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Evaluation of Landfill Site Selection by Combining Fuzzy Tools in GIS-Based Multi-Criteria Decision Analysis: A Case Study in Diyarbakır, Turkey

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Abstract: Solid waste disposal is one of the important environmental and socioeconomic problems faced by city managers with the increase in urban population. To overcome this problem, landfilling is a common and effective solution used by municipalities frequently. This study aims to assess and identify suitable potential areas for municipal solid waste disposal. For this purpose, a criteria determination and evaluation commission consisting of experts from various institutions and disciplines was established. Fourteen criteria, including environmental, economic and sociocultural sensitivities, were selected via the experience of an expert team and a wide literature search. The criteria used in this study were standardized by using fuzzy membership functions and feature values turned into continuous values. The Stepwise Weight Assessment Ratio Analysis (SWARA) method, in which expert opinions are effective, was used to determine the criterion weights. A site suitability map was obtained by using the Weighted Linear Combination (WLC) method with standardized thematic maps and the criterion weight variables. As a result of this study, 3.44% of the total study area was determined suitable for a solid waste storage area. These determined areas were found in different locations of study and numbered on the map and each of them was selected as an alternative storage area candidate. Developed methodology was validated via exploration and observation of candidate areas by the expert team. The proposed methodology can be used for similar scale cities with its ease of use, flexibility and expert opinion.

Keywords: landfill site selection; multi-criteria decision making (MCDM); geographic information systems (GIS); SWARA; fuzzy membership function; municipal solid waste

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1. Introduction

In the projection made by the United Nations, it was estimated that 66% of the world's population will live in cities by 2050 [1]. Cities today consume about 70% of the world's resources, resulting in greenhouse gas emissions and the production of solid waste. This means significant challenges to environmental and social sustainability [2]. The rapid increase in the world population, urbanization, the high material consumption of developed economies, the increase in product complexity, the use of substances that may cause environmental problems in the production of consumer goods and changes in lifestyles and income levels necessitate the establishment of effective and sustainable waste management systems [3]. The sustainability of a waste management system requires it to be economically efficient, socially acceptable and compatible with environmental components. Effective and sustainable waste management optimizes the impact of solid waste and its disposal on residents and other environmental components, and also minimizes the cost of providing services. The inspiration of this study is to develop a methodology that will contribute to these sustainability principles and identify suitable landfill sites.

Municipal solid waste (MSW) disposal is one of the intricate problems to be managed for both developed and developing societies [4,5]. If not managed properly, municipal solid waste is a major threat to public health and other environmental components. Uncontrolled disposal of solid wastes without taking necessary and sufficient precautions carries risk potentials, such as public health problems, pollution of underground and surface water resources, dents, fire, landslide and explosion. There have been many events in different countries and scales, such as the event that took place in China in 2015, resulting in the destruction of 33 houses and the death of 77 people [6–9]. Waste disposal is a serious and worrying problem for every society, regardless of its level of development. The method of dealing with this problem depends on the economic, technical and social capabilities of the society, as well as on the spatial and geographical conditions. Although different techniques such as recycling, reuse, composting, decomposition and waste-to-energy conversion are used for the reduction and disposal of solid waste [10–12], solid waste disposal by landfilling is an integral part of every waste management plan [13,14].

A landfill as a disposal method for urban solid wastes has environmental, geographical and socioeconomic limitations and also carries the risk of encountering serious social conflicts [15–18]. The first and most important stage of the solid waste landfill process is the selection of the landfill site, which includes conflicting environmental and socioeconomic concerns. Landfill site selection is a typical multi-criteria decision making (MCDM) problem with conflicting objectives of criteria. MCDM is a set of systematic procedures to design, evaluate and select decision alternatives based on conflicting and disproportionate criteria [19]. The fact that the decision criteria are composed of spatial variables and components causes the inadequacy of traditional decision-making methods. Solving problems involving spatial criteria needs decision support tools that can process and evaluate spatial variables. To meet this need, scientists have frequently used GIS in their spatial decision-making researches over the past few decades, along with different MCDM methods [20–22].

In their literature review, Özkan et al. [23] determined that GIS was used with different MCDM methods in 106 articles from 2005–2019 for the determination of suitable solid waste storage locations only. GIS-MCDM integration has found the opportunity to be used in a wide range of subjects and purposes. Çelik [24,25] used this method in modeling the static water level (SWL) in groundwater for the Turkey Diyarbakır Upper Tigris Basin. Gil-García et al. [26] used it to identify suitable potential offshore sites for a wind farm in the Gulf of Maine in the USA Atlantic Ocean. Eren et al. [27] used this method to find a place for a bike-sharing station in İzmir, Turkey. Özkan et al. [28] used it to determine a suitable location for solid waste landfill in Samsun, Turkey. Arabameri et al. [29] used it in mapping groundwater potential and estimating the spatial distribution of groundwater in the Shahroud plain of Iran. Saraswat et al. [30] applied it to determine the spatial suitability of solar and wind farm locations in India. Foroozesh et al. [31] successfully applied it to identify suitable areas for sustainable urban development in Iran. In this study, GIS was combined with the SWARA method to determine suitable areas for landfill in the province of Diyarbakır.

The SWARA method, which was first developed and used by Keršulienė et al. [32], was preferred for the determination of criterion weights with its practical and simple mathematics, its ability to effectively reflect expert preferences on the model and its ability to use free scales. SWARA, which has attracted the attention of researchers in recent years, has been integrated with GIS and/or different MCDM methods and used by many scientists in many different subjects and different studies [33,34]. Panahi et al. [35] integrated the SWARA method with GIS to investigate the spatial interaction between floods and impact factors and to map the flood risk in Northern Iran's Gulistan province. Popovic et al. [36] used the SWARA-WSM model for the selection of the most suitable place for the construction of a tourist hotel in Serbia. Yücenur et al. [37] used the SWARA-WASPAS model in the selection of the sea current energy generation facility planned to be established in Turkey. Mostafaeipour et al. [38] ranked the 20 Afghan provinces with wind energy potential using the SWARA-EDAS model. Volvačiovas et al. [39] used SWARA to select a strengthening strategy for government buildings in Lithuania. Pamucar et al. [40] evaluated the airport service quality in Spain using the SWARA method. Ghenai et al. [41] used the SWARA method in the evaluation of the sustainability indicators of renewable energy systems. Zolfani at al. [42] used it in the shopping center location selection in Tehran. Wei Chen et al. [43] effectively used it in spatial modeling of landslide susceptibility in the Shaanxi province, China. The multi-criteria decision model created with the SWARA-GIS integration was used for the first time (as far as is known) with this study to determine suitable areas for urban solid waste landfill.

In Turkey, 67.2% of the 32 million 209 thousand tons of waste collected by municipalities' waste services is sent to landfills, 20.2% to municipal dumps and 12.3% to recycling facilities [44]. The Diyarbakır province, which is one of the metropolitan cities located in the southeast region of Turkey, was chosen as the application area in this study. The population of the study area has increased unusually due to social, economic and especially security reasons, and significant inadequacies have emerged in the solid waste disposal system, as in the other infrastructure facilities of the city. The lack of a landfill center in the city chosen as the application area creates significant difficulties for the residents and other environmental components. The struggle of city managers with this problem should be handled with a scientific method. The aim of the presented study is to develop a methodology for determining potential areas suitable for landfills that will contribute to sustainable urban development by using GIS-SWARA and fuzzy membership functions and to apply this methodology to the Diyarbakır urban area.

2. Materials and Method

With the contribution of the literature and the participation of scientists and experts from different institutions and disciplines, 14 criteria that affect the solid waste storage site selection were selected. For each criterion selected, various data and maps were obtained from different institutions or maps were created using existing data. Since these compiled maps and data did not have a common format and size, and had different coordinate systems and scales, the standardization of these data and maps was achieved using the WGS 1984 standard of ArcGIS 10.3 software. In this study, ArcGIS 10.3 and related tools were used as GIS software and Python for graphic drawings.

2.1. Study Zone

The Diyarbakir urban area in the southeast of Turkey was chosen as the application area of the model developed in this study. Being one of the oldest cities in Anatolia, being on the trade routes and at the same time on the banks of the Tigris, Diyarbakir has become a center of trade and culture. Diyarbakır is located at the eastern end of the basalt plateau of Karacadağ, on a plain 100 m high from the Tigris Valley. Located at an altitude of 650 m above sea level, between 37°30′–38°43′ N latitudes and 40°37′–41°20′ E longitudes, Diyarbakır's surface area is 15,355 km^2. Its plains are home to large, arable and fertile lands irrigated by the Tigris River and its tributaries. The city draws attention with its rapid population growth and it hosts 1,783,431 people according to 2020 data [45]. According to the data of the same year, the daily solid waste production per capita was 1.1 kg/person, and the total waste production was 706,291 tons/year [44]. The location of the working area is shown in Figure 1.

Figure 1. Application area of the developed model, Diyarbakır.

2.2. Study Steps

1. The purpose of the research was determined and a criteria selection and evaluation commission consisting of experts on the subject was established.
2. Site selection criteria suitable for the environmental and economic characteristics and priorities of the study area were determined with expert opinion and literature support.
3. Thematic maps were obtained/created and uploaded to the database to make the determined criteria functional
4. To apply membership functions to thematic maps, the following operations were applied, although with different combinations for each map:
    i. For each criterion requiring distance analysis, new raster maps were created using the Euclidean distance function.
    ii. In order to operate the fuzzy function on categorical data, firstly classification (Classify) functions, and then division (Divide) functions, in accordance with the desired sensitivity, were applied.
5. Fuzzy membership function study parameters and class ranges were determined for each criterion.
6. Constraint maps were determined to eliminate areas that are not strictly suitable, and the eliminated areas were obtained by combining the constraints.
7. Criterion weights were obtained by using the SWARA method with expert opinions.
8. WLC overlay analysis was performed on the criteria weights as a result of SWARA and maps obtained by fuzzy membership function were applied to each criterion, to obtain a criteria suitability map.
9. The site suitability map was obtained by multiplying the constraint map and the criterion suitability map obtained by WLC.
10. The model was tested and verified by an expert team visiting the appropriate areas identified by the proposed method.

The flow chart of the developed methodology is presented in Figure 2.

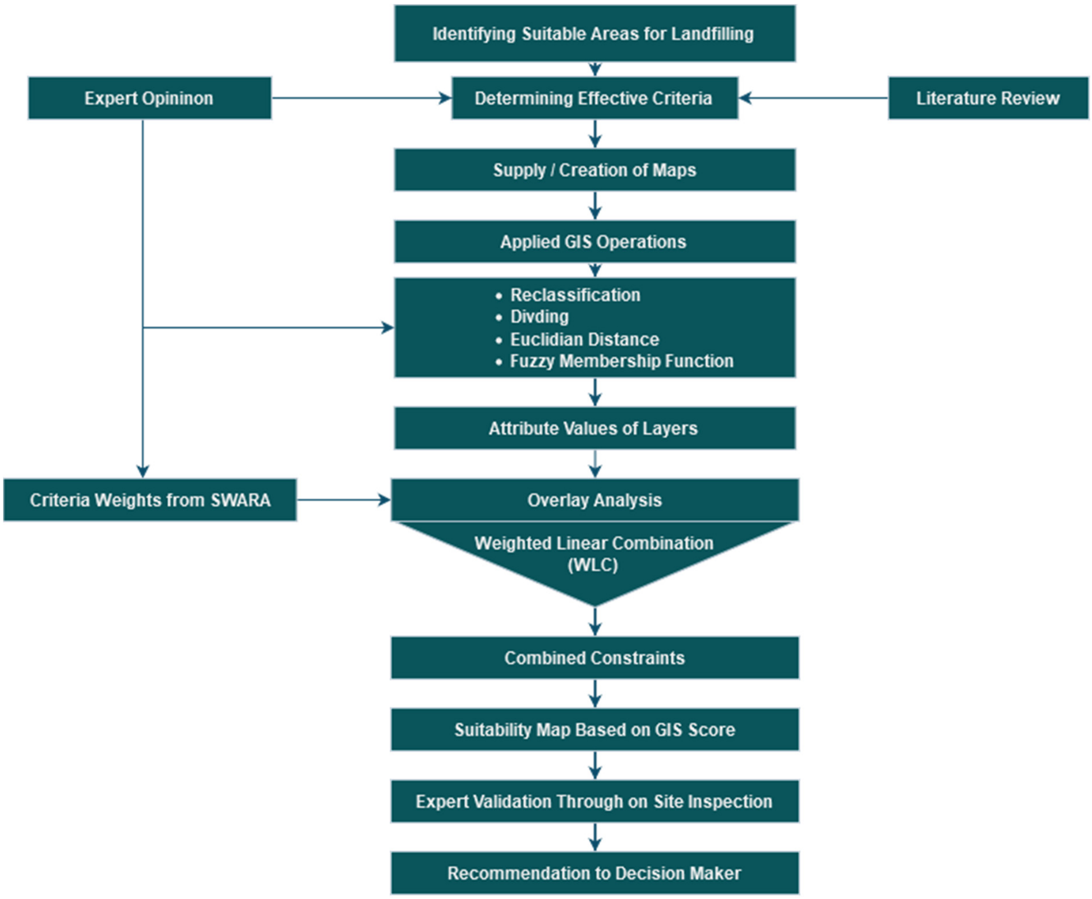


Figure 2. Flow chart of the proposed methodology.

2.3. Establishment and Studies of the Expert Commission

The commission was composed of a lecturer from the university, an expert from the municipal waste management department, an expert from the environment and urban planning institution and a specialist from the state water works. Support was received from this commission in determining criteria, evaluating criteria, checking suitable alternative areas determined by the model and model validation.

In the regulation on the "regular storage of solid wastes" issued in Turkey in 2010, it was specified which aspects should be evaluated in site selection, but the extent of the limitations was not stated. In this regulation, it is stated that only the distance to the settlements should be at least 1000 m. The criteria set in this regulation determine the very general framework, whereas countries have vast lands with very different geographical and topographic characteristics. Therefore, regional characteristics as well as national and international norms should be taken into account in the site selection of solid waste storage facilities. It is a very important task of experts to determine the effective criteria for site selection and the limits of these criteria, taking into account national and international norms as well as regional conditions.

2.4. Criteria

Selecting the appropriate criteria is an important part of the MCDM problem. In general, many features may be present for a decision problem; however, experts should limit the criteria to be evaluated in the model to the most important elements for various reasons [15]. There is no consensus in the literature in terms of the number of criteria used in studies to determine the landfill solid waste location and the importance levels of the criteria. Due to the nature of the business, different geographies and places have different environmental and topographic features and also restrictive conditions and national laws.

Demesouka et al. [3] scanned 36 articles and Özkan et al. [23] scanned 106 articles in their studies and revealed the different methods, criteria and criterion weights used in these studies conducted in different parts of the world. In the mentioned study, Özkan et al. [23] determined a total of 42 different criteria and the frequency of use of these criteria in 106 articles. Accordingly, the first seven most frequently repeated criteria came to the fore as the distance to the surface waters, the distance to the residential areas, the distance to the roads, the slope, the use of the land, the geology and the groundwater. In this study, 14 criteria were selected that reflect the environmental and socioeconomic sensitivities of the application area with the contribution of the legal legislation, the contribution of the literature and expert opinion. The collective list of the criteria used, the working parameters, the applied fuzzy membership functions, the criteria maps standardized with the functions and the criterion weights obtained as a result of SWARA are presented in Table 1.

Table 1. Criteria, Operating Parameters, Criterion Weights, Fuzzy Function Charts and Standardized Criteria Maps.

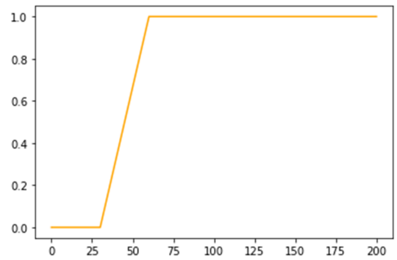
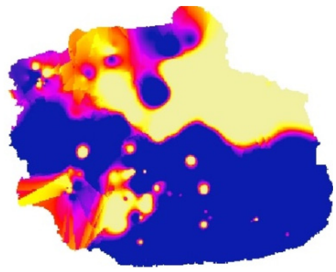
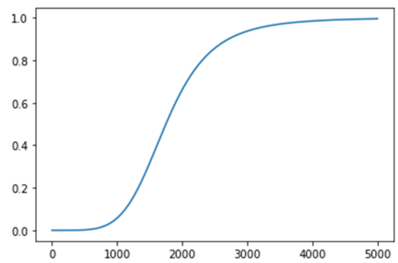
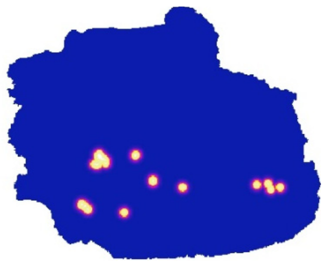
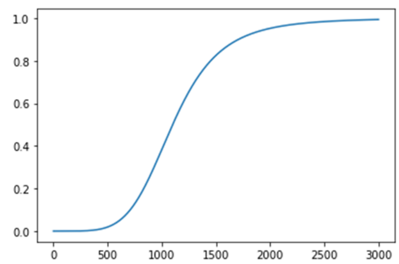
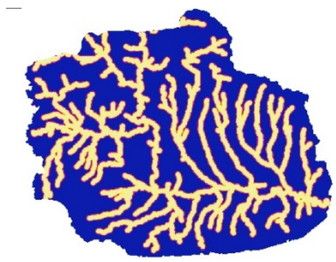
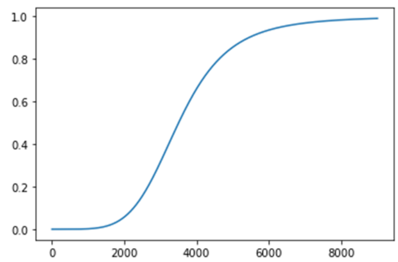
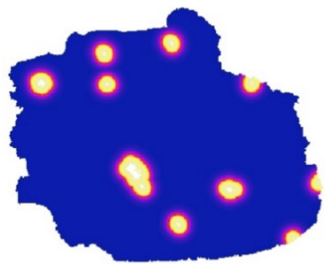
Criterion Name and Operation Parameter	Criterion Weight (W_j)	Fuzzy Function Graphic μ (x)	Fuzzy Map
Groundwater Level (C3) Linear (30; 60)	0.110		
Distance to Lakes (C1) Large (1750; 5)	0.105		
Distance to Rivers (C2) Large (1100; 5)	0.105		
Distance to Residential Areas (C4) Large (3500; 5)	0.097		

Table 1. *Cont.*

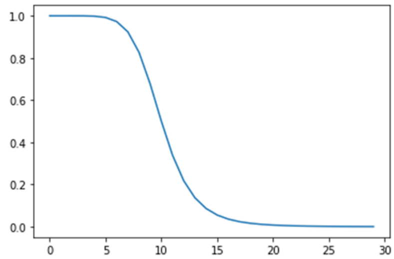
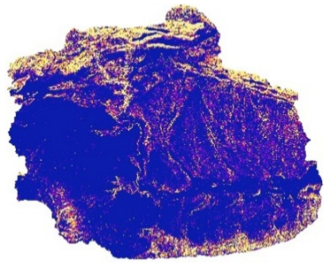
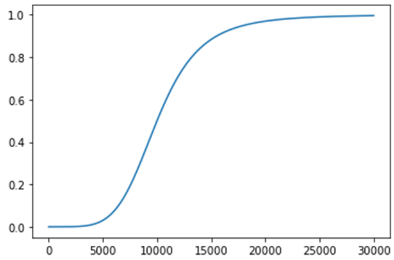
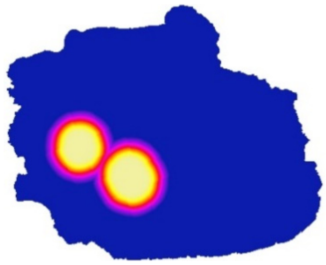
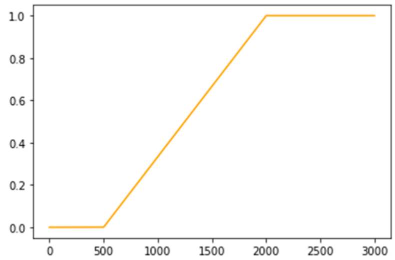
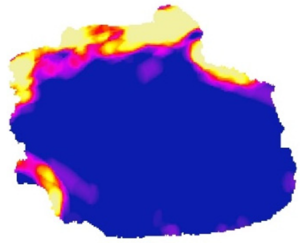
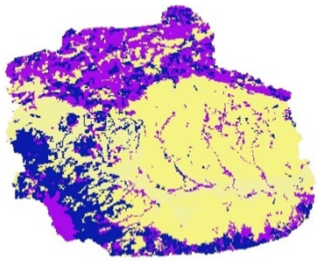
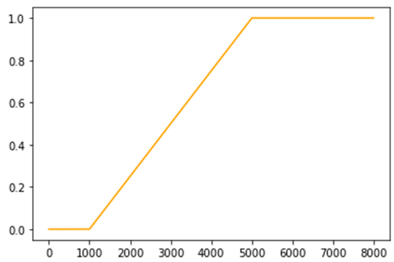
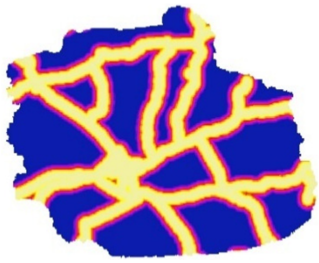
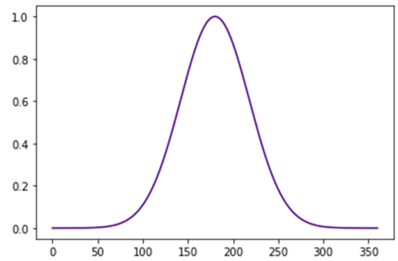
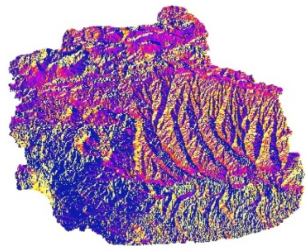
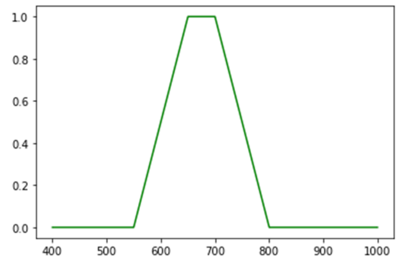
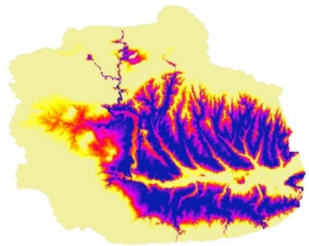
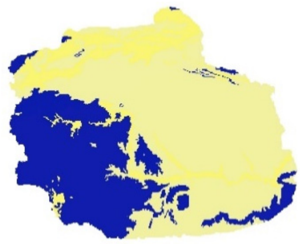
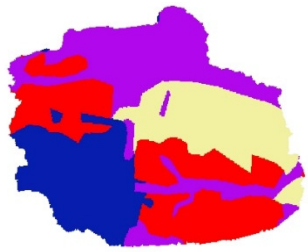
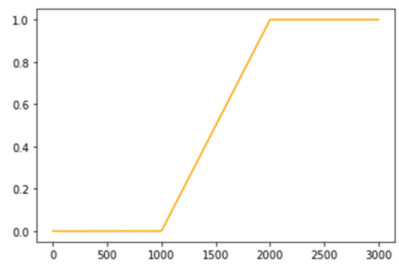
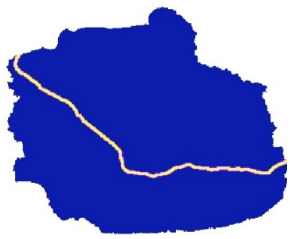
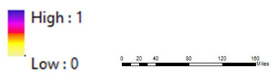
Criterion Name and Operation Parameter	Criterion Weight (W_j)	Fuzzy Function Graphic μ (x)	Fuzzy Map
Slope (C5) Small (10; 7)	0.073		
Distance to Airports (C6) Large (10,000; 5)	0.069		
Distance to Fault Lines (C7) Linear (500; 2000)	0.063		
Land Use Status (C8) User-defined Linear (0;10)	0.064	The study area was classified with the Reclassify tool in an appropriate range (1–10) according to the current land uses and converted to the range [0,1] with a linear function.	
Distance to Highways (C9) Linear (1000; 5000)	0.067		

Table 1. *Cont.*

Criterion Name and Operation Parameter	**Criterion Weight (W_j)**	**Fuzzy Function Graphic μ (x)**	**Fuzzy Map**
Aspect (C11) Gaussian (225; 5)	0.047		
Elevation (C10) Trapezoid (550; 650 and 800; 700)	0.045		
Geological Structure (C13) User-defined Linear (0; 9)	0.055	It has been reclassified to reflect the geological suitability of the study area. Next, the linear function was applied to convert the class values to the range [0,1].	
Soil Cover (C12) User-defined Linear (0; 10)	0.061	The study area was classified in the range (1–10) with the Reclassify tool according to its suitability for the landfill area and converted to the range [0,1] with a linear function.	
Distance to Railways (C14) Linear (1000; 2000)	0.037		 

2.4.1. Distance to Surface Waters (C1 & C2)

Chemical reactions that occur during landfilling create toxic liquids. Leakages caused by natural disasters or building wear over time pose a risk of contaminating surface waters. This risk is a serious threat to the surface waters near the landfill and to all living things that use these surface waters. Because of this obvious threat, it is desirable for landfills to be away from surface waters, but there is no consensus in the literature on how far they should be. Bahrani et al. [46] assigned a membership value for distance from 0 up to 1000 m from the surface waters and reached a value of 2000 m 1 with a linear increasing function. The membership function used in this study assigned the value 0 to places up to 1000 m away, thus making a preventive contribution to the selection of these areas for sanitary landfills. Since rivers and lakes were separate in the data we obtained, two different maps were used for this criterion. Rivers, lakes, reservoirs and other surface waters were evaluated under this criterion.

2.4.2. Groundwater (C3)

Natural disasters or damages that may occur in the building over time cause the leakage of toxic liquids during storage and deterioration of groundwater quality. This makes natural resources unusable and poses a health risk for humans and all living things. For this reason, it is desirable that the groundwater level in the region to be allocated for the landfill is quite low. The linear membership function used for the groundwater level in this study assigned the value 0 up to 30 m depth, and the maximum membership value reached 1 only at 60 m.

2.4.3. Distance to Residential Areas (C4)

Solid waste landfills should be at a sufficient distance from residential areas due to their effects such as bad odor, appearance, noise, safety concerns and lowering property prices. This distance appears in a wide range in the literature according to different expert opinions and local conditions. In this study, the function defined for distance to residential areas assigned a value of 0 to distances up to 1000 m and supported the location of these facilities in places far from residential areas.

2.4.4. Slope (C5)

The slope of the land is important in controlling the flow of surface water around the landfill, as well as the cost of plant construction and waste transfer. A high slope is undesirable as it will increase the risk of contamination by facilitating the flow of leachate [15]. In this study, the slope map was obtained from the Digital Elevation Model (DEM) map.

2.4.5. Distance to Airports (C6)

Birds, especially eagles, feeding on landfills impair flight safety [47], due to the risk of bird strikes, which may cause the aircraft to be damaged or even crash during landing and take-off [48]. It is desirable that solid waste landfills are away from airports.

2.4.6. Distance to Fault Lines (C7)

It is undesirable to place sanitary landfill centers on or near fault lines, as breaks and cracks may occur as a result of seismic activities and it may cause dirty and toxic liquids to leak in waste storages and cause groundwater pollution.

2.4.7. Land Use Status (C8)

Land can be divided into classes such as agricultural land, woodland, reservoirs, rivers and lakes, barren and uncultivated areas, and pastures. By classifying the land in the study area according to its use and characteristics, barren and uncultivated areas are potentially the most suitable areas for landfill, as they are the least economically valuable areas. For the use of fuzzy membership function in categorical data, a column representing the suitability value of the land was added to the attribute table. After that the effect level of each cell in the corresponding layer was linearly standardized over the values in this column.

2.4.8. Distance to Highways (C9)

Accessibility plays an important role in land use change or reorganization, especially in and around settlements [49]. Highways are one of the most important variables that determine the trend and speed of urbanization, especially in developing countries, and this is so important that the development and growth of many cities resulted from their location on the main roads. Considering the growth and expansion rate and direction of cities, it is necessary to carefully determine the distance to highways in areas with urbanization potential. Although it is desired that the solid waste storage areas are far enough from the main roads due to aesthetic concerns such as appearance and bad smell, it is preferred to be close to the main roads due to economic reasons such as new road construction and operating costs. Generally, a distance less than 500 m is not considered appropriate, and 1000–2000 m from the main road is considered optimal [50].

2.4.9. Elevation (C10)

Altitude is a factor that must be evaluated relative to the altitude of the relevant urban area. It gets economically appropriate according to the level of proximity to the altitude of the urban area. A land at a higher or lower altitude increases the cost of transportation and facility construction, whereas a lower altitude increases flood risks. Therefore, the limitations and values vary from region to region and depend on the topographical situation [51]. In this study, places close to the city's altitude, which are regions with an altitude of 650–700 m, received full points, and as the altitude values increased or decreased from this range, suitability values decreased linearly.

2.4.10. Aspect (C11)

The aspect criterion, which can be defined as the direction of the slope, is evaluated according to the openness to the prevailing winds for the relevant area. Areas that are open to strong winds are not considered suitable for landfills due to the risk of odor and dust spreading. Landfills should be built in wind-free locations [52]. The prevailing wind direction in the study area was the directions between the north-northwest-west vectors, and the areas with this aspect took a value of 0.

2.4.11. Soil Cover (C12)

The type of soil and the thickness of the soil cover play a role in facilitating or preventing leaks. Soil permeability should have the feature to prevent leakages that may occur due to deformation of the insulation layer that may occur over time or seismic movements in the storage area. In general, soil with low permeability (clay) is assigned the highest value, soil with high permeability (sand) is assigned the lowest value and other soils are assigned intermediate values [46]. In the map used in the study, seven soil classes were classified by giving their suitability values and standardized using a linear fuzzy membership function depending on the range of these values.

2.4.12. Geological Structure (C13)

In this criterion, a suitability assessment was made for landfill, considering the geological structure and permeability of the land. The most suitable geological barrier is that of cohesive and clayey rocks, and the most unsuitable are those of sand, gravel and highly fractured sandstone or limestone [50]. Karst and sandy soils have high permeability, some layers such as marl, flysch, ophiolite and granite have medium permeability, and clay soils, rocks and shale layers have low permeability and are the most suitable places for landfilling [53]. There are a total of 15 geological classes on the map obtained, and their suitability scores were given according to the literature and expert opinions, and they were standardized with a linear function according to the range of the given scores.

2.4.13. Distance to Railways (C14)

Since solid waste transportation is not carried out by railways, there is no economic reason to require the solid waste center to be close to the railways. Solid waste landfills should be located at a sufficient distance from the railways so that passengers using the railway are not exposed to negative aesthetic effects such as bad odor and appearance. The membership function used in this study gave a value of 0 for areas up to 1000 m and supported the removal of solid waste areas from railways.

2.5. Proposed Method

2.5.1. Fuzzy Membership Functions

The data used in this study were obtained from different institutions and organizations in different formats and structures, with different units and sizes. These data must be standardized in order to be comparable and analyzable. There are seven different fuzzy membership functions defined in the Arc GIS library for this process. However, in this study, the most appropriate fuzzy membership functions, which were determined by the literature support and expert opinions, were used for the standardization of the data in the map layers. Fuzzy membership functions are functions that can generate values in the range of [0,1]. The value of zero (0) of the function indicates not being a member of the relevant cluster, whereas the value of one (1) indicates full membership, and closeness to 1 for values between zero and one indicates the strength of membership in the cluster.

Since fuzzy membership functions are specific to continuous input data, it is not possible to directly apply a fuzzy membership function to criteria with categorical data (such as soil type and cover, land use status and geological structure). In the literature studies, two ways were found to solve this problem: the first is to standardize it by adding a new column to the table attribute columns of the maps with categorical data, assigning values in the range of [0,1] to represent the suitability of each class with expert opinions and literature support; and the second way is to apply (Reclassify) the relevant layer in ArcGIS and then Divide according to the desired precision.

ArcGIS fuzzy membership functions used in this study were Gaussian, large, small and linear and they were calculated with Equations (1)–(4), respectively. For these equations, $\mu(x)$ represents the membership value, f_1 is spread value, f_2 is midpoint, min is zero-freedom value of $\mu(x)$ and max is the defined value of $\mu(x)$ to reach one. If the minimum is greater than the maximum, a negative linear relationship (negative slope) is established. Middle point is X_i, which makes the Gaussian function 1 or makes the small and large functions 0.5. The spread parameter defines the shape and character of the transition zone. The fuzzy linear transform function assigns a membership value of 0 (definitely not a member) to every value below the minimum and 1 (definitely a member) to every value above the maximum. If it is between the minimum and maximum values specified by the user, it applies a linear function as shown in Formula 4. If the maximum value is less than the minimum value, there is a decreasing linear relationship.

$$\mu(x) = e^{-f_1 * (x - f_2)^2} \tag{1}$$

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{-f_1}} \tag{2}$$

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{f_1}} \tag{3}$$

$$\begin{aligned} \mu(x) &= 0 && if\ x < \min \\ \mu(x) &= \frac{x - min}{max - min} && if\ min \leq x \leq max \\ \mu(x) &= 1 && if\ x > max \end{aligned} \tag{4}$$

The trapezoidal function is not in the library of ArcGIS but was obtained by a method developed with special effort for use in ArcGIS. Firstly, a linear ascending and a linear descending function was applied to a map, and we obtained two different maps. Then, using the raster calculator with equal weights for these two maps, we obtained a new map. Finally, we rescaled this new map between 0.5 and 1 using the linear function.

2.5.2. Calculation of Criterion Weights with the SWARA Method

The SWARA method, proposed by Keršulienei at al. [32] and implemented in 2010, gives decision makers and policy makers the chance to set their priorities according to the purpose of the company or institution based on their own knowledge and experience. In this method, any consistent scale can be used to reflect expert opinions. In this method, with the increase in the number of criteria, there is no loss of consistency in the criteria weights and the effect of expert preferences on the final decision can be easily understood. In addition to having simple math, this method uses less pairwise comparisons compared to other weighting methods (such as AHP), which reduces computational cost and saves time.

To develop decision-making models, criteria for the solution of the problem were determined with the support of expert opinion and literature, and then the criteria were ranked in decreasing order according to the experience and knowledge of the experts. Starting with the second criterion, the participant expressed the relative importance of criterion j with respect to the previous criterion ($j-1$) and did this for each specific criterion. Kersuliene et al. [32] determined the relative importance of criteria (G_j) and we took $\left(G_j\right)$ values from experts and calculated the coefficient (K_j).

Next, the coefficient K_j was determined as follows:

$$K_j \quad \begin{cases} 1 & j = 1 \\ G_j + 1 & j > 1 \end{cases} \tag{5}$$

The primary weight of each criterion (Q_j) was calculated as follows:

$$Q_j = \frac{X_{j-1}}{K_j} \tag{6}$$

The relative weights of the evaluation criteria (W_j) were expressed as follows:

$$W_j = \frac{Q_j}{\sum_{j=1}^{n} Q_j} \tag{7}$$

where W_j represents the relative weight of the j-th criterion and m represents the total number of criteria.

Table 2 is a kind of comparison matrix and shows the steps of converting expert opinions and relative importance values to criterion weights in the SWARA method. In order to determine the weights of the criteria used in this study, the experts whose features are specified in Section 2.3 were asked to rank the criteria according to the degree of importance and to indicate how important the consecutive criteria are from each other. Since each expert determined the order and importance level of the criteria according to her/his own experience, different criteria rankings were formed. After receiving expert opinions, criteria weights were calculated for each expert with the SWARA method defined in Section 2.5.2.

Table 2. Criteria Comparison and Weight Values of Experts.

Expert 1				Expert 2				Expert 3				Expert 4			
C_n	K_j	Q_j	W_j	C_n	K_j	Q_j	W_j	C_n	K_j	Q_j	W_j	C_n *	K_j	Q_j	W_j
C3		1.000	0.140	C3		1.000	0.113	C3		1.000	0.122	C3		1.000	0.110
C1	1.000	1.000	0.129	C7	1.000	1.000	0.102	C1	1.110	0.901	0.100	C1	1.000	1.000	0.100
C2	1.000	1.000	0.129	C1	1.100	0.909	0.093	C2	1.000	0.901	0.100	C2	1.000	1.000	0.100
C4	1.000	1.000	0.129	C2	1.000	0.909	0.093	C4	1.200	0.751	0.083	C4	1.000	1.000	0.100
C5	1.000	1.000	0.129	C6	1.000	0.909	0.093	C8	1.000	0.751	0.083	C6	1.000	1.000	0.100
C12	1.400	0.714	0.092	C4	1.200	0.758	0.078	C5	1.200	0.626	0.069	C9	1.000	1.000	0.100
C9	1.400	0.510	0.066	C11	1.000	0.758	0.078	C6	1.000	0.626	0.069	C7	1.450	0.690	0.069
C8	1.250	0.408	0.053	C8	1.200	0.631	0.065	C7	1.000	0.626	0.069	C8	1.200	0.575	0.057
C10	1.330	0.307	0.040	C9	1.200	0.526	0.054	C13	1.000	0.626	0.069	C13	1.000	0.575	0.057
C13	1.000	0.307	0.040	C13	1.000	0.526	0.054	C12	1.000	0.626	0.069	C5	1.200	0.479	0.048
C11	1.500	0.205	0.026	C14	1.000	0.526	0.054	C9	1.450	0.431	0.048	C10	1.000	0.479	0.048
C6	2.000	0.102	0.013	C5	1.200	0.438	0.045	C11	1.000	0.431	0.048	C14	1.000	0.479	0.048
C7	1.000	0.102	0.013	C10	1.000	0.438	0.045	C10	1.000	0.431	0.048	C11	1.250	0.383	0.038
C14	1.000	0.102	0.013	C12	1.000	0.438	0.045	C14	1.500	0.288	0.032	C12	1.000	0.383	0.038

* Criteria Number.

Table 3 contains the criteria names sorted by criterion number, the criterion weights calculated for each expert and the average criterion weights, which will be used in the model.

Table 3. Criteria Weights and Average Weights of Experts.

	Expert 1	Expert 2	Expert 3	Expert 4	AVG
Criteria	W_j	W_j	W_j	W_j	W_j
Distance to Lakes (C1)	0.129	0.093	0.100	0.100	0.105
Distance to Rivers (C2)	0.129	0.093	0.100	0.100	0.105
Groundwater (C3)	0.129	0.102	0.111	0.100	0.110
Distance to Residential Areas (C4)	0.129	0.078	0.083	0.100	0.097
Slope (C5)	0.129	0.045	0.069	0.048	0.073
Distance to Airports (C6)	0.013	0.093	0.069	0.100	0.069
Distance to Fault Lines (C7)	0.013	0.102	0.069	0.069	0.063
Land Use Status (C8)	0.053	0.065	0.083	0.057	0.064
Distance to Highways (C9)	0.066	0.054	0.048	0.100	0.067
Elevation (C10)	0.040	0.045	0.048	0.048	0.045
Aspect (C11)	0.026	0.078	0.048	0.038	0.047
Soil Cover (C12)	0.092	0.045	0.069	0.038	0.061
Geological Structure (C13)	0.040	0.054	0.069	0.057	0.055
Distance to Railways (C14)	0.013	0.054	0.032	0.048	0.037

2.5.3. WLC Method

The Weighted Linear Combination (WLC) technique is a decision rule for deriving composite maps using GIS. It is one of the most frequently used decision models in GIS [54].

W_k: k. the weight of the criterion (obtained with SWARA in this study).

X_{ik}: i. unit area, k. its value in the criterion (obtained by fuzzy membership function in this study).

n: the total number of criteria.

S_i: i. criterion suitability value of the unit area (GIS score).

$$S_i = \sum_{k=1}^{n} W_k \cdot X_{ik} \tag{8}$$

2.6. Constraint Layers

With the constraint layers, it was aimed to determine the areas that are not allowed to be used for landfill. It was stated that the areas determined by these restrictions cannot be used for landfilling, that is, they will be excluded from the evaluation. The seven constraints in the study and their constraint distances are given in Table 4.

Table 4. Constraints, Working Ranges and Obtained Constraint Maps.

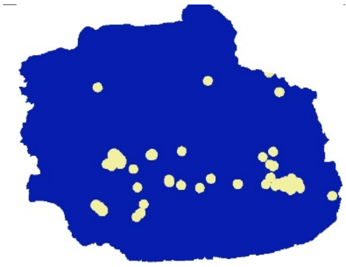
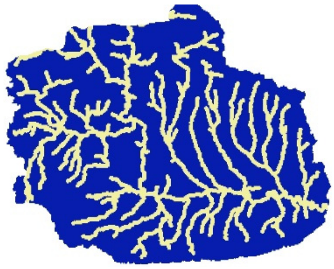
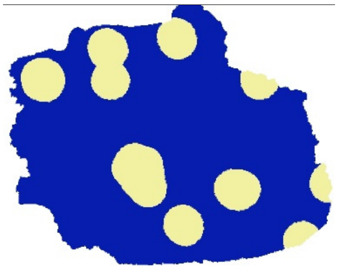
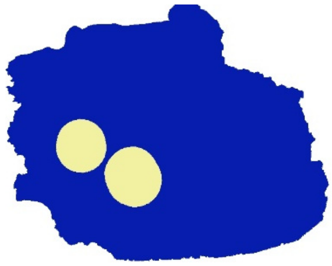
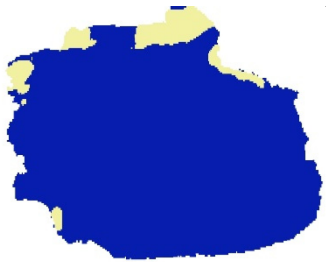
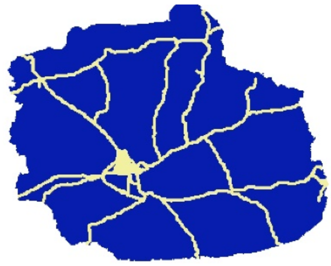
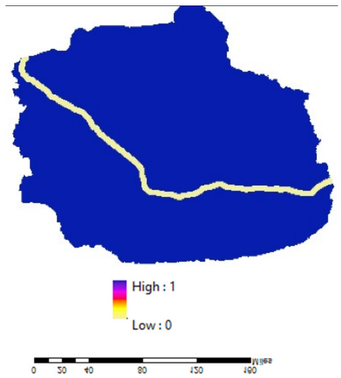
Constraint Name	Working Ranges	Constraint Map
Distance to Lakes	0, $x < 400$ 1, $x \geq 400$	
Distance to Rivers	0, $x < 400$ 1, $x \geq 400$	
Distance to Residential Areas	0, $x < 1000$ 1, $x \geq 1000$	
Distance to Airports	0, $x < 5000$ 1, $x \geq 5000$	
Distance to Fault Lines	0, $x < 300$ 1, $x \geq 300$	

Table 4. *Cont.*

Constraint Name	Working Ranges	Constraint Map
Distance to Highways	0, x < 500 1, $x \geq 500$	
Distance to Railways	0, x < 1000 1, $x \geq 1000$	

T_{ih}: suitability value for the unit area i in h constraint (a value of 1 indicates compliance with this restriction, a value of 0 indicates noncompliance with this restriction). l: the total number of constraints, C_i: i. field evaluability (1 evaluable, 0 not evaluable).

$$C_i = \prod_{h=1}^{l} T_{ih} \tag{9}$$

The Raster Calculator tool in ArcGIS was used to identify disallowed areas. With this tool, fields to be disqualified (not eligible) were assigned a 0, and fields that could be evaluated for storage were assigned a 1. For it to have a value of 1, it must have been able to take the value 1 from all constraints. This was performed with Formula 9, and as a result of restrictions, areas that could be considered for landfill and areas that were not allowed were obtained.

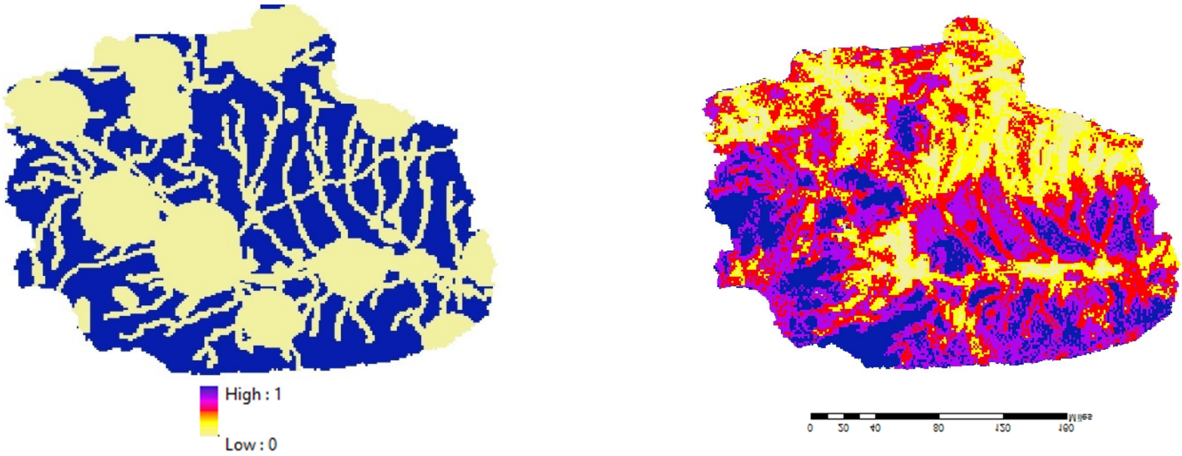
By multiplying with Formula 10 the combined constraints map and criteria suitability map pixels values, the final suitability map was obtained. L_i indicates the final landfill suitability value, S_i was described in Formula 8 and C_i was in Formula 9.

$$L_i = S_i \cdot C_i \tag{10}$$

3. Results and Discussion

The aim of this study is to determine suitable potential areas for solid waste landfills by using GIS-MCDM and fuzzy membership functions. Euclidean distance analysis, which gives the distance from each cell in the raster to the nearest source, was performed for all distance reporting factor maps. The maps used in the model were standardized with the appropriate fuzzy functions (linear, gaussian, small and large) in ArcGIS. However, two problems were encountered when standardizing the maps. First, standardization of attribute values for maps containing categorical data (area use, geology and soil cover) was performed by adding a column to each table and assigning a suitable value between [0,1] to each row of these columns. The second problem was the absence of a trapezoidal function in ArcGIS, as it was necessary to use this function for the elevation criterion, which is important in terms of transportation costs. For this reason, the authors solved the problem with the method described in Section 2.5.1.

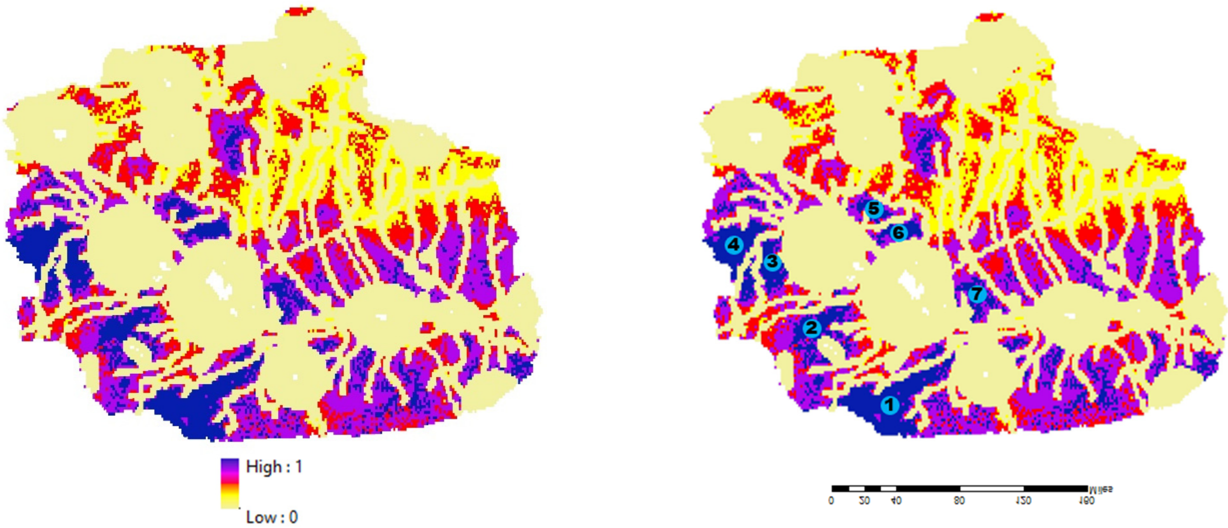
Constraints and their limits were determined to sort out areas where the establishment of sanitary landfills was strictly prohibited. By using the Raster Calculator interface in ArcGIS, for each constraint, a value of 0 was assigned for not allowed areas and value of 1 was assigned for allowed areas. Then, these map layers with values of 0 and 1 were multiplied with the Raster Calculator. Thus, the areas where the construction of solid waste landfills was not allowed (areas with the value 0) were determined. These excluded areas constituted 55% of the total study area and are shown in Figure 3a.



(**a**) (**b**)

Figure 3. Combined Constraint and Criterion Suitability Maps. (**a**) Combined Constraint Map; (**b**) Criterion Suitability Map.

After the thematic maps were standardized and criterion weights were obtained, the Weighted Linear Combination (WLC) method was applied by using the Weighted Sum function of ArcGIS and the criterion suitability map was obtained, as shown in Figure 3b. The final land suitability map was obtained by formula 10 using the obtained criterion suitability map and the combined constraint map. It is shown in Figure 4a. This map was divided into 6 suitability classes with the Reclassify function according to the GIS scores. Details of classified areas are given in Table 5.



(**a**) (**b**)

Figure 4. (**a**) Final suitability map, (**b**) Location of candidate sites.

Table 5. Study Area Suitability Index and Distribution Percentages.

Index	Suitability Class	Area (ha)	Percentage (%)
0	Not Suitable	332,500	54.68
1	Poor Suitable	82,600	13.59
2	Less Suitable	87,400	14.37
3	Suitable	47,200	7.76
4	Very Suitable	37,500	6.16
5	Most Suitable	20,900	3.44

According to the GIS scores obtained, the study area was divided into 6 classes as Not Suitable, Poor Suitable, Less Suitable, Suitable, Very Suitable and Most Suitable. Availability of alternative regions in sufficient number and size allowed us to determine areas with a GIS score of 0.85 and above as the most suitable areas in the study. The most suitable areas were labeled 1 to 7 and referred to as candidate regions (Figure 4b). Candidate areas were selected only from within the most suitable areas because the most suitable areas were of the variety and size to meet the landfill facility area requirement. The size of the areas in the most suitable category from which the candidates were selected was approximately 3.44% of the total area.

Candidate 1 is located in the southwest of the city, in an area with arid and bare rocks, and the slope ratio is such that it does not increase the construction costs. Its distance to the nearest main road is approximately 1850 m, its distance to the city center is approximately 24 km and its size is 6796 hectares. Candidate areas 2, 3 and 4 are on the west and northwest axis of the city and are approximately 12, 14 and 21 km away from the nearest residential area, respectively. These areas are non-agricultural dry areas. Candidate areas 5 and 6 are non-agricultural areas and far enough away from water resources, in the north of the main settlement area and 16 and 8 km away from the city center, respectively. Candidate 7 is an arid, non-agricultural area east of the city center and approximately 14 km from the city. Candidate areas offer a wide range of choices for decision makers, as they are large enough and spread over different parts of the city. These areas provide competencies to respond to many different priorities of decision makers. Statistical values of these areas are given in Table 6.

Table 6. Statistical Values of Suitable Candidate Areas.

	Area (ha)	Minimum	Maximum	Range	Mean	STD
Candidate 1	6796	0.880	0.936	0.056	0.916	0.017
Candidate 2	1738	0.880	0.922	0.042	0.893	0.008
Candidate 3	2629	0.856	0.907	0.051	0.886	0.014
Candidate 4	4969	0.880	0.946	0.067	0.916	0.020
Candidate 5	847	0.857	0.916	0.059	0.877	0.018
Candidate 6	1827	0.859	0.909	0.050	0.882	0.016
Candidate 7	2094	0.856	0.880	0.024	0.868	0.007

Minimum is the smallest GIS score of the cells in the relevant candidate area. Maximum is the largest GIS score of the cells in the relevant candidate area. Range is the largest difference between the GIS score of the respective candidate site. Mean is the mean of the GIS score of the cells in the candidate site. STD represents the standard deviation of the GIS score at each candidate location.

The risk of contaminating both ground and surface water sources is a major concern in the selection of landfills. The scarcity of freshwater resources in the world and the problem of access to these resources necessitate the protection and efficient use of these resources. As in this study, distances to underground and surface water resources were the most important criteria in many studies [18,20,28,55]. Surface waters were represented by two different criteria, and it was understood that all four experts agreed on the importance of surface waters. The most suitable areas determined by the developed methodology are far enough from the water resources and the methodology was able to protect these resources by identifying suitable sites for landfilling at a sufficient distance from these vital sources. Another issue that experts attach importance to in the selection of landfills and determined by the methodology is that these storage areas are far from the living and need areas that people use individually and collectively. In addition, in order to minimize the construction and transportation costs, the slope, elevation and road distance criteria that will affect these costs were taken into account by the experts and the methodology was determined accordingly.

Using integer scales (such as 1–3, 1–5, or 1–10) when standardizing map layers [15,55–58] makes attribute values in the map layer discrete and creates sharp differences in class transitions. Since these attribute values of the layers (formula 8, Xik value in this study) are used to determine site suitability, it can lead to incorrect positioning decisions. In the model developed using SWARA-GIS-fuzzy functions (SWARA-GIS-2F), the criteria were standardized by applying a fuzzy membership function suitable for each criterion to overcome this problem. Thus, the attribute values of the layer were changed depending on the relevant variable and the relational attribute values were assigned to the layer. This feature of the SWARA-GIS-2F model can contribute to producing more accurate results than models using integer scales.

Since the model will produce results according to the maps provided, possible erroneous values in the maps may cause the model to produce erroneous results. In order not to be exposed to such a problem, the attributes of each thematic map were shared with the experts of the subject and passed through their examination. Insufficient thematic maps to represent environmental, economic or sociocultural criteria will reduce the accuracy and authenticity of the results. Incorrect selection of the standardization functions that will determine the attribute values in the map layers weakens the ability of the method to perform the precise decision-making function.

In many studies [15,20,46,47,55,56,58], the criteria were hierarchized and the lower-level criteria were given a share of the weights in the main criteria. Since many comparisons are made in these hierarchical structure transitions, unfair sharing may occur between the weights of the criteria and may create a misleading effect on the results. The developed SWARA-GIS-2F methodology weights the criteria by evaluating them at the lowest level, and this feature does not lead to a misleading situation.

Since the determination of weights in the developed methodology is based on expert knowledge and experience, lack of knowledge and experience may lead to suboptimal and unsuccessful plant positioning. Since the scope of this study is limited to identifying potential areas suitable for landfills, a second MCDM method was not included in the model for ranking candidate sites. The selection process among suitable potential areas can be determined by the economic and technical feasibility studies of the relevant institution.

The suitability value of a pixel depends on the features in each map layer used as criteria. For example, it is desirable for the groundwater level to be deep, and as the depth of the groundwater level in a pixel increases, the suitability value in that pixel also increases. Similarly, in other thematic maps, the attribute values change according to their suitability for the purpose. Accordingly, the difference of suitability values in candidate places is related to the level of meeting the criteria.

Candidate sites 1 and 4 are ideally close to highways and ideally far from settlements and water resources. Because of these properties, they got the highest suitability values. Candidates 2 and 3 got lower scores than candidates 1 and 4 because they are close to water bodies and airports. The 5th and 6th candidates got relatively lower scores as they are closer to the residential areas and surface water sources and have higher elevations and slopes. In addition to being close to residential areas and water resources, the 7th candidate received a low score from the geological structure criteria and was the candidate with the lowest score.

As a result of this study, seven suitable areas for the solid waste landfill facility in the Diyarbakır province were determined and the suitability of these places was observed and verified on site by visits made by the expert team. This study will guide the administrators of the Diyarbakır province and cities of similar scale in the selection of municipal solid waste sites and will be an example of SWARA-GIS and fuzzy functions integration in the site selection problems for relevant researchers.

4. Conclusions

1. The SWARA-GIS-2F methodology was developed in this study and was used for the first time to identify potential areas suitable for regular solid waste storage facilities in Diyarbakır.
2. The methodology has determined that it is not possible to use 55% of the land belonging to the Diyarbakır province for solid waste landfills.
3. The developed methodology determined the GIS scores of the areas that can be used for landfill. According to these scores, 6 suitability levels were determined by reclassification. The percentage values of the sizes of the areas from the unsuitable to the most suitable were 54.68%, 13.59%, 14.37%, 7.76%, 6.16% and 3.44%, respectively.
4. The developed methodology determined 3.44% of the Diyarbakır province area as the most suitable place for sustainable landfills. The total size of these areas, which are clustered in 7 different regions of the city, is approximately 20,900 hectares.
5. The most suitable areas were labeled 1 to 7 and referred to as candidate regions. The sizes of these candidate members, from candidate 1 to candidate 7, were 6796, 1738, 2629, 4969, 847, 1827 and 2094 hectares, respectively. Each of these seven candidate sites is more than enough to meet the needs of a landfill facility.
6. These seven candidate sites, scattered across different parts of the city, have given city managers and decision makers a lot of freedom for landfill selection. City administrators who will make the final decisions can evaluate sensitivities involving social and political issues that were not covered in this study.

Suggestions for future research:

1. The maps used to develop models reflect the situation at the time they were produced. However, land uses designed by public institutions and/or private companies will not be visible on the maps. In order to obtain more accurate results and to obtain more sustainable models, it is suggested that these planned land uses should be mapped and reflected in the model.
2. It is suggested that publicly owned lands can be included in the model as a criterion so that the cost of land to be allocated for landfill will not be an economic burden to the municipality.

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