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Geoprocessing for municipal solid waste disposal: a multi-criteria analysis in the CICANASTRA consortium

Geoprocessamento para destinação de resíduos sólidos urbanos: uma análise multicritério no consórcio Cicanastra

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Resumo: A gestão de Resíduos Sólidos Urbanos (RSU) representa um dos principais desafios ambientais da atualidade, alinhando-se às metas dos Objetivos de Desenvolvimento Sustentável (ODS), que visam reduzir os impactos ambientais até 2030. Esse problema se agrava em municípios de pequeno porte, onde a ausência de fontes naturais exploráveis – e, consequentemente, a falta de royalties – limita os investimentos em infraestrutura para a destinação adequada dos resíduos. A disposição irregular de RSU causa impactos que exigem intervenções e soluções sustentáveis. Nesse cenário, a Política Nacional de Resíduos Sólidos (PNRS), instituída pela Lei Federal nº 12.305/2010, estabelece diretrizes para a erradicação de lixões e incentiva a implantação de aterros sanitários por meio da cooperação intermunicipal, otimizando recursos e ampliando a vida útil dessas estruturas. Para garantir a escolha de locais adequados à instalação de aterros, o geoprocessamento otimiza a seleção de aterros integrando múltiplos critérios espaciais. A metodologia utilizou Sistemas de Informação Geográfica e lógica booleana para o cruzamento de critérios técnicos via classificação binária (1 – Apto; 0 – Inapto), atendendo às normas ABNT NBR 10004:2004 e NBR 13896:1997. Como as diretrizes determinam restrições absolutas, abdicou-se de métodos de ponderação multicritério, como Lógica Fuzzy ou AHP. A flexibilização dessas abordagens violaria o caráter excludente da legislação tornando a lógica booleana a abordagem coerente com a normativa. Sob essa premissa, foram analisados fatores como proximidade de núcleos urbanos, restrições ambientais e uso do solo. Os resultados indicam que apenas 5% da área total do Consórcio Intermunicipal CICANASTRA atende aos critérios estabelecidos, com destaque para os municípios de Medeiros e São Roque de Minas. Além de demonstrar a eficácia do geoprocessamento na gestão sustentável de resíduos, o estudo resultou no desenvolvimento de um modelo gráfico automatizado, exportado para Python e disponibilizado no GitHub, promovendo a democratização da metodologia e sua replicação em outros contextos.

Palavras-chave: geoprocessamento; resíduos sólidos urbanos; análise multicritério; lógica booleana; SIG.

Abstract: The management of Municipal Solid Waste (MSW) represents one of today's foremost environmental challenges, aligning with the targets of the Sustainable Development Goals (SDGs), which aim to reduce environmental impacts by 2030. This problem is compounded in small municipalities, where the absence of exploitable natural resources – and, consequently, the lack of royalty revenue – limits investment in infrastructure for proper waste disposal. Irregular MSW disposal causes impacts that call for sustainable interventions and solutions. Within this context, Brazil's National Solid Waste Policy, established by Federal Law No. 12,305/2010, sets out guidelines for eliminating open dumps and encourages the implementation of sanitary landfills through intermunicipal cooperation, optimizing resources and extending the operational lifespan of these facilities. To ensure the selection of sites suitable for landfill installation, geoprocessing optimizes landfill site selection by integrating multiple spatial criteria. The methodology employed

Geographic Information Systems (GIS) and Boolean logic to cross-reference technical criteria through binary classification (1 – Suitable; 0 – Unsuitable), in accordance with the Brazilian Association of Technical Standards (ABNT) standards NBR 10004:2004 and NBR 13896:1997. Because these guidelines establish absolute restrictions, multi-criteria weighting methods such as Fuzzy Logic or the Analytic Hierarchy Process (AHP) were not used. Applying these more flexible approaches would undermine the exclusionary nature of the legislation, making Boolean logic the approach most consistent with the regulatory framework. Under this premise, factors such as proximity to urban centers, environmental restrictions, and land use were analyzed. The results indicate that only 5% of the total area of the CICANASTRA Intermunicipal Consortium meets the established criteria, with the municipalities of Medeiros and São Roque de Minas standing out. In addition to demonstrating the effectiveness of geoprocessing in sustainable waste management, the study led to the development of an automated graphical model, exported to Python and made available on GitHub, promoting the democratization of the methodology and its replication in other contexts.

Keywords: geoprocessing; municipal solid waste; multicriteria analysis; Boolean logic; Geographic Information Systems.

1. Introduction

The management of Municipal Solid Waste (MSW) in Brazil has advanced through the development of regulations aimed at establishing guidelines for the environmentally sound disposal of these materials. An important milestone in this process was the 2002 publication of the document prepared by the Special Temporary Study Committee on Solid Waste (ABNT/CEET-00:001.34), which classified solid waste according to its nature, contributing to safer and more sustainable disposal practices (ABNT NBR 10004:2004). Despite this regulatory progress, the implementation of effective solutions for waste disposal still faces significant challenges, particularly in the final stages of the process (Blasius et al., 2023).

The final disposal of solid waste is one of the most critical phases of environmental management, as it involves the definitive placement of materials classified according to ABNT NBR 10004:2004. However, waste characterization, although essential, does not by itself guarantee environmentally sound disposal. In practice, the Brazilian reality is still marked by the use of open dumps and controlled landfills, contrary to the guidelines of the Brazilian National Solid Waste Policy (PNRS), established by Federal Law No. 12,305/2010, which, in Article 7, items II and V, sets out the order of priority in waste management – non-generation, reduction, reuse, and recycling – and the elimination and remediation of open dumps, prioritizing disposal in duly licensed sanitary landfills.

Even more than a decade after the enactment of the PNRS, inadequate waste disposal practices persist, particularly in small municipalities. This difficulty is not limited to a shortage of financial and technical resources; it also stems from the absence or inadequacy of Municipal Integrated Solid Waste Management Plans, required by the legislation itself as a condition for accessing federal funding; a shortage of specialized technical staff in municipal administrations; and the institutional coordination challenges involved in forming and maintaining intermunicipal consortia (Ministério do Meio Ambiente [MMA], 2022). Added to this are political resistance to regional cooperation and the lack of accessible methodologies to help public managers select technically suitable sites for final waste disposal, making PNRS implementation a challenge that goes beyond financing and requires integrated territorial planning solutions.

This scenario reinforces the need for more effective approaches that minimize uncertainty in site selection and promote greater economic feasibility for the implementation of sanitary landfills.

Within this context, geoprocessing stands out as an essential tool for the territorial planning of municipal solid waste management. By using Geographic Information Systems (GIS) combined with Boolean logic, it is possible to simultaneously analyze multiple environmental and regulatory criteria, ensuring more precise decision-making aligned with legal guidelines (Blasius et al., 2023; Elkhrachy et al., 2023). This approach enables the identification of suitable sites for sanitary landfills by integrating digital cartographic databases, mathematical modeling, and spatial analysis.

The use of geoprocessing for solid waste management is not exclusive to Brazil and has been applied in various international contexts. Recent studies demonstrate its effectiveness in selecting waste disposal sites across different socio-environmental realities, such as the work of Añasco Quispe & Sánchez Vásquez (2022) in Azángaro, Peru; Elkhrachy et al. (2023) in Najran, Saudi Arabia; and Macalam et al. (2023) in Butuan, Philippines. However, the applicability of this methodology must be adapted to local specificities, since the choice of analysis criteria depends on the environmental, social, and economic particularities of each region.

In small municipalities without royalty[1] revenue, the lack of infrastructure and technical resources represents an additional challenge for solid waste management. Accordingly, geoprocessing applications become even more relevant, as they support decision-making in a systematic and replicable way.

This scenario is exemplified by the Intermunicipal Consortium of Serra da Canastra, Alto São Francisco, and Médio Rio Grande (CICANASTRA), located in the west-central region of Minas Gerais and comprising eight small cities: Medeiros, São Roque de Minas, Vargem Bonita, Piumhi, Doresópolis, Capitólio, Pimenta, and Córrego Fundo, with a total population of 75,786 inhabitants and an area of 5,548 km^2 (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024). These municipalities lie within the Alto São Francisco and Médio Rio Grande watersheds, where most still rely on open dumps or controlled landfills, in non-compliance with PNRS guidelines.

1 Royalties are financial payments made by companies or individuals that exploit natural resources (e.g., minerals, oil, or gas) to the holder of the rights to those resources (Moraes, 2023).

Accordingly, this study uses spatial analysis with GIS and Boolean logic to identify and classify the areas best suited for an intermunicipal sanitary landfill within CICANASTRA's territory. The analysis considers environmental, regulatory, topographic, and land-use criteria established by NBR 13896/1997 and other relevant legislation. As part of this work, an automated graphical model was developed, exported to Python, and published on GitHub, so the methodology can be replicated in other contexts

2. Methodology

2.1. Study area characterization

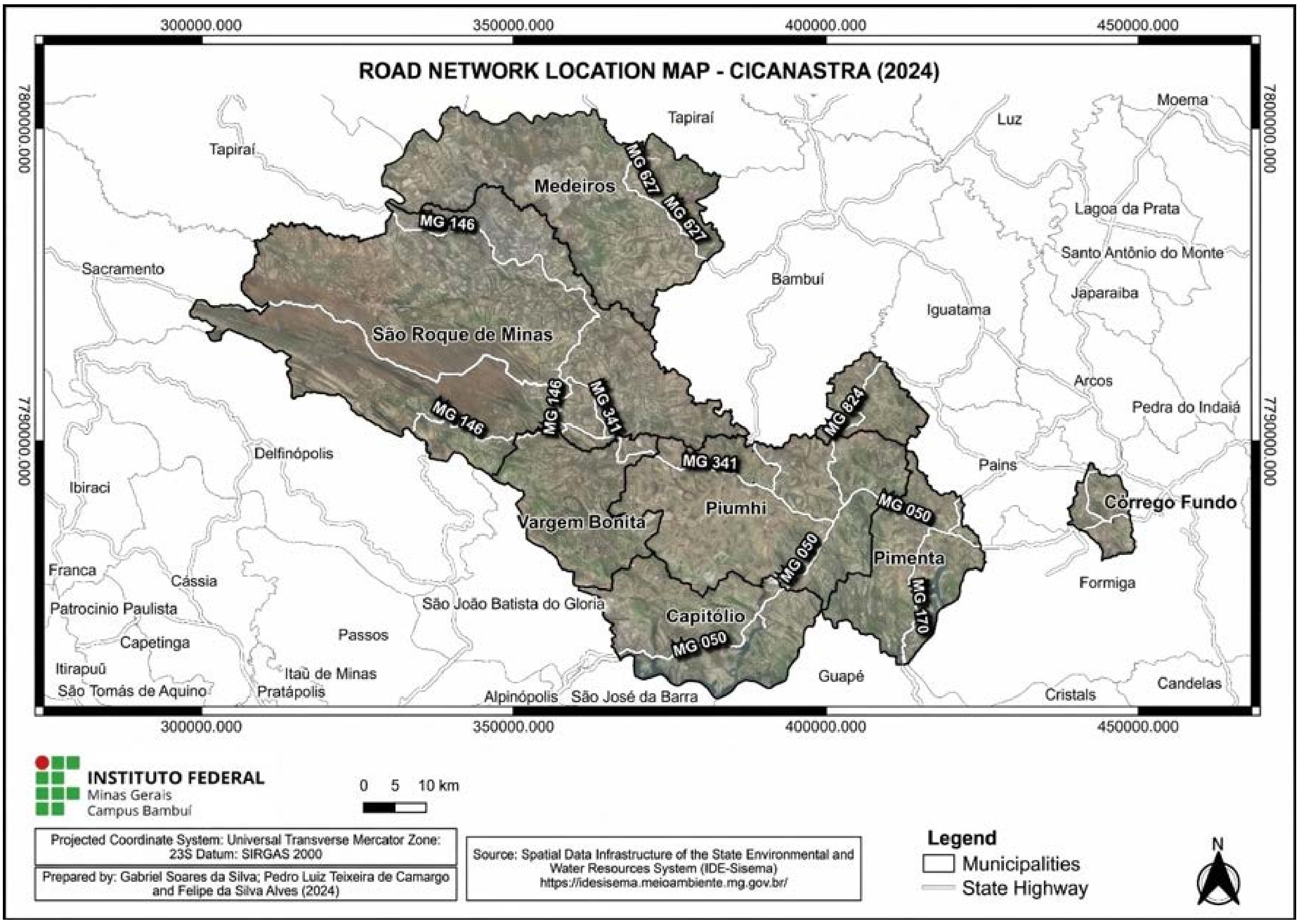
The study area covers the territory of the CICANASTRA Intermunicipal Consortium, spanning 5,548.099 km^2. Its geographic boundaries and regional road network are shown in Figure 1.

This region was selected for its ecological significance and the environmental challenges it faces, described below.

The territory is part of the Cerrado biome, recognized as a biodiversity hotspot with fauna and flora threatened with extinction (MMA, 2024). Part of the area lies within the Serra da Canastra National Park (PNSC)

Figure 1

Geographic boundary and road network of the CICANASTRA consortium.



and includes the recently created Serras e Águas de Piumhi Environmental Protection Area (APA), on the border between the cities of Piumhi and Pimenta. This reinforces the need for strict land-use and occupation guidelines. The presence of the Rio Grande, which supplies the Furnas Hydroelectric Power Plant (UHE Furnas), imposes additional restrictions on landfill siting, requiring a minimum setback from water bodies under NBR 13896/1997.

The regional economy is driven by agriculture and livestock farming – most notably Queijo Canastra cheese – and by ecotourism. These factors contributed to 17.5% population growth between 2000 and 2022 (IBGE, 2022). Despite this growth, the consortium's municipalities have no royalty revenue, which limits investment in sanitation infrastructure. This is evident in Table 1: most municipalities still rely on open dumps or controlled landfills, in non-compliance with Law 12,305/2010, generating roughly 34,425 tons of solid waste per year.

2.2. Tools and data processing

Geoprocessing has become an essential tool for spatial analysis and modeling across many areas of territorial management, from urban planning to environmental monitoring (Câmara & Ortiz, 1998). Its application in siting sanitary landfills is well documented in both national and international literature (Blasius et al., 2023; Elkhrachy et al., 2023).

In this study, spatial analysis was carried out in QGIS. Data were organized in two formats: vector data, for discrete elements such as municipal boundaries, roads, and infrastructure; and raster data, for continuous data such as elevation and land use (Quoos & Figueiró, 2023). Figure 2 illustrates the distinction between the two models. The data were structured into five thematic groups: population centers, environmental zoning, transport infrastructure, topographic data, and land use and occupation.

Table 1 MSW disposal methods in CICANASTRA consortium municipalities (2021).

Municipality	MSW disposal method
Capitólio	Controlled landfill
Córrego Fundo	Small-scale sanitary landfill
Doresópolis	Controlled landfill
Medeiros	Open dump
Pimenta	Controlled landfill
Piumhi	Controlled landfill
São Roque de Minas	Controlled landfill
Vargem Bonita	Open dump

SOURCE: Adapted from the National Sanitation Information System (SNIS, 2021).

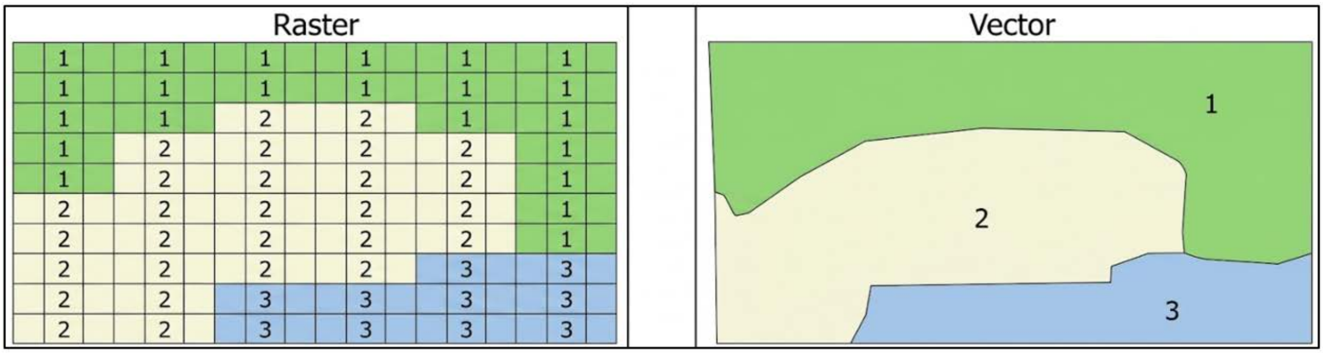


Figure 2
Comparison of raster and vector data models.

To combine the restrictive criteria, we used Boolean logic – a mathematical approach based on logical operators (AND, OR, and NOT) that classifies each area in binary terms as suitable (1) or unsuitable (0) (Ibrahim, 2021). We chose this approach because it best matches the exclusionary nature of the applicable standards, particularly NBR 13896/1997, whose restrictions are absolute and allow no trade-off between criteria. This rules out multi-criteria weighting methods such as Fuzzy Logic or AHP. The entire process was automated using QGIS's graphical modeler, exported to Python (PyQGIS), and made available on GitHub (GitHub, 2024).

2.3. Restriction criteria and area selection

Exclusion criteria were defined based on current environmental standards and federal legislation, as shown in Table 2. For each criterion, thematic maps were generated to serve as the cartographic inputs for the spatial analysis, presented below.

Figure 3 shows the distribution of population centers – municipal seats, villages, and rural clusters – that define the 500-meter exclusion buffer set by NBR 13896/1997. Figure 4 shows the regional hydrography, highlighting rivers, streams, and the headwaters of the São Francisco River, which set a minimum 200-meter setback from the watercourse (Lei nº. 12.651/2012).

Table 2 Criteria and restrictions for selecting suitable areas.

Criterion	Parameter considered	Reference
Population centers	≥ 500 m from urban areas	NBR 13,896/1997
Transport infrastructure	≥ 15 m from state highways and ≥ 20 km from airfields	Law No. 13,913/2019; Law No. 12,725/2012
Environmental zoning	Exclusion of APAs and Conservation Units	Law No. 9,985/2000
Slope	1%-30%	NBR 13,896/1997
Land use and occupation	Exclusion of agricultural areas, mining sites, and native vegetation	MAPBIOMAS (2021)

Figure 3 Map of population centers, municipal seats, and rural clusters.

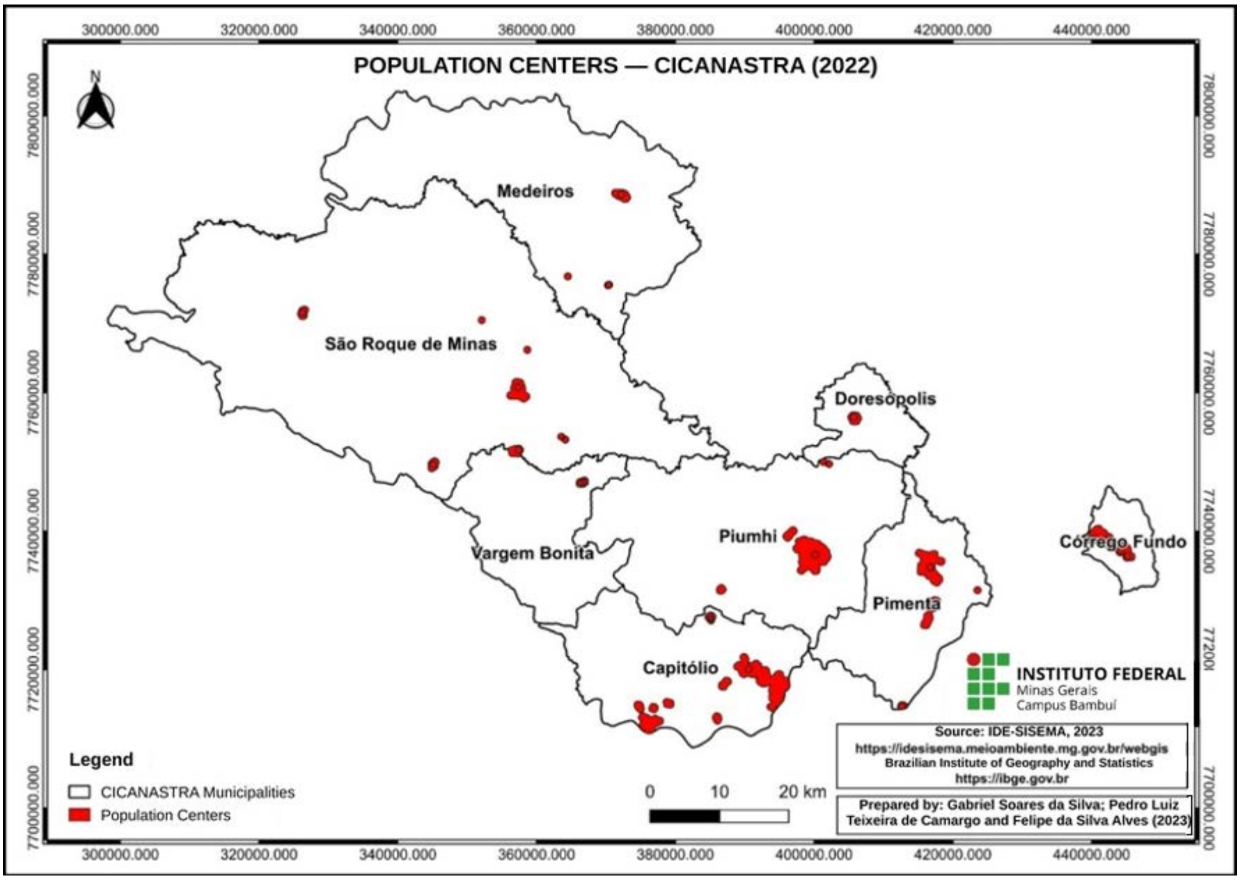
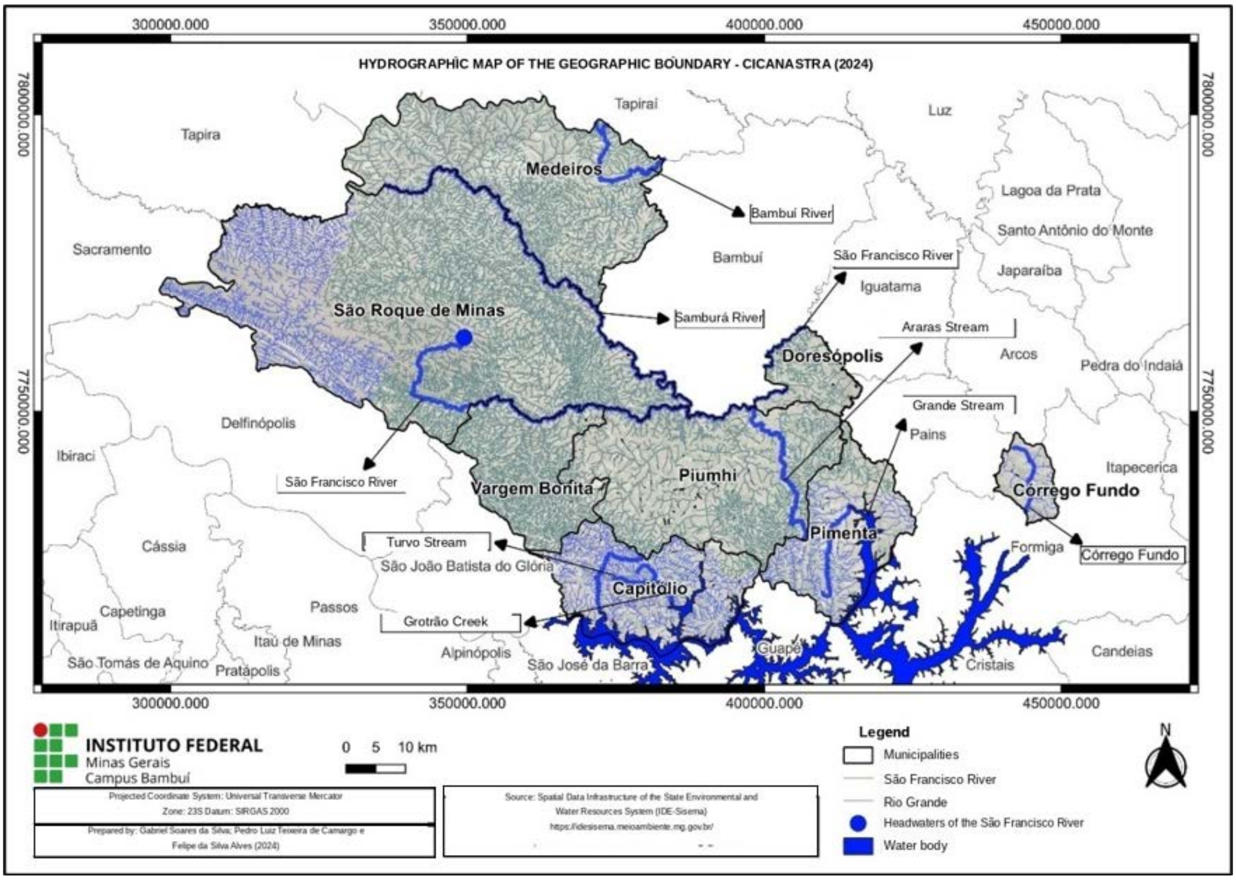


Figure 4 Hydrographic map of the CICANASTRA consortium's geographic boundary.



Figures 5, 6, and 7 show respectively the transport infrastructure, environmental zoning, and topographic data maps, whose restrictions are detailed in Table 2 above.

Figure 8 shows the land use and occupation map. Forest, savanna, water bodies, mining sites, and urban zones were classified as unsuitable, while pasture and non-vegetated areas showed greater potential for landfill siting (Silva et al., 2023).

2.4. Kernel density estimation

After applying Boolean logic, the centroids of areas classified as suitable (value 1) were extracted, converting the resulting polygons into point features. Kernel density estimation (KDE) was then applied to this set of points, using a 2,000-meter search radius and a 30-meter output resolution. This generated a continuous surface expressing the spatial concentration intensity of viable areas – i.e., regions with a higher density of suitable points represent zones with greater aggregate suitability for landfill siting.

The continuous values from the Kernel surface were then classified into five intervals using the natural quantile breaks method, translating concentration intensity into five qualitative suitability categories: Unfeasible, Inadequate, Acceptable, Adequate, and Feasible. This classification step does not alter the exclusion criteria set by the Boolean logic, which remain

Figure 5
Transport infrastructure map.

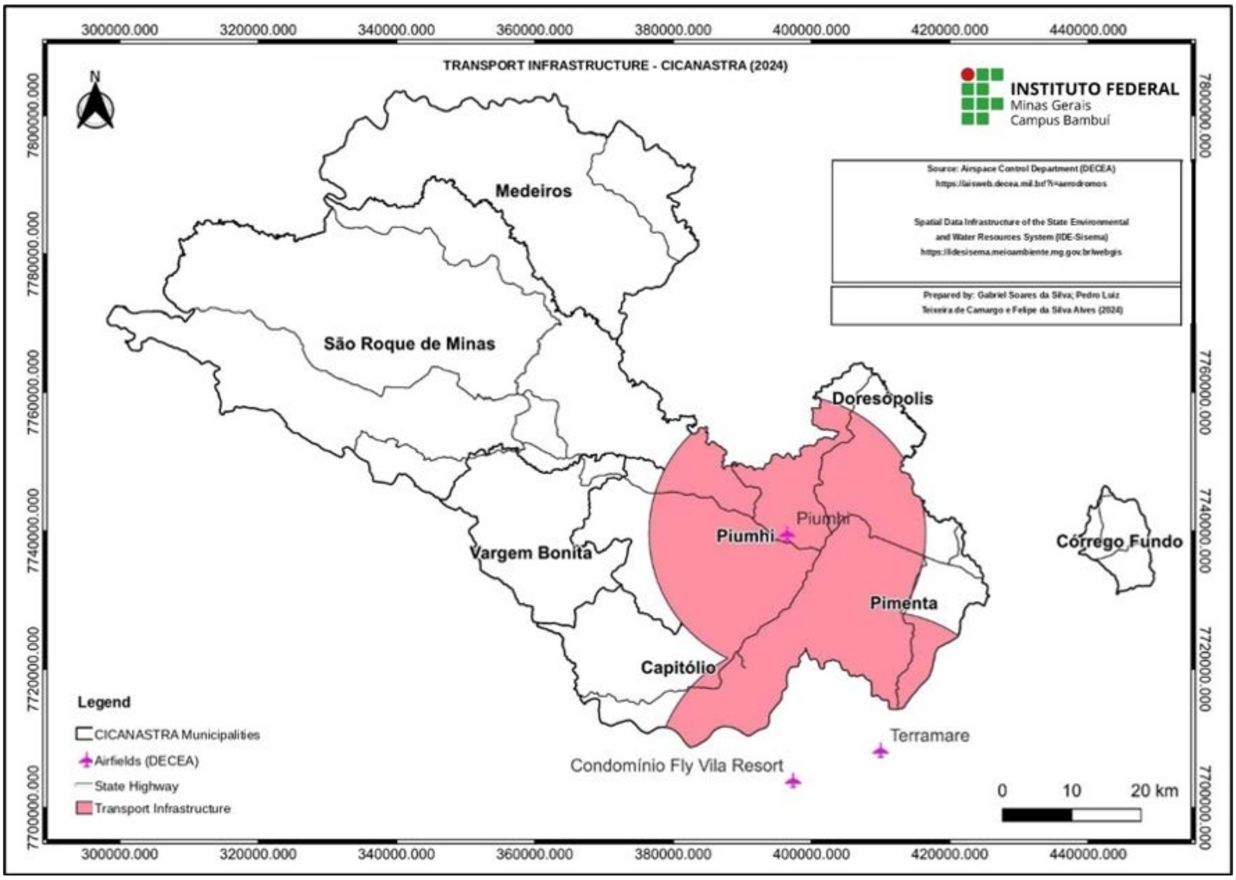


Figure 6 Environmental zoning map.

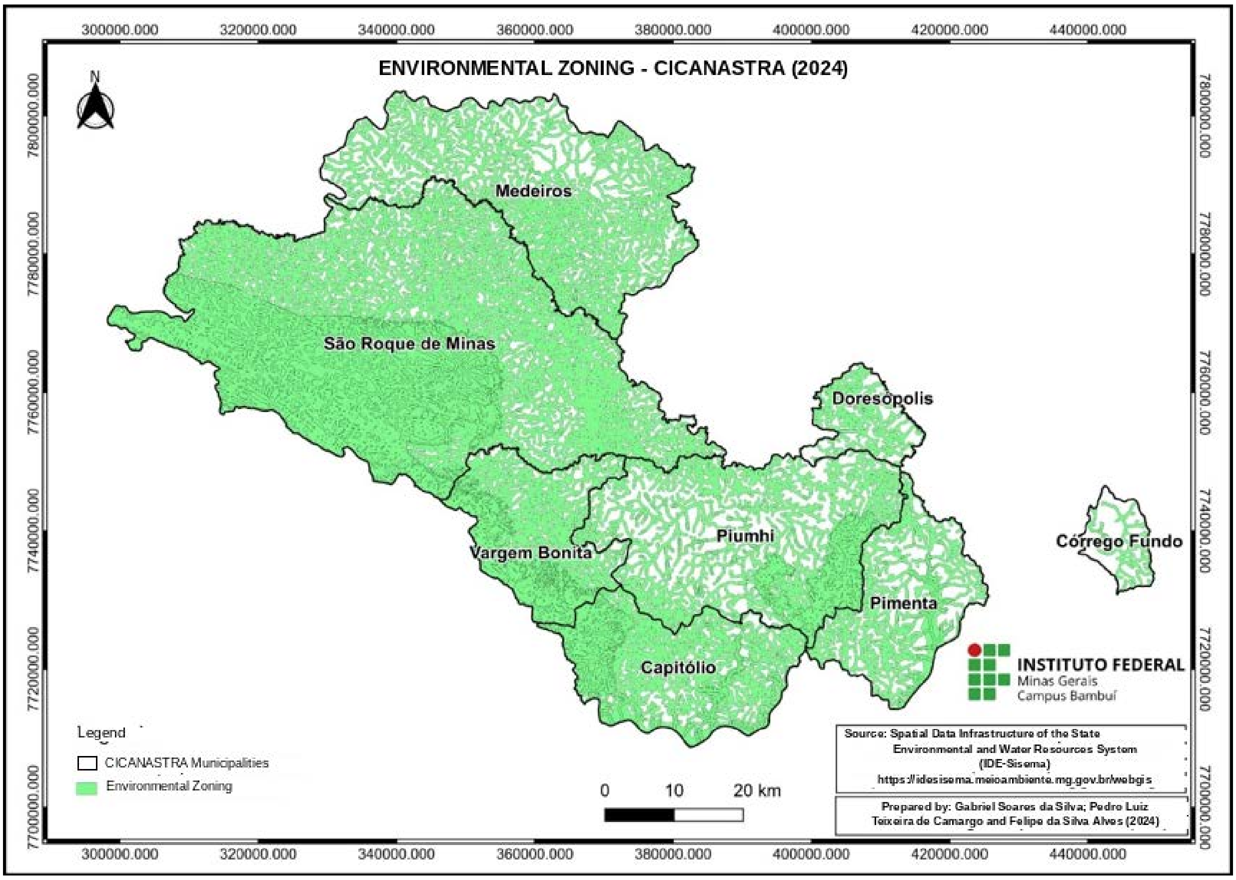
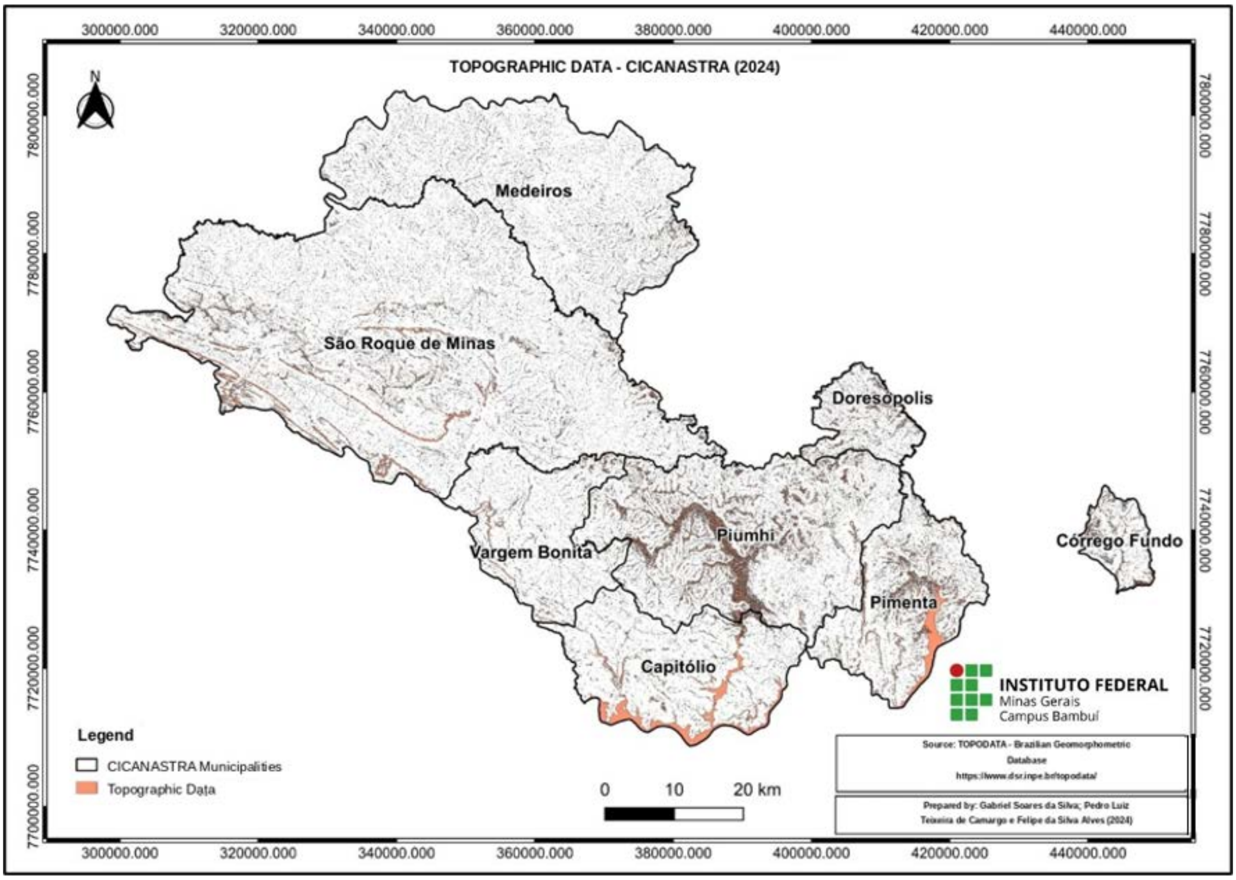


Figure 7 Topographic data map.



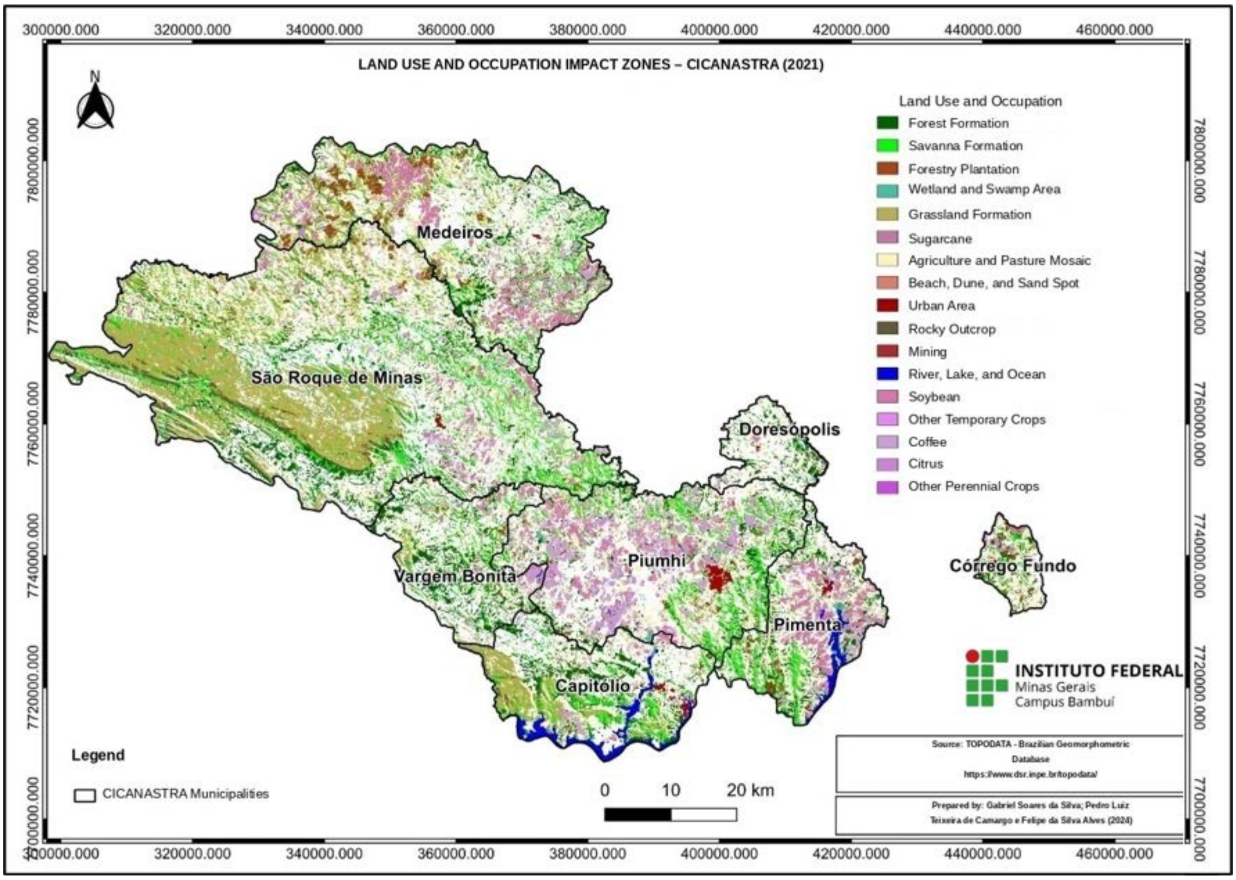


Figure 8
Land use and occupation map.

absolute and binary. Rather, it identifies, within the suitable areas, the zones with the highest concentration of potential, helping prioritize field studies. This entire process (e.g., centroid extraction, density estimation, and quantile classification) is built into the automated graphical model available on GitHub.

2.5. Sizing the required area

Environmental legislation requires a minimum operational lifespan of 10 years for sanitary landfills (NBR 13896/1997), while Normative Deliberation COPAM No. 244/2022 sets this at 15 years for the state of Minas Gerais. This study adopted a 30-year project horizon, exceeding both minimum requirements. This decision was based on technical and strategic considerations: extending the operational lifespan reduces the need to identify, license, and implement a new site in the short term – a process that, as this study shows, is complex and constrained, given that only 5% of CICANASTRA's territory meets the suitability criteria. In small municipalities with no royalty revenue, securing a new landfill site within 15 years would pose a major financial and institutional challenge. Adopting a 30-year horizon, however, means a larger accumulated volume of leachate. It requires a base liner system, drainage, and leachate treatment sized for this longer timeframe – aspects to be detailed during the executive design and environmental licensing stages, in accordance with NBR 13896/1997 and current state legislation.

The sizing calculation started from a population projection based on IBGE census data (2000, 2010, and 2022), applying arithmetic, geometric, and declining-rate growth models (Table 3). These formulations, described by Tsutiya (2006) and Qasim (1985), are widely used in sanitary engineering literature for sizing solid waste disposal systems. The geometric model was adopted because it best reflects regional dynamics (Messias, 2018). The following variables were considered: population served, landfill operational lifespan, daily per capita waste generation in Brazil's Southeast region, compacted waste density, and MSW stacking height.

3. Results and Discussion

3.1. Analysis of results

The results of this study are essential for understanding the feasibility of building a sanitary landfill within the CICANASTRA intermunicipal consortium. The methodology, based on geospatial techniques and mathematical modeling, made it possible to identify areas with potential to host this infrastructure, which is essential for solid waste management. The analysis considered factors such as population growth, land use and occupation, environmental zoning, transport infrastructure, and topographic restrictions. The main findings are discussed below, supported by the cartographic representations produced in this study.

Table 3 Calculation methods for population growth projection.

Projection model	Description	Applied formula	Author
Arithmetic growth	A simple approach for estimating future population. Assumes the population grows at a constant rate over time.	$P = Pi + Ka * (t - ti)$ $Ka = \frac{p2 - p1}{t2 - t1}$	(Tsutiya, 2006)
Geometric growth	Assumes the population grows at a constant percentage rate over time. A model suited to developing urban or semi-urban areas.	$P = Pi * e^{Kg*(t-ti)}$ $Kg = \frac{lnp2 - lnp1}{t2 - t1}$	(Tsutiya, 2006)
Declining growth rate	A population projection model that accounts for a gradual decline in growth rate over time, relevant in contexts where the population starts with high growth that slows due to social, economic, or environmental factors.	$Ps = \frac{2 * P0 * P1 * P2 - (P1^2) * (P0 + P2)}{P0 * P2 - P1^2}$ $P = P0 + (PS - P0) * [1 - e^{-Kd*(t-t0)}]$ $Kd = \frac{-\ln[(PS - P2)/(PS - P0)}{t2 - t0}$ $\frac{dP}{dt} = kd * (Ps - P)$	(Qasim, 1985)

P = estimated population in the given year; **Pi** = initial population; **Ka, Kg, Kd** = coefficients; **t** = projected year; **ti** = initial year; **P0, P1, P2** = populations in the base years **t0, t1, t2; Ps** = saturation population; **dP/dt** = population growth rate over time.

3.2. Population projection and waste generation

The first factor analyzed was population growth, a key determinant of future solid waste management demand. Figure 9 shows the demographic projection through 2054, based on different calculation methods. According to the geometric projection, the consortium's population will reach approximately 100,432 inhabitants by 2054, directly affecting MSW generation.

Based on these data, Table 4 shows the estimated MSW production over the next 30 years. The projection indicates a cumulative volume of 1,320,813 tons of solid waste by 2054. However, since roughly 20.3% of this waste will go to selective collection (Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais [ABRELPE], 2023), the final volume to be sent to the landfill will be 1,052,688 tons.

The projected 32.5% increase in waste generation over 30 years – from 35,275 tons/year in 2024 to 50,855 tons/year in 2054 – highlights the urgent need for structural solutions to MSW management in the consortium. In small municipalities with no royalty revenue, this steady increase places growing pressure on municipal budgets and on the environment. Without proper disposal, there are risks of contamination to soil, water resources, and the biodiversity of the Cerrado – an already threatened biome present across CICANASTRA's entire territory (MMA, 2024). In this sense, the sizing presented here is not merely a technical exercise; it is the quantitative foundation for a public-policy decision with long-term environmental and social impacts.

Figure 9
Population growth rate.

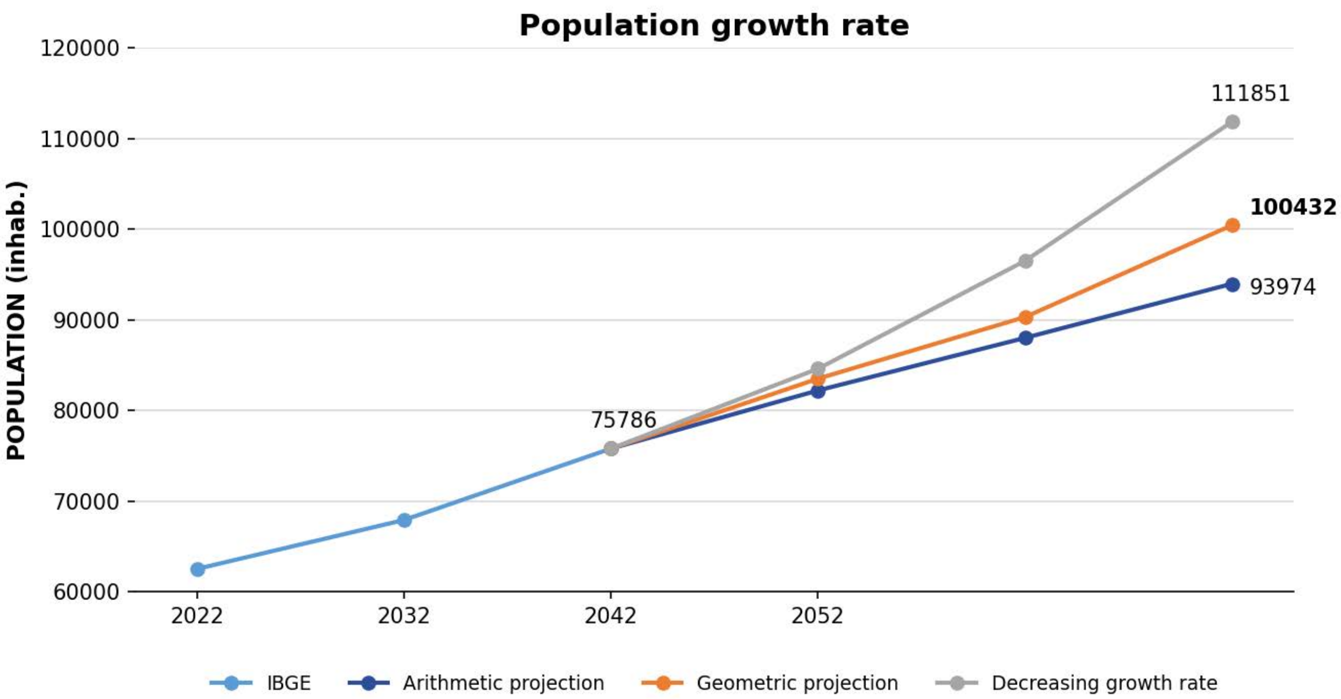


Table 4 Annual MSW production.

MSW generation (tons/year) in the CICANASTRA Intermunicipal Consortium							
2024	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
35,275	35,708	36,146	36,589	37,038	37,493	37,953	38,418
2032	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
38,889	39,367	39,849	40,338	40,833	41,334	41,841	42,355
2040	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**
42,874	43,400	43,933	44,472	45,017	45,569	46,128	46,694
2048	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**30-year cumulative total**
47,267	47,847	48,434	49,028	49,630	50,238	50,855	**1,320,813**

Figure 10 shows the simulated area required for the sanitary landfill, based on the total volume of waste generated. Equation 1 calculates the space needed to accommodate that volume.

Equation 1 – Waste volume calculation

$$V_{RSU} = \frac{P_{RSU}}{\gamma}$$

Where:
V_{MSW} = volume of waste sent to the landfill
P_{MSW} = 1,052,688 tons (total MSW mass over 30 years)
$\boldsymbol{\gamma}$ = 9.3 kN/m³ (specific weight of compacted waste, converted from kN/m³ to tons/m³)

Equation 2 – Cover soil volume calculation

$$V_{solo} = 0{,}3 * V_{RSU}$$

Where:
V_{MSW} = volume calculated in the previous step.
The factor 0.3 corresponds to the 30% of the waste volume allocated to soil cover.

Equation 3 – Total volume of waste and soil

$$V_{total} = V_{RSU} + V_{solo}$$

The resulting value corresponds to an expected volume of 147,150 m³ over 30 years. To calculate the required area, a maximum trench depth of 5 meters was assumed.

Equation 4 – Required area based on stack height

$$A = \frac{V_{total}}{h}$$

Where:
h = 5 m is the stack height
A is the area in square meters. To convert to hectares: 1 hectare = 10,000 m^2.

The calculated area of 29,430 m^2 is equivalent to roughly 3 hectares, considered ideal for the landfill. The analysis indicates that meeting future demand will require a minimum of 3 hectares, with a deposition height of 5 meters.

3.3. Environmental and urban restrictions

Applying the restrictive criteria set out in Table 2 excluded significant portions of CICANASTRA's territory. Analyzing the thematic maps presented in Section 2.3 clarifies how each criterion contributed to the final configuration of unsuitable areas.

The population-proximity criterion (Figure 3) showed that the scattered distribution of villages and rural clusters across the territory imposes substantial restrictions, especially in the more densely occupied parts of Piumhi and Capitólio, where overlapping urban buffers significantly reduced the available area.

The transport infrastructure map (Figure 5) showed that state highways

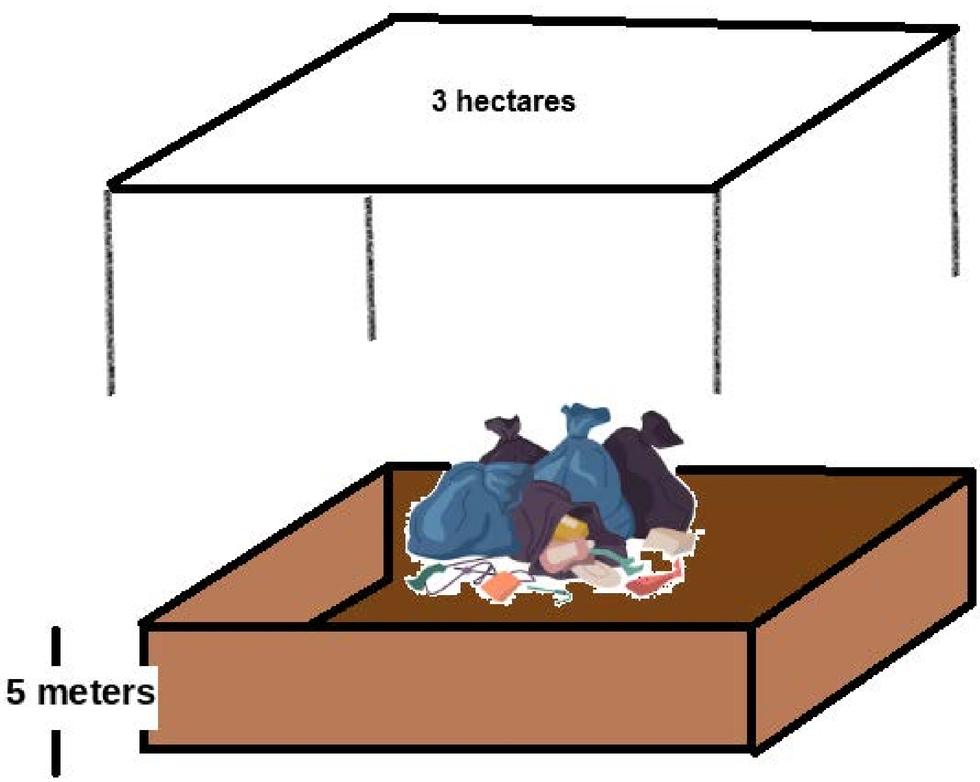


Figure 10
Minimum area required for landfill implementation.

– particularly MG-050 and MG-341 – and airfields in the region create significant exclusion zones, particularly along the road corridors that cross the consortium from east to west.

The environmental zoning analysis (Figure 6) showed that the Serra da Canastra National Park (PNSC) and the Serras e Águas de Piumhi APA represent one of the most territorially extensive restrictions, ruling out large portions of São Roque de Minas and Vargem Bonita.

The topographic data (Figure 7) indicated that areas with slopes above 30% or below 1%, unsuitable due to drainage and soil stability issues, are concentrated in the mountainous regions, eliminating areas in the municipalities bordering the PNSC.

Finally, the land use and occupation map (Figure 8) showed that Cerrado formations, riparian forests, and savanna areas, fragmented across the territory, combined with urban and mining zones, made up the criterion with the widest spatial distribution of restrictions. Pasture and bare soil areas, concentrated mainly in Medeiros and São Roque de Minas, retained the greatest potential after this criterion was applied.

Combining all these criteria through Boolean AND operators produced the consolidated suitability map presented in the following section.

3.4. Identification of suitable areas

The spatial analysis showed that 95% of the consortium's area is unsuitable for a sanitary landfill, due to environmental, urban, and topographic restrictions. Only 5% of the total area was classified as suitable, totaling approximately 28,821.879 hectares.

Figure 11 shows the distribution of these areas, highlighting that Medeiros and São Roque de Minas have the largest number of suitable sites. This may be related to factors such as lower population density and less infrastructure that would otherwise rule out landfill siting.

Figure 12 reinforces this analysis, illustrating the split between unsuitable areas (red) and suitable areas (green). Most of the consortium's territory is unsuitable for the project, making a careful evaluation essential for selecting the best site.

To deepen the analysis, a heat map was generated using Kernel interpolation. This map classified the suitable areas into different feasibility levels, based on the criteria shown in Figure 12. The categories were organized into five levels of spatial density, defined using the quantile classification method applied to the continuous surface generated by the KDE from the centroids of the suitable polygons identified through Boolean logic:

Unfeasible (red): Regions outside the concentration range of suitable centroids, corresponding to areas excluded by the Boolean logic.

Inadequate (orange): Very low density of suitable centroids, indicating spatial isolation of the viable polygons.

Figure 11 Map of areas suitable for sanitary landfill implementation

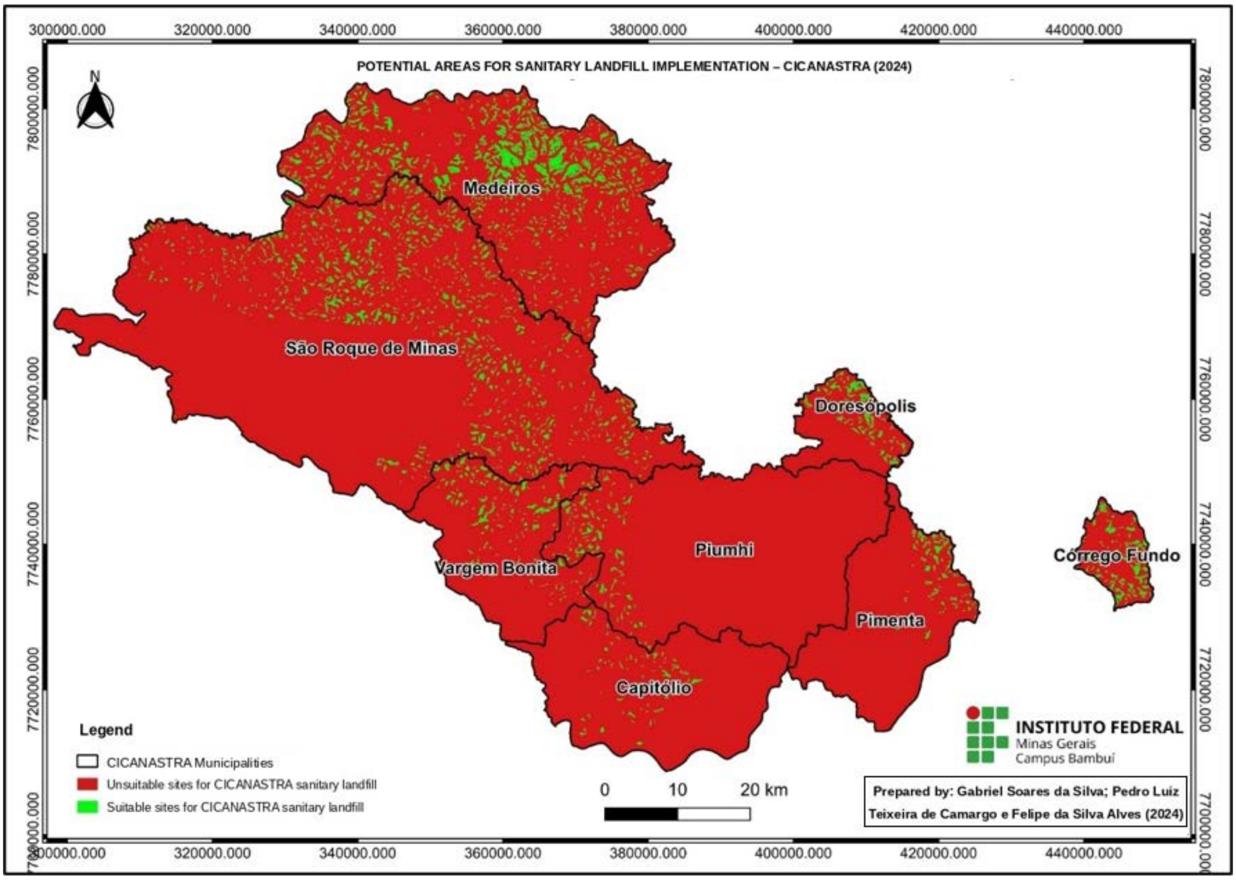
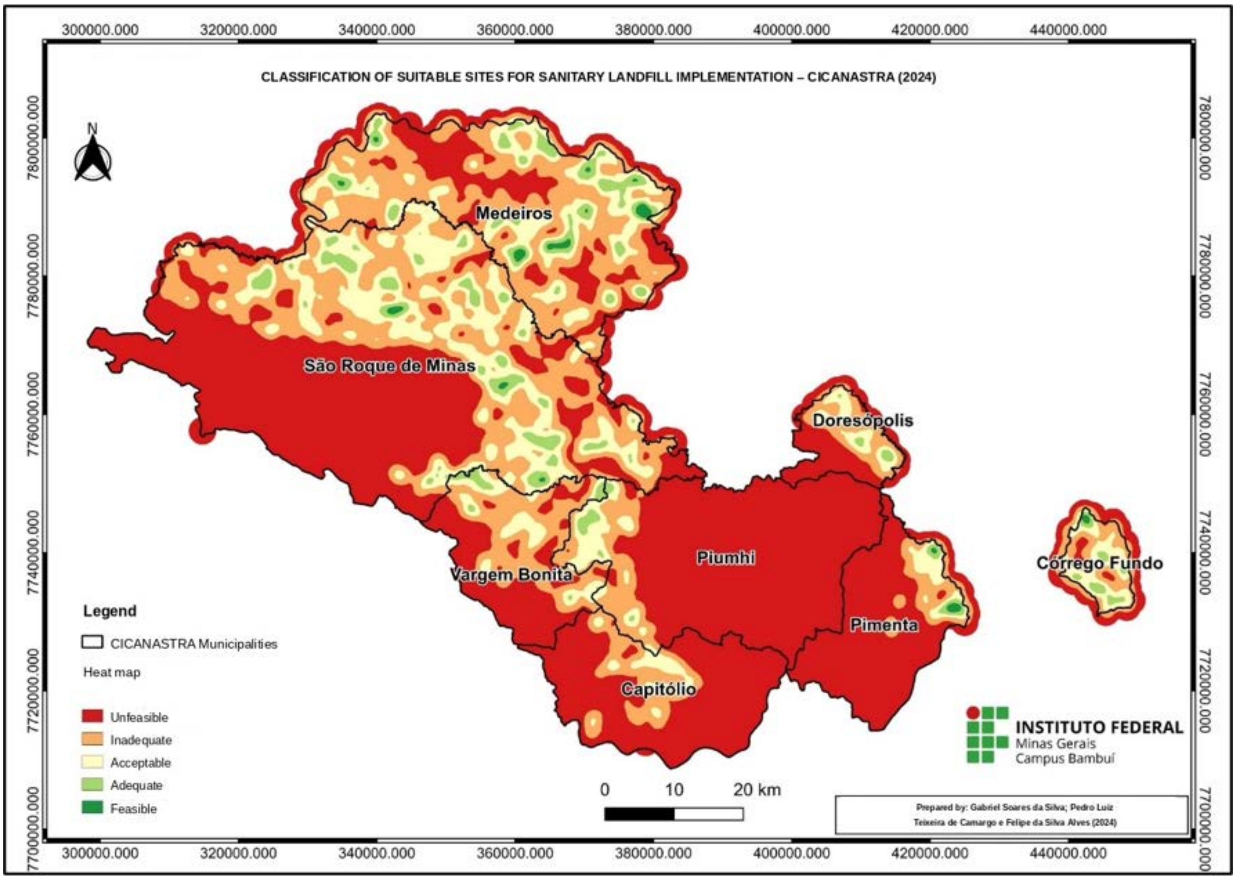


Figure 12 Location map of the ideal and adequate areas



Acceptable (yellow): Moderate centroid density, with scattered suitable areas showing no significant concentration.

Adequate (light green): High density of suitable centroids, indicating spatial clustering favorable to implementation.

Feasible (dark green): Maximum concentration of suitable centroids, representing the priority hotspots for field studies and on-site assessments.

Figure 11 shows that less than 2% of the consortium's territory can be classified as "Ideal". This highlights the need for detailed, participatory, joint planning to choose the most suitable site.

3.5. Final classification and strategic planning

The consortium's logistical analysis reveals a notable territorial imbalance. Medeiros and São Roque de Minas hold most of the identified suitable areas. Municipalities such as Capitólio, Piumhi, and Córrego Fundo, by contrast, sit on the periphery of these zones, which means longer transport distances. This should be factored into the landfill's operational planning, particularly when sizing intermunicipal logistics.

This point carries more weight when set against the region's current waste-disposal situation. Piumhi, a CICANASTRA member, contracts a private company that serves 31 municipalities in the region for MSW disposal (Prefeitura de Piumhi, 2026). Neighboring municipalities in the same regional context – such as Dores do Indaiá – send their waste to the Integração Resíduos Sanitary Landfill (Integração Resíduos, 2024), located on highway BR-354 in Bambuí (Silva et al., 2024), at distances considerably greater than those separating CICANASTRA's municipalities from the suitable areas identified in this study.

According to data from FIPE/Abetre, disposal costs at small-scale landfills run around R$269.00 per ton, while larger regional landfills operate at R$85.64 per ton (Agência Minas, 2021). Given CICANASTRA's generation volume of roughly 34,425 tons per year, the difference between the individualized private model and the consortium model could mean substantial savings for municipal budgets – funds that, in municipalities with no royalty revenue, could be redirected to other infrastructure needs. In this sense, building the intermunicipal landfill in the areas identified here would offer not just an environmental solution, but a more cost-effective and self-sufficient approach to solid waste management for the consortium.

Figure 12 shows the final classification of suitable areas, organized by feasibility level for landfill implementation. Kernel interpolation identified the locations with the highest density of viable points – the areas best suited for field studies and on-site assessments.

Finally, the distribution of suitable areas by municipality shows that Medeiros and São Roque de Minas offer the best conditions for the intermunicipal sanitary landfill. That said, proximity to state highways such as MG-050 and MG-341 should also factor into optimizing waste transport logistics.

4. Final considerations

This study demonstrated the effectiveness of geoprocessing as a decision-support tool for selecting suitable sites for sanitary landfills, applied to the CICANASTRA Intermunicipal Consortium. By integrating regulatory, environmental, topographic, and land-use criteria through Boolean logic and Kernel density estimation, the study identified and spatially classified the areas with the greatest suitability for the project, providing objective technical grounding for solid waste management planning in the region.

The results show that only 5% of the consortium's total area offers favorable conditions for the intermunicipal sanitary landfill – approximately 28,821.879 hectares – concentrated mainly in Medeiros and São Roque de Minas. The heat map generated through Kernel interpolation of the suitable polygons' centroids reinforces this finding, identifying the hotspots with the highest density of viable areas and helping prioritize field studies.

Still, the final feasibility of these areas requires on-site validation, including geological and hydrogeological analyses to confirm soil stability, adequate water table depth, and permeability compatible with the landfill's liner requirements. Practical implementation will depend on further steps: technical site inspections, specific environmental studies, and compliance with environmental licensing requirements. It's also worth noting that the 3-hectare, 30-year sizing assumes a 20.3% selective-collection diversion rate. If this target is not met, the required area will be proportionally larger – something that should be reassessed during executive design based on the actual performance of municipal recycling programs.

Another crucial aspect is the social and governance dimension of implementing the intermunicipal sanitary landfill. Selecting sites by technical criteria, while necessary, is not enough on its own to ensure the project's viability. Studies on waste management in small-municipality contexts show that social acceptance among communities near the selected areas, community participation in decision-making, and adherence to environmental justice principles are decisive factors for the success of projects like this one. Accordingly, we recommend that the steps following this study include public consultation processes and engagement with local communities, particularly in Medeiros and São Roque de Minas, where the areas of greatest suitability are concentrated. Participatory planning, combined with alignment to PNRS public policy and a stronger governance structure for the CICANASTRA consortium, will be essential to make the intermunicipal sanitary landfill financially and operationally viable – and socially legitimate. In addition, complementary actions such as environmental education programs and incentives for selective collection should be promoted to reduce the volume of waste sent to the landfill.

Finally, one of this study's key contributions is the automated graphical model that integrates Boolean exclusion logic and Kernel density estimation for feasibility classification, exported to Python and made available on GitHub. This tool allows the methodology to be fully replicated – from binary classification through to generating the quantile-based heat map – in other consortia and municipalities, helping democratize access to geoprocessing technologies applied to solid waste management.

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