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RECEIVED 14 June 2025

ACCEPTED 24 September 2025

PUBLISHED 21 October 2025

CITATION

Aguiñaga-Vallejo M, Paredes-Verduga C,
Jácome-Cornejo M, Briones-Bitar J,
Jaya-Montalvo M, Morante-Carballo F,
Suárez-Zamora S, Aguilar-Aguilar M,
Berrezueta E and Carrión-Mero P (2025)
Multi-criteria site selection for solid waste
disposal: integration of center of gravity and
AHP-GIS analysis in Guayas, Ecuador.
Front. Sustain. 6:1647171.
doi: 10.3389/frsus.2025.1647171

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Multi-criteria site selection for solid waste disposal: integration of center of gravity and AHP-GIS analysis in Guayas, Ecuador

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Introduction: The selection of optimal sites for solid waste disposal is a critical aspect of management, especially from an environmental and logistical perspective. In Guayas province (Ecuador), many solid waste disposal sites have been implemented without technical-environmental planning, exacerbated by financial constraints that hinder their effective management. Given this context, this study proposes integrating the concept of the Gravity Center of Waste Production (GCWP) into the traditional criteria for selecting Final Disposal Sites (FDS) by combining Analytical Hierarchical Analysis (AHP) and geographic information systems, strengthening logistics management and the development of inter-municipal partnerships in the north of Guayas province.

Methods: The study addressed a diagnostic stage, the evaluation of FDS selection criteria, and the identification of suitable areas through mapping.

Results: The municipalities present limitations for the adequate operation of FDS, most of which are open-air dumps. Therefore, three groups were proposed as possible partnerships between cantons. The AHP analysis showed that criteria related to water conservation were the highest-scoring, as opposed to land use and land cover. The selected sites are as close as possible to the GCWP for optimal waste disposal. The results were validated through the analysis of four different scenarios and the participation of authorities in charge of territorial management.

Discuss: The proposed methodological approach is a viable alternative for cantons, districts, or municipalities with budgetary constraints, as it seeks to be a helpful management tool for waste disposal within a framework of intermunicipal cooperation.

KEYWORDS

municipal solid waste, open dump, analytical hierarchical analysis, environmental restrictions, inter-municipal cooperation

1 Introduction

Globally, the final disposal of solid waste poses a significant challenge to environmental conservation because it is associated with the production of greenhouse gases, soil degradation, water source contamination, and adverse impacts on public health (Ma et al., 2022; Vinti et al., 2021; Zeng et al., 2021). Annually, solid waste production is estimated at 2.01 billion tons, which is expected to increase to 3.4 billion by 2050 (The World Bank, 2018).

Developed countries have greater financial, technological, and institutional capacity to sustainably manage solid waste through sustainable approaches such as recycling, energy recovery, safe storage, and controlled disposal (Guadagnin et al., 2018). On the other hand, owing to economic, cultural, and political factors, developing countries resort to less expensive solutions with little technological involvement for safe disposal and potential reuse (Chalhoub, 2018).

Landfills are a standard method of waste disposal in developing countries, and incorporate engineering techniques aimed at environmental protection, such as soil waterproofing, leachate collection and treatment, gas capture, daily waste covering, and continuous site monitoring (Tchobanoglous and Kreith, 2002). In areas where economic resources are scarce, open dumps are used, which offer no environmental protection measures for solid waste disposal (Das et al., 2019; Herrera-Franco et al., 2024).

In this context, various studies have highlighted the benefits of inter-institutional cooperation between small municipalities, showing a reduction in management service costs, improvements in operational efficiency, access to adequate infrastructure, and greater ease of obtaining financing (Araya-Córdova et al., 2021; Struk and Bakoš, 2021). On a global scale, the United Nations Environment Programme estimates that approximately 40% of the waste generated worldwide is deposited in open dumps; in Latin America and the Caribbean, this figure reaches approximately 145,000 tons per day (United Nations, 2024).

Ecuador generates approximately 5.3 million tons of solid waste per year, with a per capita rate of 0.81 kg per inhabitant per day (Ministerio de Ambiente Agua y Transición Ecológica, 2023). Forty-seven percent of Ecuador's solid waste corresponds to open dumps, most of which are concentrated in coastal regions (Ministerio de Ambiente Agua y Transición Ecológica, 2023). Thirty-eight percent of the waste is generated in Guayas province (5,500 tons per day), where 68% of the FDS operates without technical or environmental control (Ministerio de Ambiente Agua y Transición Ecológica, 2023). Some municipalities in Guayas province lack their own disposal sites, instead resorting to informal agreements with neighboring municipalities. This situation has led to the transfer of waste to facilities outside the province.

Most of these open-air dumps are located in the northern part of the province, which constitutes the study area. According to field verification and analysis using tools such as Google Earth, many do not comply with the minimum environmental provisions required by national regulations (Figure 1; Ministerio del Ambiente Agua y Transición Ecológica, 2003).

The selection of optimal sites for the final disposal of solid waste is a critical aspect of land-use planning and the sustainability of the management system (Süleyman Sefa and Burhan Baha, 2017; Tulun et al., 2021). Although various studies address this issue

by integrating multi-criteria methods and Geographic Information Systems (GIS) to generate zoning maps (Tulun et al., 2021; Durlević et al., 2022; Karakuş et al., 2020; Othman et al., 2021; Rame et al., 2022; Kamdar et al., 2019; Alkaradaghi et al., 2019), most focus on physical and environmental criteria (e.g., proximity to water sources, population centers, roads, geomorphology, protected areas, land use, and land cover). These types of studies generally apply criteria such as proximity to water sources, population centers, distance to roads, terrain geomorphology, protected areas, as well as land use, coverage, and characteristics (Donevska et al., 2021; Mat et al., 2017), without incorporating collaborative approaches between municipalities.

In inter-municipal collaboration contexts, the selection of disposal sites should also consider criteria such as equidistance between cantons and the relative volume of waste generated, which can be addressed through the concept of Gravity Center of Waste Production (GCWP), commonly used in transfer station planning (Wang et al., 2020; Toro et al., 2016). Within the framework of inter-municipal collaboration aimed at ensuring the safe and optimal final disposal of solid waste, the study posed the following research questions (RQ):

RQ1. What solid waste management criteria can be integrated into the generation of multi-criteria maps for FDS selection?

RQ2. How does the GCWP concept influence the selection of FDS compared to traditional criteria?

This study aims to integrate the GCWP concept with traditional criteria for selecting FDS by combining the Analytic Hierarchy Process (AHP) method with GIS tools. The process is applied in the north of the Guayas province (Ecuador) as a case study to identify optimal areas for the location of FDS under a centralized management approach, contributing to the strengthening of inter-municipal alliances in contexts with limited resources. The study does not cover the technical design or economic evaluation of the proposed sites.

2 Materials and methods

The methodology offers a centralized approach to solid waste management, with a comprehensive perspective that incorporates the GCWP concept in the selection of areas suitable for final disposal, optimizing transportation routes to the FDS, reducing operating costs associated with solid waste transport, and facilitating informed decision-making. This approach addresses environmental, logistical, geomorphological, and territorial aspects, thus strengthening inter-municipal management. The study consisted of three phases (i) Solid waste management diagnosis, (ii) Evaluation of limiting criteria for the FDS location, and (iii) Development of a suitability map for the shared solid waste disposal (Figure 2).

2.1 Stage I: solid waste management diagnosis

The study conducted surveys based on open-ended and multiple-choice questions through Google Forms, targeting the authorities responsible for solid waste management in the

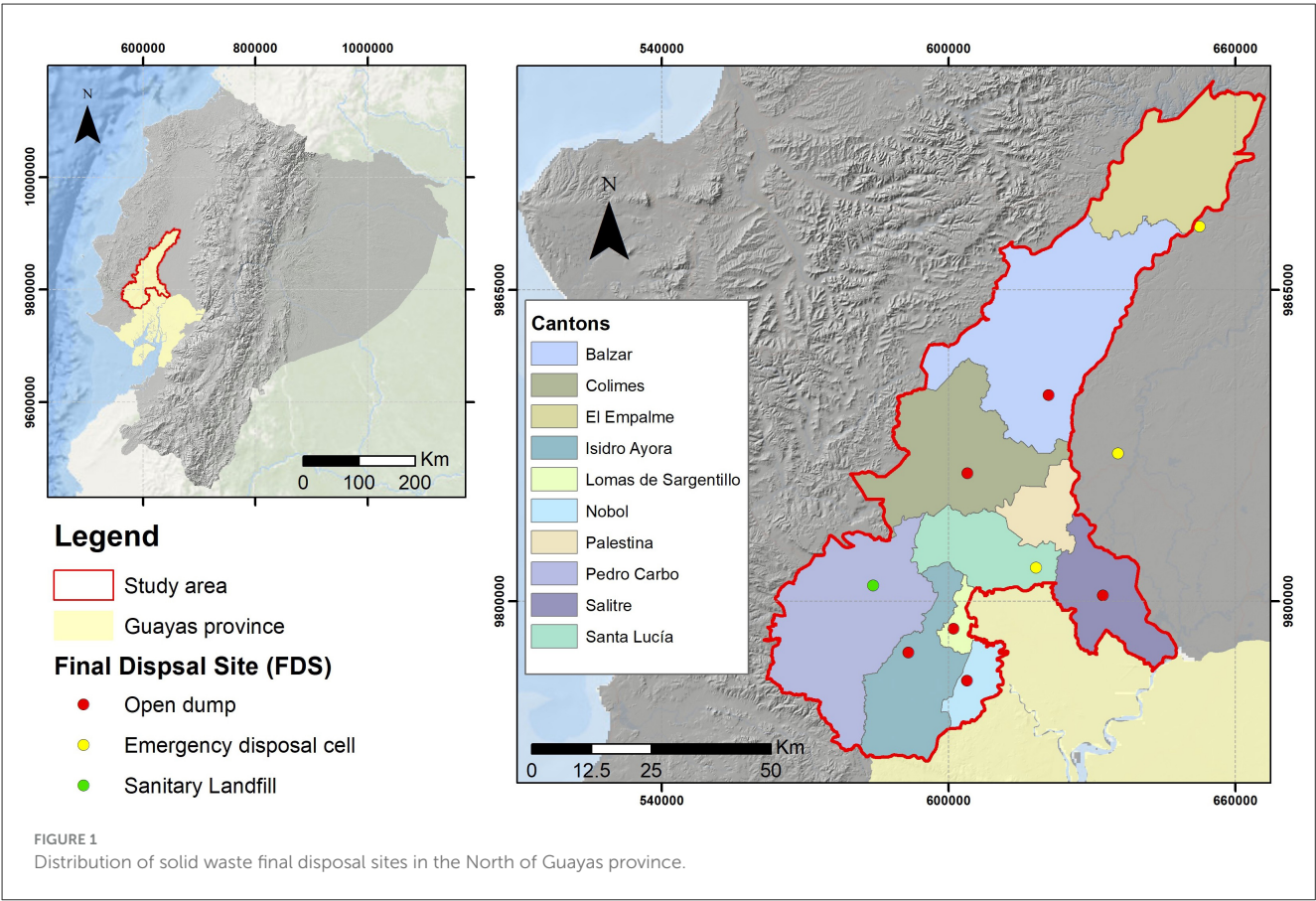


FIGURE 1
 Distribution of solid waste final disposal sites in the North of Guayas province.

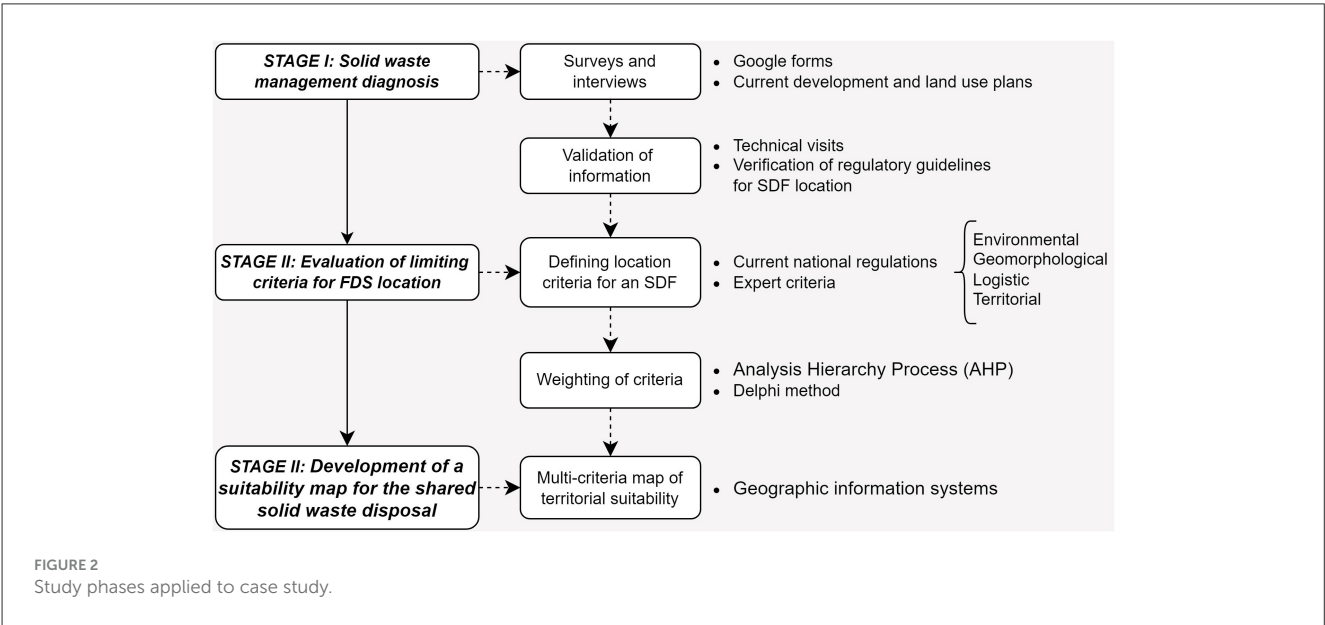


FIGURE 2
 Study phases applied to case study.

10 cantons, and addressed three interest areas: (a) type of management, (b) collection service, and (c) operation and capacity of final disposal sites. The survey results were supplemented with information available in current planning and land use reports for each municipality and interviews with municipal authorities responsible for environmental management, which allowed the identification of management constraints related to funding and the current status of the SDF. The information obtained in this first stage was corroborated through field visits, assisted by technical staff from the Environmental Management Department of the Guayas Provincial Government, to assess compliance with current environmental regulations regarding the presence of nearby

TABLE 1 Selection criteria for FDS location.

Criteria		Justification	Metadata		
			Name	Scale	Reference
Environmental	Wells	Essential resources that are vulnerable to contamination by leachate infiltration	Hydrogeological map of Ecuador	1:250,000	Secretaría Nacional del Agua, 2014
	Aquifers				
	Rivers		Open access cartography from the Military Geographic Institute (IGM). Version 4.0	1:50,000	Instituto Geográfico Militar del Ecuador, 2013
	Flood zones	During the winter season, the Guayas province is affected by flooding, which could pose a risk to the operation of the FDS	Map of Land Cover and Land Use and Agricultural Production Systems in Continental Ecuador	1:25,000	Ministerio de Agricultura y Ganadería del Ecuador, 2020
Logistic	Roads	Easy access must be guaranteed, while avoiding conflicts over landscape impact	Open access cartography from the Military Geographic Institute (IGM). Version 4.0	1:50,000	Instituto Geográfico Militar del Ecuador, 2013
	GCWP	Optimizes collection routes, reducing associated costs	Calculated	-	-
Geomorphological	Geological faults	It poses a risk to soil stability and facilitates the migration of leachates into the subsoil	Map of quaternary faults and folds of Ecuador and its offshore regions	1:1,250,000	USGS, 2003
	Slopes	Determines conditions such as ground stability and construction costs	Geopedological Map of Continental Ecuador	1:25,000	Ministerio de Agricultura y Ganadería del Ecuador, 2020
	Permeability	Soil with a high degree of permeability involves the risk of infiltration by leachates	Geopedological Map of Continental Ecuador		
Territorials	Population centers	Health risk from exposure to contaminants	Map of Land Cover and Land Use and Agricultural Production Systems in Continental Ecuador		
	Land use	Identifying unproductive areas minimizes social conflicts	Map of land cover and land use and agricultural production systems in continental Ecuador		

population centers, crops, water pollution, access roads, and proper leachate management (Ministerio del Ambiente Agua y Transición Ecológica, 2003). The tons of solid waste per day analyzed in this study were obtained from information available from the state agency in charge of environmental management (Ministerio de Ambiente Agua y Transición Ecológica, 2023) and public documentation from the Provincial Decentralized Autonomous Government of Guayas (Gobierno Autónomo Descentralizado Provincial del Guayas, 2012).

2.2 Stage II: evaluation of limiting criteria for FDS location

2.2.1 GCWP calculation

Under a collaborative inter-institutional management approach, and to avoid operational overload, the study proposed three possible clusters based on the proximity between cantonal capitals (the primary urban centers of a canton),

- Cluster 1 (South zone): Pedro Carbo, Isidro Ayora, Lomas de Sargentillo and Nobol.
- Cluster 2 (North zone): Balzar and El Empalme.

- Cluster 3 (Center zone): Colimes, Palestina, Santa Lucía and Salitre.

For each cluster, the GCWP was determined according to the spatial distribution and waste production of the cantonal capitals (Equation 1) and a sensitivity analysis was applied to the GCWP of each cluster, individually modifying the daily waste production of each canton by $\pm 10\%$, to observe how much the location of the GCWP changes due to errors or changes in waste production.

$$GCWP (X_c; Y_c) \rightarrow X_c = \frac{\sum_{i=0}^n (x_i * w_i)}{\sum_{i=0}^n w_i};$$

$$Y_c = \frac{\sum_{i=0}^n (y_i * w_i)}{\sum_{i=0}^n w_i} \quad (1)$$

X_c : X coordinates of the GCWP.

Y_c : Y coordinates of the GCWP.

x_i : X coordinate of the canton capital.

y_i : Y coordinate of the canton capital

w_i : Solid waste production in tons/day.

According to local regulations, FDS must be designed for a minimum useful life of 10 years (Ministerio del Ambiente Agua

TABLE 2 Criteria and subcriteria for FDS selection.

Criteria		Units	Sub-criteria	Reclassify	Suitability	Reference
Environmental	Distance from wells	Meters	0–500 500–1,000 1,000–1,500 1,500–2,000 >2,000	- 25 50 75 100	Excluded area Low Media High Very high	Ministerio del Ambiente Agua y Transición Ecológica, 2003; Bilgilioglu et al., 2022
	Distance from aquifers	Meters	0–1,000 1,000–2,000 2,000–3,000 3,000–4,000 4,000–5,000 >5,000	- 20 40 60 80 100	Excluded area Very low Low Media High Very high	Alkaradaghi et al., 2020; Silva López et al., 2022
	Distance from rivers	Meters	0–1,000 1,000–2,000 2,000–3,000 3,000–4,000 4,000–5,000 >5,000	- 20 40 60 80 100	Excluded area Very low Low Media High Very high	Alkaradaghi et al., 2020; Cobos Mora and Solano Peláez, 2020
	Flood risk	Meters	Without risk Low Media High Not applicable	100 75 50 25 -	Very high High Low Excluded area -	Alkaradaghi et al., 2020; Silva López et al., 2022
Logistical	Distance from roads	Meters	0–500 500–1,000 1,000–2,000 2,000–3,000 3,000–5,000 >5,000	0 100 80 60 40 20	Excluded area Very high High Media-high Media-low Low	Ministerio del Ambiente Agua y Transición Ecológica, 2003; Alkaradaghi et al., 2020; Silva López et al., 2022
	Distance from GCWP	Meters	0–1,000 1,000–5,000 5,000–10,000 10,000–20,000 20,000–30,000 >30,000	100 80 60 40 20 0	Very high High Media-high Media-low Low Very low	Toro et al., 2016; Cobos Mora and Solano Peláez, 2020
Geomorphological	Distance from faults	Meters	0–1,000 1,000–2,000 2,000–3,000 3,000–4,000 4,000–5,000 >5,000	0 20 40 60 80 100	Excluded area Very low Low Media High Very high	Sisay et al., 2025; Bilgilioglu et al., 2022; Alkaradaghi et al., 2020; Silva López et al., 2022
	Slopes	Percentage	0–5 5–12 12–25 >25	100 70 35 0	Very high High Low Excluded area	Bilgilioglu et al., 2022; Silva López et al., 2022; Cobos Mora and Solano Peláez, 2020
	Permeability	Category	Very low Low Media High Very high	100 75 50 25 0	Very high High Media Low Very low	Bilgilioglu et al., 2022; Silva López et al., 2022; Cobos Mora and Solano Peláez, 2020
Territorials	Distance from population centers	Meters	0–1,000 1,000–2,000 2,000–3,000 3,000–4,000 4,000–5,000 >5,000	- 20 40 60 80 100	Excluded area Very low Low Media High Very high	Ministerio del Ambiente Agua y Transición Ecológica, 2003; Simşek and Alp, 2022
	Land use	Category	Water bodies/anthropized area Forest Farm land Scrublands Other lands	0 25 50 75 100	Very low Low Media High Very high	Alkaradaghi et al., 2020; Silva López et al., 2022; Mallick, 2021

TABLE 3 Characteristics of the waste collection service.

Cantón	A	B	C	D	E
Balzar	70–80%	Dump truck, garbage truck (compactor)	No	5	2
Colimes	80–90%	Dump truck, garbage truck (compactor)	No	2	1
El Empalme	70–80%	Dump truck, garbage truck (compactor)	No	4	4
Isidro Ayora	80–90%	Garbage truck (compactor)	No	2	1
Lomas de Sargentillo	80–90%	Dump truck, garbage truck (compactor)	No	2	1
Nobol	90–100%	Dump truck, garbage truck (compactor)	No	3	2
Palestina	70–80%	Dump truck, garbage truck (compactor)	No	2	2
Pedro Carbo	70–80%	Dump truck, garbage truck (compactor)	No	3	0
Salitre	-	No answer	No	-	-
Santa Lucia	60–70%	Dump truck, garbage truck (compactor)	No	2	0

A: Coverage (%) of collection service, B: Type of vehicle used for waste collection, C: Is source separation applied?, D: Number of collection units, E: Number of collection units in good condition.

TABLE 4 Characteristics of final waste disposal sites.

Canton	A	B	C	D	E	F	G	H	I
Balzar	OD	29.2	26.7	No	Register	No	No	2002	24
Colimes	OD	3.0	15	No	No	No	No	2012	8
El Empalme	EDC	36.4	36.1	Yes	Register	No	Collection and storage	2023	50
Isidro Ayora	OD	5.9	9	No	Certificate	No	No	2000	5.47
Lomas de Sargentillo	OD	11	13.3	No	No	No	No	1994	8
Nobol	OD	10.8	20	No	No	No	No	1998	9.63
Palestina	EDC	8.9	8.9	Yes	Register	Yes	Collection and storage	2023	50
Pedro Carbo	SL	22.9	36.7	No	Register	Yes	Collection and storage	2019	19.1
Salitre	OD	8.1	8.1	No	No	No	-	-	-
Santa Lucia	EDC	10.1	22	No	Register	No	Collection and storage	2019	5

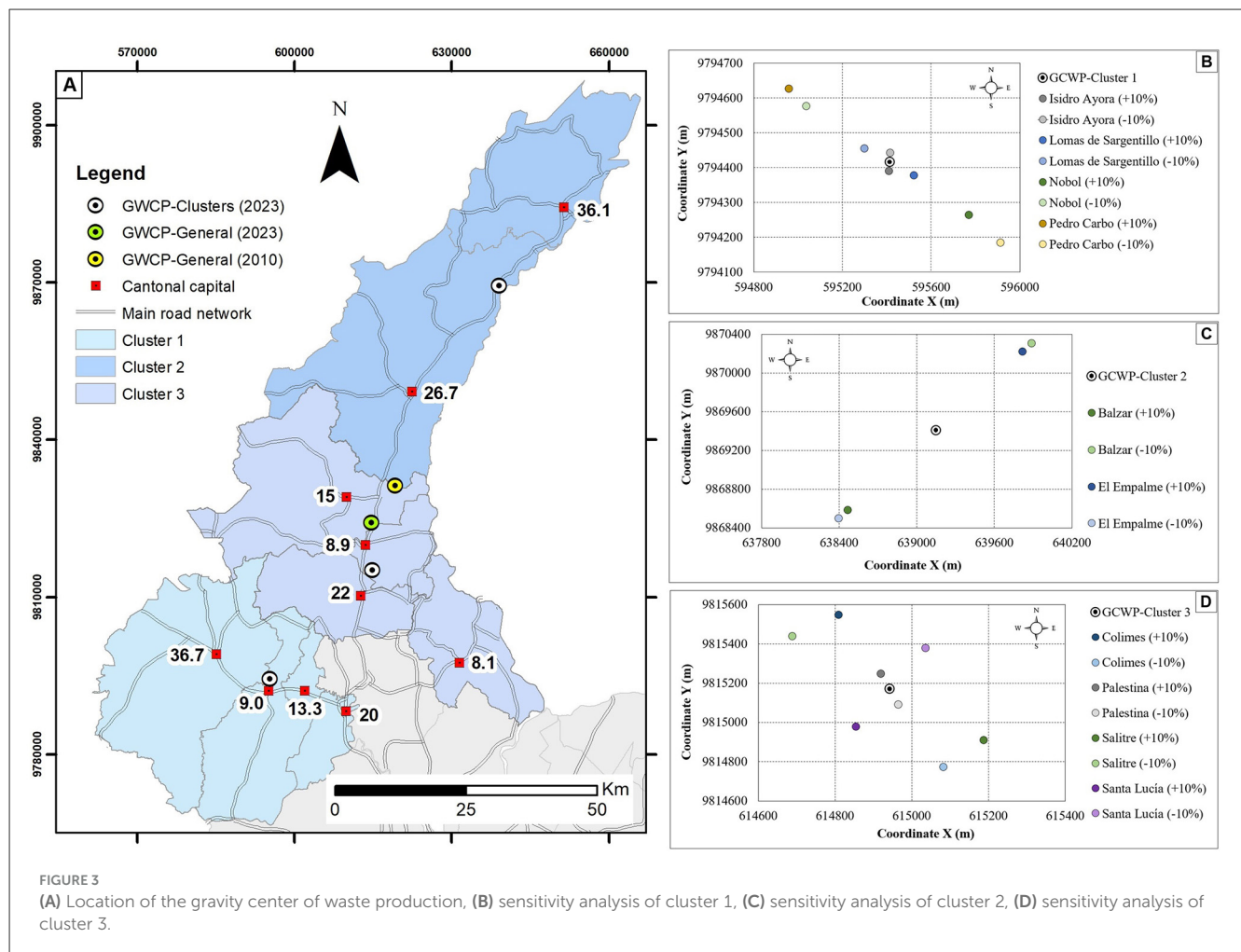
A: Type of final disposal site, B: Solid waste production 2010 (ton/day); C: Solid waste production 2023 (ton/day), D: Weighbridge availability, E: Type of environmental permit, F: Waste recycling, G: Leachate management, H: Start of operation year, I: Final disposal site surface (ha).

y *Transición Ecológica*, 2003). Therefore, a population projection was made until 2040 using the least squares method, using the population and housing censuses of 1990, 2001, 2010, and 2022 as base information (INEC, 2022). Additionally, the study estimated the projection of per-capita production considering two aspects: (i) due to a lack of historical data, the per-capita production of 2023 was taken as the base year (estimated according to population data and daily waste production), and (ii) the annual growth rate of waste production linked to cantonal economic growth. This last point was quantified by the average annual increase rate of the Gross Added Value corresponding to the period 2018–2023 (Banco Central del Ecuador, 2025), under the assumption that economic growth is associated with greater consumption of goods, which generates greater waste production (Kinnaman, 2006; Kaza et al., 2018; Shah et al., 2023; Razzaq et al., 2021). The results obtained made it possible to identify possible displacements of the GCWP over time due to the increase in waste production and contrast them with possible variations according to the sensitivity analysis.

2.2.2 Criteria used for AHP

The GCWP was integrated into 11 criteria grouped into four axes (environmental, logistics, geomorphological, territorial), considered according to the local context, current regulations, and several studies on similar topics (Ministerio del Ambiente Agua y *Transición Ecológica*, 2003; Toro et al., 2016). The inclusion of the GCWP corresponds to a logistics strategy that complements the evaluation of traditional criteria that can directly influence the technical feasibility of FDS. It allows guiding decision-making from the perspective of optimizing transport routes in the context of intermunicipal collaboration. The resources used for the geospatial analysis consisted of cartographic information available in the geoportals of state institutions related to territorial management and planning (Table 1).

The obtained cartographic information was processed in ArcMap version 10.5 software to convert it into raster layers with a spatial resolution of 30×30 m. Each criterion converted into raster was classified into sub-criteria using ranges, classes, or buffer zones, and assigned a numerical value “x” on a scale of 0 to 100



using the “Reclassify” tool, according to the following categorical ranges: (a) very low: $0 \leq x \leq 20$, (b) low: $20 < x \leq 40$, (c) medium: $40 < x \leq 60$, (d) high: $60 < x \leq 80$, and (e) very high: $80 < x \leq 100$ (Table 1). It is worth mentioning that exclusion areas were applied to criteria where the presence of an FDS may represent a risk of affecting the environment, site operation, or violating guidelines established in current regulations. However, the permeability and location of the GCWP do not represent an absolute risk because technical measures or management strategies can be applied (Table 2).

This study assigned weights to the 11 criteria using the AHP method, which involves making comparisons between pairs of criteria to reflect their relative relevance to the objective (Saaty, 1984). The AHP method uses a scale from 1 to 9, where 1 indicates that criterion A is equally relevant to criterion B, and 9 indicates that criterion A is much more relevant than criterion B. The scores assigned to each criterion are organized in a matrix that allows the generation of a vector that reflects the weighting of the criteria under matrix algebraic operations (Prascevic and Prascevic, 2017; Chaiyaphan and Ransikarbum, 2020). The results obtained are validated using a consistency index that must be less than or equal to 0.1; otherwise, the results are discarded and must be readjusted (Saaty and Vargas, 2012; Qi and Zhou, 2020). In this case, the study

employed the Delphi method, involving a focus group comprising professionals from civil engineering, environmental engineering, and geology, to generate consistent results and minimize bias (Kharat et al., 2016a). The weights obtained by each author were averaged to obtain a representative and consensus value, ensuring the robustness of the weights assigned to the criteria.

2.3 Stage III: development of a suitability map for the shared solid waste disposal

Considering the suitability of each subcriterion presented in Table 2 and the weights obtained in the AHP, a raster calculator was used to integrate both components and obtain a territorial suitability map. The resulting product consisted of a raster in which each pixel had a value ranging from 0 to 100 (according to the scale established above). This was classified using the natural breaks method, which minimizes the variance between classes, such that the numbers within each class are as similar as possible. The resulting classes were classified according to the suitability ranges used to categorize the subcriteria to identify potential areas

TABLE 5 Projection of waste production until 2040.

Cantons	2023			2030			2035			2040		
	P	PPC	SWP	P	PPC	SWP	P	PPC	SWP	P	PPC	SWP
Balzar	57,829	0.46	26.66	61,385	0.67	41.29	63,468	0.88	55.91	65,554	1.15	75.64
Colimes	26,251	0.57	15.00	28,609	0.84	23.98	30,158	1.09	33.11	31,789	1.43	45.71
El Empalme	79,767	0.45	36.09	83,913	0.66	55.24	85,830	0.86	74.01	87,419	1.12	98.72
Isidro Ayora	14,305	0.63	9.00	16,977	0.91	15.52	18,727	1.19	22.42	20,554	1.56	32.22
Lomas de Sargentillo	22,254	0.60	13.33	25,257	0.87	22.02	27,046	1.1	30.88	28,822	1.49	43.11
Nobol	23,850	0.84	20.00	28,609	1.24	35.47	19,392	1.62	31.49	31,789	2.12	67.61
Palestina	18,019	0.49	8.87	18,963	0.69	13.02	30,158	0.89	27.13	19,701	1.17	23.21
Pedro Carbo	52,177	0.70	36.67	59,521	1.03	61.35	64,445	1.35	87.00	69,684	1.76	123.21
Salitre	61,060	0.13	8.11	63,361	0.19	11.97	64,150	0.24	15.87	64,564	0.32	20.92
Santa Lucia	43,700	0.50	22.00	46,319	0.72	33.38	47,609	0.94	44.94	48,659	1.23	60.16

Population (P), Production per-capita in kg/person/day (PPC), Solid waste production in ton/day (SWP).

TABLE 6 Shift of the GCWP compared to the year 2023.

ID	Year	GCWP coordinates		GCWP displacement		Distance (m)
		X (m)	Y (m)	ΔX (m)	ΔY (m)	
Cluster 1	2030	595,615.781	9,794,320.38	−201.92	95.43	223.34
	2035	594,039.499	9,794,985.27	1,374.36	−569.44	1,487.66
	2040	595,392.675	9,794,403.67	21.19	12.15	24.43
Cluster 2	2030	639,064.832	9,869,305.29	83.21	100.86	130.75
	2035	638,988.181	9,869,212.39	159.86	193.77	251.20
	2040	638,888.648	9,869,091.75	259.40	314.41	407.60
Cluster 3	2030	614,808.15	9,815,423.95	133.96	−253.40	286.63
	2035	614,644.266	9,815,910.77	297.84	−740.22	797.89
	2040	614,658.756	9,815,720.6	283.35	−550.05	618.75

Negative values of ΔX indicate a shift to the left, while negative values of ΔY indicate a downward shift.

for municipal solid waste disposal located near the GCWP of each cluster.

The location of the proposed FDS was verified using satellite images and with the participation of authorities related to territorial management in the province of Guayas. Furthermore, because the weighting of criteria using AHP is subject to variations related to the perspectives of different experts, four different scenarios were explored to evaluate whether the suitability of the sites chosen for FDS placement changed. Based on the AHP results, the original weights were reassigned to give greater weight to the criteria with lower scores (which have been better evaluated in other studies) and generate the suitability map according to the proposed scenarios:

(a) Scenario 1: change in the position of the GCWP criterion in the ranking of criteria, to analyze its influence on site selection.

(b) Scenario 2: prioritization based on logistics criteria, seeks to simulate contexts where efficiency in transportation and collection are central objectives (Abdulhasan, 2019).

(c) Scenario 3: configures the suitability of the land based on the proposed territorial criteria (population and land use; Alanbari et al., 2014; Alkaradaghi et al., 2020; Dolui and Sarkar, 2021).

(d) Scenario 4: It focused on analyzing the suitability of the terrain based on geomorphological aspects (slope, permeability, geological faults; Chaturvedi et al., 2025; Sisay et al., 2025).

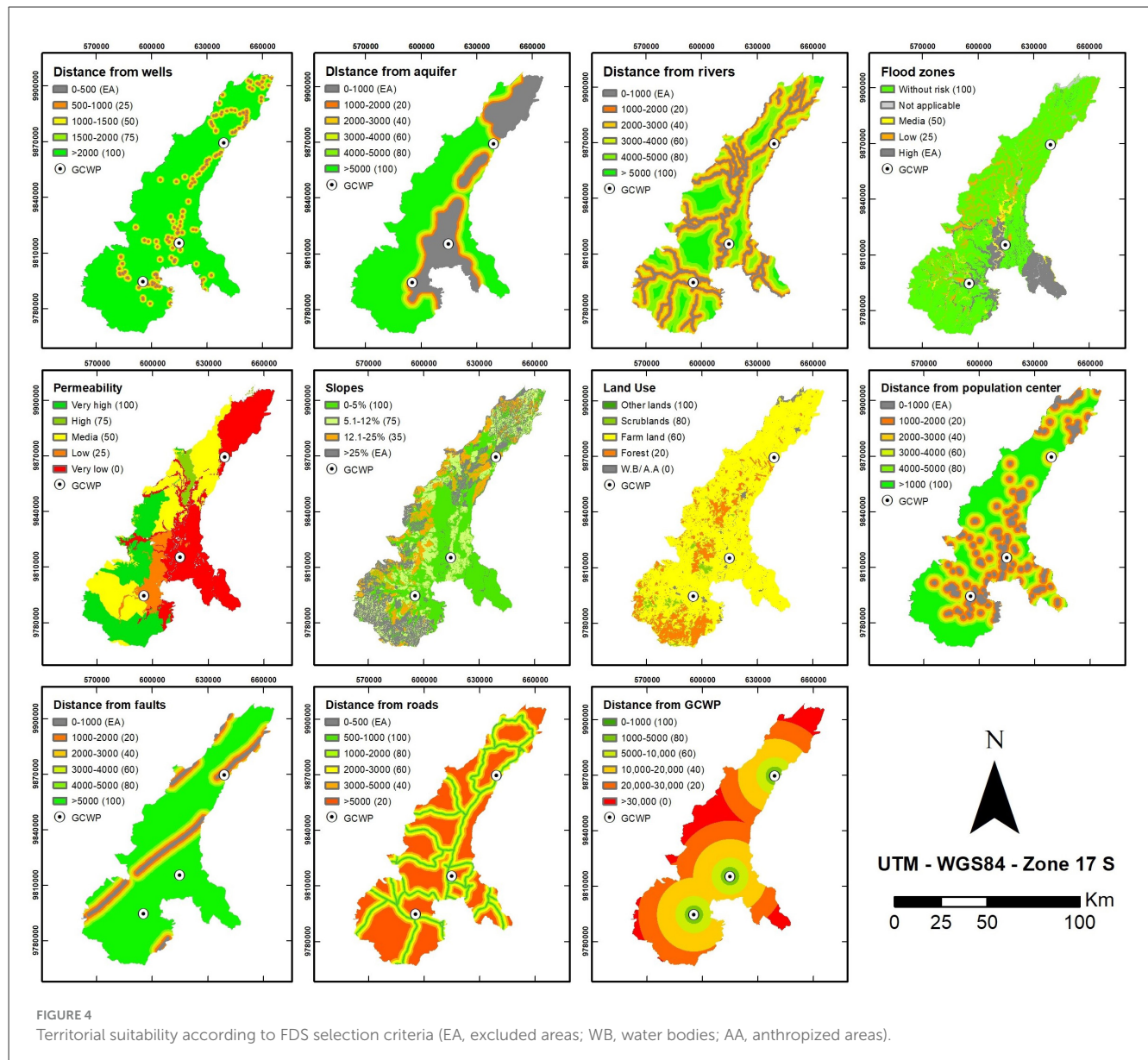
3 Results

3.1 Initial characterization through surveys and technical visits

3.1.1 Management modality

Solid waste management is carried out by the environmental management department of each municipality, which is responsible for collecting, transporting, and disposing of solid waste in both urban and rural areas. The cantons of El Empalme and Palestina are part of municipal associations with cantons outside the province of Guayas, so the final disposal stage is carried out collaboratively outside the province.

On the other hand, municipalities identified that the main challenges in solid waste management are strongly linked to the



following aspects: (a) lack of economic and human resources, (b) need for equipment and infrastructure renewal, (c) lack of training of operational staff, and (d) environmental awareness on the part of the community. To a lesser extent, they also reported the need to reduce the amount of solid waste entering FDS and implement measures for waste reuse.

3.1.2 Collection service

Municipalities report coverage of over 70%; however, in the case of Santa Lucía, coverage is between 60% and 70%. In general, collection in urban areas is carried out using compactor trucks. By contrast, dump trucks are used in rural areas because of the limited availability of vehicles and lower waste production in these areas. However, half of the collection vehicles in the cantons were in poor condition, except for the cantons of El Empalme and Palestina. Furthermore, waste is not separated from the source, meaning that the materials are not formally recycled (Table 3).

3.1.3 Final disposal sites

Six of the 10 cantons used open dumps (OD), three used emergency disposal cells (EDC), and Pedro Carbo reported having a sanitary landfill (SL; field verification showed that the sanitary landfill does not operate correctly). The 10 cantons generate 196 tons of waste per day, a figure estimated because there are no controls on the amount of waste entering the FDS. Environmental permits correspond to registrations or certificates that should be assigned to low-impact activities. Only two cantons use organic matter, but only on a pilot scale, and none treat leachate (Table 4).

Other aspects verified in the field are the lack of adequate machinery for minimal control operations. In winter, access roads for transporting waste to and within the FDS become challenging for vehicle and machinery operations because of the unstable terrain. On the other hand, in some FDS, informal recycling is carried out without protective measures, with exposure to hazardous waste. Additionally, the presence of homes and crops within a radius of approximately 100 m was observed.

TABLE 7 Weighting of criteria obtained from the focus group.

Criteria	Evaluators								Average	Rank
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		
Aquifers	0.196	0.167	0.069	0.192	0.116	0.230	0.225	0.162	0.170	1
Water wells	0.202	0.180	0.057	0.099	0.116	0.137	0.160	0.162	0.139	2
Rivers	0.146	0.168	0.080	0.148	0.178	0.061	0.121	0.026	0.116	3
Floods	0.122	0.146	0.127	0.061	0.178	0.040	0.103	0.054	0.104	4
Population centers	0.028	0.041	0.152	0.162	0.121	0.121	0.027	0.068	0.090	5
Permeability	0.041	0.073	0.107	0.170	0.077	0.050	0.040	0.123	0.085	6
Slopes	0.048	0.048	0.069	0.023	0.038	0.035	0.066	0.207	0.067	7
Roads	0.072	0.079	0.119	0.035	0.024	0.077	0.059	0.068	0.067	8
GCWP	0.061	0.036	0.107	0.049	0.030	0.119	0.052	0.019	0.059	9
Land use	0.024	0.042	0.069	0.016	0.085	0.091	0.026	0.068	0.053	10
Geological faults	0.060	0.018	0.046	0.045	0.039	0.039	0.121	0.045	0.052	11
CR (<0.1)	0.068	0.082	0.099	0.066	0.044	0.099	0.039	0.096	0.074	

CR, Consistency index.

3.2 Weighting of criteria using AHP

Figure 3A shows the GCWP-General location (corresponding to the entire study area) from 2010 to 2023, where a displacement of 8.4 km to the south was evident during that period. The locations of the GCWP of the three proposed clusters for 2023 are also shown. The analysis of Cluster 1 showed a greater variation in the position of the GCWP due to the production of Pedro Carbo waste, such that by reducing its production by 10%, the GCWP had a maximum displacement of 549.89 m to the southeast (Figure 3B). In the case of Cluster 2, the maximum displacement of the GCWP was 1181.44 m to the southwest, owing to the reduction in production in the El Empalme canton (Figure 3C). Finally, the location of the GCWP of Cluster 3 was mainly conditioned by the production of Salitre and Colimes, where the reduction in the production of Colimes generated a maximum displacement of 421.85 m toward the southeast (Figure 3D).

Table 5 shows the population projection, per-capita production, and daily solid waste production for the cantons in the study area. By 2040, Pedro Carbo canton is expected to generate the most significant amount of waste, followed by El Empalme, Balzar, and Nobol; while the cantons with the lowest waste production are Isidro Ayora, Palestina, and Salitre.

Table 6 shows the displacement of the GCWPs of clusters 1, 2, and 3 concerning the GCWP location in 2023. Based on the projection of waste production, it can be seen that the GCWPs of clusters 2 and 3 present displacements of <1 km, with the GCWP of Cluster 2 moving the least distance. The projected production in Cluster 1 generates a GCWP displacement of 1.71 km in 2035, but this distance would be reduced in 2040.

Figure 4 shows the territorial suitability for each of the 11 SDF selection criteria and the relative position of the GCWP. The GCWP falls within exclusion zones for aquifers, rivers, population centers, and geological faults. Aquifers and population centers imposed the most significant restrictions in the analysis. In the case of aquifers, exclusion zones accounted for 21% of the

study area, while areas restricted by population centers comprised 13%. Most of the territory corresponds to land with agricultural potential and a medium degree of suitability (60% of the study area).

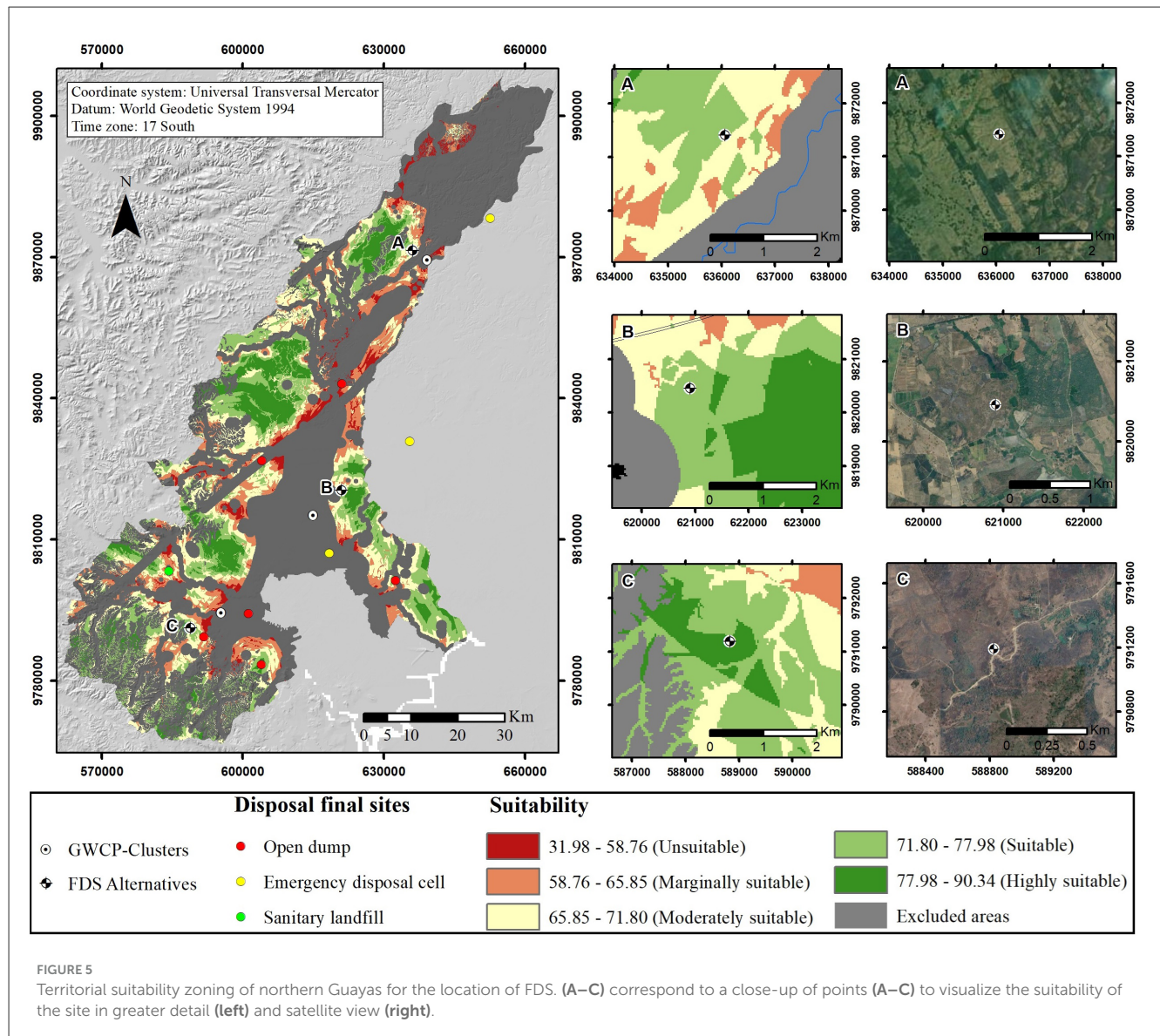
According to the assessments carried out by the focus group, a consistency level of <0.1 was achieved in the results, meaning that the criteria related to surface and groundwater sources were the most relevant for the study (individual results for each comparison matrix are presented as Supplementary material). Other pertinent criteria included flooding, distance to population centers, and soil permeability (Table 7).

3.3 Territorial suitability for the location of FDS

On a scale of 0 to 100, the suitability values ranged from 31.98 to 90.34, with a mean suitability of 70.81 and a standard deviation of 7.62. Approximately 28% of the territory is suitable for the location of an FDS, while exclusion zones account for 39% of the territory. In this context, four of the FDS were located in exclusion zones, two were located in areas with a low degree of suitability, and only one was located in an area of high suitability. Furthermore, the calculated GCWPs fell in unsuitable zones; therefore, the study located the FDSs of the three proposed clusters in areas with high suitability within a 10-km radius of the calculated GCWPs (Figure 5).

Figure 6 shows the position of the proposed FDS relative to access routes and the three most highly weighted criteria (aquifers, wells, and rivers). In most cases, the cantonal capitals are located between 5 and 20 km from the proposed FDS (Figure 6).

Table 8 shows the reordering of the criteria in contrast to the results obtained from the AHP. Scenario 1 shows territorial suitability under the assumption that the GCWP criterion has remained in an intermediate position in the ranking, where it can



be seen that the proposed FDS area remains suitable, as in the conditions of Scenario 2. The conditions under Scenario 3 indicate that the area chosen for FDS-B has a medium degree of suitability, as do the FDS A-C areas in Scenario 4 (Figure 7).

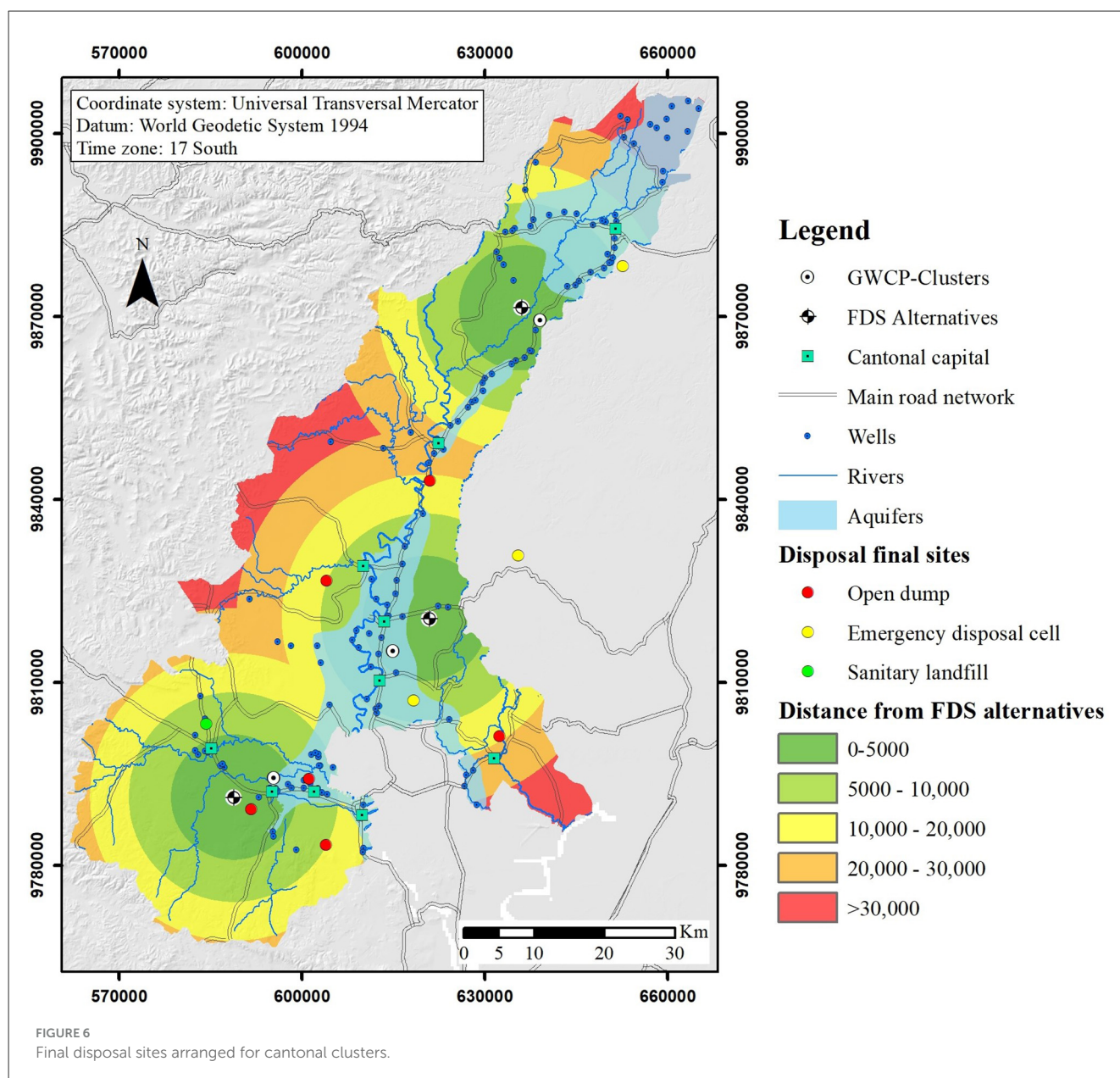
4 Discussion

4.1 Institutional conditions and viability of the inter-municipal approach

The SDFs in the study area revealed various deficiencies in their management and operation, mainly related to financial and cultural constraints. These problems are consistent with those reported in other studies analyzing the challenges facing developing countries in waste management, which also highlight a lack of education, governance problems, and the adoption of new technologies (Zhang et al., 2024; Maalouf and Agamuthu, 2023).

According to Almansour and Akrami (2024), these difficulties can be overcome by implementing policies that promote recycling, tax waste-generating activities, and encourage producer accountability.

Despite the individual financial constraints of the 10 cantons analyzed, collectively they have the economic potential to implement final disposal strategies through joint management in compliance with current environmental regulations (Ministerio del Ambiente Agua y Transición Ecológica, 2003). For example, within the same province, the Milagro Canton, with a population of 195,943 inhabitants, waste production of 133 tons per day, and an average annual economy of \$638,703.54 (1.32 times less than the case study; Banco Central del Ecuador, 2025), has a facility that operates a sanitary landfill equipped with machinery for waste compaction and the daily service cover that includes a gas venting system, continuously records the quantity of incoming waste, features security measures and perimeter fencing, and employs conventional methods for leachate treatment (Ministerio de Ambiente Agua y Transición Ecológica, 2023). Struk and Bakoš



(2021) analyzed 664 municipalities in the Czech Republic, where those that operated a collaborative management model generated annual savings of 13.5% in solid waste management costs during the period 2010–2019.

In this sense, the study by Villalba Ferreira et al. (2022), developed in the province of Azuay in Ecuador, carried out a comparative analysis between different management modalities (indirect, transactional, and collaborative), highlighting collaborative management as an efficient means to achieve better environmental sustainability indicators and facilities to meet the financial and technical demand in the operation of an FDS. The study mentions that smaller municipalities should work on collaborative governance agreements as strategies to achieve the desired results, which may involve agreements for the definition of responsibility, economic contributions, and decision-making mechanisms. In the financial field, the administration of the

associated municipalities must ensure the continuity of operations without being interrupted due to lack of resources, so financial sustainability should be achieved through actions based on increasing own income, diversification of economic mechanisms, efficient management of funds and resources, and monitoring of direct costs (Panassenko, 2022; Tominski et al., 2017).

4.2 Multi-criteria evaluation and territorial restrictions

The weighting of criteria obtained through AHP reflects a clear prioritization of environmental factors, particularly the protection of water resources (aquifers, wells, and rivers), followed by aspects such as flood risk and proximity to population centers. Logistics criteria, such as proximity to access roads and the GCWP, obtained

TABLE 8 Reordering of selection criteria.

Rank	Original		Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Weights	Criteria				
1	0.17	Aquifers	Aquifers	Roads	Population centers	Permeability
2	0.139	Water wells	Water wells	GCWP	Land use	Slopes
3	0.116	Rivers	Rivers	Aquifers	Aquifers	Geological faults
4	0.104	Floods	Floods	Water wells	Water wells	Aquifers
5	0.09	Population centers	Population centers	Rivers	Rivers	Water wells
6	0.085	Permeability	GCWP	Floods	Floods	Rivers
7	0.067	Slopes	Permeability	Population centers	Permeability	Floods
8	0.067	Roads	Slopes	Permeability	Slopes	Population centers
9	0.059	GCWP	Roads	Slopes	Roads	Roads
10	0.053	Land use	Land use	Land use	GCWP	GCWP
11	0.052	Geological faults	Geological faults	Geological faults	Geological faults	Land use

Italic values are the weights obtained according to Table 7.

lower values, which is consistent with current environmental regulations and the need to minimize territorial impacts. This hierarchy demonstrates a precautionary approach to the location of FDS without underestimating the operational value of GCWP within the overall analysis.

The relevance of the criteria varies in each study; for example, Ali et al. (2023) assigned the highest weighting to the criterion of distance from the road network, which is associated with reduced operational and construction costs of landfills. This discrepancy depends on the objectives of the study, local context, available information, and the subjectivity of experts (Sahid et al., 2023; Hidalgo Zambrano et al., 2021; Carrión-Mero et al., 2024). To reduce bias due to the adaptive nature of multi-criteria analyses (Kharat et al., 2016a,b), suggest the application of methodologies such as Delphi or fuzzy techniques.

The suitability of the areas selected for FDS siting was contrasted using four scenarios, prioritizing the relevance of the lowest-scoring criteria. At first glance, Scenario 2 differs most from the original scenario, whereas Scenarios 1, 3, and 4 are the most similar but with significant variations. The suitability of the selected sites was not affected by Scenarios 1 and 2, ranging from high to superior suitability; however, Scenario 3 affected the location of FDS-B, and Scenario 4 affected FDS-A-C. Despite these variations, the proposed areas remain at a medium-suitability level, reflecting their technical and environmental feasibility.

4.3 Logistics and spatial dynamics application of GCWP

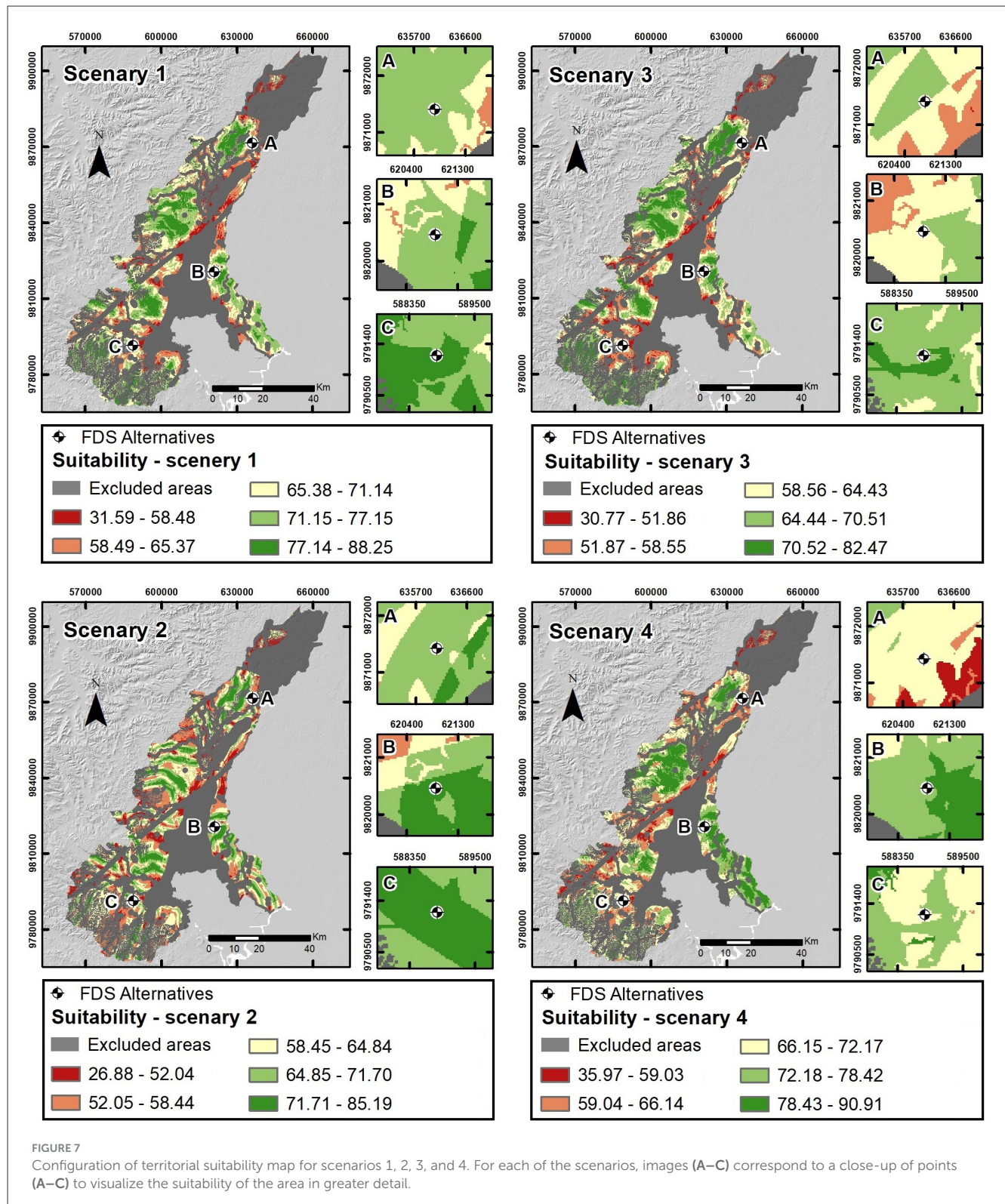
According to the scientific literature (Aremu, 2013; Jacobsen et al., 2013; Merchán-Sanmartín et al., 2022), waste collection and transportation costs can represent a considerable fraction of a municipality's budget. In this study, although the distances between the proposed FDS and the main waste generators do not necessarily

imply a direct reduction in logistics costs, the proposal seeks to support decision-making through a collaborative management approach between institutions to reduce the impacts associated with the poor operation of FDS, whose remediation actions can incur high investment costs.

Additionally, the poor operation of FDS exposes competent authorities to sanctions, as specified by the legal framework of each country. In Ecuador, the Organic Environmental Code establishes fines for the inefficient operation of FDS based on reported tax information, which can increase by 50% in the case of aggravating factors (Corte Constitucional del Ecuador, 2019). There have been reports of municipalities being fined between \$ 58,000 and \$127,000, in addition to the cost of remediation actions for the damage caused (Ministerio de Ambiente Agua y Transición Ecológica, 2022; Ministerio del Ambiente Agua y Transición Ecológica, 2012).

Therefore, to optimize waste transportation at the territorial level, this study defined three zones for the location of SDFs based on proximity to GCWPs and the suitability map obtained. The proposed FDS sites are located 20 to 30 km from population centers, which for our study corresponds to a low suitability range, contrasting with the study in Cobos-Mora et al. (2023). In such cases, the implementation of transfer stations has achieved a 30% reduction in transport costs, as reported in other studies (Corporación Eléctrica del Ecuador, 2010; Secretaría Nacional del Agua, 2014; Instituto Geográfico Militar del Ecuador, 2013; Paul et al., 2020). According to Rathore and Sarmah (2019), transfer stations are appropriate when FDS are more than 15 km away from the points of generation.

On the other hand, waste generation can vary depending on population growth and local economic development (Adeleke et al., 2021; Asefa et al., 2021), which affects the location of the GCWP. At the level of the proposed clusters, although the waste production of the cantons will have an appreciable increase in 2040, the maximum



displacement of the GCWP concerning 2023 would be 618.75 m, corresponding to Cluster-3. In contrast, the GCWP of the entire study area shifted 8.4 km southward in the province over a period of 13 years (2010–2023), which is equivalent to 2.85 km/year. This variation in the position of the GCWP is more abrupt in countries with high levels of economic development and population growth, such as China, where intense environmental pressures associated

with waste generation have led to a displacement of the GCWP of up to 287.5 km in 11 years (26.1 km/year; Wang et al., 2020), which is approximately nine times faster. Identifying potential long-term displacements of the GCWP can be a valuable tool for establishing governance strategies that promote sustainable practices and minimize waste production in growth areas (Luo et al., 2023).

4.4 Limitations and future lines of research

In general, historical data on solid waste generation in Ecuador are scarce, particularly in open dump and emergency disposal cell systems where daily incoming waste quantities are not monitored. Under these conditions, it is challenging to make projections that accurately reflect the variability in waste production, thereby hindering the estimation of the future trajectory of the GCWP as a long-term territorial planning tool. One of the limitations of this study is that the criteria were analyzed statically despite being subject to changes over time, such as population growth, changes in land use and land cover, and waste production (Kang et al., 2024).

This study can be adapted to financially constrained municipalities seeking to improve their solid waste disposal management through inter-municipal cooperation. Depending on the context, the use of other criteria, such as waste production projections, more precise mapping of existing aquifers, and weather conditions, can strengthen this type of study. Other research could address the impact of the spatial dynamics of the FDS selection criteria on long-term land availability. Additionally, the application of AHP in selecting technologies for the utilization of solid waste and leachate in developing countries could also be addressed.

5 Conclusions

The multicriteria analysis generated a suitability map for locating final disposal sites (FDS), integrating 11 environmental, geomorphological, logistical, and territorial criteria. The results showed that approximately 28% of the study area is suitable for final disposal. Owing to the dispersed population and the distances involved, it is recommended to consider locating two or more FDS to improve operational efficiency.

Although the GCWP criterion received low weighting in the AHP method, its inclusion allowed its contribution to be compared to traditional criteria, highlighting that in contexts such as northern Guayas, the protection of water resources prevailed as a limiting factor. However, GCWP remains a strategic criterion for optimizing collection routes and reducing transportation costs.

The proposed method is a replicable tool that combines spatial analysis of waste generation with multi-criteria assessment, offering technical support for territorial planning processes in inter-municipal management schemes. Although this study used a static approach, incorporating generation projection data would allow solutions to be better adapted to future scenarios. Future research could focus on the selection of waste recovery and treatment technologies in the context of inter-institutional cooperation in developing countries this type of study.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The participants provided written informed consent to participate in this study.

Author contributions

MA-V: Writing – review & editing, Funding acquisition, Validation, Conceptualization, Supervision. CP-V: Validation, Supervision, Conceptualization, Funding acquisition, Writing – review & editing. MJ-C: Validation, Methodology, Supervision, Conceptualization, Writing – review & editing. JB-B: Writing – original draft, Formal analysis, Conceptualization, Supervision, Methodology, Validation, Data curation. MJ-M: Methodology, Data curation, Conceptualization, Writing – original draft. FM-C: Validation, Formal analysis, Supervision, Conceptualization, Writing – review & editing, Methodology. SS-Z: Conceptualization, Data curation, Methodology, Writing – original draft. MA-A: Methodology, Conceptualization, Writing – original draft. EB: Conceptualization, Supervision, Writing – review & editing, Validation, Formal analysis. PC-M: Methodology, Writing – review & editing, Supervision, Validation, Conceptualization, Formal analysis.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by “Diagnóstico y estrategia para la gestión sostenible de residuos sólidos en la provincia del Guayas,” code CIPAT-003-2024.

Acknowledgments

We express our sincere gratitude to the Decentralized Autonomous Provincial Government of Guayas for the logistical support provided during the development of this study, within the framework of the Tripartite Agreement for Inter-institutional Cooperation between the Decentralized Autonomous Provincial Government of Guayas, the Escuela Superior Politécnica del Litoral (ESPOL), and the public services company ESPOL-TECH E.P. in the implementation of the project Diagnosis of Waste Management for Sustainable Management Guidelines for the Municipalities of the Province of Guayas.

Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2025.1647171/full#supplementary-material>

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