state of São Paulo were spatialized in order to verify how many are in suitable areas. It is expected that the classification carried out in this study can support the competent authorities in the management of municipal waste, particularly in the selection of suitable locational alternatives for the implementation of sanitary landfills.

Keywords: Geographic information system (GIS), Landfill sites, Analytical Hierarchy Process (AHP).

Introduction

Defining landfill sites is an important issue due to decreasing land availability caused by the population and urban growth (REZAEISABZEVAR; BAZARGAN; ZOHOURIAN, 2020), which consequently increases the amount of municipal solid waste (MSW) generated (OSRA; KAJJUMBA, 2020).

The world population generates about seven to ten billion tons of solid waste per year, comprising household, commercial, industrial, and civil construction waste (UNEP ISWA, 2015). From this amount, two billion tons corresponds to MSW, which increases in line with population growth (FRACALANZA; BESEN, 2016).

In Brazil, the largest economy in Latin America, proper disposal in landfills received almost 60% of all MSW collected. The remainder, 40%, was dumped in inappropriate places, that is 30.3 million tons of MSW ending up going to dumps or uncontrolled landfills, which do not have a set of systems and measures necessary to protect the people's health and the environment against damage and degradation (ABRELPE, 2021).

Using a scientific method for site selection is essential to avoid environmental issues, such as soil and water contamination (BAHRANI et al., 2016; DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2014), social problems such as the Not In My Backyard (NIMBY) syndrome (SIMSEK et al., 2014; YILDIRIM, 2012) and economic issues that refer to the landfill site feasibility (NASCIMENTO et al., 2020; SUMATHI; NATESAN; SARKAR, 2008).

Although, finding those suitable areas for landfill sitting is a complicated task due to several criteria that must be considered (REZAEISABZEVAR; BAZARGAN; ZOHOURIAN, 2020). To make the procedure more accurate and convenient, many researchers have used GIS-based (Geographic Information System) multi-criteria decision making (MCDM) to eliminate this complexity (Gorsevski et al., 2012; Yazdani et al., 2017; Santhosh and Sivakumar Babu, 2018; Kamdar et al. 2019; Langa et al. 2021).

Regarding the remarkable efficiency of GIS in site selection and the numerous criteria involved in decision making, the combination of GIS with AHP has been used as a powerful tool in landfill site selection processes. For example, Kara and Doratli (2012) used GIS and AHP to find suitable areas in Northen Cyprus, and Al-Ruzouq et al.(2018) used those tools to find suitable areas in Polog Region, located in the Macedonia Republic, while Khodaparast et al. (2018) used GIS and AHP to find suitable areas in Qom city, Iran. GIS is a convenient tool to be used in landfill site-selection studies.

The present study aimed at multi-criteria analysis, using a hierarchical analytical process in a GIS computational modeling environment, to classify areas in the state of São Paulo, in terms of their degree of suitability as a locational alternative for a sanitary landfill. The proposed innovation lies in the use of 15 analysis criteria, selected based on a systematic review and meta-analysis of 57 articles, which analyzed locational alternatives for the implementation of sanitary landfills.

Methods and study area

Study area

São Paulo is the most populous state in Brazil, with approximately 46,6 million inhabitants in 2021, living in 645 municipalities, with a total area of 248.219,481 km^2 (IBGE, 2021). It presents a relatively high relief, with 85% of its surface between 300 to 900 meters (m) of altitude, 8% below 300 m, and the remaining 7% above 900 m. The state is also the biggest MSW producer in Brazil, generating approximately 40.8 thousand tons per day (CETESB, 2020).

The restrictions for landfill sites were applied to Sao Paulo state because it is the most populous state in Brazil, with approximately 22% of the total inhabitants, with the country's highest economic activity concentration (DALMO et al., 2019), representing almost one-third of its GDP (IBGE, 2019).

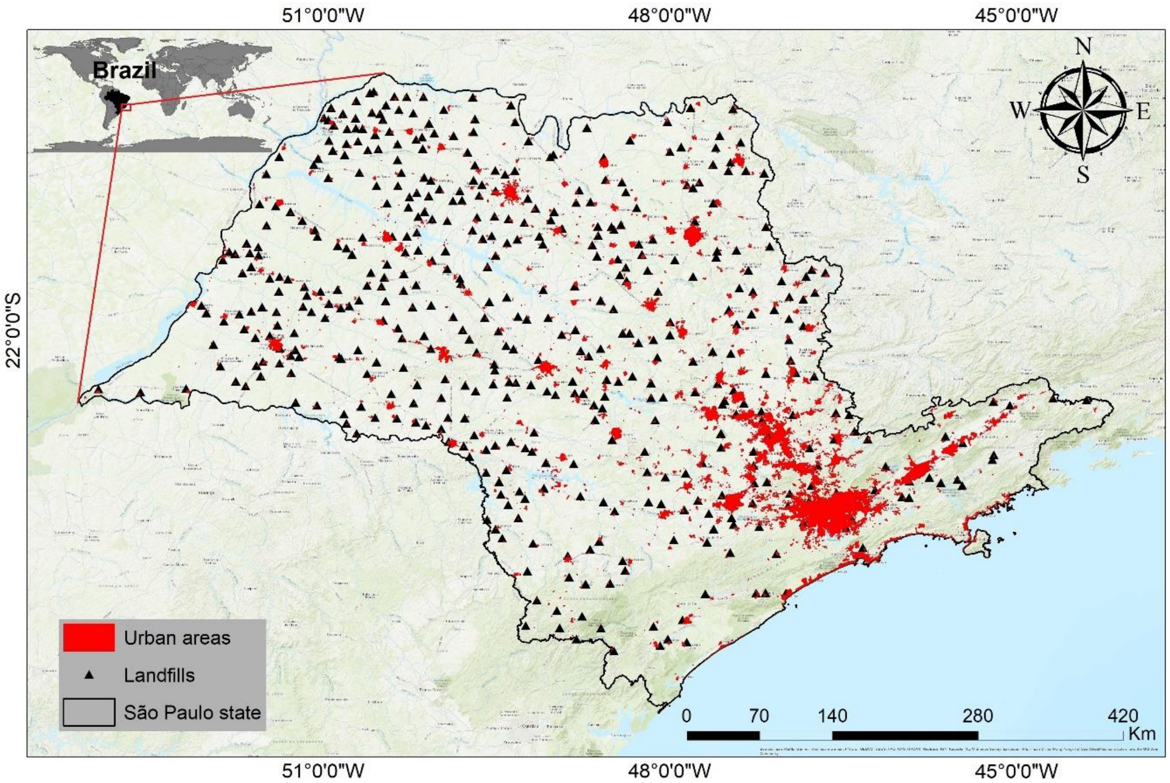

Figure 01 - Location of landfills in the state of São Paulo, Brazil.

Method

Identifying MSW's disposal areas requires an extensive assessment of several factors (MELKNEW, 2022). This study integrates GIS and AHP based on specific evaluation criteria to select new appropriate MSW disposal places in São Paulo State. Various criteria can be considered in the landfill siting, and this study followed sequential steps. The first step grips the evaluation criteria selection. This study selected the requirements based on a scientific article entitled "A worldwide meta-analysis review of restriction criteria for landfill siting using geographic information systems" (NASCIMENTO et al., 2020). The article systematically reviewed and statistically analyzed the most environmental, economic, and social restrictions used in the academic literature from 1996 to 2018.

This article used the five most cited environmental, social, and economic criteria found in the meta-analysis review. The five environmental criteria are (i) distance from surface waters, (ii) distance from groundwater founts, (iii) distance from protected areas, (iv) slope, and (v) distance from faultlines. The five social criteria are (i) distance from urban areas, (ii) land use, (iii) distance from cultural, archaeological, and tourism areas, (iv) distance from parks and recreation centers, and (v) distance from agricultural areas. The five economic criteria are (i) distance from roads, (ii) distance from airports, (iii) distance from powerlines, (iv) distance from industries, and (v) distance from gas and oil pipelines.

The flowchart illustrating the general methodology structure is shown in (Figure 02).

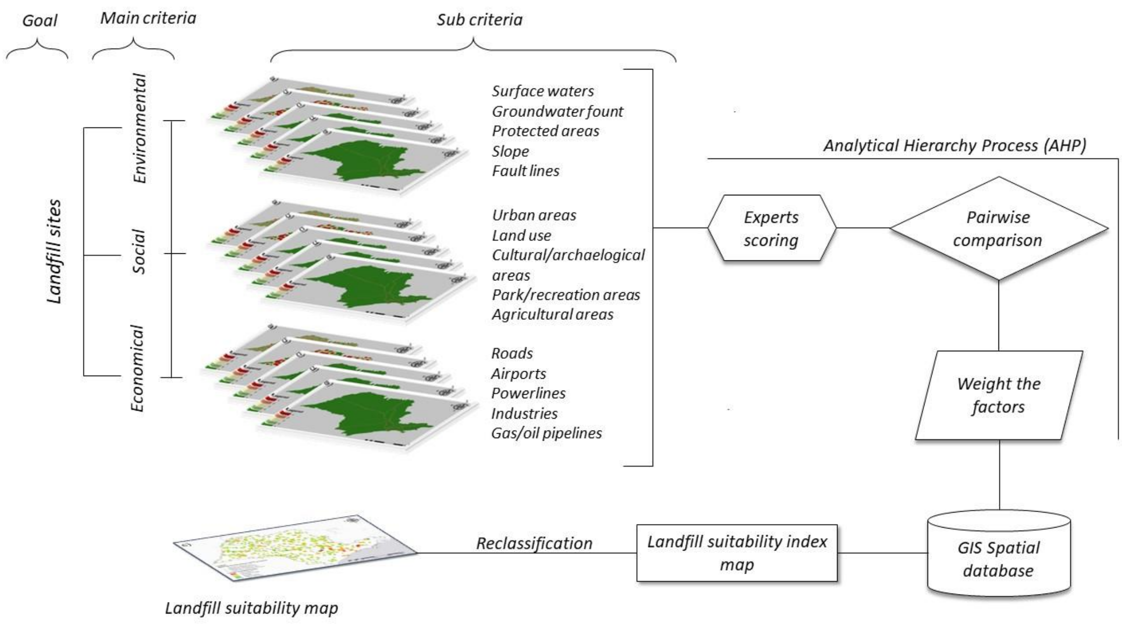

Figure 02 - Methodology flowchart**.**

The second step in criteria selection is preparing each criteria layer using various GIS spatial analysis processes. The spatial database used in this study was created using several data sources at different scales (Table 01). All data layers were stored, projected, manipulated, analyzed, and visualized using ArcGIS version 10.5. The data were georeferenced using the World Azimuthal Equidistant. First, the Euclidean Distance tool was used, and all the data were resampled to a resolution of 30m, and then the Reclassify tool was used. In this step, the images were reclassified into five categories: 1- Unsuitable, 2- Less suitable, 3-Moderate suitable, 4-Suitable, and 5-Very suitable. Finally, in the third step, the AHP was used to give weights to each criterion and compare them. Finally, the Weighted overlay tool was used to develop the final suitability map.

Three scenarios were created: environmental, social, and economic. Then, four scenarios were created from the environmental, social, and economic using different weights. First, a scenario with equal importance between environmental, social, and economic criteria. Second, where it was given 60% of importance for the environmental scenario, 20% for the social, and 20% of importance to the economic criteria were given. The other two scenarios repeat the same methodology as the previous one, but one is assigned the importance of 60% for the social criterion and the other assigns the value of 60% for the economic criterion.

Table 01 - Spatial data used to create the scenarios for landfill sites in the state of São Paulo, Brazil.

Parameter	Source	Scale
Distance from surface waters	(IBGE, 2017)	1:250.000
Distance from groundwater fount	(CPRM-SIAGAS, 2016)	-
Distance from protected areas	(MMA, 2016)	1:25000
Slope	(CPRM, 2010)	1:50.000
Distance from faultlines	(CPRM, 2006)	1:1.000.000
Distance from urban areas	(EMBRAPA, 2015)	1:250.000
Land use	(MAPBIOMAS, 2021a)	1:250.000
Distance from cultural and archaeological areas	(IPHAN, 2014)	1:250.000
Distance from parks and recreation areas	(Open Street map 2021)	-
Distance from agricultural areas	(MAPBIOMAS, 2021a)	1:250.000
Distance from roads	(Open Street map 2019)	-
Distance from airports	(ANAC, 2013)	-
Distance from powerlines	(MAPBIOMAS, 2021b)	1:250.000
Distance from industries	(Open Street map 2021)	-
Distance from gas and oil pipelines	(MAPBIOMAS, 2021b)	1:250.000

Weighting criteria

The AHP model is a type of multi-criteria decision-making process (MCDM) that can be used to examine complicated physical, economic, and technological issues, involving pairwise comparisons of decision variables, in this case, the spatial factors (Vaidya; Kumar, 2006; Ishizaka; Labib, 2011). According to Razandi et al. (2015), first, it is necessary to define the problem, create the criteria to be used and apply the pairwise comparisons and the comparison matrix. Then, an eigenvalue technique must be used for the weights of each criterion and, finally, compute the matrix consistency index.

For constructing the paired comparison matrix, each factor is classified concerning the other factors, assigning a relative dominance value between 1 and 9. The consistency index (CI) of a comparison matrix is calculated from the following calculation:

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

where λ_{max} is the largest or main eigenvalue of the matrix, and n is the order of the matrix.

The consistency ratio (CR) is obtained by comparing the CI to the appropriate value in a set of numbers where each is an average random CI derived from a sample of randomly generated reciprocal matrices using 1/5, 1/4, …, 1 ..., 4, 5, in the case of this article:

$$CR = CI/RI$$

where RI is the mean of the resulting CI depending on the order of the matrix.

A CR above 0.1 indicates inconsistent treatment of particular factor ratings, necessitating a review of the judgments in the matrix (Saaty, 2003). In general, the AHP calculates the relative weights of each determinant based on a questionnaire survey; these weights are used to generate a pairwise comparison matrix.

Tables 02 to 04 shows the criteria chosen for the location and the landfill selection value and their respective bias (environmental, social, and economical).

Table 02: Environmental criteria used for landfill site selection suitability, value, and respective bias

criteria	value	bias
Distance from surface waters (m)	<200	1
	200-300	2
	300-500	3
	500-800	4
	>800	5
Distance from groundwater fount (m)	<100	1
	100-200	2
	200-400	3
	400-500	4
	>500	5
Slope (%)	<2	1
	2-5	5
	5-10	4
	10-20	3
	20-30	2
	>30	1
Distance from protected areas (m)	<250	1
	250-500	2
	500-750	3
	750-1000	4
	>1000	5
Distance from fault lines (m)	<100	1
	100-300	2
	300-500	3
	500-1000	4
	>1000	5

Table 03: Social criteria used for
landfill site selection suitability, value, and respective bias

criteria	value	bias
Distance from urban/residential areas (m)	<500	1
	500-1000	2
	1000-2000	3
	2000-3000	4
	>3000	5
Land Use	Forest Formation	1
	Savanna Formation	1
	Mangrove / Wooded Restinga	1
	Flooded Field and Swamp Area	1
	Countryside Training	2
	Apicum / Rocky Outcrop	1
	Other Non-Forest Formations	2
	Pasture	5
	Agriculture	3
	Soy / Cane / Rice	4
	Other Temporary Crops	4
	Coffee	3
	Citrus	3
	Other Perennial Crops	3
	Forestry	3
	Agriculture and Grassland Mosaic	3
	Beach, Dune, and Sand	1
	Urbanized Area	1
	Mining / Other Non-Vegetable Areas	4
	River, Lake, and Ocean / Aquaculture	1
Distance from cultural heritage/archeological/tourism areas (m)	<2000	1
	2000-3000	2
	3000-4000	3
	4000-5000	4
	>5000	5
Distance from parks/recreation areas(m)	<500	1
	500-1000	2
	1000-2000	3
	2000-3000	4
	>3000	5
Distance from agricultural areas (m)	<400	1
	400-800	2
	800-1000	3
	1000-3000	4

>3000	5

Table 04: Economical criteria used for
landfill site selection suitability, value, and respective bias

criteria	value	bias
Distance from roads (m)	<100	1
	100-300	2
	300-500	3
	500-3000	4
	3000-5000	5
	>5000	1
Distance from airports (km)	<10	1
	10-15	2
	15-20	3
	20-25	4
	>25	5
Distance from power lines (m)	<30	1
	30-130	2
	130-200	3
	200-250	4
	>250	5
Distance from industries	<750	1
	750-1000	2
	1000-2000	3
	2000-3000	4
	>3000	5
Distance from gas and oil pipelines (m)	<250	1
	250-500	2
	500-750	3
	750-1000	4
	>1000	5

Environmental restrictions

Distance from surface waters

These criteria primarily aim to avoid surface water pollution by solid waste. By creating leachate and gaseous pollutants, landfills pose a risk to lakes, wetlands, ponds, and rivers, necessitating the creation of a buffer zone away from surface waterways (REZAEISABZEVAR; BAZARGAN; ZOHOURIAN, 2020). This criterion was the most cited in the articles reviewed by NASCIMENTO et al. (2020), it was used in more than 77% of them.

Groundwater fount

Among the various negative impacts a landfill can cause if it is in inappropriate conditions, groundwater pollution is one of the most critical problems to deal with (Santhosh and Sivakumar Babu, 2018). This criterion aims to avoid groundwater pollution, locating landfills on or close to aquifers should be avoided(Rahmat et al., 2017).

Distance from protected areas

This criterion aims to ensure that the landfill site is far from sensitive areas to keep threatened or endangered species free from landfill pollution and harmful human activities (Nascimento et al., 2020; Mahmood et al., 2021).

Slope

The slope affects drainage, soil water content, erosion potential, and overland and subsurface flow velocity (Donevska et al., 2012; Gorsevski et al., 2012; Nascimento et al., 2017). A steep slope increases drainage from the landfill to the downstream, which raises downstream water pollution hazards, intensifies engineering work, and increases the risk of landslides (Djokanović et al., 2016; Nascimento et al., 2017). A flat location, on the contrary, would have an impact on runoff drainage. This criterion is very important to ensure appropriate landfill construction and operation.

Distance from faultlines

Fault lines and fracture zones increase rock permeability, increasing groundwater pollution's danger (SAATSAZ; MONSEF; RAHMANI, 2018). The primary purpose of this criterion is to prevent landfill damage and pollution leakage that earthquakes and earth movement could cause. Hence avoiding faults is also vital for landfill siting (REZAEISABZEVAR; BAZARGAN; ZOHOURIAN, 2020).

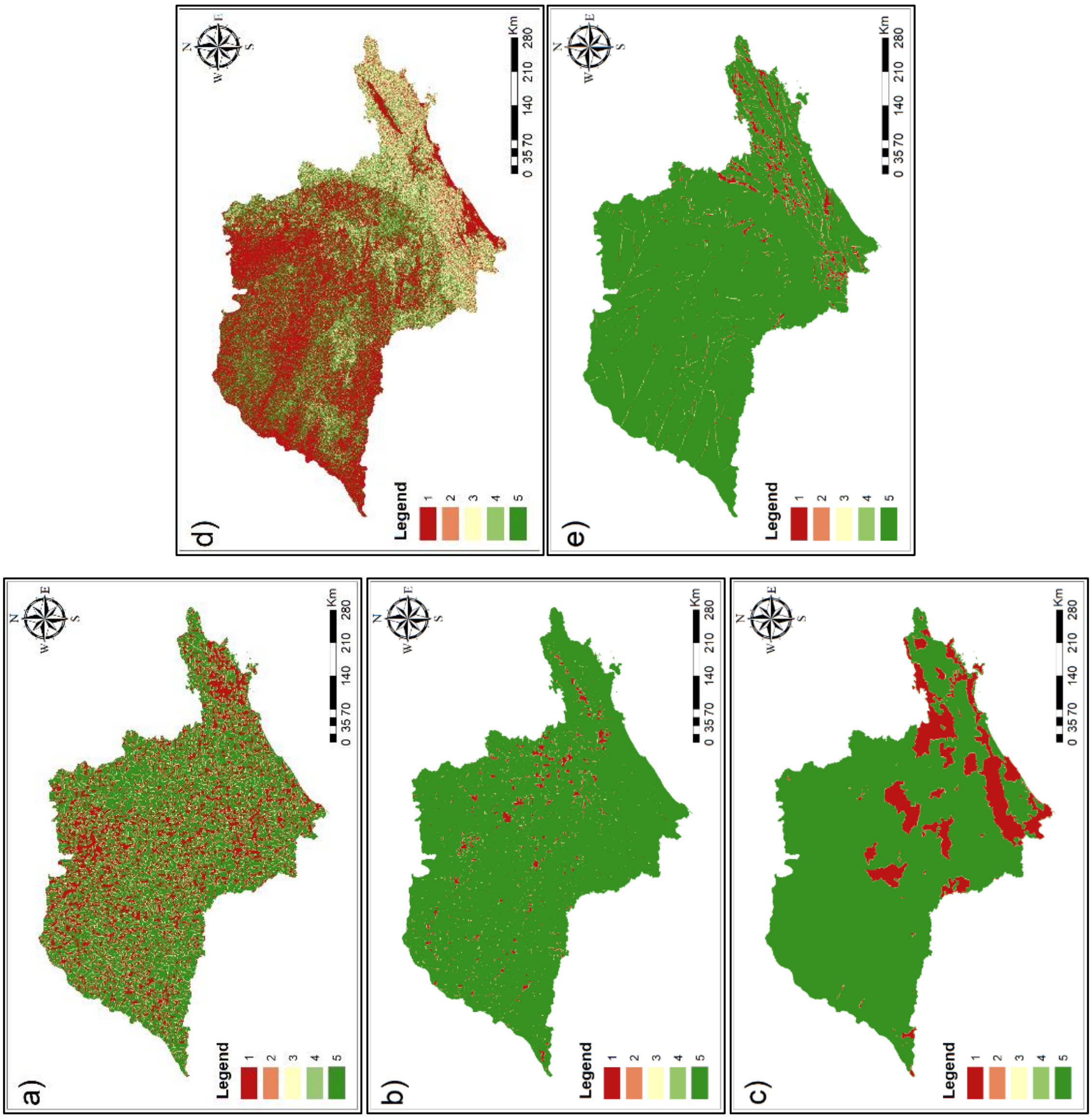

Figure 03 - Maps for each restriction considering the environmental scenario for landfill site selection. a) Distance from surface water, b) Distance from groundwater fount, c) Distance from protected areas, d) Slope and e) Distance from fault lines.

Social restrictions

Distance from urban areas

This criterion aims to determine the permissible distance for a landfill, taking into account waste logistics and the welfare of inhabitants. The chosen place should be close enough to the city for convenient disposal and low transportation costs, yet far enough away to avoid causing health or environmental issues (AKSOY; SAN, 2017). The chosen land should not be too far from the waste generation source because this will increase transportation costs and clean-up times, which are very important in disaster recovery (CHENG; THOMPSON, 2016). A landfill is considered to have a significant impact on those living near a site due to excessive noise, traffic, odor, litter, and the presence of scavengers (GHOBADI; BABAZADEH; BAGHERI, 2013).

Land use

Land use defines the use of the natural environment by humans. Land use classes include agricultural land, forests, and areas influenced by human activities, such as settlements and industrial, military, and archeological zones. Land use maps distinguish these classes and include plans for currently unused land (SIMSEK et al., 2014). It is an essential criterion in site selection planning due to its reliance on understanding both the natural environment and the kinds of land uses envisaged ((RAHMAT et al., 2017).

Distance from cultural and archaeological areas

Aiming to protect and preserve national cultural heritage, including various paleontological, archaeological, and historical sites, cultural and archaeological areas are considered inappropriate to be within or near a landfill site (CHABUK et al., 2016; KONTOS; KOMILIS; HALVADAKIS, 2003).

Distance from parks and recreation areas

This criterion aims to guarantee the protection of recreation areas from the inconvenience generated by the proximity of a sanitary landfill can cause, such as a bad smell. This criterion was taken into consideration in fewer than 6% of all articles reviewed by NASCIMENTO et al., (2020), this value is considered very low since these areas are important for socializing and recreation.

Distance from agricultural areas

This criterion prevents productive areas from municipal solid waste disposal (NASCIMENTO et al., 2020). The distance from agricultural areas was used in approximately 16% of articles reviewed by NASCIMENTO et al.(2020), and the values varied from 50 m, used by Charnpratheep et al.(1997) for rice and orchard fields, to 800 m, used by Motlagh and Sayadi (2015), which did not specify the type of agriculture.

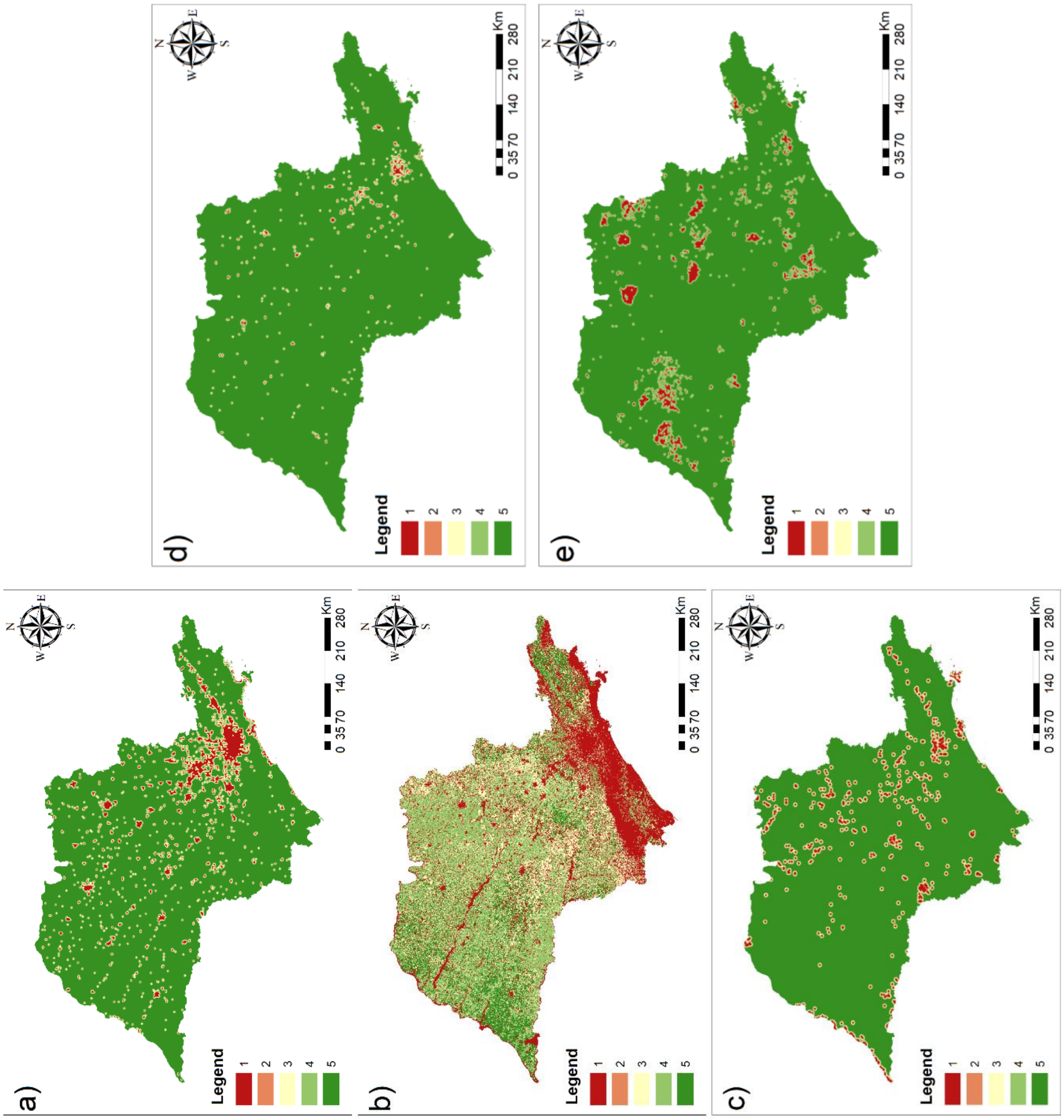

Figure 04 - Maps for each restriction considering the social scenario for landfill site selection. a)Distance from urban areas, b) Land use, c) Distance from cultural and archaeological areas , d) Distance from park and recreation areas and e) Distance from agricultural areas.

Economic restrictions

Distance from roads

The major goal of this criterion is to find a balance between logistics needs and regulatory distance from transportation infrastructures when establishing a landfill, which should be located at a reasonable distance from existing roads in order to save money on road building (NASCIMENTO et al., 2020).

Distance from airports

The landfill site should be far from any airport/airbase to prevent birds from disrupting aircraft during landing and take-off (MALLICK, 2021). Furthermore, airplane traffic may cause waste dust to rise (AHMAD; AHAMAD; YUSOFF, 2013). However, the primary goal of this criterion is to guarantee that the landfill site is located far enough away from the airport to prevent aircraft crashes.

Distance from powerlines

This criterion aims to ensure the maintenance of public utilities such as power lines, excluding areas with this infrastructure, but a landfill also requires electricity for its operation. So, an electricity supply is also crucial for landfill siting and can't be very far (DEMESOUKA; VAVATSIKOS; ANAGNOSTOPOULOS, 2014).

Distance from industries

This criterion aims to guarantee that the sanitary landfill will not harm the industries, either by the devaluation of the area due to the proximity, or the bad smell, the noise or even soil and water contamination. The distance from industries was used in less than 9% of articles reviewed by (NASCIMENTO et al., 2020) and could be considered as a geographical restriction since it depends on whether or not the city has industries.

Distance from gas and oil pipelines

This criterion aims to protect from serious impact of spontaneous fires that result from combustion of solid waste on the gas pipelines distance, also to avoid damage to this type of infrastructure (CHABUK et al., 2016).

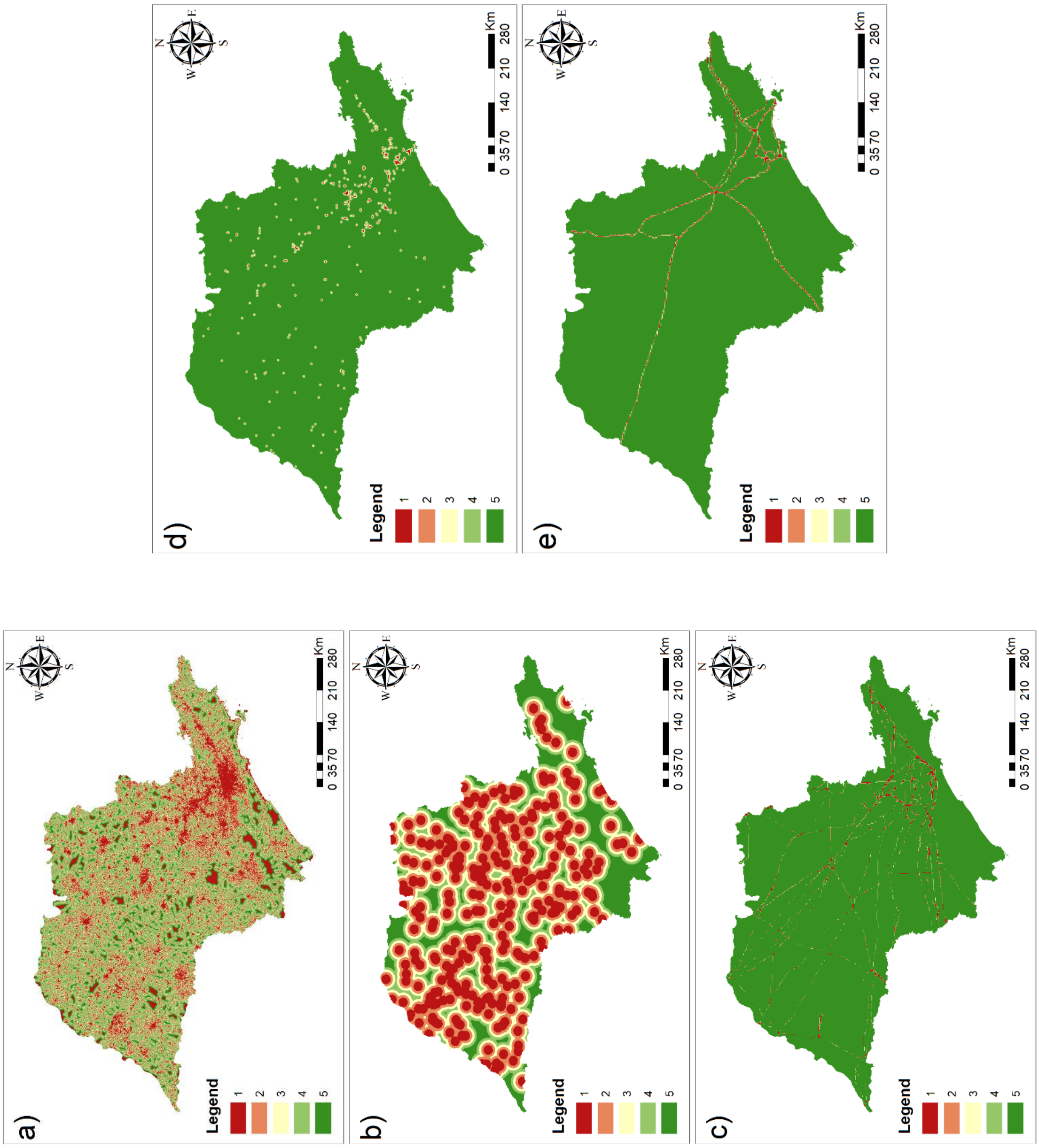

Figure 05 - Maps for each restriction considering the economic scenario for site selection. a) Distance from roads, b) Distance from airports, c) Distance from power lines, d) Distance from industries, and e) Distance from gas and oil pipelines.

Results

The evaluation results of the different weighting criteria using GIS and AHP regarding the importance of environmental, social, and economic biases are shown in Figure 06, after a reclassification into five classes: unsuitable, less suitable, moderate suitable, suitable, and highly suitable.

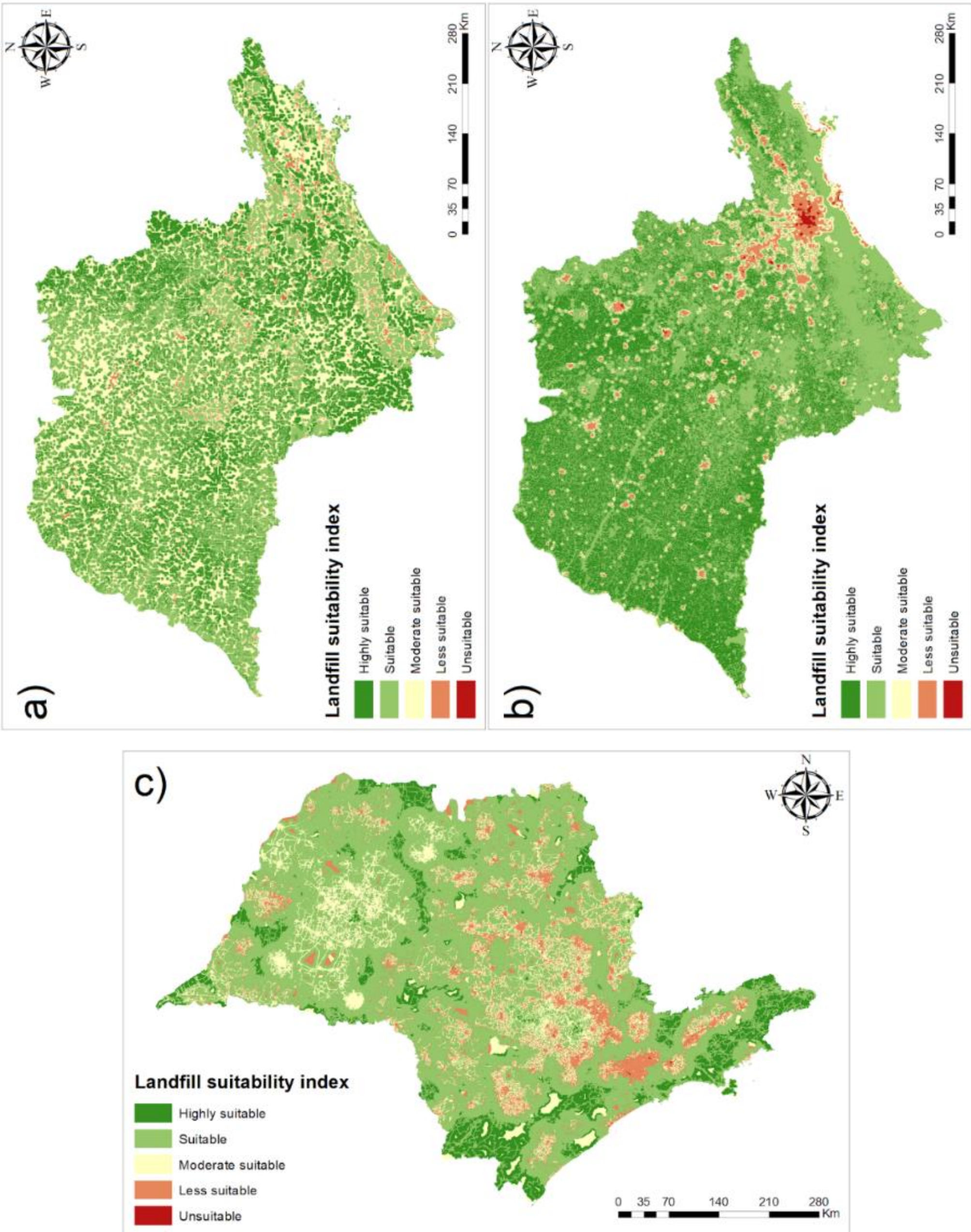

Figure 06: Landfill Suitability Map using: a) environmental criteria; b) social criteria and c) economical criteria.

After that, the class areas were calculated, aiming to conclude which of the three biases under analysis is the most restrictive/permissive for the installation of sanitary landfills. Table 05 below shows the results obtained, concluding that the social criteria are the most restrictive since it has the largest area classified as "Unsuitable"; still, being the most permissive bias with the highest amount of area classified as "Highly Suitable".

Table 05: Area of each classification by bias.

Classification	Environmental (km²)	Social (km²)	Economical (km²)
Unsuitable	50	616	81
Less suitable	6.205	8.444	28.253
Moderate Suitable	69.197	16.477	107.046
Suitable	113.340	125.365	89.250
Highly Suitable	60.007	97.897	24.169

Below are Tables 06, 07 and 08 that show the paired assessments of environmental, social and economic criteria for the implementation of sanitary landfills. In determining the AHP weight of the environmental bias, the surface water criterion is the most effective to acquire the maximum weight (40.82%) followed by groundwater fount (23.89%), while the failure criterion is determined as the least effective with a weight of 6.33%. On the social side, urban areas (46.87%) and land use (28.64%) are the most effective criteria and, finally, on the economic side, distance from roads (45.84%) and airports (26.46%) are the most effective. About the CR, all biases had their consistency ratio values lower than 0.1, which indicates a good consistency of the judgments used for the comparison.

Table 06: Pairwise evaluation of environmental factors.

Matrix		Slope	Surface waters	Protected areas	Groundwater fount	Faultlines	Weight
		1	2	3	4	5	
Slope	1	1	1/3	1	1/2	3	14,48%
Surface waters	2	3	1	3	2	5	40,82%
Protected areas	3	1	1/3	1	1/2	3	14,48%

Groundwater fount	4	2	1/2	2	1	3	23,89%
Faultlines	5	1/3	1/5	1/3	1/3	1	6,33%

λ_{max} =5.075 and CR = 0.017 ≤ 0.1

Source: adapted from BPMSG (2022).

Table 07: Pairwise evaluation of social factors.

Matrix		Land Use	Urban Areas	Cultural /Archaeological	Agricultural Areas	Recreation areas	Weight
		1	2	3	4	5	
Land Use	1	1	1/3	4	5	4	28,64%
Urban Areas	2	3	1	4	6	4	46,87%
Cultural /Archaeological	3	1/4	1/4	1	2	1	9,48%
Agricultural Areas	4	1/5	1/6	1/2	1	1/2	5,53%
Park/ Recreation Areas	5	1/4	1/4	1	2	1	9,48%

λ_{max} =5.159 and CR = 0.035 ≤ 0.1

Source: adapted from BPMSG (2022).

Table 08: Pairwise evaluation of economical factors.**Matrix**		Roads	Powerlines	Industries	Airport	Gas/Oil and Pipelines	Weight
		1	2	3	4	5	
Roads	1	1	3	5	3	5	45,84%

Powerlines	2	1/3	1	1	1/3	3	12,44%
Industries	3	1/5	1	1	1/3	1	8,77%
Airport	4	1/3	3	3	1	5	26,46%
Gas/Oil and Pipelines	5	1/5	1/3	1	1/5	1	6,50%

λ_{max} =5.211 and CR = 0.047 ≤ 0.1

Source: adapted from BPMSG (2022).

After evaluating the criteria for each bias individually, criteria of importance were established for each of them. Figure 07 below shows four maps of the adequacy of sanitary landfills, the first with the three biases with equal importance, the second with the environmental bias with 60% importance, and the others with 20% each, the third in the same way but with the social bias standing out over the others and, finally, the economic bias with greater importance.

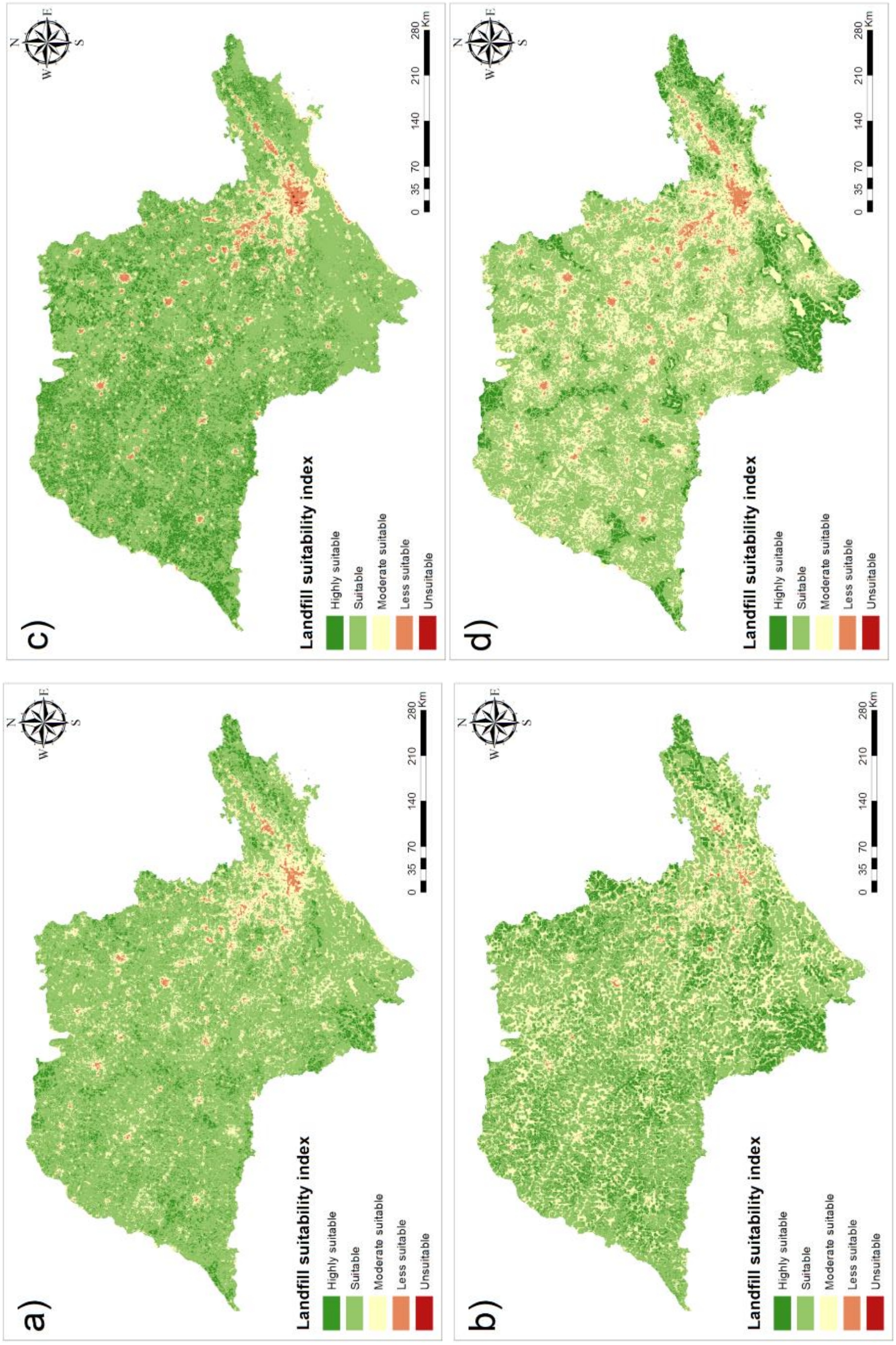

Figure 07: Landfill Suitability Map with a) equal importance of biases; b) most important: environmental bias; c) most important: social bias and d) most important: economical bias.

Table 09 below illustrates the area per square kilometer of each class on each of the maps. It is possible to conclude that when the three biases are placed on an equal footing, it is the approach that has the smallest area in the "Unsuitable" class, being quite permissive when compared to the other approaches. When the social bias is evaluated as the most important, it is the most restrictive approach, since it contains the largest amount of area in the "Unsuitable" class, despite having the largest area within the "Highly Suitable" class.

Table 09: Area of each classification by the importance of bias.

Classification	**Equal importance (km^2)**	**Environmental - most important bias (km^2)**	**Social - most important bias (km^2)**	**Economical - most important bias (km^2)**
Unsuitable	5	10	76	20
Less suitable	3.220	2.054	5.965	6.547
Moderate Suitable	39.225	60.704	22.688	81.278
Suitable	184.507	148.222	173.895	142.866
Highly Suitable	21.842	37.809	46.175	18.088

Based on the procedures previously performed, an analysis was carried out on the location of sanitary landfills already installed in the state of São Paulo, seeking to assess in which class they are located and, if located in "Unsuitable" or "Less Suitable" areas, whether they receive a lot of solid waste. Figure 08 below illustrates the location of sanitary landfills classified according to their location and reception of solid waste, even concerning environmental, social, and economic biases.

It is possible to conclude that according to the location of the sanitary landfills located in the state of São Paulo, according to the criteria of the three biases, none are located in an "Unsuitable" location. That said, map a) presented only nine landfills in the "Less Suitable" class, while 251 and 96 landfills are in the "Suitable" and "Highly Suitable" classes, respectively. Map b), which deals with the social bias criteria, showed 16 landfills in the "Less Suitable" class, 308 in the "Suitable" class, and 86 in the "Highly Suitable" class, with the bias with the highest number of landfills in the last two classes.

Finally, map c) shows the result of the locations of landfills in the state of São Paulo using only the criteria of economic bias. Analyzing the map, it is possible to verify that most of the verified landfills are in the "Less Suitable" and "Moderate Suitable" classes (104 and 270, respectively).

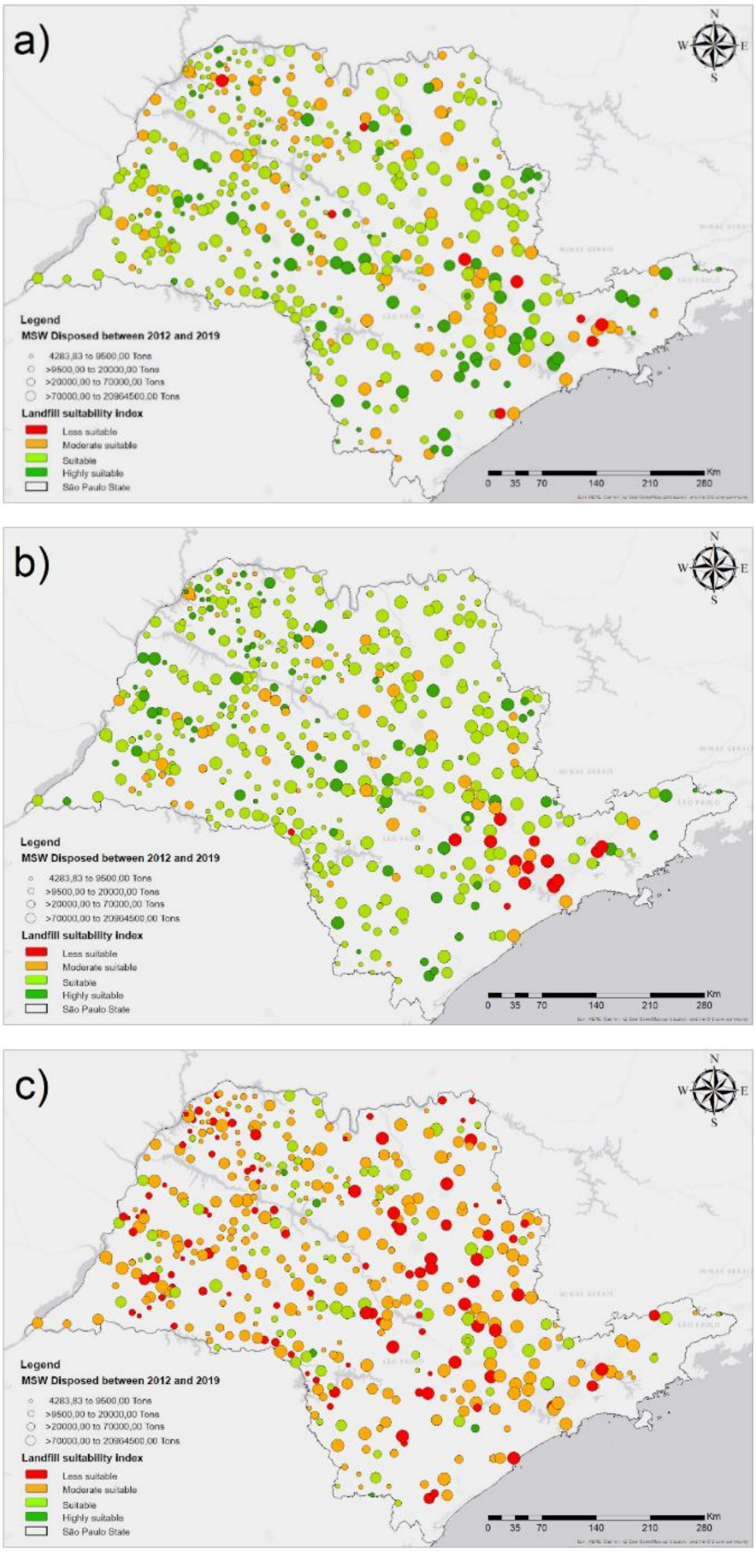

Figure 08: Location of sanitary landfills and classification of their location according to a) environmental bias criteria; b) social bias criteria and c) economic bias criteria.

Then, the location of these landfills was evaluated using the criteria used in Figure 09. Therefore, in the map a), with the criteria of equal importance, it is possible to verify that most of the landfills are located in the "Suitable" (62,85%) and "Moderate Suitable" (35,24%), while only three are situated in the "Less Suitable" class, similar behavior to map b) which contains 66.45% and 26.75% in the respective classes.

The map in letter c) illustrates the sanitary landfills classified with the criteria of social bias standing out over the others. The figure illustrates that most landfills are located in the "Suitable" classes with 74.95%. Letter d) of Figure 09 illustrates the distribution of sanitary landfills located in the state of São Paulo with the criteria of economic bias standing out over the others, demonstrating that 62.42% of the landfills were classified in "Less Suitable" areas, presenting the worst result among the maps in the figure.

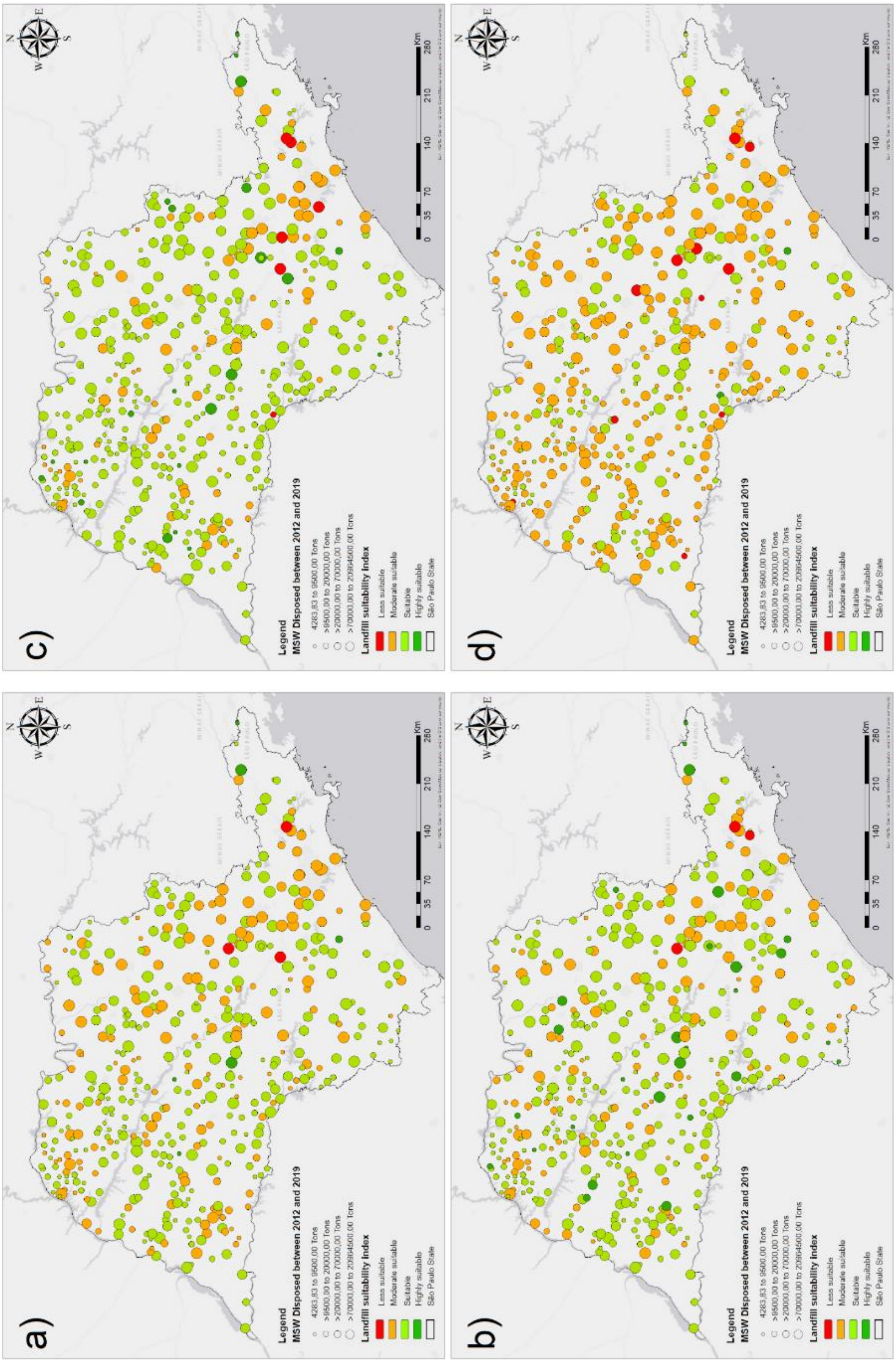

Figure 09: Location of sanitary landfills and classification of their location according to a) equal importance of biases; b) most important: environmental bias; c) most important: social bias and d) most important: economical bias.

Discussion

The use of geographic information systems has intensified in several areas of knowledge, such as utilities (Nourjou; Hashemipour, 2017; Moura; Procopiuck, 2020; Matos et al., 2021), commerce (Trubint, 2012; Astbury; Thurstain-Goodwin, 2014), government tools (Tsai et al., 2009; Ganapatim, 2011) and, as in this study, urban planning (Gao et al., 2006).

In this sense, studies that deal with the choice of places for implementation of sanitary landfills using multi-criteria decision processes (MCDP) have already been widely carried out. Melo et al. (2006) carried out this type of analysis in the city of Cachoeiro de Itapemirim in the state of Espírito Santo and found 15 areas between 20 and 200 acres apt to receive sanitary landfills. Alves et al. (2009) carried out similar studies for cities in the state of Rio de Janeiro, but they sought to assess whether an existing sanitary landfill was in accordance with all the criteria established by law and found that only some parts of the landfill in question met the criteria.

Chang et al. (2008), Zamorano et al. (2008), and Özkan et al. (2020), all with the same objective, but in different locations, used fuzzy methodologies to successfully reach the desired results, evidencing the multiple approaches that geographic information systems allow to reach significant results.

About the AHP, Alkaradaghi et al. (2019) used various MDCP methods for landfill site selection in Sulaymaniyah Province, Iraq. The results obtained in a way that, according to the methodologies used, are used in 80% of the area, are not left, each method classified a confusion between the methods. The method in question is widely used for this type of study, Aksoy and San (2019) used it with the same objective in the city of Antalya, Turkey, dealing with the criteria of DEM, aspect, slope, temperature, precipitation, earthquake zone, distance to road, visibility from the road, distance to population density, geology, landslide density, and distance to a fault line and obtained the results that the geology criterion (20.19%) was the one with the greatest weight, while the temperature (1.36%) had the lowest. In addition to these two studies, there are several others with the application of the MDCP technique used in this project (Ghobadi et al., 2013; Djokanovic et al., 2016; Chabuk et al., 2017; Rahmat et al., 2017; Saketa et al., 2017; Adewumi et al., 2019; Saketa et al., 2022).

The main difference between this article and those mentioned above is the size of the study area, which is much larger than the others, and the comparison between criteria of different biases (environmental, social, and economic). In the literature review carried out to carry out this work, the only article found that performs very similar procedures in a larger study area was by Nascimento et al. (2017), who spatially evaluated the environmental susceptibility of landfills throughout the state of California in the United States.

In the Brazilian scenario, few works address this issue in contexts as comprehensive as the state of São Paulo. Nascimento and Silva (2014) carried out a case study of a GIS-based approach to identify problems in locating suitable areas for the installation of a new landfill in the municipality of Bauru and concluded that there are few suitable and moderately suitable areas in the city, and the most of the municipality is unable to install a new landfill.

In a larger context, Senkiio et al. (2022) carried out a methodological approach integrating MCDP and logistic analysis to propose suitable areas for consortium landfills in the Paraíba do Sul River basin and found that 69% of the study area is inadequate to support the installation of a consortium landfill. Of the others, 26.03% were classified as highly adequate, so 11 areas were selected to be destined for joint landfills to serve the region for 20 years.

Morais et al. (2021) estimated the distances traveled to dispose of MSW on a regional scale considering all municipalities in the state of São Paulo and found that the number of sanitary landfills decreased, especially individual ones, which receive MSW only from the city where it is located, however, The number of consortium landfills is increasing, as is the number of municipalities that share the same disposal site, causing the distances to transport MSW from urban areas to final disposal sites to increase by around 55% from 2012 to 2017, contributing to high fuel consumption and greenhouse gas emissions.

Conclusions

In this work, GIS and AHP were combined to select suitable landfill sites throughout the state of São Paulo, Brazil. The landfill site selection criteria taken into account were: Slope, Distance from surface waters, Distance from protected areas, Distance from groundwater founts, Distance from fault lines, Distance from roads, Distance from power lines, Distance from industries, Distance from airports, Distance from urban residential areas, Distance from agricultural areas, Distance from the cultural heritage, Distance from gas and oil pipelines and Land Use. In this context, all these criteria were separated into environmental, social, and economic biases.

The results obtained showed that the AHP method worked satisfactorily, and that, for the environmental bias, the criteria with greater weight were surface water and groundwater fount, respectively; as for the social bias, the biggest criteria were urban areas and land use. Finally, on the economic side, distance from roads and airports are the most effective. To improve the model's assertiveness, it is recommended that future studies evaluate the inclusion of new criteria such as NDVI, precipitation, and land surface temperature, among others.

By carrying out this work, environmental planners and public managers can apply them to inappropriate sites for landfills, identifying criteria priorities and selecting the most appropriate site in each criterion.

3. CONSIDERAÇÕES FINAIS

Neste trabalho, as abordagens SIG e AHP foram combinadas, como alternativa metodológica para classificar o grau de adequação de alternativas locacionais, destinadas à implantação de aterros sanitários no estado de São Paulo, Brasil. Como critérios de análise foram considerados: Declividade do solo, Distância das águas superficiais, Distância das áreas protegidas, Distância das fontes subterrâneas, Distância das falhas, Distância das estradas, Distância das linhas de energia, Distância das indústrias, Distância dos aeroportos, Distância de áreas residenciais urbanas, Distância de áreas agrícolas, Distância do patrimônio cultural, Distância de gasodutos e oleodutos e Uso do Solo. Tais critérios foram organizados e analisados de forma integrada nos cenários ambiental, social e econômico.

A partir dos resultados obtidos pode-se considerar que o método AHP proporcionou uma abordagem satisfatória para o propósito do estudo. Para o cenário ambiental, os critérios com maior peso foram as águas superficiais e subterrâneas, respectivamente; do ponto de vista econômico, a distância de rodovias e aeroportos apresentam o maior peso. Para melhorar a assertividade do modelo, recomenda-se que estudos futuros avaliem a inclusão de novos critérios como NDVI, precipitação, temperatura da superfície terrestre, entre outros.

Espera-se que a classificação realizada neste estudo possa apoiar as autoridades competentes na gestão de resíduos municipais, particularmente, na seleção de alternativas locacionais adequadas para implantação de aterros sanitários.

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