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ORIGINAL RESEARCH ARTICLE

Geographic information systems-based multicriteria model for sustainable landfill site selection and environmental protection in developing regions: A case study of Arbieto, Bolivia

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Abstract

In many developing countries, the final disposal of municipal solid waste remains an environmental and public health problem due to the use of open dumpsites without technical planning or environmental control. Similar conditions have been reported in Asia, Africa, and Latin America, where inadequate waste disposal contributes to groundwater contamination, surface water pollution, greenhouse gas emissions, soil degradation, and health risks for nearby communities. Studies conducted in India, Ghana, Jordan, Ethiopia, Iran, Iraq, Ecuador, Pakistan, Bangladesh, Indonesia, the Philippines, China, Nepal, Sri Lanka, Malaysia, Peru, and Central Asia have highlighted the importance of geographic information systems (GIS) and multicriteria analysis for improving landfill site selection and supporting sustainable waste management. This is the case in the municipality of Arbieto, Cochabamba, Bolivia, where only one community has a reconditioned dumpsite that does not meet technical or sanitary standards. To address this situation, a GIS-based multicriteria model was applied using ArcGIS software, considering variables such as slope, hydrology, geology, vegetation cover, accessibility, land use, productive potential, groundwater recharge zones, protected areas, and distance to populated centers. The model integrated environmental, technical, geological, hydrological, and social criteria to identify suitable areas for final waste disposal. The selected areas present suitable slope conditions, adequate separation from rivers and populated centers, favorable geological and lithological characteristics, and compliance with environmental protection requirements. The results confirm that combining spatial analysis and multicriteria evaluation is an effective strategy for landfill planning in rural municipalities. The study concludes that the municipality of Arbieto should prioritize implementing a controlled sanitary landfill in the selected areas to improve environmental management and reduce the impacts associated with open dumping. The proposed GIS-based multicriteria methodology may also serve as a replicable planning tool for rural municipalities in Bolivia and other regions facing similar solid waste management challenges.

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1. Introduction

Inadequate management of municipal solid waste continues to create severe environmental pressures and public-health risks in many developing countries, particularly in rural and peri-urban areas where engineered disposal facilities remain lacking.[1,2] Similar conditions have been documented across developing regions in Asia, Africa, and Latin America, where improper waste disposal contributes to groundwater contamination, surface water pollution, greenhouse gas emissions, soil degradation, and increased exposure of nearby communities to environmental health hazards.[3-5] In Bolivia, many municipalities still rely on open dumping because of limited technical capacity and insufficient long-term planning for waste treatment and final disposal.[1,2] Arbieto, located in the department of Cochabamba, illustrates this situation clearly: although it encompasses 67 communities, only the central settlement in District 1 operates a reconditioned dumpsite, and even this facility lacks basic controls for leachate and gas emissions.[6]

National epidemiological assessments report that municipalities relying on open dumping present significantly higher rates of acute diarrheal diseases and respiratory infections, largely due to soil contamination, inadequate waste handling, and the frequent burning of solid waste.[7] These public health and environmental concerns are also recognized in the Arbieto Territorial Development Plan (PTDI 2021–2025), which identifies open burning and informal waste disposal as persistent problems affecting local communities.[6] The remaining communities in Arbieto lack formal collection systems and typically burn or bury waste,[8] further aggravating soil and water pollution.

Selecting an adequate site for the final disposal of municipal solid waste constitutes a complex territorial planning problem because it requires the simultaneous evaluation of environmental, hydrological, geological, technical, social, and legal constraints over a wide geographic area.[9-11] In rural municipalities such as Arbieto, these challenges are intensified by fragmented land use, proximity to agricultural areas, environmentally sensitive zones, dispersed settlements, variable topography, and limited technical information. Recent studies across developing regions emphasize that improper landfill siting may intensify land-use conflicts, hydrogeological vulnerability, and long-term public health risks.[12-14]

To address these challenges, geographic information systems (GIS) integrated with multicriteria decision-making (MCDM) analysis have become widely adopted tools for landfill site selection because they enable the integration of environmental, technical, and social criteria into a spatial decision-making process.[15-17] These approaches facilitate the identification of environmentally suitable locations and support sustainable waste management and territorial planning.

Remote sensing, GIS, analytical hierarchy process (AHP), and multicriteria analysis have been used for solid waste disposal site selection under different territorial conditions in Ethiopia, India, and other developing regions.[18-20] More recent applications have incorporated alternative multicriteria and geospatial approaches, including spherical fuzzy technique for order preference by similarity to ideal solution and geospatial optimization, to improve the evaluation and ranking of potential landfill locations.[21,22]

The selection process must also consider the environmental standards and technical feasibility requirements governing final disposal facilities. Reviews of site-selection criteria emphasize the importance of environmental restrictions, while technical feasibility assessments highlight the need to evaluate the physical and territorial characteristics of candidate locations before implementation.[23,24] Comparable GIS-based applications in Ecuador, Ethiopia, and Mexico further demonstrate the usefulness of spatial multicriteria evaluation for identifying suitable final disposal areas.[25-27]

The effectiveness of final disposal planning is also closely related to the broader municipal waste management system. Studies of urban solid waste management and final disposal in Brazil, together with research on collection systems in Bali and comparative analyses of waste management practices in developing Asian countries, demonstrate that collection performance, waste characteristics, urban conditions, and existing management practices influence the sustainability of municipal waste systems.[28-30]

At the national level, solid waste management and final disposal are governed by the Bolivian legal and technical framework, particularly Law No. 755, Supreme Decree No. 2954, and NB 757, which establish the institutional,

environmental, and technical basis for integrated waste management and the location of municipal final disposal systems.[31-33] Similar site evaluation and multicriteria approaches have also been applied in Bolivian municipalities including Tarata, Tiquipaya, and Cobija, demonstrating their growing relevance under rural and peri-urban conditions.[34-36]

In this context, the present study aims to identify the most suitable site for the final disposal of municipal solid waste in Arbieto by applying a spatial multicriteria analysis using GIS. The working hypothesis is that integrating environmental, geological, hydrological, technical, and social criteria enables the identification of technically feasible, environmentally safe, and socially acceptable landfill sites. The proposed methodology is intended to support municipal decision-making and provide a transferable planning framework for rural municipalities in Bolivia and other developing regions facing similar solid waste management challenges.

2. Materials and methods

This study implements a geospatial MCDM approach to identify optimal locations for sanitary landfill siting in the municipality of Arbieto (Cochabamba, Bolivia). The analysis is based on a GIS-supported multicriteria framework adapted to the environmental and territorial characteristics of the study area. The analysis was conducted using ArcGIS v. 10.4.1 (Esri, United States), utilizing the Spatial Analyst toolbox for raster processing and overlay analysis. To ensure reproducibility, the model followed a Boolean logic overlay structure where all environmental, technical, legal, and social variables were standardized into a binary suitability scale (0 = unsuitable, 1 = suitable). This approach applies non-compensatory decision rules, ensuring that only locations meeting all predefined suitability criteria are classified as suitable.[15]

2.1. Study area and data collection

The municipality of Arbieto, structured into seven districts and 67 communities, was defined as the spatial domain for this study, employing geospatial data whose reliability is underpinned by the use of official sources and standardized remote sensing products. The primary cartography, including layers for land use, productive potential, and administrative boundaries, was obtained from the municipality's 2021–2025 PTDI (Territorial Plan for Integral Development),[6] while topography was analyzed using a Digital Elevation Model provided by the Military Geographical Institute of Bolivia to ensure precision in slope analysis. Furthermore, environmental and geological information regarding hydrography, road networks, population centers, geological formations, and lithology was integrated from official municipal records to evaluate terrain stability and permeability. Finally, vegetation cover was determined through the processing and classification of Landsat imagery, ensuring that land surface conditions were fully updated. These datasets were integrated into a GIS-based multicriteria framework to identify environmentally and technically suitable landfill locations. The selected variables represent the principal environmental, technical, hydrological, geological, and social constraints recommended for landfill site selection.[23,24]

2.2. Data pre-processing and software versions

All vector datasets (shapefiles) were standardized to the WGS 84/UTM zone 20S coordinate reference system prior to spatial analysis. Euclidean distance calculations, raster standardization, and Boolean overlay procedures were subsequently executed in ArcGIS v. 10.4.1 using the Spatial Analyst toolbox to integrate environmental, technical, legal, and social criteria into a unified GIS-MCDM framework.

Eleven spatial criteria, derived from official cartographic data in the PTDI and national geospatial repositories, were represented as individual spatial layers.[6] Each layer (Figure 1) was standardized according to regulatory thresholds using a strict Boolean logic framework, classifying pixels as suitable (1) or unsuitable (0).[15,33]

2.3. Study workflow

A GIS-based multicriteria methodology was implemented in ArcGIS v.10.4.1 to identify suitable areas for sanitary landfill siting in the municipality of Arbieto. The workflow includes the definition of the research problem and objective, data collection, GIS processing, spatial suitability analysis, identification of candidate landfill sites, evaluation of results, and final site selection (Figure 2).

2.3.1. Multicriteria criteria and processing in ArcGIS

The eleven spatial criteria, slope (C1), hydrography (C2), road access (C3), proximity to population centers (C4), vegetation cover (C5), land use (C6), productive potential (C7), geology (C8), lithology (C9), water recharge (C10), and protected areas (C11), were operationalized in ArcGIS v. 10.4.1 using Spatial Analyst tools (e.g., Slope, Euclidean Distance, Reclassify, and Raster Calculator). C_i (x, y) = {1 if criterion *i* is satisfied at location (x, y); 0, if not satisfied}, where C_i (x, y) is the value of criterion *i* at the spatial point (x, y).

To calculate the final suitability (Sx,y), a strict Boolean overlay procedure was executed through the logical intersection operator (AND)[17] (**Equation 1**) and the logical intersection operator (AND):[15]

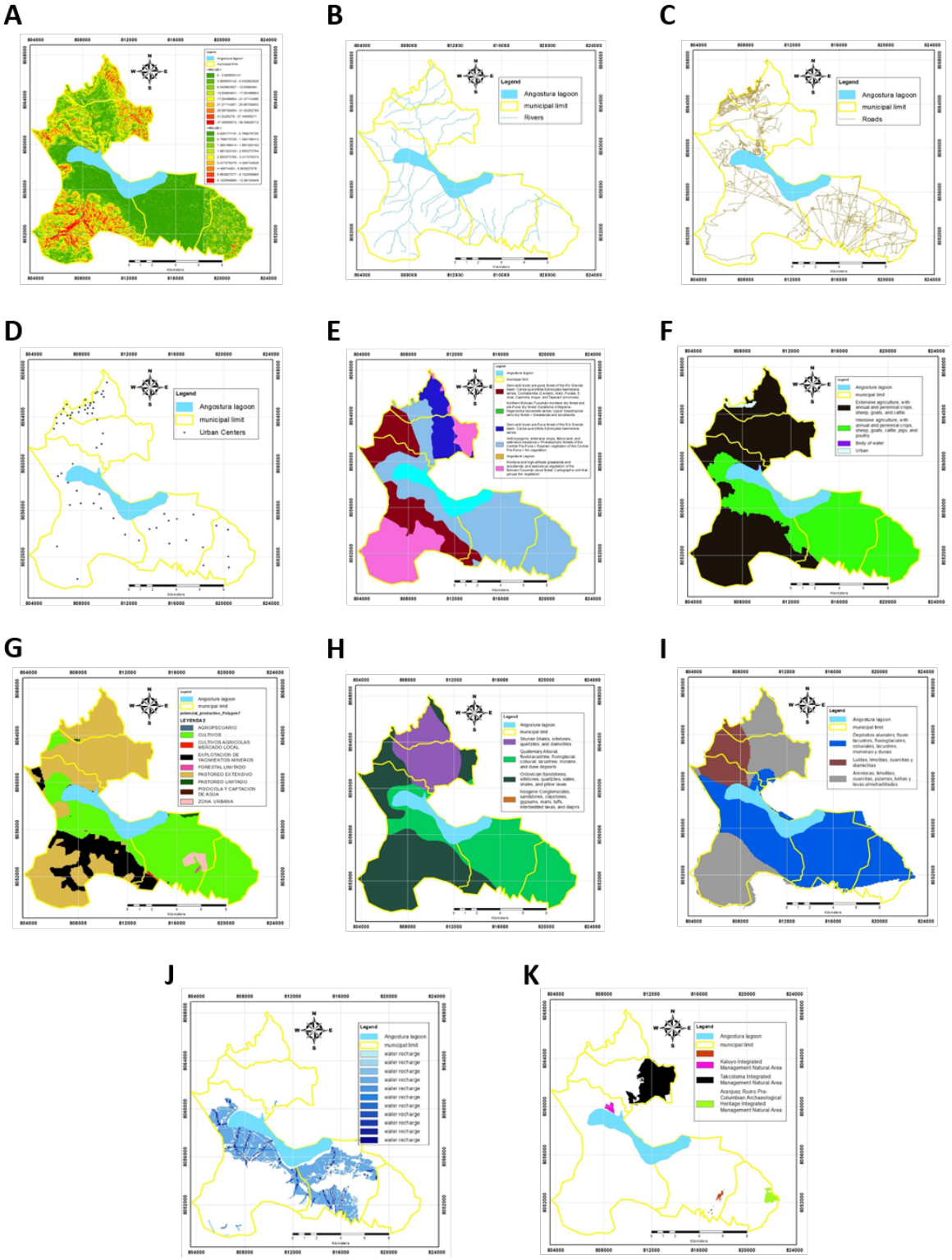


Figure 1. Maps and shapefiles required for applying the multicriteria model for final disposal site selection of solid waste. (A) Slope raster from the Digital Elevation Model. (B) River shapefile. (C) Road network shapefile. (D) Shapefile of urban centers. (E) Vegetation cover shapefile. (F) Land use. (G) Productive potential. (H) Geology shapefile. (I) Lithology. (J) Water recharge. (K) Protected areas.

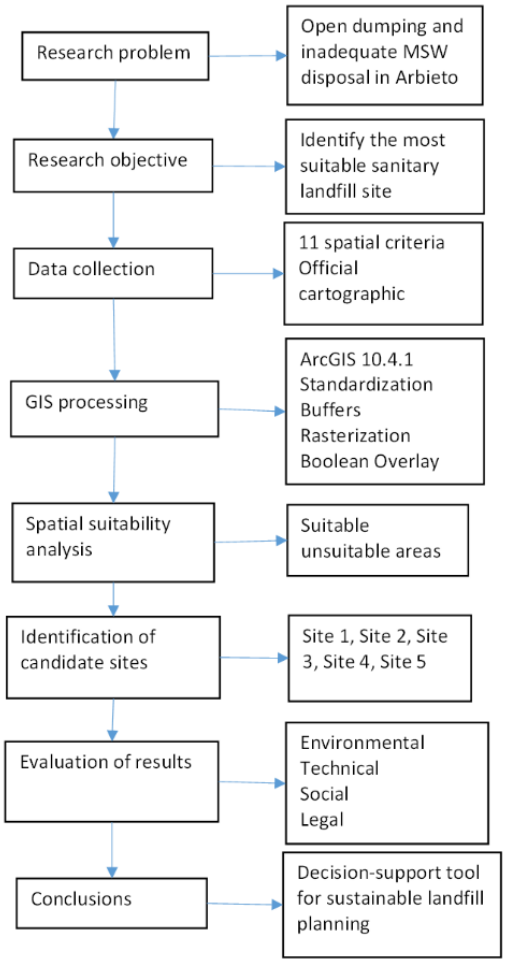


Figure 2. Geographic information systems (GIS)-based methodological workflow. Abbreviation: MSW: Municipal solid waste.

$$S(x,y) = C_1(x,y) \wedge C_2(x,y) \wedge \ldots \wedge C_n(x,y) \quad (1)$$

Under this non-compensatory approach, a location was classified as suitable only when all eleven criteria simultaneously satisfied the Boolean condition (value = 1); otherwise, it was excluded from the final suitability map.

The suitability thresholds and GIS processing procedures applied to each criterion are summarized in Tables 1 and 2.

From a methodological perspective, comparative studies on Boolean, AHP, and fuzzy models applied to landfill site selection using GIS describe the Boolean approach as a non-compensatory decision rule in which all criteria are converted into binary values (0–1) and combined using logical operators of intersection (AND) or union (OR).[15] In the present study, the intersection (AND) operator was applied, meaning that compliance with every criterion was mandatory. Under this structure, a location is considered suitable only when all binary layers simultaneously take the value 1. Consequently, if any criterion takes the value 0, the site was automatically excluded from consideration, since no trade-offs between variables are permitted.

Table 2 describes the GIS processing workflow and Boolean standardization procedure used to classify the study area into suitable and unsuitable zones for sanitary landfill development.

2.3.2. Model workflow

The GIS-based multicriteria workflow consisted of sequential data preparation, criterion standardization, Boolean overlay analysis, and generation of the final suitability map for sanitary landfill siting in the municipality of Arbieto (Figure 2).

First, the thematic layers described in Section 2.1 were imported into ArcGIS and prepared for spatial analysis. Second, the slope layer was generated from the Digital Elevation Model using the Slope tool within the Spatial Analyst extension. This raster layer represents terrain inclination and constitutes a key environmental criterion for landfill stability and construction feasibility.

Third, Euclidean distance analyses were performed for rivers, roads, and settlements using the Euclidean Distance tool. The resulting distance rasters were subsequently classified according to the regulatory thresholds defined in Table 1.[33]

Fourth, all continuous raster layers were standardized through reclassification into binary suitability maps using the Reclassify tool. The eleven criteria were transformed into raster layers with values of 1 (suitable) or 0 (unsuitable), according to the thresholds established in Table 1.

Fifth, the binary layers corresponding to all criteria were combined using the Raster Calculator tool to perform a Boolean overlay operation. The logical intersection (AND) of the eleven binary layers generated the final suitability map, where only locations satisfying all criteria were classified as suitable.[15]

Finally, the resulting suitability raster was exported and converted into both raster and vector (shapefile) formats to facilitate validation, mapping, and spatial visualization of the selected sites. These outputs served as the basis for identifying candidate landfill areas and for subsequent spatial interpretation and decision-making.

Table 1. Criteria for sanitary landfill site selection

Criteria	Suitable (green; value = 1)	Unsuitable (red; value = 0)
1. Slope	Slope >3% and <12%	Slope <3% or >12%
2. Rivers	Distance to rivers >500 m	Distance to rivers <500 m
3. Access roads	Distance to roads >200 m and <1,500 m	Distance to roads <200 m or >1,500 m
4. Population centers	Distance to communities >1,000 m	Distance to communities <1,000 m
5. Vegetation cover	High-mountain grasslands and montane and high-mountain scrublands; saxicolous vegetation of the Bolivian-Tucuman Montane Edge; anthropogenic areas (extensive crops, fallow lands, and extensive grasslands); phreatophytic forests of the Central Prepuna; riparian vegetation of the Central Prepuna; no vegetation	Lower semi-arid prepuna forest of the Río Grande basin; Bolivian-Tucuman montane dry forest and northern prepuna; no vegetation (Angostura Lagoon)
6. Land use	Extensive agro-pastoral use, with annual and perennial crops and livestock production (sheep, goats, and cattle)	Intensive agro-pastoral use, with annual and perennial crops and livestock production (sheep, goats, cattle, pigs, and poultry); water bodies; urban areas
7. Productive potential	Agro-pastoral use; extensive grazing; limited grazing	Agricultural crops; agricultural crops for local markets; mining exploitation areas; limited forestry use; pisciculture and water catchment areas; urban areas of importance and environmental and social sensitivity
8. Geology	Silurian: shales, siltstones, quartzites, and diamictites. Ordovician: sandstones, siltstones, quartzites, slates, shales, and pillow lavas	Quaternary: alluvial, fluviolacustrine, fluvioglacial, colluvial, lacustrine, moraine, and dune deposits. Neogene: conglomerates, sandstones, claystones, gypsum, marls, tuffs, interbedded lavas, and diapirs
9. Lithology	Shales, siltstones, quartzites, and diamictites; sandstones, siltstones, quartzites, slates, shales, and pillow lavas	Alluvial, fluviolacustrine, fluvioglacial, colluvial, lacustrine, morainic, and aeolian deposits
10. Water recharge	Areas located outside groundwater recharge zones	Areas located within groundwater recharge zones
11. Protected areas	Areas located outside protected areas	Protected areas, including Tackoloma Integrated Management Natural Area, Kaluyo Integrated Management Natural Area, and Aranjuez Ruins Integrated Management Natural Area and Pre-Columbian Archaeological Heritage

Note: Author's elaboration based on GEO GISS[23,24] and Bolivian technical regulations.[31,33]

3. Results

This section presents the results of the multicriteria model developed for sanitary landfill site selection in the Municipality of Arbieto, Cochabamba, using the ArcGIS software. The spatial analysis identified the areas suitable for sanitary landfill development according to the established multicriteria framework.

3.1. Individual criterion mapping

The results of each criterion are presented in Figure 3. In this table, areas classified as suitable are represented in green (value = 1), while areas classified as unsuitable are represented in red (value = 0).

Figure 3 summarizes the binary classification obtained for each spatial criterion incorporated into the GIS-based multicriteria model. The resulting maps illustrate the spatial distribution of the suitability and restriction zones associated with each criterion.

The spatial distribution of the criteria reveals that environmental restrictions vary considerably across the municipality. Hydrography, groundwater recharge zones, protected areas, and population centers generated the largest exclusion areas, whereas slope, geology, and lithology primarily constrained terrain suitability.

3.2. Final suitability mapping

The final suitability map was obtained by applying a Boolean

Table 2. Procedure for sanitary landfill site selection using the multicriteria model

Step	GIS command	Command parameters
Data import	Add data	Digital Elevation Model: ASTGTM2_S18W066, ASTGTM2_S18W067; shapefiles: rivers, roads, urban centers; rasters: vegetation cover, land use, productive potential, geology, lithology, water recharge, protected areas
Slope	ArcToolbox>Spatial Analyst Tools>Surface > Slope> Input raster	Digital Elevation Model
Distance	ArcToolbox > Spatial Analyst Tools > Distance > Euclidean Distance > Input features	Rivers, Roads, Urban Centers
Reclassification	ArcToolbox > Spatial Analyst Tools > Reclassify > Raster input	Slope; Euclidean rivers; Euclidean roads; Euclidean urban centers; vegetation cover; land use; productive potential; geology; lithology; water recharge; protected areas
Classification	>Classify > method: equal interval	Classes: Slope (3), rivers (2), roads (3), urban centers (2); break values: slope: 3%–12%, rivers: 500 m, roads: 200–1,500 m, urban: centers 1,000 m
Binary reclassification	>Old values > new value	Old values: (suitable criterion values) new value = 1; old values: (unsuitable criteria values) new value = 0
Symbology	Layer Properties > Symbology > Classified	Value 1: green color; value 0: red color
Overlay result	ArcToolbox > Spatial Analyst Tools > Map Algebra > Raster Calculator	Final suitability raster= Criterion1 ∧ Criterion2 ∧ Criterio3 ∧ Criterion4 ∧ Criterion5 ∧ Criterion6 ∧ Criterion7 ∧ Criterion8 ∧ Criterion9 ∧ Criterion10 ∧ Criterion11

Source: Author's elaboration on GEO GISS.[21]

intersection of all criteria layers in ArcGIS (**Equation 1**):

$$S(x,y) = C_1(x,y) \wedge C_2(x,y) \wedge \ldots \wedge C_n(x,y) \quad (1)$$

where $S(x, y)$ represents the final suitability at location (x, y), and nine C_1 is a binary criterion layer.

Only locations satisfying all eleven criteria were classified as suitable. The resulting map identified the candidate areas that satisfied the complete set of selection criteria.

The suitable areas identified are mainly located in zones with moderate slopes, adequate distance from rivers and population centers, favorable geological conditions, and accessible connection to the road network. Most of these areas are situated in the rural sectors of the municipality, where land use conflicts and environmental restrictions are comparatively lower.

Figure 4 presents the final raster suitability map generated in ArcGIS, showing the spatial distribution of suitable and unsuitable areas for landfill implementation. Six candidate landfill sites (Sites 1–6) were identified and are indicated on the map. The suitable zones are concentrated in specific sectors of Districts 3, 5, and 6, where all selection criteria were simultaneously fulfilled. The geographic identification of each candidate site, including the corresponding community name, Easting and Northing coordinates, and area, is presented in Table 3.

Figure 5 shows the satellite visualization of the final landfill site selection. This representation provides a more detailed interpretation of the selected areas and their territorial context, including proximity to roads, surrounding land use, and topographic characteristics. The satellite imagery facilitates the visual interpretation of the selected sites within their surrounding territorial context.

3.3. Identified site alternatives

Following the Boolean multicriteria analysis, the suitable polygons identified throughout the municipality were grouped into six suitable zones according to their spatial continuity and geographic location (Table 3). These zones represent the principal areas suitable for sanitary landfill development and served as the basis for the subsequent prioritization of candidate alternatives.

The six candidate sites correspond to the areas satisfying

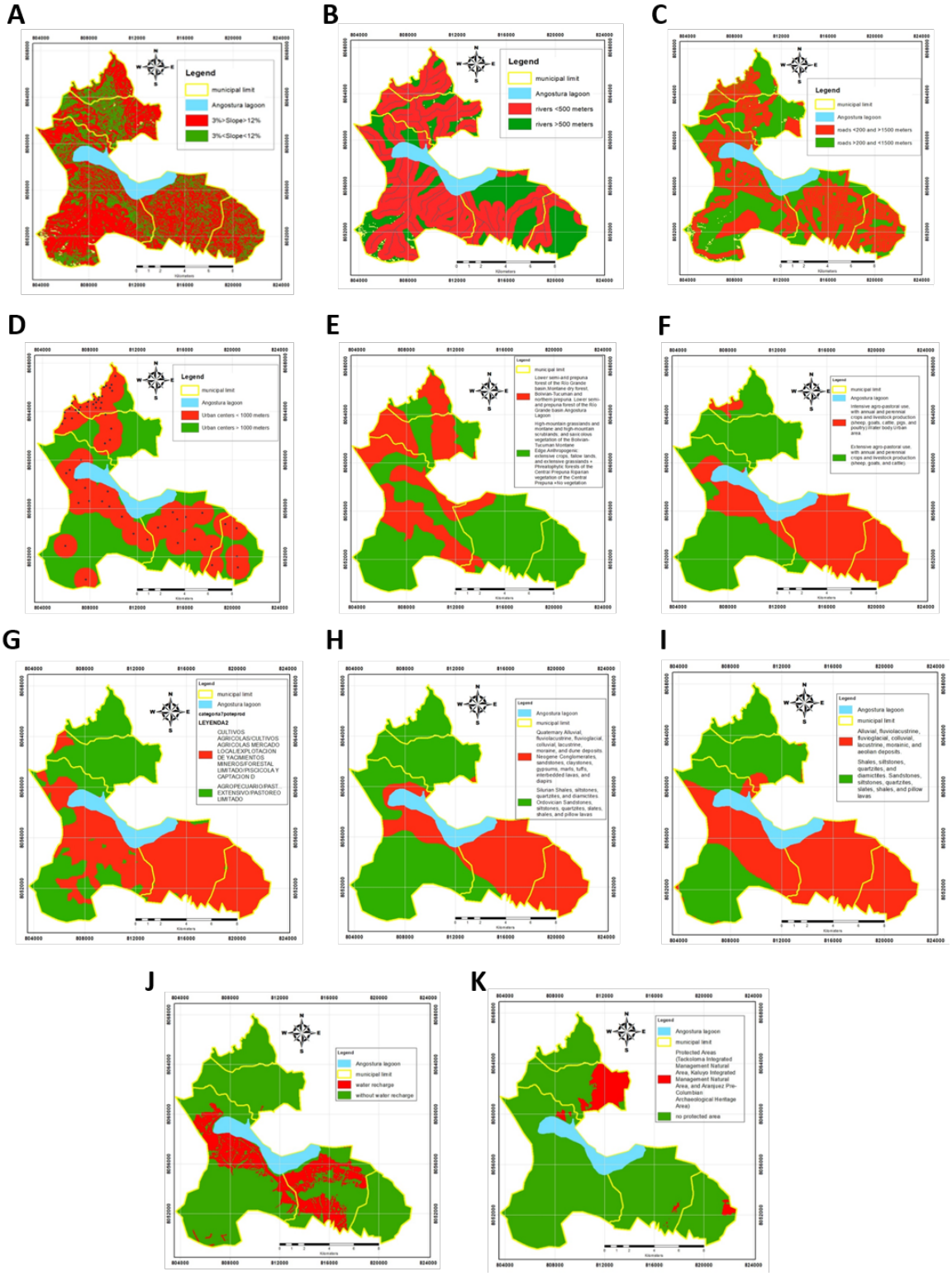


Figure 3. Criteria results for sanitary landfill site selection. (A) Criterion 1: Slope. (B) Criterion 2: Rivers. (C) Criterion 3: Roads. (D) Criterion 4: Urban centers. (E) Criterion 5: Vegetation cover. (F) Criterion 6: Land use. (G) Criterion 7: Productive potential. (H) Criterion 8: Geology. (I) Criterion 9: Lithology. (J) Criterion 10: Water recharge. (K) Criterion 11: Protected areas.

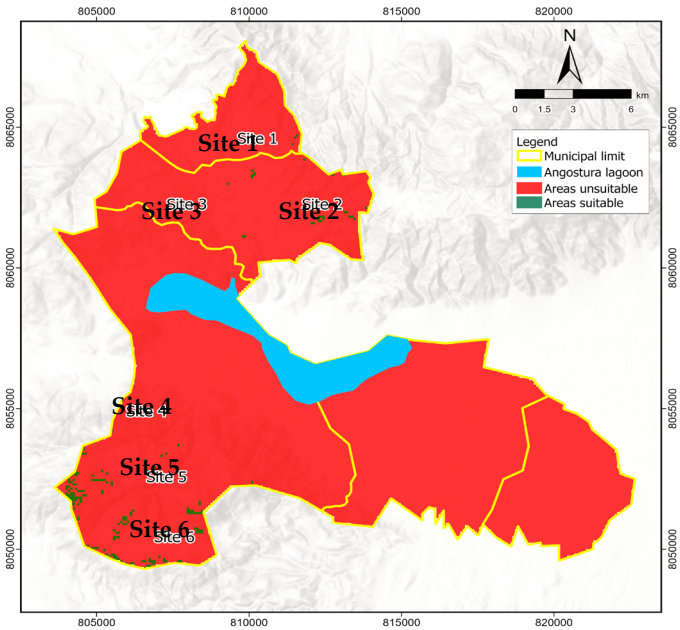


Figure 4. Final suitability map identifying optimal landfill locations (ArcGIS raster output)

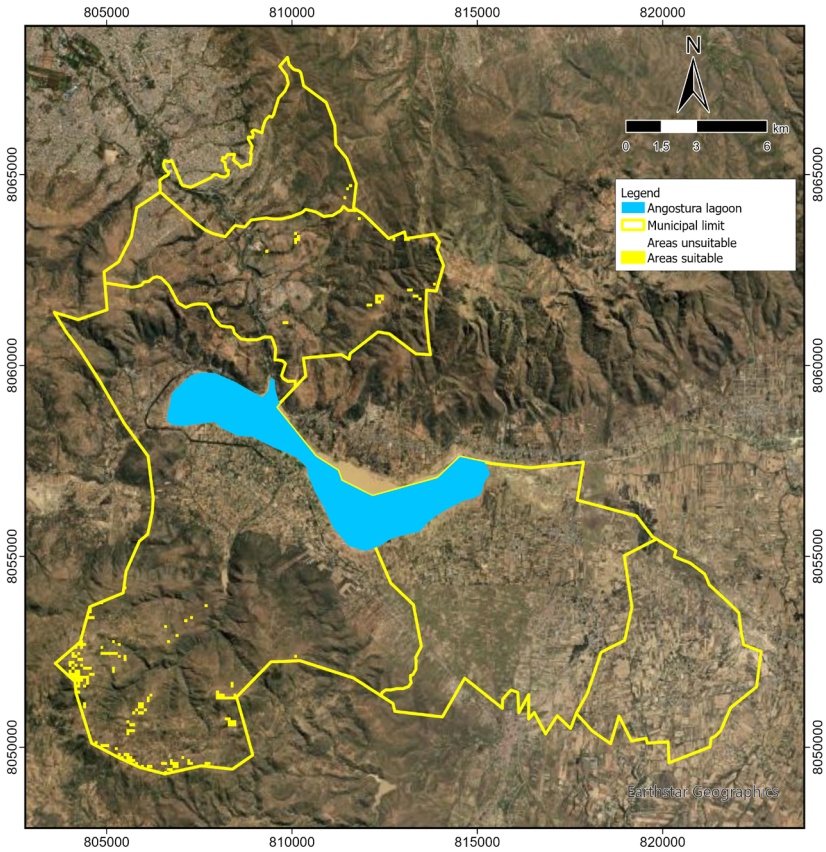


Figure 5. Satellite map of the final landfill site selection in ArcGIS

Table 3. Landfill site alternatives identified

Site	Zone	Community	Easting (m)	Northing (m)	Area (m^2)
1	Northern zone	Llave Mayu–Canelas	811,586.00	8,064,713.00	4,032.00
2	Northern zone	Olimpo–Tackoloma	813,098.00	8,063,295.00	4,134.00
3	Central zone	Olimpo–Las Lomas–Canelas	809,315.00	8,063,010.00	8,314.00
4	Southwest zone	Achiota	804,215.00	8,051,858.00	129,453.00
5	South–central zone	Achiota–Patachurigua	805,617.00	8,049,747.00	83,239.00
6	Southern zone	Patachurigua	808,356.00	8,050,662.00	42,689.00

all eleven selection criteria defined in the multicriteria model.

Based on this result, six potential sanitary landfill zones were delimited within the municipality of Arbieto. The UTM coordinates and areas of these sites are presented in Table 3. The identified locations correspond to the northern zone in District 6, in the communities of Llave Mayu–Canelas; the north central zone in District 5 in Olimpo–Tackoloma; and the central zone in Olimpo–Las Lomas–Canelas; while the southwest zone in Achiota, the south-central zone in Achiota–Patachurigua, and the southern zone in Patachurigua are located in District 3.

All identified sites satisfied the predefined suitability thresholds for slope, hydrography, road accessibility, distance from populated areas, geology, lithology, land use, groundwater recharge, and protected areas established in the multicriteria model.

A possible sensitivity analysis would allow assessment of how small variations in the established parameters may influence the final suitability classification. For example, modifying the minimum distance threshold from rivers, roads, or populated centers could alter the classification of areas as suitable or unsuitable. Sensitivity analysis is widely recommended in multicriteria spatial models because it helps evaluate the robustness of the methodology and the influence of individual criteria on final decision-making outcomes.[18-17] Similar GIS–MCDM studies developed in Iran, Iraq, India, and Jordan have also highlighted the importance of sensitivity analysis for evaluating the stability of landfill suitability classifications under different environmental and territorial scenarios.[21,22]

For instance, if the distance threshold from rivers is reduced from 500 m to 300 m, some zones currently classified as unsuitable could become suitable, increasing the available area. Conversely, if the threshold is increased to 700 m, technically adequate areas may be excluded, reducing the number of feasible location alternatives. A similar effect may occur if the road distance range is modified from the established 200–1,500 m interval, or if the minimum distance to population centers is increased beyond 1,000 m. Changes in slope limits (3–12%) or in geological and lithological suitability classes could also significantly influence the final selection of suitable sites. Such variations may directly affect the level of environmental protection achieved by the model, particularly regarding potential impacts on water resources, ecosystems, and nearby settlements.

Carrying out these controlled variations on one or more criteria would make it possible to identify which variables exert the greatest influence on the final site-selection outcome and to provide decision-makers with a clearer range of potential scenarios. In addition, visual representation through comparative maps of the resulting areas under different thresholds would help illustrate how such variations modify the surface potentially available for the future sanitary landfill.[25,27] This type of analysis may also strengthen sustainable waste governance processes by supporting more transparent, evidence-based, and environmentally informed territorial decision-making.

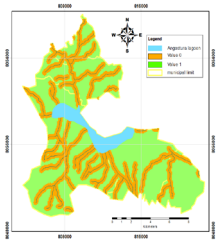
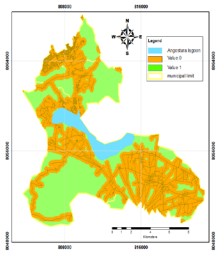
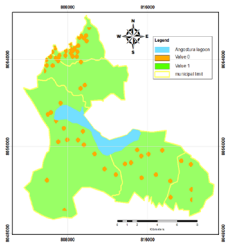
Table 4 summarizes the criteria modified for the sensitivity analysis and the corresponding parameter variations applied to evaluate changes in the final suitability classification.

Figure 6 presents the resulting final disposal site obtained under the variation of the selected parameters. The comparative spatial outputs illustrate how modifications in environmental protection thresholds directly influence the extent and distribution of technically feasible landfill areas within the municipality.

3.4. Interpretation

The Boolean multicriteria analysis identified six suitable zones that fully comply with all environmental, technical,

Table 4. Criteria modified by the sensitivity analysis

Criterion	Map	Description
2. Rivers		Value 1: green color: distance to rivers > 500 m; value 0: red color: distance to rivers < 500 m
3. Roads		Value 1: green color: distance to roads > 200 m and <1,500 m; value 0: red color: distance to roads < 200 m or >1,500 m
4. Urban centers		Value 1: green color: urban centers located more than 100 m away; value 0: red color: urban centers located within 0–100 m

and regulatory requirements. From these, three priority candidate sites, Site 1 (0.40 ha), Site 3 (0.83 ha), and Site 4 (12.95 ha), were selected for detailed evaluation based on road accessibility, separation from populated centers and protected areas, minimal occupation of agricultural land, and overall operational feasibility for sanitary landfill implementation.

While all six locations are technically viable, a comparative spatial evaluation revealed distinct operational and territorial differences across the municipality:

(i) Site 1 (0.40 ha): Located in District 6, this site represents the most suitable alternative for the northern sector; despite its smaller area, its greater distance from protected areas, favorable slope and geological conditions, and minimal agricultural encroachment make it a viable option for local waste infrastructure.

(ii) Site 2 (0.41 ha): Although technically compliant, satellite imagery revealed a higher density of existing infrastructure and transport routes in its immediate surroundings, requiring additional planning constraints and leading to its exclusion from final prioritization for Districts 4 and 5.

(iii) Site 3 (0.83 ha): Selected as a priority alternative for Districts 4 and 5, this site has adequate separation from populated centers due to its significant distance from populated centers, low agricultural land occupation, and adequate road connectivity.

(iv) Site 4 (12.95 ha): Prioritized as the most favorable site overall and specifically for Districts 1, 2, and 3, Site 4 combines the largest available land area with good road accessibility, low agricultural footprint, and sufficient buffer distances, allowing for long-term operational scaling and potential facility expansion.

(v) Sites 5 (8.32 ha) and 6 (0.43 ha): While satisfying all Boolean thresholds, these sites were not prioritized due to less favorable operational conditions compared to Site 4, including more remote access, closer proximity to drainage systems, and potential environmental

constraints

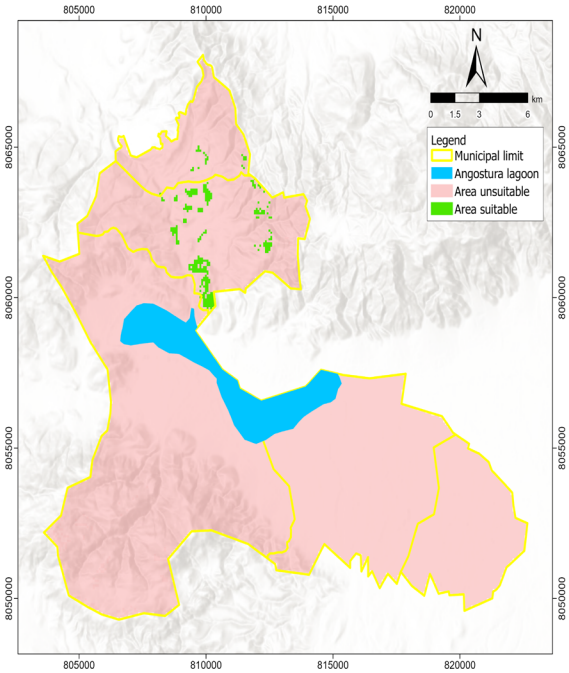


Figure 6. Variation of final disposal site under parameter changes

Overall, the comparative evaluation identified Site 4 as the most suitable alternative for future sanitary landfill development because of its larger available area and favorable environmental and operational conditions, while Sites 1 and 3 constitute feasible alternatives for the northern and central sectors of the municipality.

4. Discussion

The spatial multicriteria analysis successfully identified technically viable and environmentally safe areas for sanitary landfill siting in the municipality of Arbieto, confirming the research hypothesis. Suitable zones are predominantly concentrated in the northern sector (Districts 5 and 6, encompassing Llave Mayu–Canelas, Olimpo–Tackoloma, and Olimpo–Las Lomas–Canelas) and the southern sector (District 3, including Achiota and Patachurigua). These findings are consistent with previous GIS–MCDM studies conducted in different developing regions, where spatial analysis has been successfully used to integrate environmental, territorial, and technical criteria for landfill site selection.[9,12,16]

From an environmental perspective, the selected locations feature low terrain slopes, stable geological formations, and adequate buffer distances from surface watercourses and groundwater recharge zones. These characteristics reduce the environmental risks commonly associated with sanitary landfill development.[18,23,24]

From a social standpoint, applying buffer distances from population centers reduces potential negative externalities, including odors, visual intrusion, vector proliferation, and health risks. However, transitioning from informal dumping to a controlled facility also requires consideration of the broader municipal waste management system. Studies conducted in developing regions demonstrate that collection deficiencies, local waste characteristics, and urban conditions can strongly affect the performance and sustainability of solid waste management systems.[28-30]

Economically, concentrating suitable zones within specific districts allows municipal authorities to optimize capital investments in access roads, land acquisition, and basic infrastructure. In the medium to long term, the economic viability of an engineered sanitary landfill must also be evaluated in relation to available treatment technologies and local operating conditions. Studies of municipal solid waste treatment in developing countries demonstrate that technology selection and costs are strongly conditioned by the characteristics and capacities of local waste management systems.[3,4]

Methodologically, the non-compensatory Boolean overlay structure ensured that candidate sites strictly complied with all mandatory environmental, technical, geological, hydrogeological, and social criteria.[15] By discarding any spatial area failing a single regulatory threshold, this conservative approach eliminates subjective trade-offs. In contrast, AHP, fuzzy, and technique for order preference by similarity to ideal solution-based approaches provide complementary alternatives when weighting and comparative ranking among feasible sites are required.[16,17,21]

Institutionally, identifying these viable zones equips the Autonomous Municipal Government of Arbieto with a spatial baseline to initiate land tenure legalization, reserve territorial zones for waste infrastructure, prevent future informal settlements, and strengthen long-term municipal waste governance. These planning actions are consistent with the national integrated solid waste management framework[31,32] and the technical siting requirements established for final disposal facilities.[33] Previous site evaluation experiences in Tarata, Tiquipaya, and Cobija also demonstrate the applicability of territorial and multicriteria approaches within the Bolivian municipal context.[34-36]

To build upon these findings, future research should complement this spatial analysis with detailed hydrogeological field testing, site-specific environmental

impact assessments, social acceptance surveys, and life-cycle cost analyses. Methodologically, incorporating weighted multicriteria techniques (such as AHP or Fuzzy-AHP), dynamic land-use change scenarios, and contaminant dispersion modeling will further refine long-term environmental planning and decision-making.

5. Conclusion

The application of a GIS-based MCDM model using Boolean logic allowed the identification of technically feasible, environmentally safe, and socially acceptable locations for sanitary landfill siting in the municipality of Arbieto. Out of six compliant zones, three priority candidate sites were selected for final infrastructure planning: Alternative 1 (0.40 ha) and Alternative 3 (0.83 ha) represent the most favorable locations for Districts 4, 5, and 6, while Site 4 (12.90 ha) stands out as the most strategic long-term alternative for Districts 1, 2, and 3 due to its extensive capacity and operational scalability.

The application of the Boolean multicriteria framework ensured that the selected sites complied simultaneously with the environmental, technical, hydrogeological, and social criteria established for sanitary landfill siting.

The results provide the Autonomous Municipal Government of Arbieto with a spatial basis for future landfill planning, land-use management, and environmental decision-making. The proposed GIS–MCDM framework constitutes a replicable decision-support methodology that can be readily transferred and adapted to other rural and peri-urban municipalities facing similar technical, institutional, and environmental constraints in Bolivia and developing regions.[25-27,34-36]

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Some of the spatial datasets used in the analysis were obtained from official institutional and municipal sources and are subject to the availability and conditions of the respective data providers.

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