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Geoprocessing applied in the selection of locational alternatives for the implementation of landfills in consortia for integrated solid waste management in the state of Ceará, Brazil.

Geoprocessamento aplicado na seleção de alternativas locacionais para implantação de aterro sanitário em consórcios para gestão integrada de resíduos sólidos no estado do Ceará - Brasil

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Abstract: Sanitary landfill is a technique capable of reducing the possible negative environmental impacts arising from the disposal of solid urban waste. To this end, an environmental impact assessment must be carried out prior to its installation, and locational alternatives must be considered in order to determine the most fittedt area for implementation. Given the need to set up sanitary landfills in the state of Ceará,Brazil, the aim of this study was to identify, using geoenvironmental criteria, suitable areas for setting up sanitary landfills in consortia in that state. Using a vector database and criteria for pre-selecting areas for landfill sites, it was possible, by using QGis geoprocessing software, to apply multi-criteria analysis using the Boolean method, where vectors were superimposed, and suitable and unsuitable areas for landfill sites were determined according to the geo-environmental parameters adopted. Through the pre-selection of areas, it was possible to determine that the state of Ceará has 68.63% of areas unsuitable for landfill installation and that consortia are crucial, because in addition to making landfill operation economically viable, some municipalities do not have suitable areas throughout their territory.

Keywords: Geoprocessing; Landfill; Solid waste.

Resumo: O aterro sanitário é uma técnica capaz de reduzir os possíveis impactos ambientais negativos oriundos da destinação dos resíduos sólidos urbanos, para isto deve ser realizada a avaliação de impactos ambientais antes de sua instalação, devendo ser considerada alternativas locacionais afim de determinar a melhor área para implantação. Diante da necessidade da instalação de aterros sanitários no estado do Ceará – Brasil, este estudo teve como objetivo identificar, através de critérios geoambientais, as áreas propícias para implantação do aterro sanitário em consórcios do referido Estado. Através de base de dados vetoriais e determinação de critérios para pré-seleção de áreas para implantação de aterro sanitário foi possível, com a utilização do software de geoprocessamento QGis, a aplicação da análise de multicritérios usando o método booleano, onde os vetores foram sobrepostos e determinadas as áreas aptas e inaptas para instalação de aterro sanitário de acordo com os parâmetros geoambientais adotados. Com a pré-seleção das áreas foi possível determinar que o estado do Ceará possui 68,63% das áreas inaptas para instalação de aterro sanitário e que os consórcios são cruciais, pois além de viabilizar economicamente a operação do aterro, alguns municípios não possuem áreas aptas em todo seu território.

Palavras-chave: Geoprocessamento; Aterro sanitário; Resíduos Sólidos.

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1. Introduction

Incorrect disposal of solid waste can cause numerous negative environmental impacts, such as groundwater contamination and climate change, among others (SILVA E MOTA, 2019). One way to properly dispose of waste is through sanitary landfills, a technique used primarily in developing countries (ZHANG et al., 2019). To prevent potential impacts from anthropogenic activities, such as landfill disposal, an environmental impact assessment must be carried out prior to installation, and alternative locations must be considered to determine the best area for implementation (SÁNCHEZ, 2020). In Brazil, there are several normative criteria for choosing the area to install the sanitary landfill, and the following must be taken into account: the location must not be downstream from the water supply intake site, at a distance of 5km to 20km from the generating center; nor be located in areas of intense occupation or risk areas; they should not be on the sides of highways either (IMASUL, 2016). The locations, however, must have a slope between 1% and 30%, be at least 200m away from water bodies, comply with land use and occupation legislation, be more than 500m away from population centers (ABNT, 1997), possess naturally poorly permeable soils (ABNT, 2010), be located within a radius of 20km from airports that operate in accordance with instrument flight rules and a radius of 13km from other aerodromes (CONAMA, 1995), have a useful life of more than 15 years, and not be an area environmental vulnerability (CONAMA, 2008), among other requirements.

In Brazil, studying these areas is necessary mainly because approximately 21.99% of solid waste is still disposed of in landfills or controlled dumps (CEARÁ, 2015), while in the Northeast region of the country, this figure rises to 40.43% (SINIR, 2019). In the state of Ceará, 93% of municipalities dispose of waste in landfills, with 285 active landfills, 4 landfills without a valid operating license, 101 closed landfills (not reclaimed), and only 6 landfills with a valid operating license (CEARÁ, 2021). One alternative for making landfill projects viable for small municipalities with limited resources and qualified personnel is through consortia. This type of organization was implemented in the state of Ceará, which has 21 consortia for integrated solid waste management, leaving only 14 municipalities that are not members (SEMA, 2022). The organization of municipalities into consortia in the state of Ceará can be seen in the table below:

Table 1 - Consortia and their respective member municipalities in the state of Ceará.

Consortium	Municipality
Chapada de Ibiapaba	Guaraciaba do Norte, Viçosa do Ceará, Croatá, Carnaubal, São Benedito, Ibiapina, Ubajara.
Região Metropolitana B	Maranguape, Ocara, Chorozinho, Pacajus, Horizonte, Guaiúba, Itaitinga.
Região Metropolitana de Sobral	Pires Ferreira, Varjota, Reriutaba, Graça, Pacujá, Mucambo, Cariré, Groaíras, Forquilha, Frecheirinha, Sobral, Alcântaras, Coreaú, Meruoca, Moraújo, Massapê, Santana do Acaraú, Senador Sá.
Alto Jaguaribe - CORRAJ	Saboeiro, Catarina, Cariús, Jucás, Quixelô, Iguatu.
Cariri Oeste	Araripe, Salitre, Potengi, Assaré, Campos Sales, Antonina do Norte, Tarrafas.
Cariri Oriental	Porteiras, Penaforte, Jati, Brejo Santo, Abaiara, Mauriti, Milagres, Barro, Aurora.
Crato - COMARES UC	Nova Olinda, Crato, Altaneira, Caririaçu, Farias Brito, Jardim, Barbalha, Missão Velha, Juazeiro do Norte, Santana do Cariri.
Litoral Leste - COMARES UCV	Aracati, Beberibe, Pindoretama, Cascavel, Fortim.
Litoral Norte	Morrinhos, Marco, Martinópole, Granja, Chaval, Bela Cruz, Barroquinha, Itarema, Camocim, Acaraú, Cruz, Jijoca de Jericoacoara.
Litoral Oeste	Uruburetama, Miraima, Tururu, Itapipoca, Amontada, Paracuru, Trairi.

Consortium	Municipality
Maciço de Baturité - AMSA	Mulungu, Itapiúna, Aratuba, Capistrano, Aracoiaba, Barreira, Baturité, Guaramiranga, Pacoti, Palmácia, Acarape, Redenção.
Sertão Central - CONSERCE	Banabuiú, Ibicuitinga, Quixeramobim, Quixadá, Choró, Ibaretama.
Sertão Central 2 - CONSERCE 2	Madalena, Boa Viagem, Itatira, Canindé, Paramoti, Caridade.
Sertão Central Sul - CODESSUL	Acopiara, Dep. Irapuan Pinheiro, Piquet Carneiro, Mombaça, Milhã, Solonópole, Senador Pompeu, Pedra Branca.
Sertão Centro Sul	Ipaumirim, Baixio, Umari, Cedro, Icó, Orós, Granjeiro, Lavras da Mangabeira, Várzea Alegre.
Sertão de Crateús	Ipu, Monsenhor Tabosa, Poranga, Tamboril, Nova Russas, Catunda, Ipueiras, Hidrolândia, Santa Quitéria.
Sertão de Crateús 2	Novo Oriente, Independência, Crateús, Ipaporanga, Ararendá.
Sertão dos Inhamuns	Aiuaba, Arneiroz, Parambu, Quiterianópolis, Tauá.
Vale do Curu	Itapajé, Irauçuba, General Sampaio, Apuiarés, Pentecoste.
Vale do Jaguaribe - CGIRS VJ	Jaguaruana, Itaiçaba, Tabuleiro do Norte, Ererê, Potiretama, Iracema, Alto Santo, São João do Jaguaribe, Quixeré, Limoeiro do Norte, Russas, Palhano, Morada Nova.
Vale do Jaguaribe 2	Pereiro, Jaguaribe, Jaguaribara, Jaguaretama.
Non-Consortium Municipalities	Tejuçuoca, Umirim, Icapuí, Pacatuba, Aquiraz, Eusébio, Maracanaú, Fortaleza, São Luís do Curu, Caucaia, São Gonçalo do Amarante, Paraipaba, Tianguá, Uruoca.

Source: Adapted from SEMA (2022).

For municipalities and consortia that do not yet have a sanitary landfill, studies of alternative locations should be carried out, in which geoprocessing can be used as an important tool to assist in deciding on the appropriate area for the implementation of a sanitary landfill, being effective and low cost (CARRILHO et al., 2018).

Given the need to implement a sanitary landfill and choose the proper area to prevent and mitigate possible environmental impacts arising from the implementation of the landfill, this study aimed to identify, through geo-environmental criteria, the areas deemed most suitable for the implementation of sanitary landfills for consortia in the state of Ceará.

2. Methodology

Files were collected from databases to create maps using QGis software version 3.10.14. The databases consulted were: COGERH (Water Resources Management Company), IBGE (Brazilian Institute of Geography and Statistics), IPECE (Ceará Institute for Economic Research and Strategy), State Platform for Environmental Spatial Data of Ceará (PEDEA) of SEMA (Secretariat of the Environment), INPE (National Institute for Space Research), INCRA (National

Institute of Colonization and Agrarian Reform) and FUNAI (National Foundation for Indigenous Peoples), as shown in the table below.

Table 2: Databases used in the study

Databases	Source
Roads	SEMA (2022)
Slopes	INPE (2008)
Water bodies	FUNCEME (2022)
Protected areas	FUNAI (2023); INCRA (2010); SEMA (2022) e SEMA (2023)
Population centers	IBGE (2019)
Soil type	IPECE (2020) e COGERH (2023)
Airports and landing fields	IPECE (2020)
Municipal boundaries	IPECE (2021)

Source: The authors (2024)

The vector database used to create the map of active landfills was from 2022 and only included landfills with valid operating licenses. Therefore, through research conducted at SEMACE (State Environmental Superintendence), it was possible to identify three more landfills with valid operating and installation licenses within the scope of intermunicipal impact. The geographic coordinates collected were entered into Google Earth Pro and exported as a vector file for the insertion of these points.

As there are no specific rules for choosing the area for landfill installation in the state of Ceará, criteria were established based on legislation and bibliographic references (Table 3).

Table 3: Criteria for the pre-selection of areas for landfill implementation

Parameters	Rule	Source
Roads	300m	(IMASUL, 2016)
Slope	1% a 30%	(ABNT, 2010)
Distance from water bodies	200m	(ABNT, 2010)
Protected areas	Being outside the Conservation Unit, Indigenous Lands, and Quilombola Communities	(ABNT, 1997 e ABNT, 2010)
Distance from population centers	500m	(ABNT, 1997)
Soil type	Low permeability	(ABNT, 2010)
Distance from airports	20 km radius for airports operating under instrument flight rules and 13 km for other aerodromes	(CONAMA, 1995)

Source: The authors (2024)

With the database and criteria established, QGis software was used to create maps in accordance with the criteria for each parameter. With regard to soil classes, areas with sandy soils were considered unsuitable. Finally, a Boolean-type multi-criteria analysis was performed, in which the vectors were superimposed and the areas suitable and unsuitable for landfill installation were determined according to the geo-environmental parameters adopted.

3. Results and discussion

Four landfills with valid operating licenses from SEMACE and two landfills with installation licenses were identified (Figure 1). Of these landfills, only those located in Sobral and Limoeiro do Norte serve the consortia to which they belong, namely the Sobral Metropolitan Region Consortium and the Jaguaribe Valley Consortium, respectively. The landfill located in Caucaia receives solid waste from Fortaleza and Caucaia; the one in Porteiras receives waste only from its own municipality, and the one to be installed in Aquiraz is intended to serve its own municipality and Eusébio. The landfill located in Porteiras belongs to a private company.

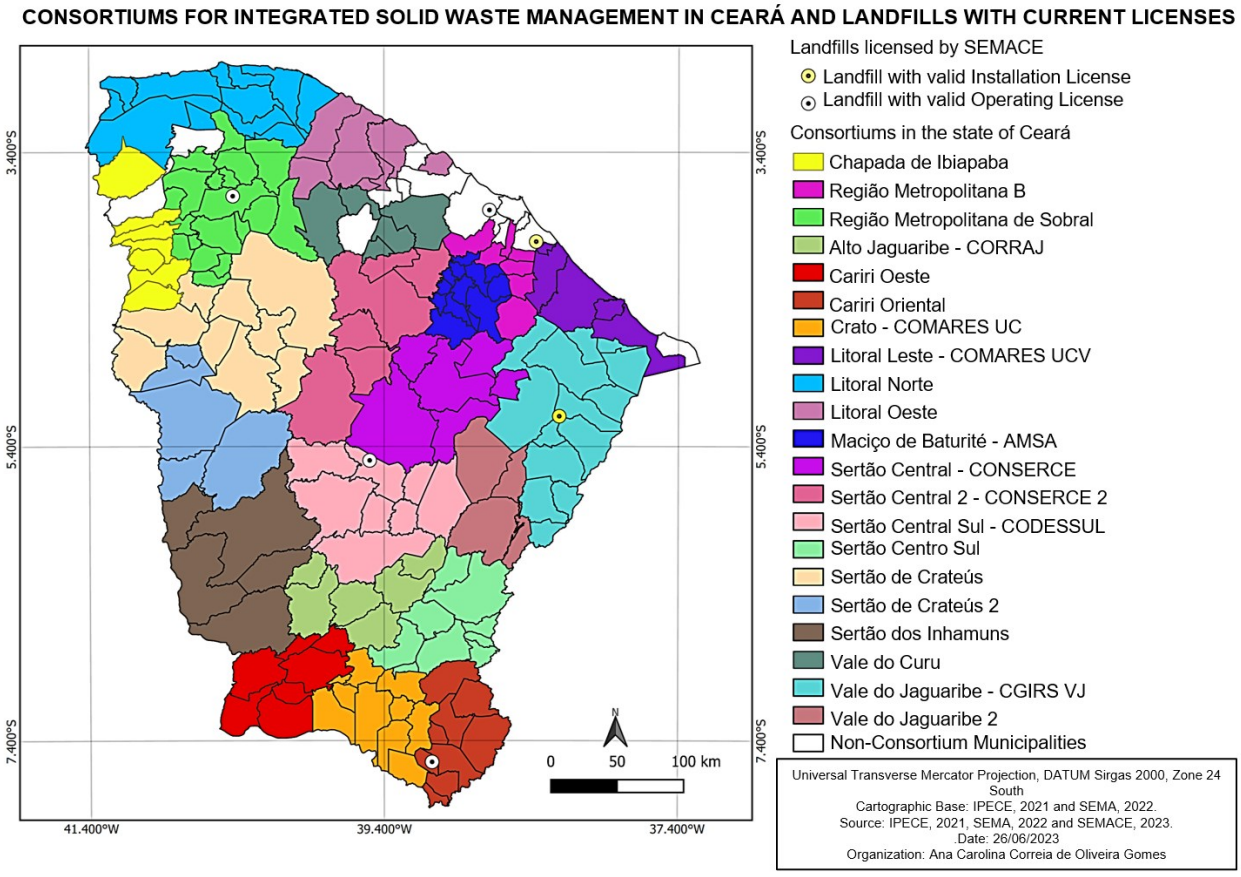

Figure 1 - Integrated Solid Waste Management Consortia in Ceará Landfills with Valid Licenses from SEMACE.

Source: The authors (2023)

The maps prepared according to the criteria for pre-selecting areas for landfill implementation (Table 3) can be viewed in Figures 2 to 10.

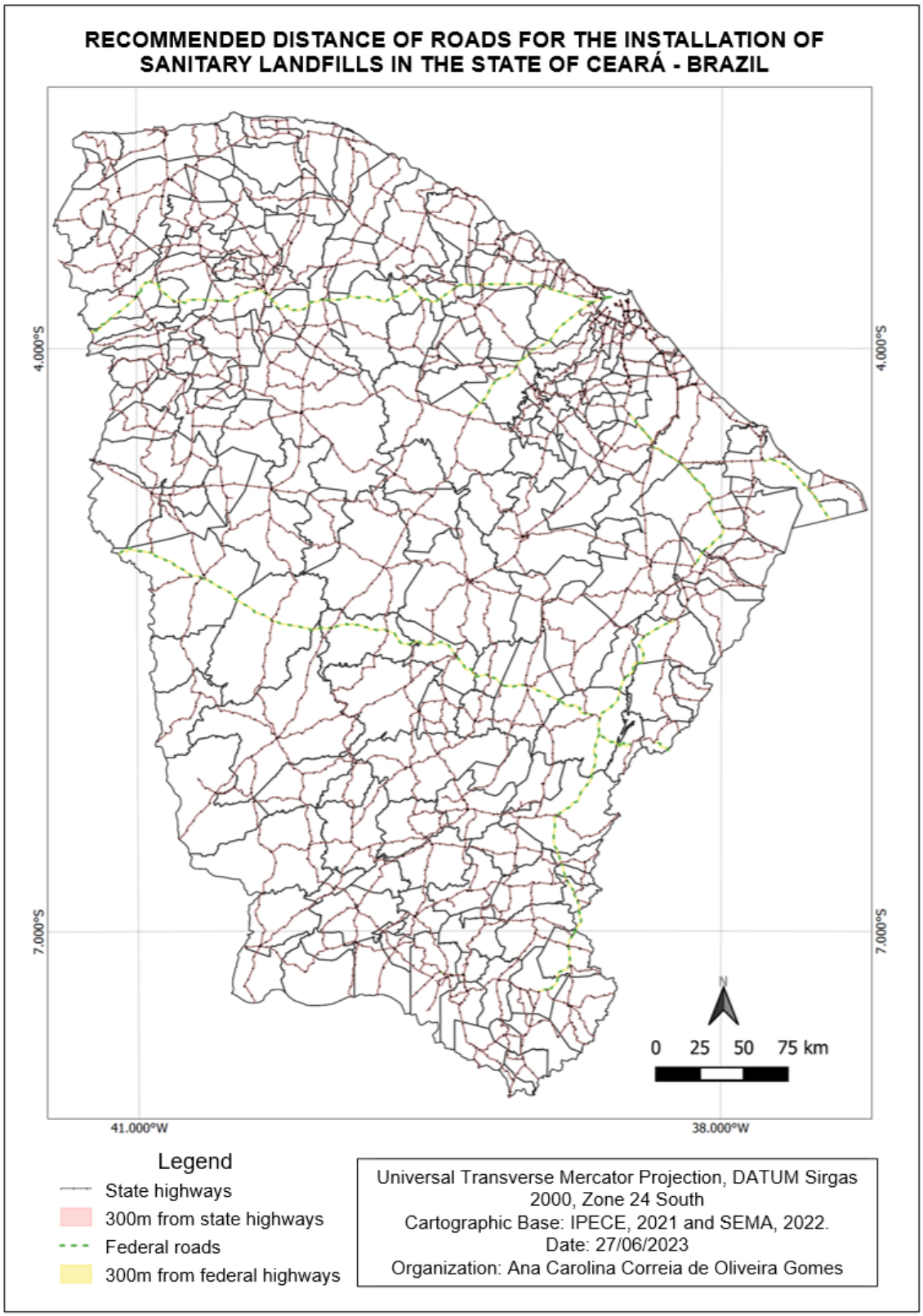

Figure 2 - Recommended distances from roads for landfill installation in the state of Ceará, Brazil
Source: The authors (2023)

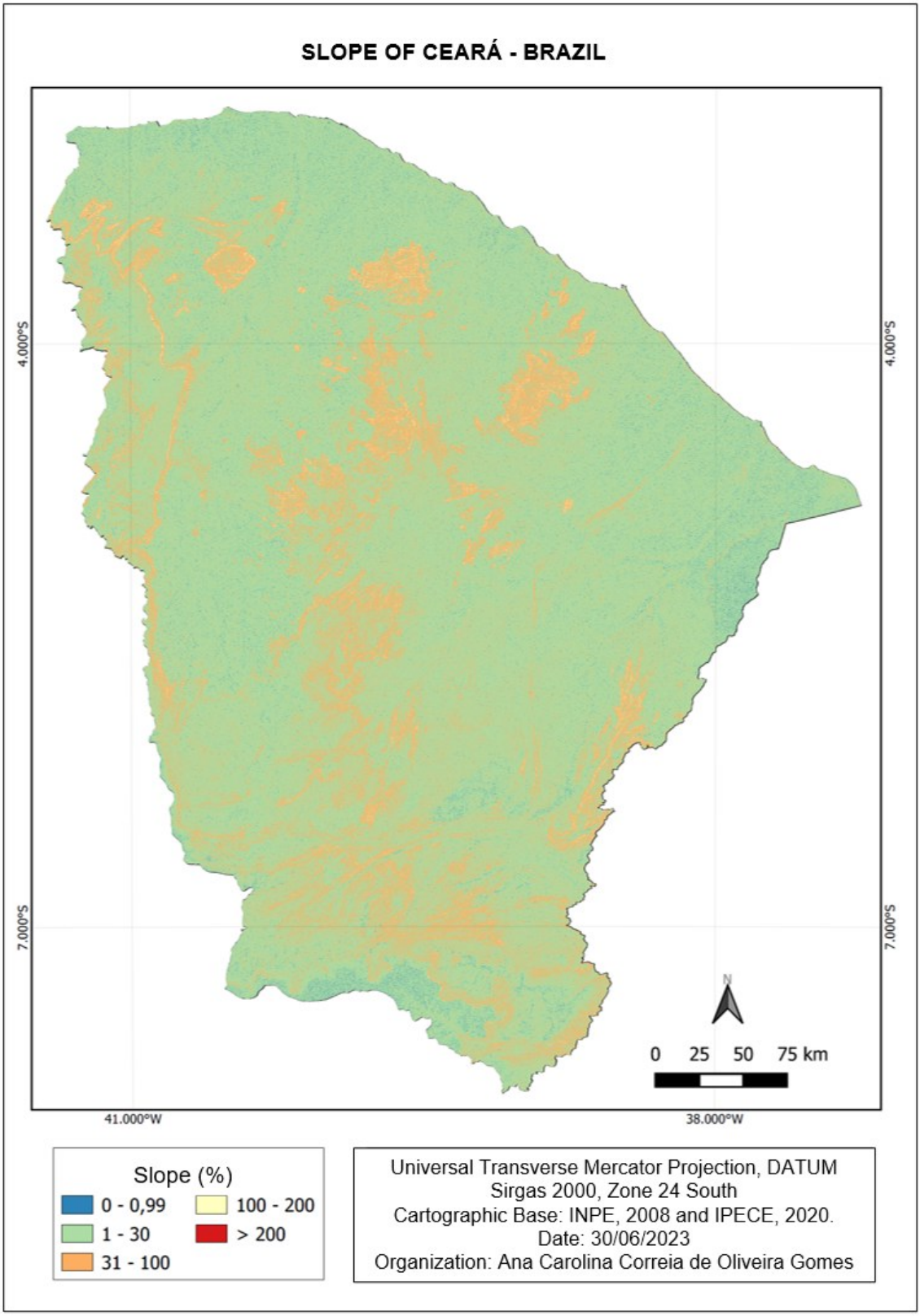

Figure 3 - Slope of the state of Ceará, Brazil
Source: The authors (2023)

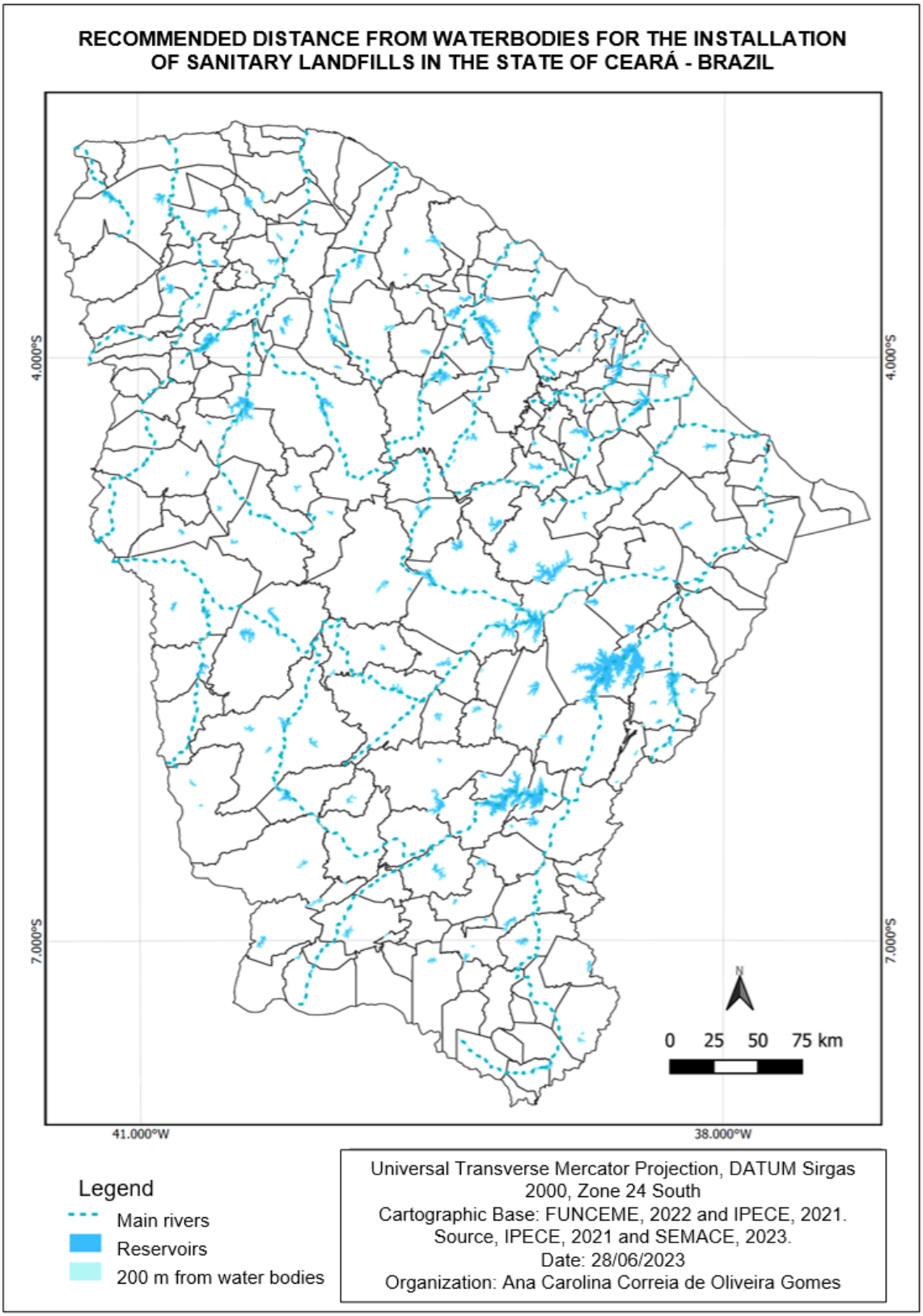

Figure 4 - Recommended distance from water bodies for landfill installation in the state of Ceará, Brazil
Source: The authors (2023).

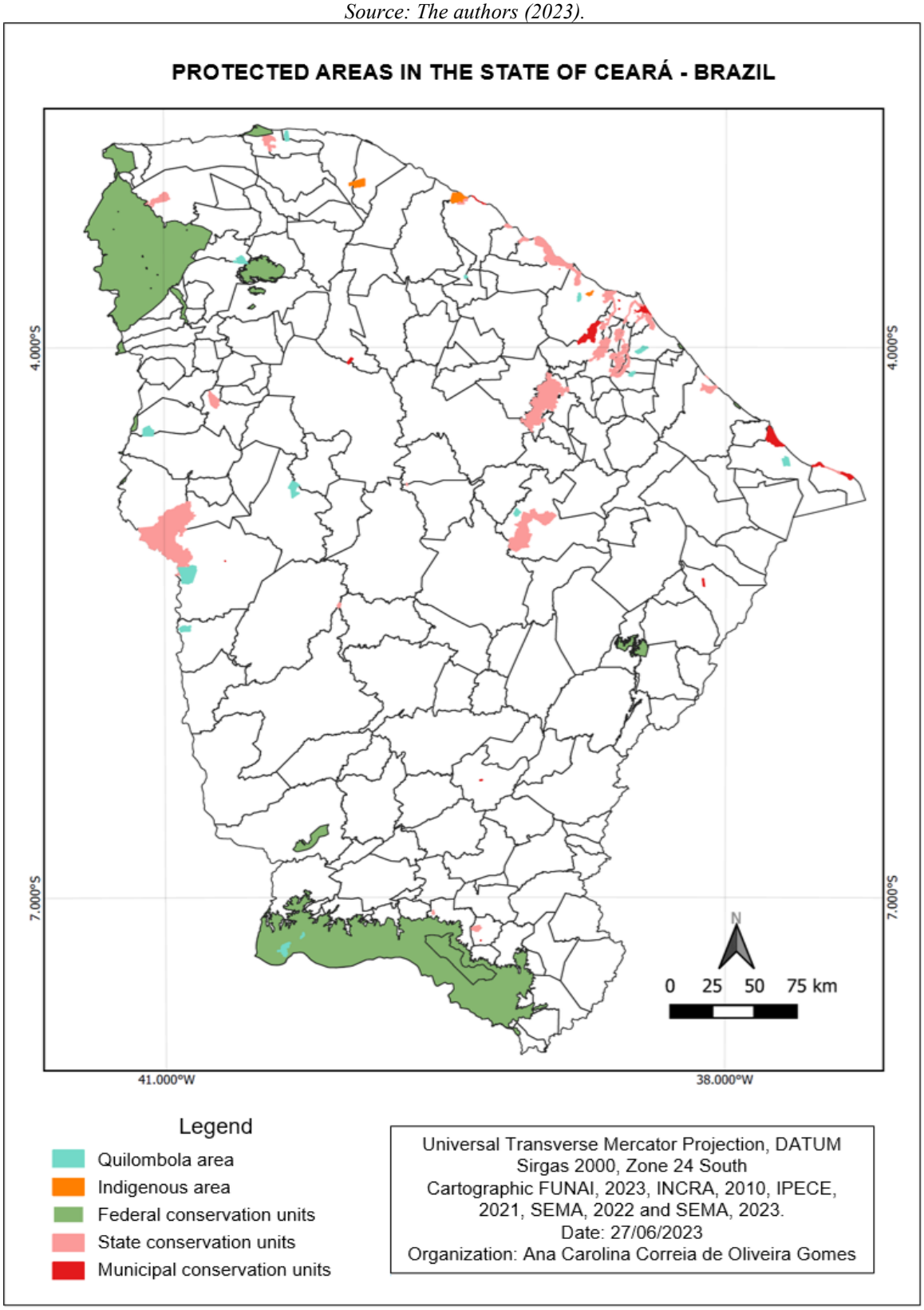

Figure 5 - Protected areas in the state of Ceará, Brazil
Source: The authors (2023)

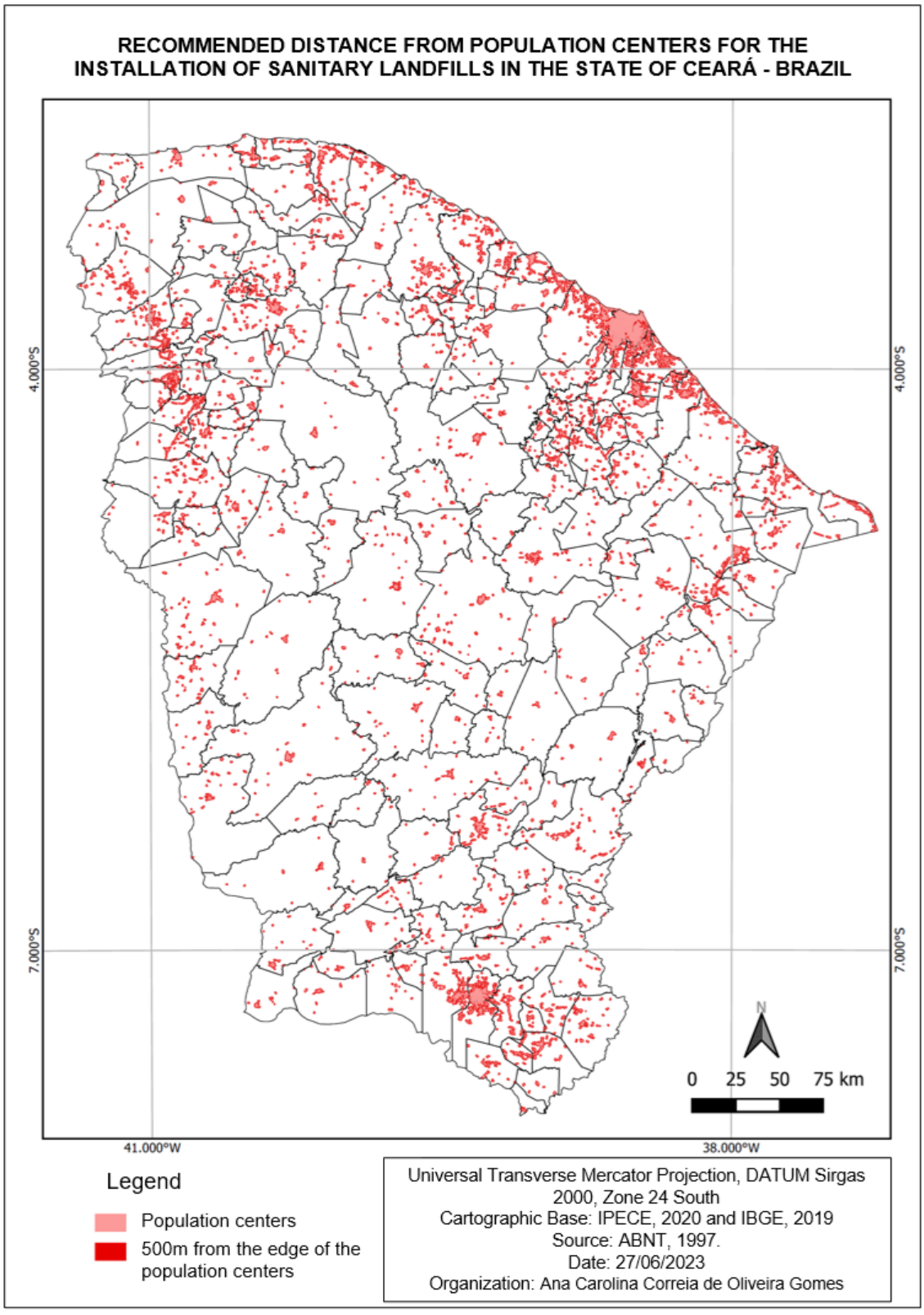

Figure 6 - Recommended distance from population centers for the installation of sanitary landfills in the state of Ceará, Brazil
Source: The authors (2023)

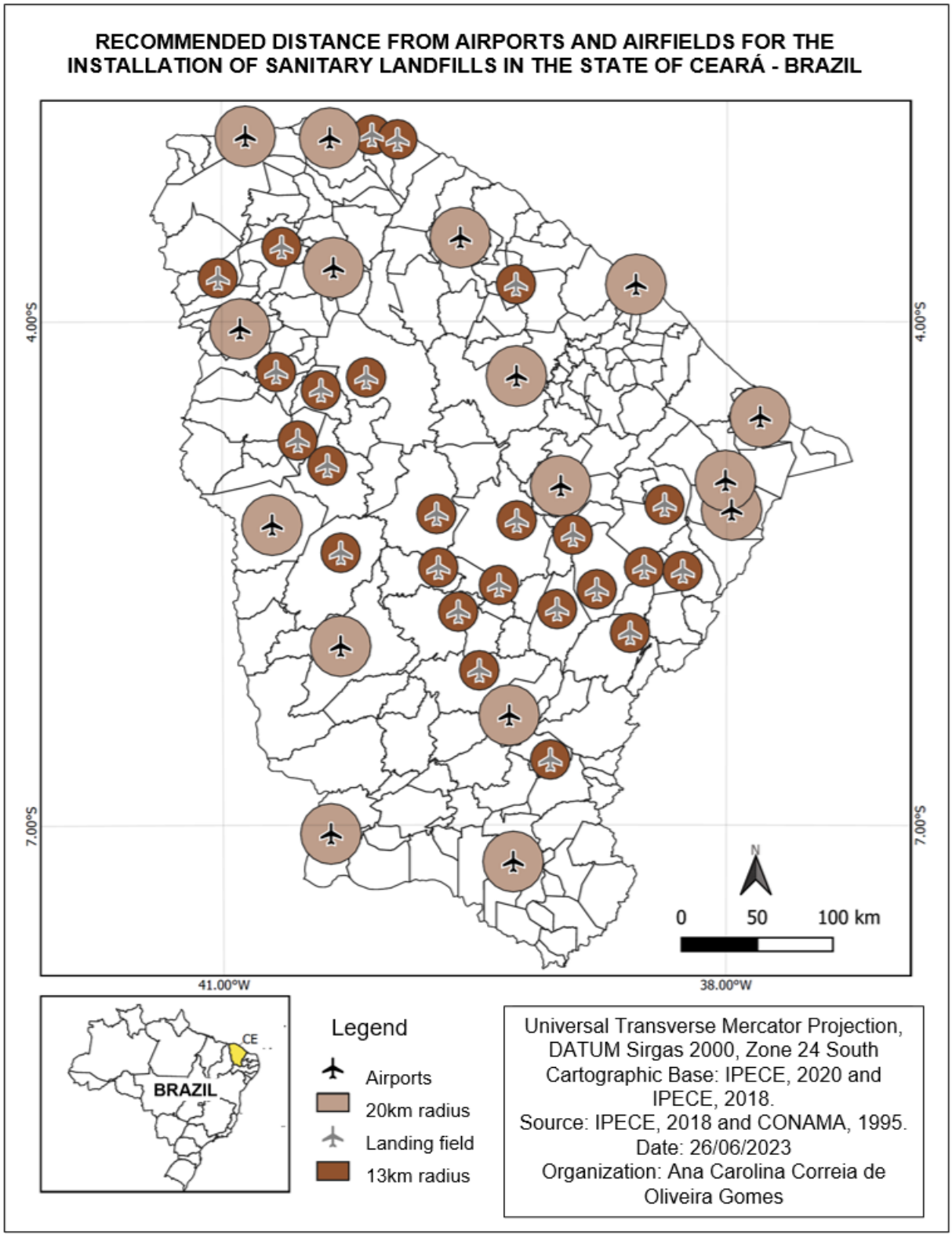

Figure 7 - Recommended distances from airports and airfields for the installation of landfills in the state of Ceará, Brazil
Source: The authors (2023)

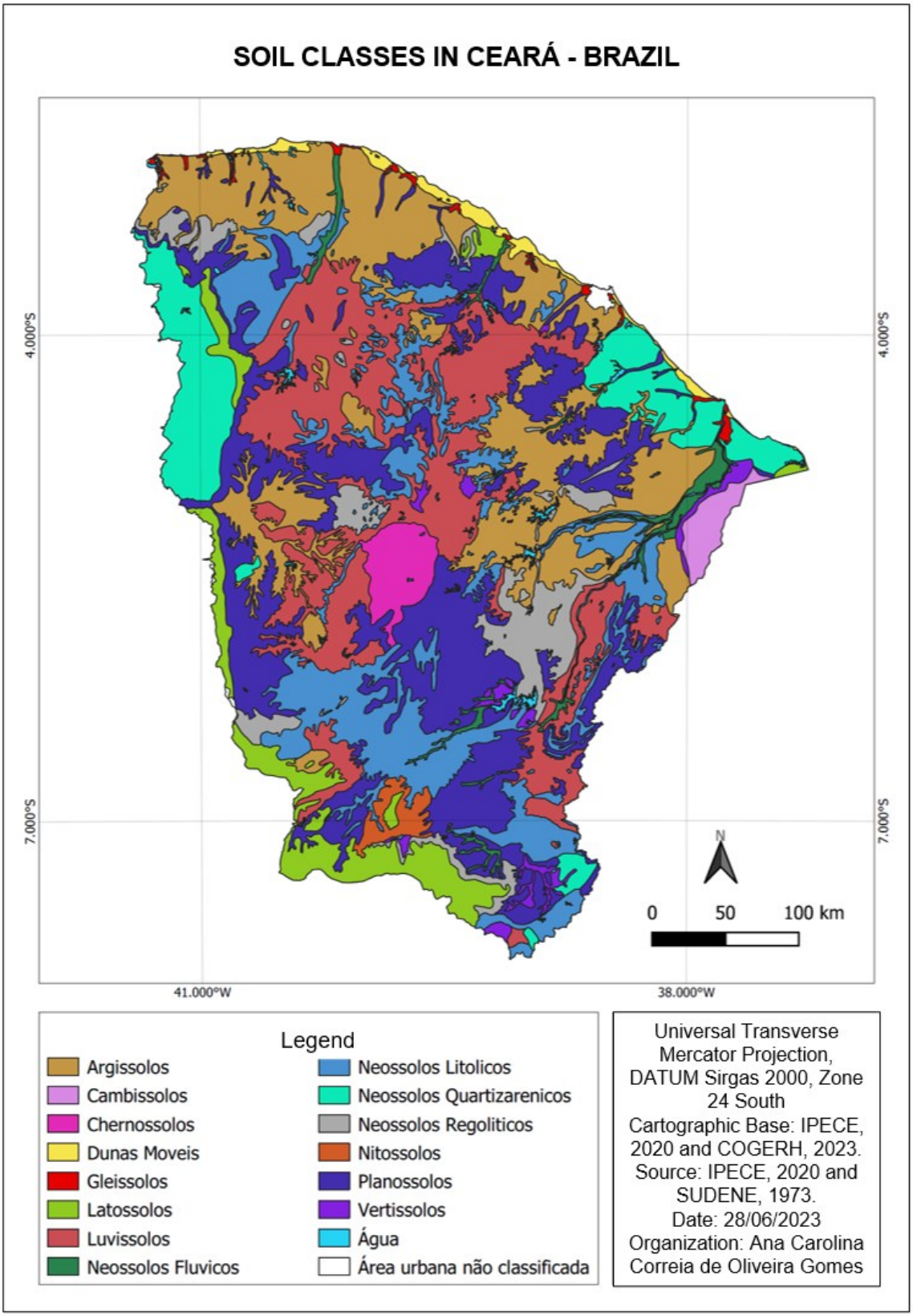

Figure 8 - Soil classes in the state of Ceará, Brazil

Source: The authors (2023)

According to the soil classes presented in the state (Figure 9), areas with Quartzarenic Neosols and shifting dunes were considered unsuitable for landfill implementation because they are sandy soils, according to EMBRAPA (Brazilian Agricultural Research Corporation, 2018), in addition to water areas.

However, Litholic Neosols and Regolitic Neosols should be avoided because they are shallow soils. Fluvic Neosols should also be used with restrictions because they are derived from alluvial sediments (op. cit.). In addition to that,according to the soil class, it is worth noting that the scale used in the preparation of the map is 1:600,000, which is not very accurate for determination, making it necessary to perform a soil analysis of each intended location when preparing the study for the installation of a sanitary landfill.

Through the application of multi-criteria analysis using the Boolean method, it was possible to determine the suitable and unsuitable areas for landfill installation, according to the geo-environmental parameters adopted (Table 3).

The results of the multi-criteria analysis adopted in this study can be seen in Figures 09 and 10, which show maps of areas that are unsuitable for landfill installation in the state of Ceará.

It should be noted that the criteria “distance from airports and landing fields” (31.51%) and “distance from population centers” (18.20%) presented a higher proportion of unsuitable areas, as can be seen in Table 4. However, it should also be noted that some of these areas overlap and, consequently, the final unsuitable areas reach a value of 68.63% for the entire state of Ceará.

Of thetotal area deemed unsuitable for the installation of landfills, the main limiting parameters were: distance from airports and landing fields (21.62%), distance from population centers (12.49%), soil type (9.73%), slope (8.72%), protected areas (7.84%), roads (6.15%), and distance from water bodies (2.08%).

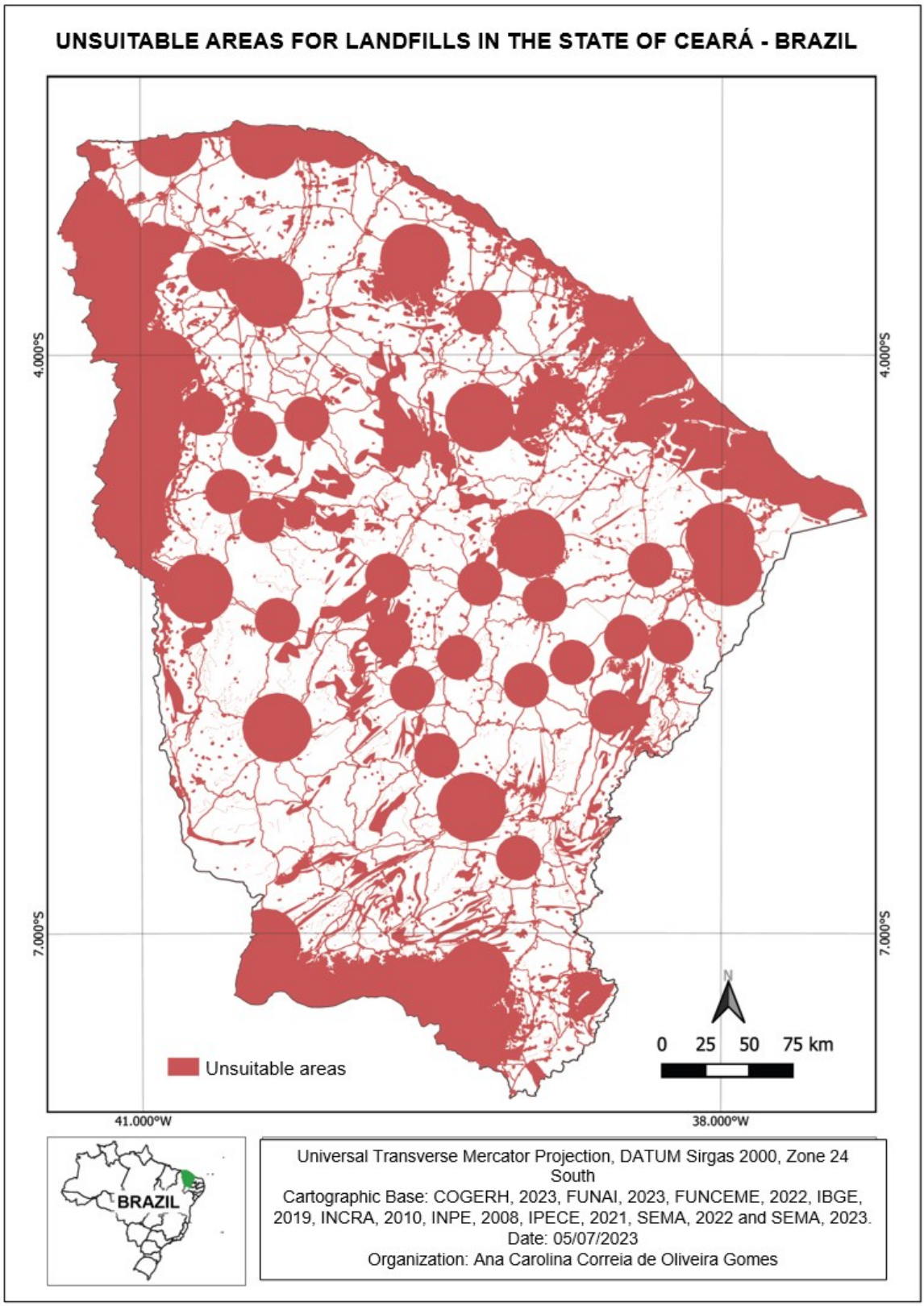

Figure 9 - Unsuitable arease for landfill installation in the state of Ceará, Brazil
Source: The authors (2023)

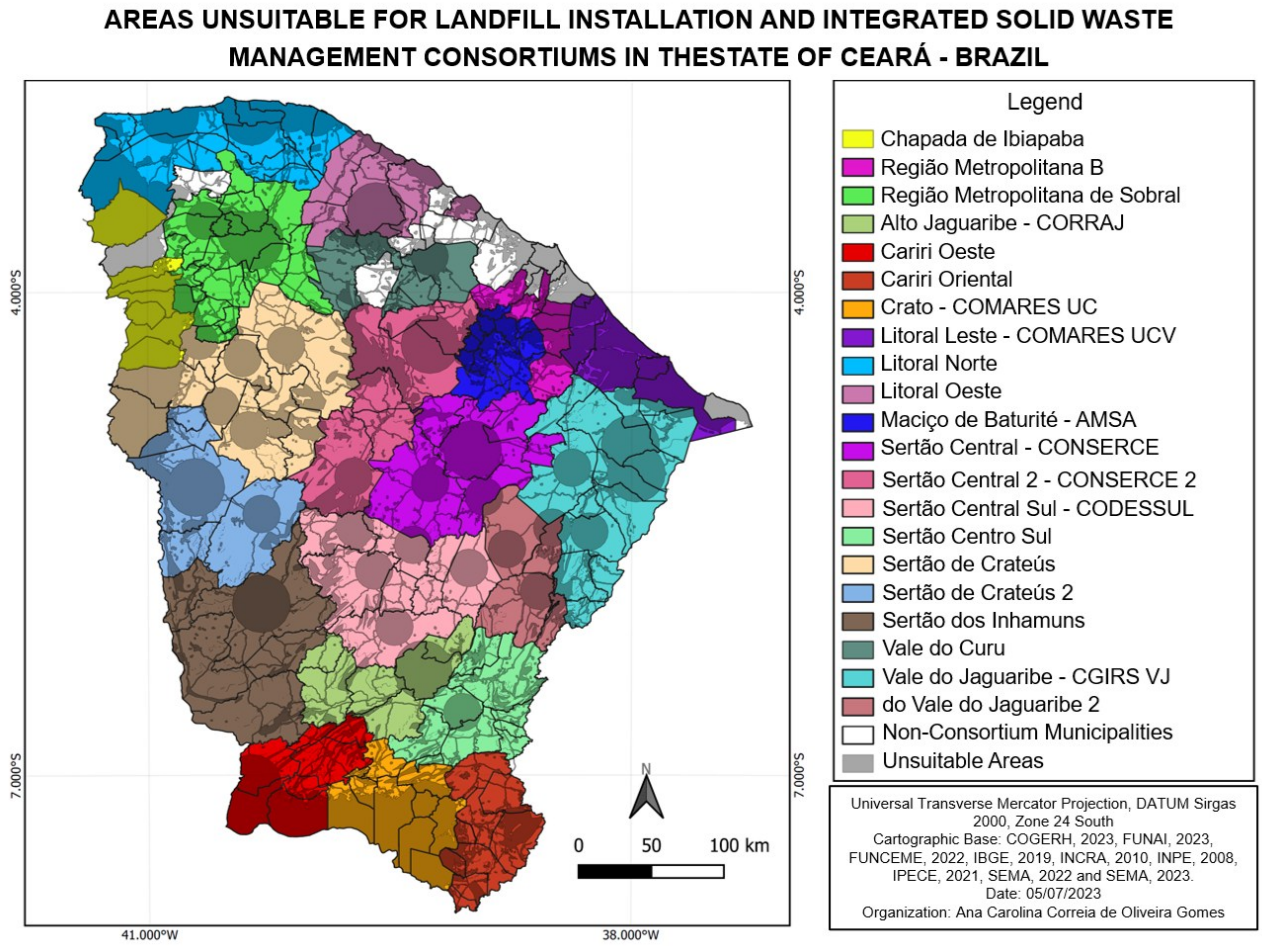

Figure 10 - Unsuitable areas for landfill installation by the integrated solid waste management consortium in the state of Ceará, Brazil
Source: The authors (2023)

Table 4 - Quantification of unsuitable areas for landfill installation in the state of Ceará according to each parameter

Parameters	Area (km²)	Proportion of total unsuitable area (%)	Proportion of total state area (%)
Roads	9.155,83	8,96	6,15
Slope	12.987,94	12,71	8,72
Distance from water bodies (only major rivers and reservoirs)	3.090,72	3,02	2,08
Protected areas	11.666,12	11,42	7,84
Distance from population centers	18.599,06	18,2	12,49
Soil type	14.488,02	14,18	9,73
Distance from airports and airfields	32.193,63	31,51	21,62

Source: The authors (2024)

It should be noted that some municipalities have their entire area classified as unsuitable, namely: Viçosa do Ceará, São Benedito, Carnaubal, Horizonte, Graça, Juazeiro do Norte, Barbalha, Mulungu, Guaramiranga, Pacoti, Salitre, Pindoretama, Cruz, Jijoca de Jericoacoara, Poranga, Fortaleza, and Aquiraz (Figure 10 and Supplementary File). This further highlights the importance of intermunicipal consortia for integrated solid waste management. Although not part of a consortium, the municipality of Fortaleza sends its municipal solid waste to the landfill located in the municipality of Caucaia, since its entire territory is unsuitable due to the minimum distance from airports and population centers. With regard to the existing consortia in the state, the quantity and proportion of unsuitable areas in each one can be seen in Table 5.

Table 5: Quantification of unsuitable areas for landfill installation in each consortium

Consortium	Unsuitable area (km^2)	Proportion in relation to total consortium area (%)
Chapada de Ibiapaba	4.058,67	97,0
Região Metropolitana B	1.442,86	58,6
Região Metropolitana de Sobral	3.567,33	41,9
Alto Jaguaribe - CORRAJ	1.914,69	35,2
Cariri Oeste	3.105,79	60,2
Cariri Oriental	1.660,15	34,3
Crato - COMARES UC	4.350,08	78,5
Litoral Leste - COMARES UCV	3.528,63	87,8
Litoral Norte	4.870,61	56,2
Litoral Oeste	2.308,50	46,0
Maciço de Baturité - AMSA	1.459,69	49,2
Sertão Central - CONSERCE	3.113,73	36,4
Sertão Central 2 - CONSERCE 2	4.378,81	47,8
Sertão Central Sul - CODESSUL	3.805,64	39,1
Sertão Centro Sul	1.711,40	29,8
Sertão de Crateús	6.549,44	50,2
Sertão de Crateús 2	3.273,47	39,9
Sertão dos Inhamuns	2.370,54	21,8
Vale do Curu	1.314,82	32,4
Vale do Jaguaribe - CGIRS VJ	4.759,10	42,0
Vale do Jaguaribe 2	2.034,36	42,7
Non-Consortium Municipalities	3.839,23	57,4

Source: The authors (2024)

The Chapada de Ibiapaba and Litoral Leste consortiums have almost all of their territory unsuitable for landfill installation, mainly due to the sandy soil characteristics of these regions. Other consortiums with a high proportion of unsuitable areas are the Crato Consortium, the Cariri Oeste Consortium, and the Metropolitan Region B Consortium. The consortiums with the smallest suitable areas in km2 are the Chapada de Ibiapaba Consortium, the Litoral Leste Consortium, the Metropolitan Region B Consortium, the Crato Consortium, and the Maciço de Baturité Consortium, respectively.

It should be noted that through the use of geoprocessing, it was possible to produce maps and tables containing suitable and unsuitable areas for landfill installation in the state of Ceará. Thus, geoprocessing proves to be an efficient tool for use in Environmental Impact Assessment studies, as verified in the works carried out by Dutra et al. (2020), Dias and Andrade (2020), Amaral and Lana (2017), Carrilho et al. (2018), Lourenço et al. (2015), and Carvalho et al. (2019).

Dias and Andrade (2020) used the following criteria for pre-selecting areas for landfill implementation in the municipality of Diamantina (MG): a distance of 200 m from watercourses or any water collection; a distance of 500 m from population centers; being outside the perimeter of Conservation Units; and being in areas with a slope between 3% and 20%. The authors found that soil was the most limiting factor in their study area, with a final value of only 0.89% of the area deemed suitable for installation.

As in this study, Dutra et al. (2020) superimposed maps to determine areas unsuitable for landfill installation, considering areas with a slope of less than 30%, low permeability soils, a minimum distance of 300 m from water bodies, a distance of 100 m from railways and highways, and 500 m from population centers. The work was carried out in the municipality of Esmeralda in Minas Gerais, so state criteria were used for the determination. It can be observed that the state of Minas Gerais is 100 m more restrictive in relation to the distances from water bodies established by ABNT (2010), but is 100 m more lenient for distances from highways than IMASUL (2016). Amaral and Lan (2017) used the same restrictions employed by Dutra et al. (2020) since their study was also conducted in Minas Gerais, in the municipality of Ouro Preto.

In the work of Lourenço et al. (2015), none of the areas in the metropolitan region of Sorocaba were classified as recommended without restrictions, due to the high polluting potential and complexity of this type of enterprise, which involves numerous negative environmental impacts that often cannot be circumvented. The authors also indicated that the ranking of the preselected areas was satisfactory, given the availability of a robust database, as was also the case in this study.

Carrilho et al. (2018), Carvalho, Junior, and Lollo (2019), and Lourenço et al. (2015) applied the attribute weighting methodology to classify areas. Different methodologies using GIS (Geographic Information Systems) presented satisfactory results for determining areas suitable and unsuitable for landfill installation, which can be used as a pre-selection of sites .

It should be noted that this study considered only geo-environmental criteria. However, other factors must also be evaluated when selecting a suitable area for a landfill installation, such as: waste reception capacity; landfill installation and operating costs; useful life; acceptability to the surrounding community; soil thickness, compressibility, and permeability; availability of cover material; alterability of geological materials; bedrock; aquifer depth; vegetation; climatic characteristics; among others.

4. Final considerations

Geoprocessing is a valuable tool in EIA work, particularly for identifying areas suitable for landfill installation.

Vector files from official databases can support this process; however,depending on the scale, field surveys and laboratory analyses may still be required..

The establishment of consortia for the implementation of sanitary landfills is important not only to reduce costs, but also because some municipalities either lack sufficient suitable land or have their entire territory classified as unsuitable..

The state of Ceará has 68.63% of areas unsuitable for landfill installation, considering the minimum distance from roads, water bodies (main rivers and reservoirs), population centers, airports, and landing fields, being outside protected areas and sandy soils.

This work presents a pre-selection of areas, which should also take into account field samples, additional factors, and political issues to enable the implementation of sanitary landfills.

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