Çanakkale Onsekiz Mart University

Journal of Advanced Research in Natural and Applied Sciences

dergipark.org.tr/tr/pub/jarnas

Open Access

e-ISSN: 2757-5195 2024, Vol. 10, Issue 2, Pages: 446-463 doi.org/10.28979/jarnas.1416814

Hazardous Solid Waste Landfill Site Selection for İstanbul, Türkiye using Multi-Criteria Decision-Making Methods and GIS Data

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Article History
Received: 11 Jan 2024
Accepted: 08 Apr 2024
Published: 25 Jun 2024

Research Article

Abstract − The high toxicity of materials in disaster waste poses a significant risk to the environment, including the air, water, soil, and all living beings. One of the commonly used disposal methods for hazardous solid waste is landfilling. The selection of sites for hazardous solid waste disposal requires extreme care and attention to multiple factors from environmental, social, and economic points of view. Considering the anticipated earthquake in Istanbul and the city's excessive population and urbanization, experts estimate that debris waste will be approximately 25 million tons. In this study, we propose a Geographic Information System (GIS) based fuzzy Multi-Criteria Decision Making (MCDM) approach to select hazardous solid waste landfill (HSWL) locations within the scope of disaster waste management for Istanbul. First, the evaluation criteria were identified through a literature review and expert opinions. Next, criteria are prioritized using the Fuzzy Analytic Hierarchy Process (FAHP). Then, GIS data for the criteria are gathered from multiple resources and entered into ArcGIS 10.8 for spatial analysis. Last, the suitability map of Istanbul for the HSWL construction is built. Considering five candidates, the Analytic Hierarchy Process (AHP) is applied to select the most suitable locations for Asian and European sites in the city. Accordingly, Fevzipaşa/Silivri for the European side and Hasanlı/Şile for the Asian side were selected as the most suitable two options. Last, a sensitivity analysis was performed to investigate the impact of the highest weight criterion on the final solution.

Keywords − *Disaster waste management, fuzzy analytic hierarchy process, geographic information system, hazardous solid waste management, multi-criteria decision making*

1. Introduction

Disasters can cause significant harm to society, damage residential areas and infrastructure, and produce extensive amounts of debris. Debris includes numerous hazardous materials, including heavy metals like lead, organic and inorganic substances with high toxicity, and asbestos. The release of asbestos-containing materials during a disaster pollutes water sources, soil, and air. It can pose serious health risks, such as lung cancer, mesothelioma, larynx, and asbestosis [1]. For instance, on February 6, 2023, two earthquakes measuring 7.7 and 7.6 magnitudes hit Kahramanmaraş, affecting 11 provinces deeply and resulting in the loss of 50,500 lives. At least 35,000 buildings were destroyed, while hundreds of thousands suffered severe and moderate damages. The disaster caused approximately 350 to 580 million tons of construction and demolition waste including around 1.5 million tons of hazardous waste, which threatened the health of people residing in the affected cities (around 13 million people) and the environment due to the emission of asbestos-containing materials [2, 3]. This unfortunate earthquake exhibits the importance of effective disaster waste management to prevent severe negative impacts on health and the environment.

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The most critical objective of disaster management is appropriately managing the waste generated by the disaster [4]. This involves selecting locations for the storage and subsequent disposal of disaster waste and removing the hazardous debris and harmful waste immediately after the disaster to minimize the damage. Due to its complex geological structure and tectonic position, numerous active faults exist in Türkiye, leading to countless earthquakes throughout history. Therefore, utmost attention should be paid to disaster waste management to mitigate its negative impacts on the community and the environment. In this regard, this study aims to support experts in selecting hazardous solid waste landfill (HSWL) sites for the anticipated earthquake in Istanbul.

According to a Kandilli Observatory and Earthquake Research Institute report, Istanbul comprises 18.7% of Türkiye’s total population, with more than 4.75 million households and 15.9 million people. It is estimated that around 70% of the buildings constructed before 2006 in Istanbul do not comply with seismic regulations, corresponding to more than 3.1 million dwellings. The anticipated Istanbul earthquake, estimated by experts to be between 7.5 and 7.6 magnitudes, will also affect eight neighboring provinces, impacting 7,870,806 households and 25,590,594 people, accounting for approximately 30% of Türkiye’s population. Taking into account the region that the potential Istanbul earthquake will affect and the number of non-seismic code-compliant structures, it is expected that nearly 25 million tons of debris will be generated after the destructive earthquake [5]. Therefore, action plans to manage the disaster waste should be taken urgently.

This study contributes to the literature by integrating Geographic Information System (GIS) data with the Fuzzy Analytic Hierarchy Process (FAHP) method to decide optimal landfill sites for the Istanbul region for hazardous solid waste, specifically disaster waste. To decide on HSWL sites for Istanbul, we developed a fuzzy Multi-Criteria Decision Making (MCDM) model that utilizes GIS data and the FAHP method. First, essential criteria that impact the location selection are collected from literature and experts’ opinions. Next, criteria are prioritized by FAHP, considering the former studies and experts’ judgments. Then, geographical information for each criterion for the Istanbul region is mapped using ArcGIS 10.8 software. Using GIS data and criteria weights, the suitability map, which demonstrates the map of zones suitable for HSWL for Istanbul, is created. Last, alternative locations are ranked using Analytic Hierarchy Process (AHP), and the best locations for Asian and European sites in Istanbul are selected. Last, sensitivity analysis is performed to examine the impact of criteria weights on the solution. The organization of the paper is as follows. The studies in the literature are presented and discussed in Section 2. The methodology that utilizes GIS data and the FAHP method is outlined in Section 3. The case study and sensitivity analysis undertaken to explore the prioritization of criteria in decision-making are detailed in Section 4. Finally, Section 5 concludes the paper.

2. Literature Review

The selection of a location for the storage and disposal of hazardous solid waste is evaluated under the name “location selection problem” in the literature. The location selection problem, first introduced by the German economist Alfred Weber in 1909, focuses on selecting a depot that provides the most suitable raw materials, labor, logistics, and unit costs for all customers. Although Weber’s work was initially conducted in the industrial field, his theory of “Location Selection” has significant importance not only in the industrial field but also in economics, mathematics, natural sciences, and many other disciplines [6].

An analysis of research related to the selection of locations for waste management and disaster waste management is outlined in Table 1. Most of these studies primarily concentrate on selecting locations for municipal solid waste landfills, with comparatively fewer investigations addressing disaster waste management. Consequently, we have incorporated studies that specifically delve into selecting sites for hazardous waste disposal. Additionally, because GIS enables the inclusion of spatial data in the solution, we considered the studies utilizing GIS. GIS is a decision support system that allows us to collect, store, update, control, analyze, and visualize information related to the Earth's surface [7]. GIS allows us to comprehensively analyze the geographic and topographic characteristics of a specific area, such as land use, accessibility, proximity to settlement areas, and slope, which are essential in the selection of hazardous solid waste disposal sites.

Table 1. Summary studies for waste disposal selection problem that utilizes GIS

Problem	Methodology	Study
Disaster waste management: Istanbul, Türkiye	GIS – Multi-objective optimization (NSGA-II)	[8]
Disaster waste management site selection Victoria, Australia	GIS – Boolean logic	[9]
Disaster waste management site selection South Korea	GIS – MCDM (WSA)	[10]
Disaster waste management site selection Wenchuan, China	GIS – MCDM (TOPSIS)	[11, 12]
Disaster waste management site selection Egyptian Mediterranean Coast	GIS – MCDM (N-OPA)	[12]
Hazardous waste disposal site selection Zanjan province, Iran	GIS – MCDM (SAW)	[13]
Hazardous waste disposal site selection Avellino in Campania region	GIS – MCDM (SAW)	[14]
Hazardous waste disposal site selection Qom Province, Iran.	GIS – MCDM (AHP)	[15]
Hazardous waste disposal site selection Western Ghana	GIS – MCDM (AHP)	[16]
Municipal solid waste landfill location selection Kupang, Indonesia	GIS – MCDM (AHP-SAW)	[17]
Municipal solid waste landfill location selection Maharashtra, India	GIS – MCDM (AHP)	[18]
Municipal solid waste landfill location selection (Peshawar district) in Pakistan	GIS – MCDM (AHP)	[19]
Municipal solid waste landfill location selection Bandar Bushehr, Iran	GIS – MCDM (FAHP)	[20]
Municipal solid waste landfill location selection Najran, Saudi Arabia	GIS – MCDM (FAHP)	[21]
Municipal solid waste landfill location selection: Dhanbad, India	GIS – MCDM (FAHP)	[22]
Waste disposal site selection Dejen town, Ethiopia	GIS – MCDM (AHP)	[23]
Waste disposal site selection Fez province, Morocco	GIS – MCDM (AHP)	[24]
Landfill site selection: Istanbul, Türkiye	GIS – MCDM (AHP)	[7]
Landfill site selection: Javanrood, Iran	GIS – MCDM (AHP-TOPSIS)	[25]
Landfill site selection: Edirne, Türkiye	GIS – MCDM	[26]
Solid waste sanitary landfill site selection: Denizli, Türkiye	GIS – MCDM (AHP)	[27]

ANP - Analytic Network Process; TOPSIS - Technique for Order Preference by Similarity to Ideal Solutions, SAW - Simple Additive Weighting, Elitist Evolutionary Multi-Objective Optimization Technique (NSGA-II); WSA: Weighted Sum Analysis; N-OPA: Neutrosophic Ordinal Priority Approach

As seen in Table 1, MCDM methods are commonly used in solving the landfill site selection problem. MCDM is a useful tool for quickly obtaining the most effective result for problems that require considering multiple criteria, such as location selection. MCDM helps determine the best alternative by considering various criteria and their importance. Among the MCDM methods, AHP is most preferred. AHP decomposes a decision-making problem into criteria and sub-criteria; it defines and evaluates each criterion's relative importance through pairwise comparisons. Then, it ranks the available alternatives based on the importance of the criteria and leads to a conclusion [28]. However, classic AHP falls short of covering the uncertain judgments and opinions of the experts in decision-making. Therefore, AHP has been extended to FAHP to include the uncertainty associated with individual assessments. Studies incorporating FAHP or other fuzzy approaches are relatively fewer than crisp MCDM approaches [29].

Studies focus on selecting disaster waste management sites are as follows: Onan et al. [8] propose a multi-objective optimization framework that employs NSGA-II and GIS data to decide on temporary disaster waste management sites and incorporate the planning for collecting and transporting disaster waste. Cheng and Thompson [9] employed GIS to generate a suitability map in Victoria, Australia, employing Boolean logic to derive map layers. In another study, Lee et al. [10] applied the WSA with GIS data to address the challenge of selecting temporary disaster waste management sites. Liu [11] utilized TOPSIS to select the most suitable location for disaster waste management in Wenchuan, China. AbdelAziz et al. [12] incorporated a fuzzy N-OPA approach for disaster waste management in the Egyptian Mediterranean Coast for flood-prone areas.

Our research stands out by integrating GIS data with FAHP methods to select optimal landfill sites for the Istanbul region for hazardous solid waste, particularly those originating from disasters. In this context, GIS accurately captures reliable spatial data, while FAHP models imprecise and uncertain expert opinions. Combining these two data types enhances decision-making processes and facilitates the efficient deployment of disaster waste management sites. This paper contributes to the existing literature in two keyways. Firstly, it introduces a three-step framework for HSWL location selection, where GIS analyses spatial data, FAHP prioritizes criteria, and AHP ranks the candidate sites. Secondly, it demonstrates the practical application of this framework through a case study in Istanbul, determining the optimal location for hazardous solid waste management.

3. Methodology

The methodology in deciding on the potential HSWL locations for Istanbul includes four steps, as presented in Figure 1. Each step is elaborated under subsections 3.1-3.4, respectively.

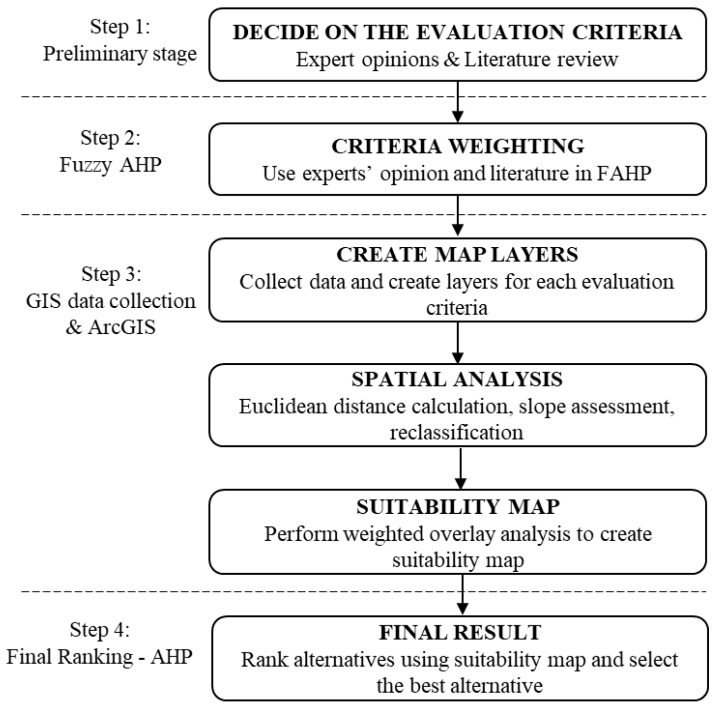

Figure 1. Methodology

3.1. Identification of Evaluation Criteria

In the scope of the research, a search was conducted on the Google Scholar search engine using specific keywords related to the study content, including "hazardous solid waste landfill" and "hazardous solid waste disposal", in addition to the terms "GIS" and "MCDM". Next, those articles are filtered to select potential evaluation criteria for HSWL site selection. Two experts with more than ten years of experience in environmental engineering with a geography background supported us in verifying the evaluation criteria gathered from the literature search. The evaluation criteria selected are described as follows.

Land cover (C1): Land cover refers to the physical or biophysical material covering the land, such as urban areas, forests, or grassland, and is essential for determining the disaster waste disposal location. For instance, forests, urban areas, agricultural lands, natural reserves, or parks cannot be selected as HSWL locations. The storage site should be as far away as possible from those areas. Additionally, population density is also a crucial factor. The greater amount of debris is expected from the regions with higher populations. Therefore, debris storage locations should not be too far from residential areas, which may create transportation challenges and increase transportation costs. Soil and rock structure (C2): Geological maps provide valuable information about the region, including soil types, rocks, and other structural features. When selecting HSWL sites, areas where the soil types have a low permeability structure are preferred. Additionally, the ground should not be soft or prone to waterlogging; it should be firm and stable. Surface (C3) and ground (C4) waters: HSWL areas should be located far from water sources to prevent the leakage of toxic materials such as asbestos, which may be released from debris. However, to reduce the emission of toxic gases by irrigating the debris, the storage areas should be relatively close to water sources. Slope (C5): The slope of the areas where debris will be piled should be as low as possible. Areas with a slope greater than 20% are excluded from the analysis. Aspect (C6): To prevent the dispersion of harmful material dust by the wind, storage areas should not be constructed in the direction of prevailing winds. Fault line (C7): The suitability of an area increases proportionally with the distance from the fault line. Roadways (C8): The proximity of waste storage sites to roads is crucial for ease of transportation and cost-effectiveness. Wind speed (C9): Wind speed can facilitate the transport of toxic particles in the form of gas and dust clouds towards residential areas; therefore, it is beneficial to prefer areas with low annual average wind speeds. Land value (C10): It is more appropriate to select locations for HSWL in areas with relatively lower land values. Table 2 presents the relationship between evaluation criteria and the other studies in the literature.

Table 2. The relationship between identified evaluation criteria and literature

Literature Summary	Criteria									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
[7]	x	x	x		x			x		x
[25]	x	x	x	x	x	x	x	x	x	x
[26]	x	x	x		x	x		x	x	
[27]	x				x	x	x	x		
[30]		x	x	x				x		
[31]	x	x	x	x			x			
[8]			x	x			x		x	x
[19]	x	x	x	x	x	x		x		x
[23]	x	x	x		x	x		x	x	
[15]	x	x	x		x		x	x		
[17]		x		x	x					
[18]	x	x	x		x	x		x		
[14]	x		x	x			x	x	x	
[24]	x		x		x			x		
[16]	x	x	x		x	x	x	x		x
[9]	x		x		x			x		

3.2. Criteria Weighting - Fuzzy Analytical Hierarchy Process

The FAHP decision-making method incorporates uncertainty and ambiguity in subjective judgments for solving MCDM problems. It helps determine the relative importance of the criteria or alternatives through linguistic terms when judgments are difficult to quantify. By employing the FAHP, we aim to assign appropriate weights to each criterion to prioritize them based on their significance in the HSWL site selection process. In our study, we opted for triangular fuzzy numbers (TFN) to capture the vagueness related to the decision-maker due to its prominent applications. A TFN can be represented as $M = (l, m, u)$. These parameters represent the smallest possible (l), the most promising (m), and the largest possible value (u), respectively. The FAHP, employing the geometric mean method, is implemented as described in [32] as follows:

Step 1: Make a pairwise comparison across evaluation criteria using linguistic terms [32] and create a fuzzy decision matrix, $\tilde{\boldsymbol{M}}$.

$$\tilde{M} = \begin{bmatrix} 1 & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ \tilde{m}_{21} & 1 & \cdots & \tilde{m}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{m}_{m1} & \tilde{m}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ 1/\tilde{m}_{12} & 1 & \cdots & \tilde{m}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{m}_{1n} & 1/\tilde{m}_{2n} & \cdots & 1 \end{bmatrix}$$

$$\tilde{m}_{ij} = \begin{cases} \tilde{9}^{-1}, \tilde{8}^{-1}, \tilde{7}^{-1}, \tilde{6}^{-1}, \tilde{5}^{-1}, \tilde{4}^{-1}, \tilde{3}^{-1}, \tilde{2}^{-1}, \tilde{1}^{-1}, \tilde{1}^{1}, \tilde{2}^{1}, \tilde{3}^{1}, \tilde{4}^{1}, \tilde{5}^{1}, \tilde{6}^{1}, \tilde{7}^{1}, \tilde{8}^{1}, \tilde{9}^{1}, 1, i \neq j \\ 1\ i = j \end{cases}$$

Step 2: Calculate the fuzzy geometric mean and fuzzy weights for each criterion using (3.1) and (3.2).

$$\tilde{r}_i = \left(\tilde{m}_{i1} \otimes \ldots \otimes \tilde{m}_{ij} \otimes \ldots \tilde{m}_{in}\right)^{1/n} \tag{3.1}$$

$$\tilde{w}_i = (\tilde{r}_i \otimes [\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_i \oplus \ldots \tilde{r}_n])^{-1} \tag{3.2}$$

In (3.1) and (3.2), $\tilde{m}_{ij}$ shows the fuzzy comparison value of criterion i with respect to criterion j. The notation $\tilde{r}_i$ refers to the geometric mean of the fuzzy comparison value of $the\ i^{th}$ criterion, whereas $\tilde{w}_i$ indicates the fuzzy weight of the criterion i, defined by TFN. Following, the center-of-area method is applied to defuzzify the weights using (3.3) [33].

$$T_i = \frac{l_{w_i} + m_{w_i} + u_{w_i}}{3} \tag{3.3}$$

Then, normalization in (3.4) is applied to non-fuzzy weights T_i to ensure the total sum of weights equals one [34]. (3.4) denotes the normalized crisp weight of criterion i.

$$N_i = \frac{T_i}{\sum_{i=1}^{n} T_i} \tag{3.4}$$

3.3. Creation of Map Layers and Spatial Analysis

Once the evaluation criteria have been identified, vector or raster data are acquired from multiple resources. The data collected from various sources has been entered to create relevant layers for each criterion in ArcGIS 10.8. The “Clip” tool is employed to cut all the layers according to the boundaries of Istanbul province. Next, spatial analysis, including slope calculation, Euclidean distance analysis, aspect identification, reclassification, and weighted overlay, are performed. In slope analysis, the slope of the area is calculated. Euclidean distance analysis calculates the closest distance between each point and its nearest source. The aspect of the area is determined by ArcToolBox – Spatial Analysis. Due to varying scales of input values for criteria, reclassification analysis is conducted to establish a uniform evaluation scale. The scale used ranges between “1” to “5”, where “1” refers to the lowest score and “5” denotes the highest score, based on the characteristic of the criterion, whether minimum or maximum better. Last, criteria weights determined by FAHP are incorporated, and weighted overlay analysis is executed. In weighted overlay analysis, the value of each cell within the map layers is multiplied by the corresponding criteria weights and then aggregated across all criteria to generate a suitability map. The suitability map shows the suitable zones based on their scores from “1” to “5”, ranging from unsuitable to very suitable.

3.4. Final Ranking – AHP

Considering the suitability scores of the regions and checking with the satellite images, candidate locations are determined to ensure that restricted areas, such as forests, residential areas, highways, or rivers, are not selected as candidate locations. Once the candidate locations are decided, the AHP method introduced by [35] is applied to select the best location for HSWL. In AHP, first, we constructed a pairwise comparison matrix, size mxm, where m refers to the alternatives (candidate HSWL sites) based on the reclassified values for each criterion. Then, each pairwise matrix is normalized by dividing each cell in the matrix into the sum of the associated columns. Last, the average of normalized values is computed for each alternative, which shows the weight of each alternative, preference vector, for the associated criteria.

4. Case Study

4.1. Data Set

Data for each evaluation criterion is presented in Table 3. Spatial analyses, including slope calculation, Euclidean distance analysis, and aspect identification, are conducted using the data in Figure 2. Next, reclassification analysis is performed using studies by [27] and [26] to ensure measurement integrity across evaluation criteria. Reclassification analysis for all evaluation criteria is presented in Tables 4 and 5.

Table 3. Data sources for evaluation criteria

Criteria	Source	Data Type	Scale	Analysis
C1	CORINE Land Cover (2018)	Raster	100m	Reclassification
C2	İstanbul ili Jeoloji Haritası (2023)			
C3	OpenStreetMap (2023)	Vector	1/25.000	Euclidean distance
C4	OpenStreetMap (2023)	Vector	1/25.000	Euclidean distance
C5	EarthExplorer USGS	Raster	25m	Slope
C6	EarthExplorer USGS	Raster	25m	Aspect
C7	MTA (2001)	Vector	1/25.000	Euclidean distance
C8	OpenStreetMap (2023)	Vector	1/25.000	Euclidean distance
C9	Global Wind Atlas (2018)	Raster	100m	Reclassification
C10	Gelir Dairesi Başkanlığı (2023)			

Table 4. Reclassification analysis for Criteria 1 and 2 (adopted from [27])

	Unsuitable (1)	Low suitable (2)	Moderately suitable (3)	Suitable (4)	Most suitable (5)
C1	Urban areas, Industrial or commercial units and public facilities, Mineral extraction sites, Non-irrigated arable land, Permanently irrigated arable land, Fruit trees and berry plantations, Broad-leaved forest, Coniferous forest, Mixed forest, Inland marshes, Water bodies	Complex cultivation, land principally occupied by agriculture, with significant areas of natural vegetation	Natural grasslands, Sclerophyllous vegetation, Transitional woodland-shrub	Pastures	Dumping ground, Bare rocks, Sparsely vegetated areas

Table 4. (Continued) Reclassification analysis for Criteria 1 and 2 (adopted from [27])

	Unsuitable (1)	Low suitable (2)	Moderately suitable (3)	Suitable (4)	Most suitable (5)
	Group A (Low Runoff Potential - Good Drainage)	Group B (Moderate Runoff Potential – Moderate Drainage)	Group C (High Runoff Potential - Restricted Drainage)	Group D (Very High Runoff Potential - Very Restricted Drainage)	Group D (Very High Runoff Potential - Very Restricted Drainage)
C2	Alluvial, Alluvial fan, Travertine	Olistostrome	Breccia, Conglomerate, Marble, Limestone, Metasandstone-Metaconglomerate-Metapelite, Quartzite-Quartz schist, Talus	Cherty limestone, Spilite Conglomerate-Sandstone-Mudstone, Dolomite, Limestone with clay, Melange, Sandstone-mudstone, Sandstone-Mudstone-limestone	Migmatite Gneiss, Peridotite, Schist, Schale

Table 5. Reclassification analysis for Criteria 3 and 9 (adopted from [26])

	Range	Value	Level of Suitability
C3	<2 km	1	Unsuitable
	2-3 km	2	Slightly suitable
	3-4 km	3	Moderately suitable
	4-5 km	4	Suitable
	>5 km	5	Very suitable
C4	<2.5 km	1	Unsuitable
	2.5-4 km	2	Slightly suitable
	4-5.5 km	3	Moderately suitable
	5.5-7 km	4	Suitable
	>7 km	5	Very suitable
C5	%0-5	5	Very suitable
	%5-10	4	Suitable
	%10-15	3	Moderately suitable
	%15-20	2	Slightly suitable
	>%20	1	Unsuitable
C6	Northwest - Southwest	3	Moderately suitable
	North - West	4	Suitable
	South – East – Southeast - Northeast	5	Very suitable
C7	0-0.5 km	1	Unsuitable
	0.5-0.75 km	2	Slightly suitable
	0.75-1.25 km	3	Moderately suitable
	1.25-2 km	4	Suitable
	>2 km	5	Very suitable
C8	0-0.1 km	1	Unsuitable
	0.1-1 km	3	Moderately suitable
	1-2 km	4	Suitable
	2-5 km	5	Very suitable
	> 5 km	1	Unsuitable
C9	0-5 km	5	Very suitable
	5-10 km	4	Suitable
	10-15 km	3	Moderately suitable
	15-20 km	2	Slightly suitable
	>20 km	1	Unsuitable

Figure 2 shows the GIS layers for each evaluation criteria after reclassification analysis. In these maps, for each particular criterion, unsuitable locations with a score of “1” are presented in light red color. In contrast, very suitable locations with a score of “5” are presented in dark red.

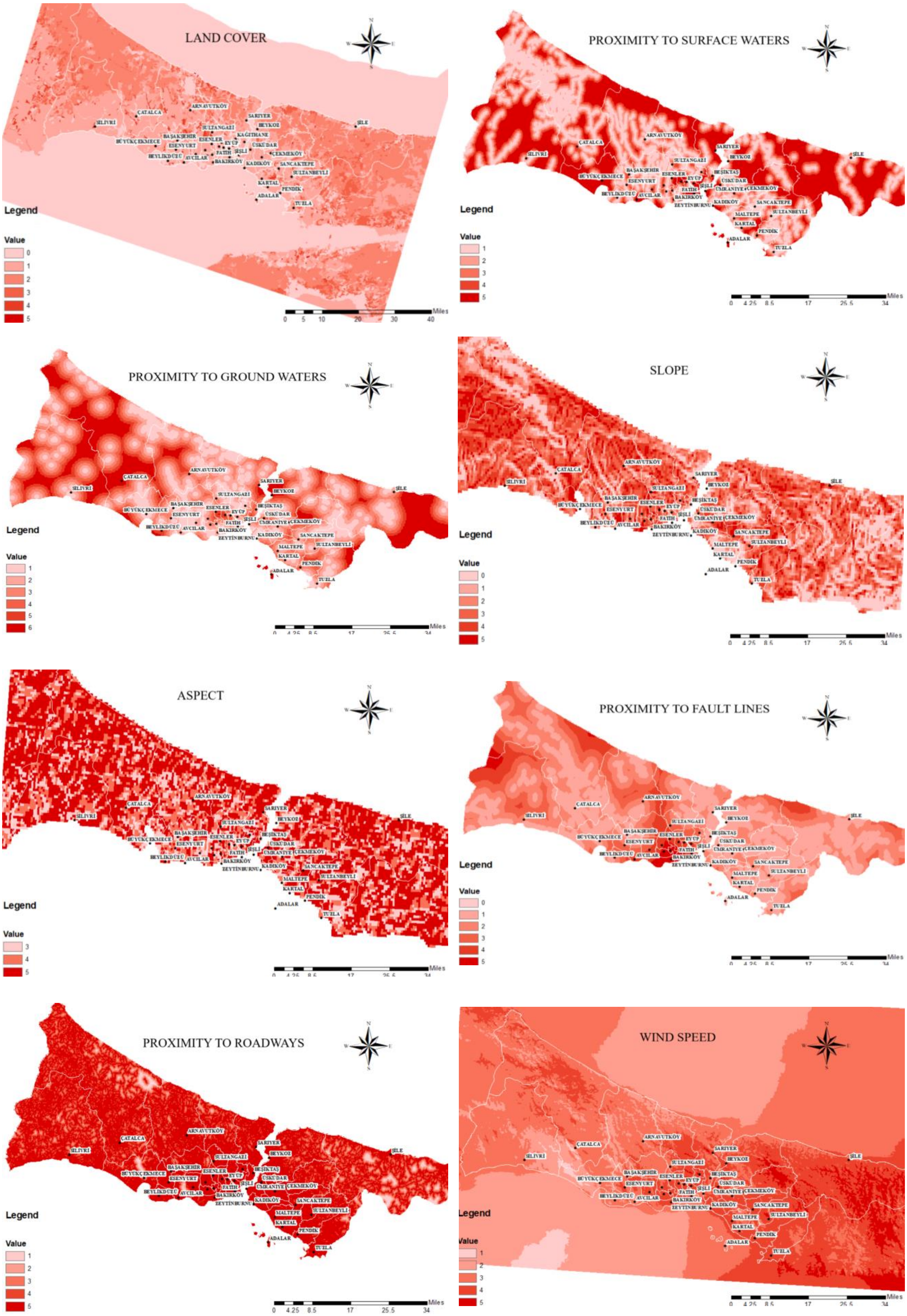

Figure 2. GIS layers for each evaluation criteria

4.2. Determination of Criteria Weights

We applied the FAHP method to prioritize the evaluation criteria. First, experts are asked to conduct a pairwise comparison using linguistic expressions. Specifically, experts are asked to evaluate the importance of each criterion against the rest of the criteria in the scale shown in Table 6. A common response from both experts for each comparison is used in the calculations.

Table 6. Linguistic terms used to define relative importance [32]

Linguistic variable	Fuzzy numbers
Extremely strong	(9,9,9)
Intermediate	(7,8,9)
Very strong	(6,7,8)
Intermediate	(5,6,7)
Strong	(4,5,6)
Intermediate	(3,4,5)
Moderately strong	(2,3,4)
Intermediate	(1,2,3)
Equally strong	(1,1,1)

The results of these comparisons are fuzzified, leading to a matrix consisting of TFN, as shown in Table 7. Table 7 shows a consistency ratio below 0.1, indicating high consistency and reliability in the experts' judgments. A consistency ratio below 0.1 ensures internal coherence in comparing criteria, allowing the matrix to be effectively utilized in subsequent stages of FAHP. Then, following the procedures outlined in Section 3.2 for FAHP, we have computed and displayed the crisp weights in Table 8. In Table 8, surface waters (0.273) followed by soil and rock structure (0.243) are determined as the two most essential criteria, whereas land value (0.009) is calculated as the least important criterion. The highest prioritized two criteria in our study, "surface waters" and "soil and rock structure" are also listed as the most frequently used criteria for landfill site selection in a review study by Donevska et al. [36] that investigates the landfill site selection methodologies and criteria. In another study Beskese et al. [37] determined soil conditions and topography as the most crucial criterion for the landfill site selection. Both studies in the literature verify the prioritization of the criteria for HSWL location selection.

4.3. Suitability Map and Final Ranking

Using the GIS layers presented in Figure 2 and criteria weights in Table 8, the "Weighted Overlay" analysis in ArcGIS 10.8 is performed to generate a suitability map. The most suitable HSWL sites have been identified based on the resulting output. Figure 3 presents the suitability map of Istanbul for HSWL construction. In Figure 3, locations with higher suitability scores are demonstrated in black color. In contrast, less suitable locations are in lighter red. According to the suitability map, five potential locations for storing solid and hazardous waste from west to east are determined as follows: Silivri, Çatalca, Arnavutköy, Beykoz, and Şile. Next, satellite images are used to select specific areas that are appropriate for the construction of the HSWL. For instance, the Riva neighborhood of Beykoz was selected as a candidate because the region is close to solid waste disposal facilities in İBB İstaç Kömürcüada. Additionally, considering the transportation cost, attention is paid to select areas not too far from residential locations [38]. Land value (C10) is also considered in alternative area determination. Specifically, Çatalca, Silivri, and Şile are included due to lower land values compared to Şişli or Beşiktaş [39]. Furthermore, the size of the candidate locations is adequate for the construction of HSWL. Figure 4 presents the satellite images for five candidate locations.

Table 7. Pairwise Comparison matrix of the criteria

		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
C1	***l***	1	4	6	5	0.25	0.13	0.33	0.17	0.11	0.11
	m	1	5	7	6	0.33	0.14	0.5	0.2	0.11	0.11
	u	1	6	8	7	0.5	0.17	1	0.25	0.11	0.11
C2	***l***	0.17	1	0.33	1	0.2	0.14	0.2	0.11	0.11	0.11
	m	0.2	1	0.5	1	0.25	0.17	0.25	0.13	0.13	0.11
	u	0.25	1	1	1	0.33	0.2	0.33	0.14	0.14	0.11
C3	***l***	0.13	1	1	0.25	0.14	0.11	0.2	0.11	0.11	0.11
	m	0.14	2	1	0.33	0.17	0.11	0.25	0.11	0.11	0.11
	u	0.17	3	1	1	0.2	0.11	0.33	0.11	0.11	0.11
C4	***l***	0.14	1	1	1	0.25	0.17	0.2	0.11	0.11	0.11
	m	0.17	1	3	1	0.33	0.2	0.25	0.11	0.13	0.11
	u	0.2	1	4	1	0.5	0.25	0.33	0.11	0.14	0.11
C5	***l***	2	3	5	2	1	0.33	0.33	0.2	0.25	0.11
	m	3	4	6	3	1	0.5	0.5	0.25	0.33	0.11
	u	4	5	7	4	1	1	1	0.33	0.5	0.11
C6	***l***	6	5	9	4	1	1	1	0.33	0.25	0.25
	m	7	6	9	5	2	1	2	0.5	0.33	0.33
	u	8	7	9	6	3	1	3	1	0.5	0.5
C7	***l***	1	3	3	3	1	0.33	1	0.2	0.33	0.11
	m	2	4	4	4	2	0.5	1	0.25	0.5	0.13
	u	3	5	5	5	3	1	1	0.33	1	0.14
C8	***l***	4	7	9	9	3	1	3	1	1	0.17
	m	5	8	9	9	4	2	4	1	2	0.2
	u	6	9	9	9	5	3	5	1	3	0.25
C9	***l***	9	7	9	7	2	2	1	0.33	1	0.25
	m	9	8	9	8	3	3	2	0.5	1	0.33
	u	9	9	9	9	4	4	3	1	1	0.5
C10	***l***	9	9	9	9	9	2	7	4	2	1
	m	9	9	9	9	9	3	8	5	3	1
	u	9	9	9	9	9	4	9	6	4	1

Table 8. Pairwise comparison matrix of the criteria

Criteria	Weights Crisp Values
C1. Land Cover	0.092
C2. Soil and Rock Structure	0.243
C3. Surface waters	0.273
C4. Groundwaters	0.203
C5. Slope	0.061
C6. Aspect	0.029
C7. Fault Line	0.053
C8. Roadways	0.018
C9. Wind	0.020
C10. Land Value	0.009

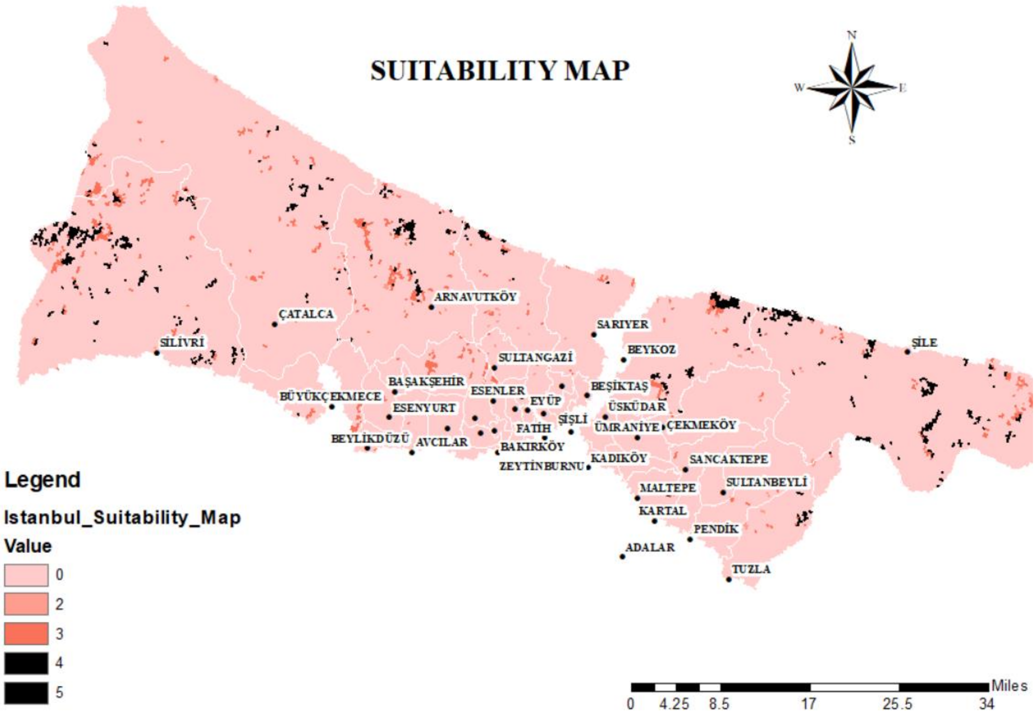

Figure 3. Suitability map

Fevzipaşa / Silivri (A1)

Örencik / Çatalca (A2)

Durusu / Arnavutköy (A3)

Riva / Beykoz (A4)

Hasanlı / Şile (A5)

Figure 4. Candidate locations for HSWL

Next, a pairwise matrix of candidates is created using the reclassified values for each criterion, as in Table 9.

Table 9. Pairwise comparison matrix of candidate locations for each criterion

C1	A1	A2	A3	A4	A5	**Weight**	**C6**	A1	A2	A3	A4	A5	**Weight**
A1	1	5	3	1	4	0.362	A1	1	2	5	4	3	0.425
A2	0.2	1	0.5	0.33	0.5	0.074	A2	0.5	1	3	3	2	0.253
A3	0.33	2	1	0.33	2	0.137	A3	0.2	0.33	1	1	0.5	0.083
A4	1	3	3	1	4	0.331	A4	0.25	0.33	1	1	0.5	0.087
A5	0.25	2	0.5	0.25	1	0.096	A5	0.33	0.5	2	2	1	0.151
C2	A1	A2	A3	A4	A5	**Weight**	**C7**	A1	A2	A3	A4	A5	**Weight**
A1	1	0.33	0.5	0.11	0.25	0.054	A1	1	3	4	2	1	0.321
A2	3	1	3	0.33	0.5	0.175	A2	0.33	1	2	0.5	0.33	0.112
A3	2	0.33	1	0.33	0.33	0.096	A3	0.25	0.5	1	0.5	0.25	0.075
A4	9	3	3	1	1	0.379	A4	0.5	2	2	1	0.5	0.171
A5	4	2	3	1	1	0.296	A5	1	3	4	2	1	0.321
C3	A1	A2	A3	A4	A5	**Weight**	**C8**	A1	A2	A3	A4	A5	**Weight**
A1	1	0.2	0.5	0.33	0.2	0.066	A1	1	1	1	1	1	0.200
A2	5	1	2	0.5	0.5	0.216	A2	1	1	1	1	1	0.200
A3	2	0.5	1	0.5	1	0.157	A3	1	1	1	1	1	0.200
A4	3	2	2	1	1	0.283	A4	1	1	1	1	1	0.200
A5	5	2	1	1	1	0.278	A5	1	1	1	1	1	0.200
C4	A1	A2	A3	A4	A5	**Weight**	**C9**	A1	A2	A3	A4	A5	**Weight**
A1	1	4	5	3	0.5	0.325	A1	1	0.5	2	0.33	0.25	0.104
A2	0.25	1	2	2	0.33	0.135	A2	2	1	3	0.5	0.33	0.169
A3	0.2	0.5	1	1	0.33	0.085	A3	0.5	0.33	1	0.33	0.33	0.079
A4	0.33	0.5	1	1	0.33	0.092	A4	3	2	3	1	0.5	0.255
A5	2	3	3	3	1	0.362	A5	4	3	3	2	1	0.393
C5	A1	A2	A3	A4	A5	**Weight**	**C10**	A1	A2	A3	A4	A5	**Weight**
A1	1	2	2	2	3	0.338	A1	1	0.5	3	2	2	0.246
A2	0.5	1	1	2	2	0.210	A2	2	1	5	3	2	0.385
A3	0.5	1	1	1	2	0.179	A3	0.33	0.2	1	0.5	0.5	0.075
A4	0.5	1	1	1	2	0.179	A4	0.5	0.33	2	1	0.5	0.120
A5	0.33	0.5	0.5	0.5	1	0.095	A5	0.5	0.5	2	2	1	0.174

The final ranking of the locations is shown in Figure 5. The ranking of candidate locations, from the highest to the lowest, is as follows: Hasanlı/Şile (A5), Riva/Beykoz (A4), Fevzipaşa/Silivri (A1), Örencik/Çatalca (A2), and Durusu/Arnavutköy (A3). Therefore, Hasanlı/Şile (A5) is the best location to construct HSWL, while Durusu/Arnavutköy (A3) is the worst candidate for HSWL construction.

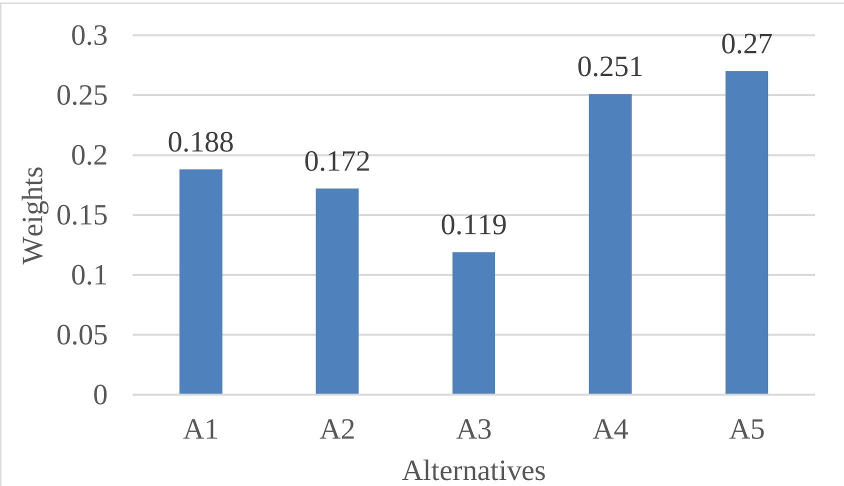

Figure 5. Ranking of alternative locations

Considering the AHP rankings, Fevzipaşa/Silivri (A1) for the European side and Hasanlı/Şile (A5) for the Asian side were chosen as the most suitable options. Silivri was also selected as a potential landfill site in studies by [37] and [7]. The total area of these two regions is 5,080,699 m^2. According to the regular waste disposal regulation published in the Official Gazette on March 26, 2010, hazardous solid waste facilities, classified as Class I, can stack waste up to 5 meters high. Therefore, the total capacity of the facilities is 25 million m^3, which is sufficient to handle the expected amount of debris.

4.4. Sensitivity Analysis

Sensitivity analysis is a common approach for methodically modifying criteria weighting and examining its influence on the solution. In this section, we explore how the final solution – the location of HSWL sites – changes in response to adjustments in the weights assigned to evaluation criteria. The percentage change in criterion i is presented in (4.4).

$$w_i = w_{i0} + w_{i0} \times YD \tag{4.4}$$

where w_{i0} presents the initial value of the i^{th} criterion, YD refers to a percentage, and w_i shows the updated value of the i^{th} criterion. For instance, when the surface water criterion was augmented by 5%, the resulting weight was computed to be 0.287. The weights of the remaining criteria must be modified to ensure that the total sum of all criteria weights equals “1”. By applying (4.5), the rest of the parameters are updated. In (4.5), w_{j0} and w_j refer to the initial and final weights of the j^{th} criterion. For instance, the initial weight of the land cover is 0.092, with a 5% increase in the surface water; the new weight of the land cover is calculated as $0.090 = (1 - 0.287) \times \frac{(0.092)}{(1-0.273)}$. The weights of the rest of the criteria are calculated similarly.

$$w_j = (1 - w_i) \times \frac{w_{j0}}{(1 - w_{i0})} \tag{4.5}$$

Table 10 presents the corresponding shifts in weights for the remaining criteria based upon the change in the weight of the criterion “Surface water”. Bold represents the baseline, a.k.a., initial weights.

Table 10. Change in criteria weights

Change in percentage	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
20%	0.085	0.225	0.328	0.188	0.056	0.027	0.049	0.017	0.018	0.008
15%	0.087	0.229	0.314	0.192	0.058	0.027	0.050	0.017	0.019	0.008
10%	0.089	0.234	0.300	0.195	0.059	0.028	0.051	0.017	0.019	0.009
5%	0.090	0.238	0.287	0.199	0.060	0.028	0.052	0.018	0.020	0.009
0%	**0.092**	**0.243**	**0.273**	**0.203**	**0.061**	**0.029**	**0.053**	**0.018**	**0.020**	**0.009**
-5%	0.094	0.248	0.259	0.207	0.062	0.030	0.054	0.018	0.020	0.009
-10%	0.095	0.252	0.246	0.211	0.063	0.030	0.055	0.019	0.021	0.009
-15%	0.097	0.257	0.232	0.214	0.064	0.031	0.056	0.019	0.021	0.010
-20%	0.099	0.261	0.218	0.218	0.066	0.031	0.057	0.019	0.022	0.010

Table 11 presents the solution with respect to the change in criteria weights. Accordingly, adjusting the surface water criterion weights in a range of 20% did not change the solution. The ranking of the candidates from most suitable to the least is as follows: Hasanlı/Şile (A5), Riva/Beykoz (A4), Fevzipaşa/Silivri (A1), Örencik/Çatalca (A2), and Durusu/Arnavutköy (A3).

Table 11. Results of the sensitivity analysis

Percentage change	Fevzipaşa/ Silivri	Örencik/ Çatalca	Durusu/ Arnavutköy	Riva/ Beykoz	Hasanlı/ Şile	Solution (best to the worst)
20%	0.179	0.176	0.122	0.253	**0.271**	A5-A4-A1-A2-A3
15%	0.181	0.175	0.121	0.253	**0.271**	A5-A4-A1-A2-A3
10%	0.184	0.174	0.121	0.252	**0.271**	A5-A4-A1-A2-A3
5%	0.186	0.173	0.120	0.251	**0.270**	A5-A4-A1-A2-A3
0%	0.188	0.172	0.119	0.251	**0.270**	A5-A4-A1-A2-A3
-5%	0.191	0.171	0.118	0.250	**0.270**	A5-A4-A1-A2-A3
-10%	0.193	0.171	0.118	0.250	**0.270**	A5-A4-A1-A2-A3
-15%	0.195	0.170	0.117	0.249	**0.270**	A5-A4-A1-A2-A3
-20%	0.197	0.169	0.116	0.248	**0.270**	A5-A4-A1-A2-A3

5. Conclusion

This study aims to select an optimal landfill site for hazardous solid waste resulting from a disaster in the Istanbul region so that harm to the environment and the health of individuals can be reduced. First, evaluation criteria for HSWL sites are determined by synthesizing studies in the literature and expert opinions. Next, those evaluation criteria are prioritized based on the experts' evaluation and judgment through the FAHP method. Then, to achieve more realistic and precise results in the site selection, spatial data analysis was performed in ArcGIS 10.8. A suitability map that demonstrates the appropriate locations for HSWL is identified. Appropriate locations in the suitability map and satellite images obtained from Google Earth are used to select the candidate locations to avoid the risk of defining residential areas as a candidate. AHP is performed to select the best location among five candidates. Accordingly, Hasanlı/Şile is the most suitable location, whereas Durusu/Arnavutköy is evaluated to be the least suitable region. However, to efficiently serve both the Asian and European sides, Fevzipaşa/Silivri for the European side and Hasanlı/Şile for the Asian side were chosen as the most suitable two options based on AHP rankings.

This research introduces a framework for determining optimal locations for HSWL in the Istanbul region, intending to mitigate the adverse effects of hazardous waste. Although the application is limited to Istanbul, the applicability of this framework extends beyond Istanbul. Decision makers can benefit from this framework for deciding on HSWL locations for different regions. The originality of the framework is integrating objective (spatial) and subjective data (expert opinions) using various techniques to assist decision-makers in selecting HSWL locations. One limitation of this study is that it does not fully cover the economic aspect of the problem. Only land prices and proximity to potential debris accumulation are considered when selecting candidate locations. However, disaster risk assessment for the areas where more debris is likely to occur [40,41] and the transportation cost to HSWL sites for cleaning up the debris [38] should be integrated in addition to land value. In a future study, we plan to analyze the region for the debris accumulation in depth and integrate transportation cost criteria in selecting the HSWL locations to address the cost, health, and environmental aspects.

Author Contributions

The first author devised the main conceptual ideas and developed the theoretical framework. The second author conducted the literature search and performed GIS analysis. The first author wrote the manuscript with support from the second author. They all read and approved the final version of the paper.

Conflicts of Interest

All the authors declare no conflict of interest.

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