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ORIGINAL PAPER

Municipal landfill site selection using TOPSIS methodology: A case study for Polatlı, Ankara, Türkiye

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Abstract

Polatlı, which is the largest and tenth out of twenty fifth most populated county of Ankara is well known for being one of the most productive agricultural districts in Türkiye in terms of its barley and wheat production. However, despite that Polatlı has a relatively dense and rapidly growing population, and bears environmental problems, it does not possess a proper municipal solid waste landfill. Since the county currently lacks a proper landfill, the municipal waste is deposited in an improper open dump site that is located to the south of the county. Concerns have been raised due to fire incidents reported and due to scattering of the waste material throughout the neighborhood of the open dump site and to the other parts of the city due to the lack of fencing at the open dump site. Another environmental problem is caused by biogas energy producing companies in the district that dump their processed animal wastes in the farm fields which endangers public health. In addition, extensive illegal waste dumping in the neighborhood of the open dump site exists. The objective of this study is to select the best alternative municipal landfill site location for the Polatlı County, Ankara. To fullfil the disposal needs of the county, landfill site selection has been performed in this study by considering criteria including, air traffic safety, geology, land use, distance to settlement, distance to roads, drainage, slope, erosion, distance to fault and distance to earthquake epicenters. These criteria have been ranked and evaluated in a GIS environment prior to selecting the best alternative landfill site through "The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)" method of Multi-Criteria Decision Analysis (MCDA). The results of the landfill site selection methodology indicated that amongst the three alternative landfill sites, the best locations to construct a landfill were chosen to be those two alternative sites that were situated north northeast (NNE) and north northwest (NNW) of Polatlı, respectively.

Keywords Municipal landfill site selection · Pairwise comparison method (PCM) · TOPSIS · Polatlı · Ankara · Türkiye

Introduction

Landfill siting is a fairly complicated and challenging process which requires that the environmental, technical and financial aspects be considered properly. Some of the landfill siting methods include Analytic Hierarchy Processes (AHP) (e.g., Tavares et al. 2011; El Baba et al. 2014; Uyan 2014), Geographic Information System (GIS) with AHP (e.g., Eskandari et al. 2013), GIS/SAW-AHP (e.g., Rathore et al. 2016), Weighted Linear Combination (WLC), GIS with WLC (GIS/WLC) (e.g., Khan and Samadder 2015), diagramming, grey systems theory (clustering), expert systems (e.g., Cao et al. 2006), Analytic Network Process (ANP) (e.g., Bahrani et al. 2016), the Simple Additive Method (SAM) (e.g., Bahrani et al. 2016), Ordered Weighted Averaging (OWA) (e.g., Gbanie et al. 2013), GIS-fuzzy logic (e.g., Khorram et al. 2015), fuzzy logic (e.g., Bahrani et al. 2016), TOPSIS (e.g., Yal and Akgün 2014), TODIM and Fuzzy-TODIM (e.g., Hanine et al. 2016), and Fuzzy AHP, Fuzzy ANP and Fuzzy TOPSIS (e.g., Beskese et al. 2015; Rezaeisabzevar et al. (2020). With each and every method possessing its own disadvantages and advantages, the purpose of each method is to rank alternative landfill sites. According to Rezaeisabzevar et al. (2020), based on the provided advantages and disadvantages of MCDM procedures, it can be concluded

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that Fuzzy-ANP, although a complex procedure, is the most preferred if all the necessary factors and effects are present. For situations where some data are missing and factors are not numerous, AHP may be the best choice. Finally, for time-critical situations that require quick decisions, the best choice may be gray theory due to its simplicity. TODIM can be used as a validation method for results obtained from other procedures. Therefore, when sufficient time, data and resources are available to make the best possible decision, the order of preference is as follows: F-ANP > ANP > F-AHP > AHP > F-TODIM > TODIM > OWA > Gray Theory > WLC.

Since the landfill siting process requires many inputs, GIS is very suitable for the site selection study due to its ability to manage large amounts of spatial data from different types of sources (e.g., Sener 2004; Sener et al. 2010; Khamehchiyan et al. 2011; Donevska et al. 2012; Nazari et al. 2012; Sahnoun et al. 2012; Yal and Akgün 2013, 2014; Öner 2019). Multi-criteria decision analysis (MCDA) on the other hand is used when handling large amounts of complex information. The main principle of this method is to split the decision problems into smaller and understandable parts, analyze each part separately, and then integrate the parts in a logical manner (Malczewski 1997). The integration of GIS and MCDA is a powerful tool for the landfill site selection problem because while GIS provides efficient manipulation and presentation of the data, MCDA supplies consistent ranking of the potential landfill areas based on different criteria (e.g., Yal and Akgün 2013, 2014). The purpose of this study was to find a suitable landfill site in the Polatlı municipality of Ankara, Türkiye by utilizing GIS and MCDA (TOPSIS).

Polatlı is the largest county of Ankara with an average elevation of 850 m and a footprint area of 3789 km². It is located in the Central Anatolia region of Türkiye, 80 km west of the capital Ankara, on the road to Eskişehir and is well known for being one of the most productive agricultural districts in Türkiye in terms of its barley and wheat production. The population of Polatlı County of Ankara which ranks the tenth out of twenty-five counties is 128895 and the annual population growth rate is 4% (TurkStat 2023). The location map of the Polatlı County is given in Fig. 1. The lowest average monthly temperature recorded at Polatlı was 0.3 °C in January and the highest average monthly temperature recorded was 23.5 °C in July. In the 2003–2023 period, the minimum monthly precipitation was in August with a monthly value of 0.9 mm and the maximum monthly precipitation corresponded to May with a monthly value of 117.40 mm (MGM 2024). The dominant wind direction of the area within the period of 2003–2023 was north northeast (NNE).

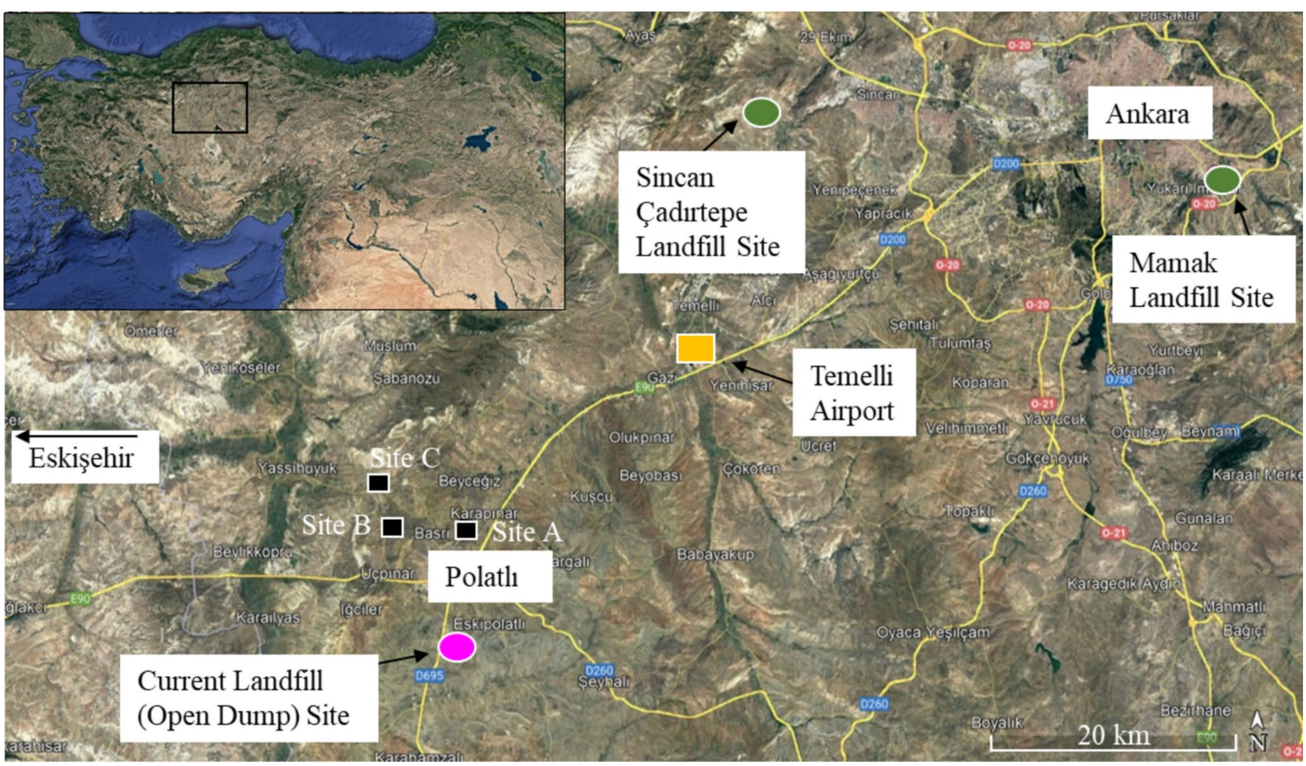

Fig. 1 Location map of the study area showing the current landfill (open dump) site, Mamak landfill site, Sincan Çadırtepe landfill site and alternative landfill sites A, B and C

Although Polatlı has a relatively dense and rapidly growing population, and has environmental problems, it does not possess a proper municipal solid waste landfill. The recyclable waste is sent to the Ankara-Mamak Landfill site that is 98 km away from the county (Fig. 1). The other municipal landfill in the area is the Sincan Çadırtepe Landfill (Fig. 1) that is approximately 59 km to Polatlı which indicates that it would not be feasible to transfer the municipal waste of Polatlı to such distant landfill sites. The remaining garbage is disposed at an improper open dump site situated to the south of Polatlı, indicated by a pink circle in Fig. 1. This site lacks a proper lining system and is located improperly with respect to the adverse dominant wind direction. Concerns have also been raised due to fire incidents reported at the site in the past, and due to scattering of the waste materials throughout the neighborhood of the dumpsite and to the other parts of the city due to the lack of fencing at the open dump site. Another environmental problem is caused by biogas energy producing companies in the district that dump their processed animal wastes in the farm fields which endangers public health. Biogas energy companies in Polatlı produce electricity with animal waste. After processing the animal wastes, the companies dump these chemically contaminated wastes in the farm fields they find empty. This illegal dumping has created dark-colored ponds of chemically contaminated animal waste in the countryside especially in the spring time following heavy precipitation. Furthermore, there is extensive illegal dumping in the neighborhood of the open dumpsite (Fig. 2). Because of all these environmental problems, since a proper landfill is needed urgently, a landfill site selection procedure considering topographical conditions, dominant wind direction (north northeast (NNE) and accessibility was performed in the capactity of a thesis (Öner 2019) to locate three alternative landfill sites; Site A, Site B and Site C as indicated in Fig. 1. Municipal landfill site selection has been conducted by considering distance to settlement, distance to roads, slope, geology, distance to fault line, drainage, land use, erosion, distance to epicenter and air traffic safety as criteria. Since groundwater was not encountered in several geotechnical boring studies that have been conducted up to depths of 50 m in the region, it was not considered as a parameter in alternative landfill site selection. After these criteria have been modeled and evaluated in a GIS environment, the best site out of the three alternative sites was selected using "The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)" Multi-Criteria Decision Analysis (MCDA). The site selection study was carried in three steps; (1) identifying the selection criteria, (2) gathering and standardizing the relevant data, and (3) performing TOPSIS analysis (Öner 2019).

Regional geology

The study area is located in the Ayaş-Temelli-Polatlı region where regional geology has contributed to the variation of the successions. Amongst the Haymana-Polatlı, Çanakçı-Yıldızlı and Ayaş successions that are present in the basins, the Çanakçı-Yıldızlı succession has been studied due to its widespread distribution in the area. It is comprised of deposits of a transition-continental environment, where the Danian-Selandian Kartal formation is the lowermost unit of this succession (Rigo de Righi and Cortesini 1959). This is overlain by Thanetian-Ilerdian Kırkkavak formation, facies which pass from a shallow marine to mudflat environment (Ünalan et al. 1976), followed by shallow marine carbonates

Fig. 2 A view of illegal waste dumping in the vicinity of the open dump site in Polatlı

of Late Thanetian-Cuisian Ilgınlıkdere formation (Rigo de Righi and Cortesini 1959; Bilgin et al. 2009) that has only been observed in the upper levels of this succession together with flysch deposits of the Cuisian-Lutetian Eskipolatlı formation (Rigo de Righi and Cortesini 1959) and the Cuisian-Lutetian Beldede formation (Ünalan et al. 1976), represented by shallow marine deposits (Fig. 3). Hançili formation that has formed from lacustrine deposits and contemporaneous volcanism overlies this succession as well as the two other successions (Akyürek et al. 1980). It has a thickness of 300–400 m and is mainly composed of clayey limestone and marl, and lesser amounts of siltstone, sandstone, pebble and rarely tuffite, gypsum and coal. The Hançili formation laterally and vertically grades into the underlying Altıntaş

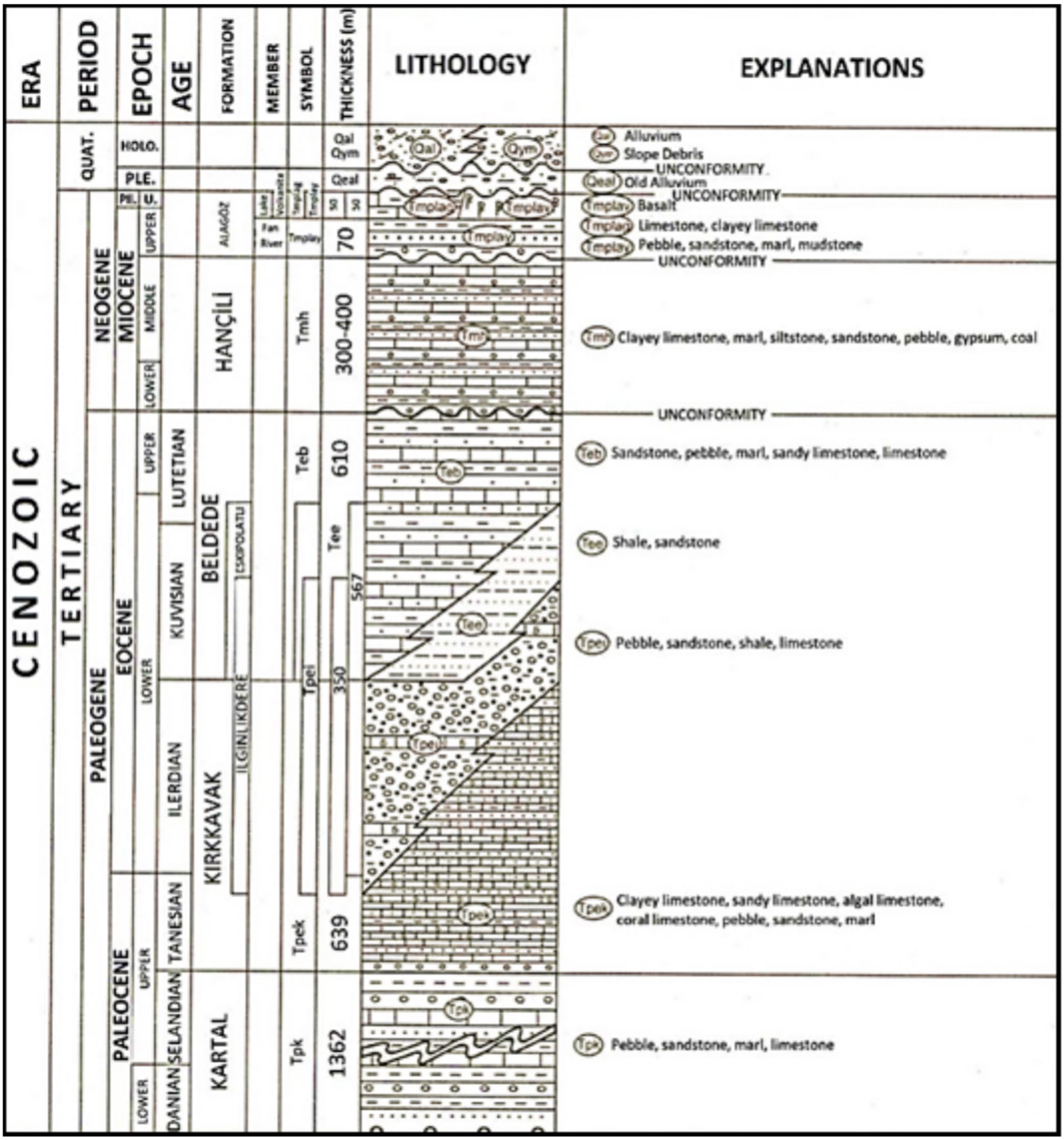

Fig. 3 Generalized stratigraphic column of the Çanakçı-Yıldızlı succession (Bilgin et al. 2009)

formation and is overlain by the Alagöz formation which is composed of fan-fluvial and lacustrine materials at the bottom, and continues with lacustrine limestones and volcanites to the top (Bilgin et al. 2009). The Alagöz formation is overlain by Pleistocene old alluvium, which is overlain by Holocene slope debris and alluvium composed of gravel, sand and mud. A detailed geological map of the area is presented in Fig. 4.

Integration of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA)

The purpose of this section was to find a suitable landfill site in the Polatlı municipality by utilizing GIS and MCDA. An ideal point method, namely, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) was applied to choose the best alternative landfill site. In constructing the GIS model for landfill site selection, a number of evaluation criteria are selected which are restricted to the availability of the data. Every attribute is represented by a criterion map. The criterion map displays the spatial distribution of an attribute which measures the degree to which its associated objective is achieved (Malcewski 1999). These maps which contain advisory information have been used in the landfill site selection process.

Standardization

Given the variety of scales on which attributes can be measured, multi-criteria analysis requires that the values contained in the various criterion map layers be transformed to comparable units. More specifically, if one needs to combine the various criterion map layers, the scales must be commensurate. A number of approaches can be used to make criterion map layers comparable. To this end, criterion maps can be classified on the basis of the types of information available for constructing the maps. This classification is related to the distinction between deterministic decisions and decisions under uncertainty (probabilistic and fuzzy decisions). Accordingly, criterion maps can

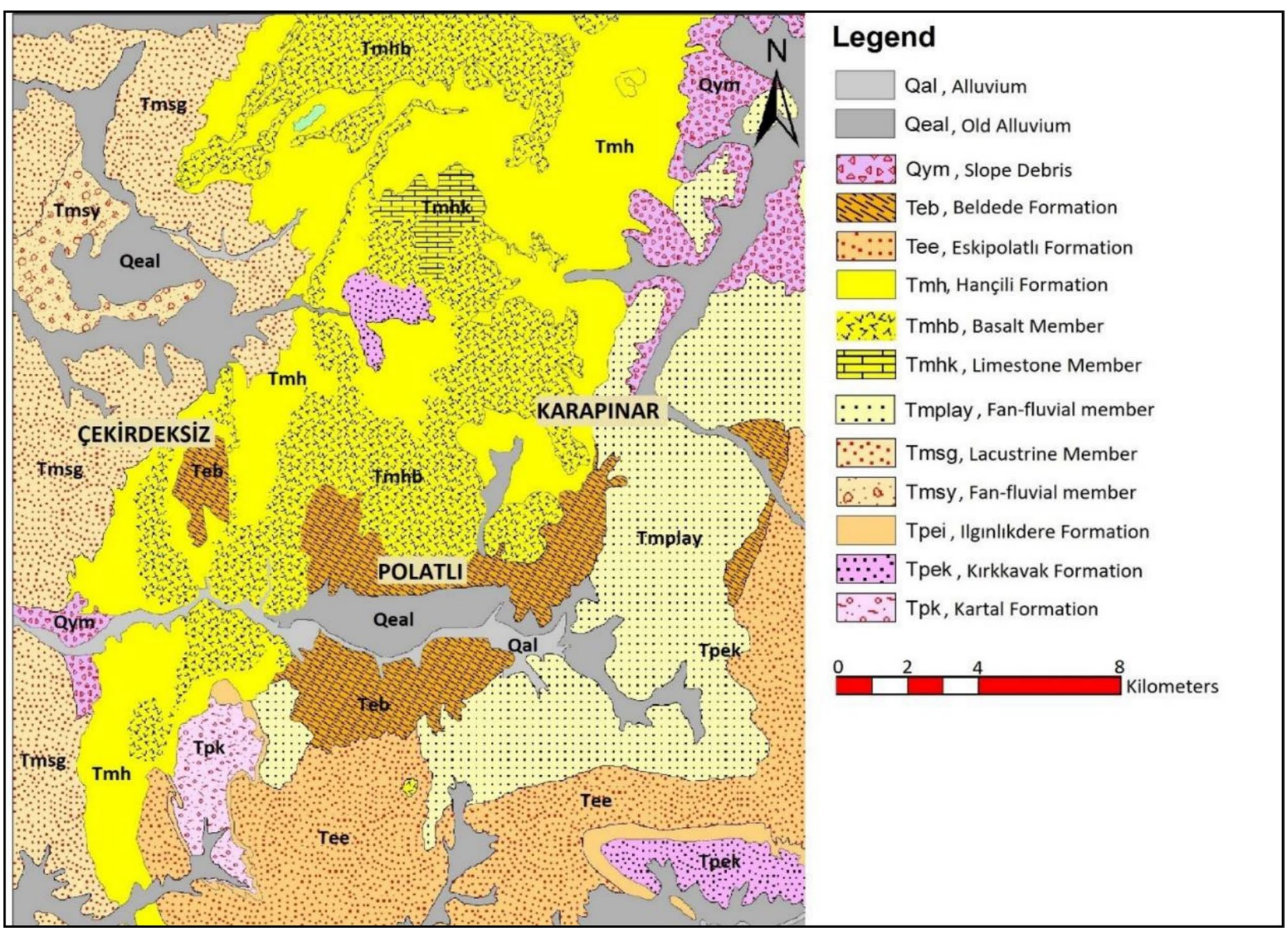

Fig. 4 1/100,000 scale geological map of the Polatlı County (Bilgin et al. 2009)

be categorized as deterministic, probabilistic, or fuzzy. A deterministic approach was selected in this study primarily due to the relative homogeneity of the geological conditions in the study area, which supports the reliability of this method for this study's specific objectives. Additionally, it is aimed to base most of the criteria on established regulations while incorporating expert judgment as a significant input to the decision-making process. Although it is recognized that a probabilistic approach (i.e., Ng et al. 2024a), could enhance the study by addressing uncertainties within the defined criteria possibly leading to a more conservative design, the primary focus was on the site-specific selection process. Similarly, a fuzzy logic approach, which could capture ambiguity in criteria, was deemed less relevant due to the clear and well-defined nature of the conditions and requirements in this case.

Deterministic maps assign a single value to each object (i.e., point, line, polygon, or pixel) in a map layer. It follows that, for deterministic criteria there will be a deterministic relationship between an alternative and its consequences. Linear scale transformation is the most frequently used deterministic method for transforming input data into commensurate criterion maps (i.e. Chou 2013). Another way of deriving commensurate criterion maps is to use value/utility function approaches. Although these approaches are based on common methodology, there is an essential difference between the value function and the utility function approach. While the value function method is applicable in deterministic situations, the utility function method is appropriate for decision situations involving uncertainty (Malcewski 1999).

Since the criterion maps used in this study are deterministic maps where a single value is assigned to each pixel, a linear scale transformation method was used to standardize the maps.

Linear scale transformation

The most common procedures in linear scale transformation are the maximum score and score range procedures. Detailed information about these procedures are given in the following paragraphs.

Maximum Score Procedure: Each raw score is divided by the maximum value for a criterion by employing Eqs. (1) and (2):

$$x'_{ij} = \frac{x_{ij}}{x_j^{max}} \quad (1)$$

$$x'_{ij} = 1 - \frac{x_{ij}}{x_j^{max}} \quad (2)$$

where, x'_{ij} is the standardized score for the i^{th} object and the j^{th} attribute, x_{ij} is the raw score, and x_j^{max} is the maximum score for the j^{th} alternative. Higher score values denote more attractive criterion values. Equation (1) is the benefit criterion where the criterion is to be maximized. Equation (2), on the other hand is the cost criterion where the criterion is to be minimized which implies that the lower the score, the better the performance is. This method that allows linear transformation of the data has a shortcoming in the interpretation of the least attractive score due to the fact that the lowest standardized score does not necessarily equal zero.

In standardizing the attributes, the score range procedure is employed:

$$x'_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \quad (3)$$

$$x'_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \quad (4)$$

where, x_j^{min} is the minimum score for the j^{th} attribute, x_j^{max} - x_j^{min} is the range of a given criterion, and the remaining terms are as defined previously. Here, Eqs. (3) and (4) represent benefit and cost criterion, respectively. Score measures range from 0 to 1, 1 being the most attractive and 0 being the least attractive score (Malczewski 1999).

Criterion weighing

A weight can be defined as a value assigned to an evaluation criterion which indicates its importance relative to other criteria under consideration (Sener 2004). There are four different methods for criterion weighing in the literature, namely, ranking, rating, pairwise comparison and trade analysis methods. In this study, the pairwise comparison method developed by Saaty (1991) within the context of the Analytical Hierarchy Process (AHP), which determines the relative importance of an entity by comparing all entities in pairs was employed. Pairwise comparison was selected since it offers a relatively structured approach to criterion weighting by evaluating two criteria at a time, reducing ambiguity and enabling consistent decision-making. In addition, the consistency of the resultant weights may be verified (Kang et al. 2024).

The main steps of this method are the development of the pairwise comparison matrix, generating the normalized pairwise comparison matrix and obtaining the criterion weights. When constructing the pairwise comparison matrix, evaluation criteria are written on the left-hand side and on top of the matrix. If the criteria on the left are more important than the top, a numerical value greater than 1 has to be used. In the opposite situation, reciprocal of that value should be used. Tables 1 and 2 show the pairwise comparison matrix and the normalized pairwise comparison matrix, respectively. It should be noted that the relative importance of the criteria listed in Table 1 have been determined by the authors of the article at their own discretion.

After generating the normalized pairwise matrix, weights of the selected criteria were determined as presented in Table 3 and the consistency of this calculation was checked by using Eqs. (5) through (7).

$\lambda max = n$ whenever $A = \{a_{ij}\}$ is consistent, otherwise:

$$\lambda max > n \tag{5}$$

Saaty (1991) defined consistency index *CI* of *A* as follows:

$$CI(A) : x = \frac{\lambda\, max - n}{\mathrm{n} - 1} \tag{6}$$

and, consistency ratio as:

$$CR(A) = \frac{CI}{\mathrm{RI}} \tag{7}$$

Here, *RI(n)* is called random index which is defined as the mean value of *CI*s for positive reciprocal PC matrices of dimension *n*. The values of *RI(n)* are given in Table 4 (Saaty 1991). According to Saaty (1991), the consistency ratio (*CR*) should be less than 0.1, otherwise the matrix would be inconsistent and the calculations would have to be re-checked.

Consequently, the Consistency Ratio (*CR*) was calculated by using the above-mentioned equations. It was determined to be the approximately 0.06 which is below 0.1 and hence, this result shows that the comparisons were consistent. The results of the calculation steps are presented in Table 5.

Multi-Criteria Decision Making (MCDM) methods

Multi-Criteria Decision Making (MCDM) methods have a significant advantage over traditional methods where all criteria need to be converted to the same unit, since they can assess a variety of options against a variety of criteria that have different units. There are a variety of MCDM methods in the literature, namely, priority based, outranking, distance based, ideal point and mixed methods. In this study, "The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)" was used as the ideal point method. The ideal point method was chosen for its precision in quantifying numerical proximity to an ideal solution, its effectiveness in handling numerous criteria, and its structured framework for defining an "ideal" alternative, offering a direct and straightforward approach to decision-making.

TOPSIS views a MCDM problem with *m* alternatives as a geometric system with *m* points in the *n*-dimensional space, where *n* represents the number of criteria to be used in the evaluation. It was developed by Hwang and Yoon (1981). It defines an index called similarity (or relative closeness) to the positive-ideal solution and the remoteness from the negative-ideal solution. Then, the alternative with the maximum similarity to the positive-ideal solution and remoteness from the negative-ideal solution is chosen (Yoon and Hwang 1995). This method has been found to be suitable for landfill site selection since it selects the alternative that is closest to the ideal solution and farthest from the negative ideal solution. This way, a landfill site alternative closest to the best and farthest from the worst can be selected, with regards to the defined criteria (e.g., Yal and Akgün 2014). Many

Table 1 Pairwise Comparison Matrix developed for the selection criteria

Evaluation criteria	Geology	Land use	Distance to settlement	Distance to roads	Drainage	Slope	Erosion	Distance to faults	Distance to epicenters
Geology	1	2	3	4	5	6	7	8	9
Land use	1/2	1	2	3	4	5	6	7	8
Distance to settlement	1/3	1/2	1	2	3	4	5	6	7
Distance to roads	1/4	1/3	1/2	1	2	3	4	5	6
Drainage	1/5	1/4	1/3	1/2	1	2	3	4	5
Slope	1/6	1/5	1/4	1/3	1/2	1	2	3	4
Erosion	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
Distance to faults	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
Distance to epicenters	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1
SUM	2.8290	4.7179	7.5929	11.4500	16.2833	22.0833	28.8333	36.5000	45.0000

Table 2 Normalized Pairwise Comparison Matrix developed for the selection criteria

Evaluation criteria	Geology	Land use	Distance to settlement	Distance to roads	Drainage	Slope	Erosion	Distance to faults	Distance to epicenters	Average
Geology	0.3535	0.4239	0.3951	0.3493	0.3071	0.2717	0.2428	0.2192	0.2000	0.3070
Land use	0.1767	0.2120	0.2634	0.2620	0.2457	0.2264	0.2081	0.1918	0.1778	0.2182
Distance to settlement	0.1178	0.1060	0.1317	0.1747	0.1842	0.1811	0.1734	0.1644	0.1556	0.1543
Distance to roads	0.0884	0.0707	0.0659	0.0873	0.1228	0.1358	0.1387	0.1370	0.1333	0.1089
Drainage	0.0707	0.0530	0.0439	0.0437	0.0614	0.0906	0.1040	0.1096	0.1111	0.0764
Slope	0.0589	0.0424	0.0329	0.0291	0.0307	0.0453	0.0694	0.0822	0.0889	0.0533
Erosion	0.0505	0.0353	0.0263	0.0218	0.0205	0.0226	0.0347	0.0548	0.0667	0.0370
Distance to faults	0.0442	0.0303	0.0220	0.0175	0.0154	0.0151	0.0173	0.0274	0.0444	0.0259
Distance to epicenters	0.0393	0.0265	0.0188	0.0146	0.0123	0.0113	0.0116	0.0137	0.0222	0.0189

Table 3 Weights of the evaluation criteria

Evaluation criteria	Weight
Geology	0.31
Land use	0.22
Distance to settlement	0.15
Distance to roads	0.11
Drainage	0.07
Slope	0.05
Erosion	0.04
Distance to fault	0.03
Distance to epicenters	0.02

Table 4 Random consistency index (RI) values according to Saaty (1991)

Matrix size	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

researchers have utilized the TOPSIS method in their selection studies (e.g., Beskese et al. 2015; Cambazoğlu et al. 2019).

In light of the information given in the above mentioned sections, initially, criteria to be used in the analysis were defined. The importance of these criteria was determined by considering the characteristics of the study area and considering similar studies in the literature followed by performing TOPSIS analysis. The following paragraph presents a summary of the analysis steps according to Malczewski (1999):

1. Determine the feasible alternatives and decision criteria (attributes).
2. Standardize each attribute map layer by transforming the various attribute dimensions (x_{ij}) to uni-dimensional attributes (v_{ij}) for this transformation to allow for a comparison of the various layers.
3. Define the weights (W_j) assigned to each attribute; where the set of weights must be such that $0 \leq w_i \leq 1$ and $\sum j$ $W_j = 1$.
4. Construct the weighted standardized map layers by multiplying each value of the standardized attribute layer v_{ij} by the corresponding weight w_i, where each cell of the layers contains the weighted standardized value v_{ij}.

Table 5 Consistency ratio calculation matrix

Consistency ratio calculation matrix	Geology	Land use	Distance to settlement	Distance to roads	Drainage	Slope	Erosion	Distance to faults	Distance to epicenters	SUM	λ	CI	CR
Geology	0.31	0.44	0.45	0.44	0.40	0.30	0.28	0.24	0.18	3.04			
Land use	0.16	0.22	0.30	0.33	0.32	0.25	0.24	0.21	0.16	2.19			
Distance to settlement	0.10	0.11	0.15	0.22	0.24	0.20	0.20	0.18	0.14	1.54			
Distance to roads	0.08	0.07	0.08	0.11	0.16	0.15	0.16	0.15	0.12	1.08			
Drainage	0.06	0.06	0.05	0.06	0.08	0.10	0.12	0.12	0.10	0.74			
Slope	0.05	0.04	0.04	0.04	0.04	0.05	0.08	0.09	0.08	0.51			
Erosion	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.06	0.06	0.35			
Distance to faults	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.04	0.24			
Distance to epicenters	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.18	9.71	0.09	0.06

5. Determine the maximum value (v_{+j}) for each of the weighted standardized map layers (the values determine the ideal point).
6. Determine the minimum value (v_{-j}) for each weighted standardized map layer (the values determine the negative ideal point).
7. Using a separation measure, calculate "the distance" between the ideal point and each alternative; where a separation can be calculated by using the Euclidean (or straight-line) distance metric:

$$S_{i+} = \left[\sum j\left(v_{ij} - v_{+j}\right)^2\right]^{0.5} \quad (8)$$

8. Using the same separation measure, determine "the distance" between the negative ideal point and each alternative:

$$S_{i-} = \left[\sum j\left(v_{ij} - v_{-j}\right)^2\right]^{0.5} \quad (9)$$

9. Calculate the relative closeness to the ideal point (c_{i+}) by using the equation:

$0 < c_{i+} < 1$; that is, an alternative is closer to the ideal point as c_{i+} approaches 1. Rank the alternatives according to the descending order of c_{i+} where the alternative with the highest value of c_{i+} is the best alternative.

Decision criteria and landfill site selection

Geographic Information System (GIS) layers

The ultimate goal of the landfill site selection process is to ensure that the disposal facility is located at the best location possible with little or no impact to the environment. In this study, criteria used in the analysis were air traffic safety, distance to roads, distance to settlement, geology, drainage, earthquake risks, slope, erosion and land use. Assignment of the criteria weights was based on previous knowledge of the criteria characteristics and local conditions of the study area, as well as on the experience of the scientists involved in the weight assignment process. For example, Sener et al. (2010) have assigned higher weight values to environmental criteria than to the economic criteria, namely, land use and distance from surface water considering the distance to Lake Beyşehir and to the dense forest areas. In the study of Sener (2004), urban centers and villages have been selected as criteria with highest weight value followed by surface water, flood, swamp and geology. Village road and railways have been given the lowest suitability values. Similarly, Yesilnacar et al. (2012) have assigned the highest weight to the settlement followed by the land use, aquifer and geology. Nas et al. (2008) have assigned the highest weight to agricultural land class since there are many cultivated areas in Konya. Yal and Akgün (2014), on the other hand, chose the settlement as the highest weighted criterion.

In this study, the highest weight has been assigned to geology followed by land use due to the potential utilization of the in-situ material as a landfill liner material. Land use of the area is also important since landfills should not be placed in highly populated areas, environmentally protected areas and irrigated lands. Detailed information on the GIS layers is presented in the following sub-sections where the ultimate goal is to select one of the three alternative landfill sites, namely, Site A, Site B or Site C that are presented in Fig. 1.

Distance to settlement

Landfills should not be placed near a residential or an urban area to avoid any kind of negative effect on population. According to Baban and Flanagan (1998), landfills should not be placed within 10 km of an urban area. Additionally, a landfill site should not be located within 250 m of a residential area according to the Turkish Solid Waste Control Regulations (TSWCR 2010). In this study, rankings suggested by Sharifi et al. (2009) were used (Table 6). The resulting map is presented in Fig. 5. Site A has a suitability score of 0.25, indicating its moderate proximity to settlements, while Site B scores 1, making it the most suitable, and Site C scores 0.75, reflecting its less favorable proximity.

Distance to roads

Information for the local roads were extracted from the topographic map produced by the General Command of Mapping (2002) and digitized in the ArcGIS software. Landfills should not be constructed very close to the roads in order not to interfere too much with the traffic (Guiqin et al. 2009). However, they should not be constructed too far away from the roads to avoid facing accessibility problems. Consequently, various researchers have used different ranking values in their studies. Sener et al. (2010) drew a 250 m buffer zone around roads and rankings were increased linearly away from these roads. Nas et al. (2008) stated that landfills should not be placed within 200 m of any existing highways or city streets. In the study herein, a buffer zone of 100 m was applied to all existing roads and the suitability ranking was increased linearly away from the alternative landfill sites. The related ranking values are presented in Table 7. The road suitability map is presented in Fig. 6. All three sites A, B, and C have the same suitability score of 0.25 for distance to roads, indicating limited suitability based on distance to roads.

Table 6 Suitability rankings based on the distance to settlements (Sharifi et al. 2009)

Distance to settlement (m)	Rank
0–500	0
500–1000	0.25
1000–1500	0.5
1500–2000	0.75
> 2000	1

Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) of the area was gathered from the publicly available "Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM)". The ASTER GDEM covers land surfaces between 83°N and 83°S and is composed of 22,600 1°-by-1° tiles. The ASTER GDEM is in GeoTIFF with geographic latitude and longitude coordinates and a 1 arc- second (30 m) grid of elevation postings. GDEM is referenced to the WGS84/EGM96 geoid. Estimated accuracies are 20 m at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data.

The DEM of the region was created by utilizing the ArcGIS software. First, topographical maps were gathered from the General Command of Mapping. Then, topographical contours were digitized by using the ArcGIS software. The minimum curvature method was employed in creating the DEM as presented by Fig. 7.

Slope

Constructing a landfill in a steep slope would excessively increase the excavation costs while flat areas might be unsuitable due to flooding problems. For these reasons, many researchers have used different rankings for slope values in their site selection studies. According to Bagchi (1994), areas with slope values greater than 15% should be considered as unsuitable and below 15% suitable for siting a landfill. Akbari et al. (2008), on the other hand, stated that slopes steeper than 20% are not suitable for landfills. In the study herein, slope values were categorized in four classes as presented in Table 8.

The slope map of the study area was generated from the Digital Elevation Model (DEM). The slope tool was utilized in the ArcGIS software to transform DEM into a slope map layer. The resultant map presented by Fig. 8 was separated into four suitability classes as mentioned above. Site A and Site C both have the highest slope suitability with a score of 1, while Site B is slightly less suitable with a score of 0.75.

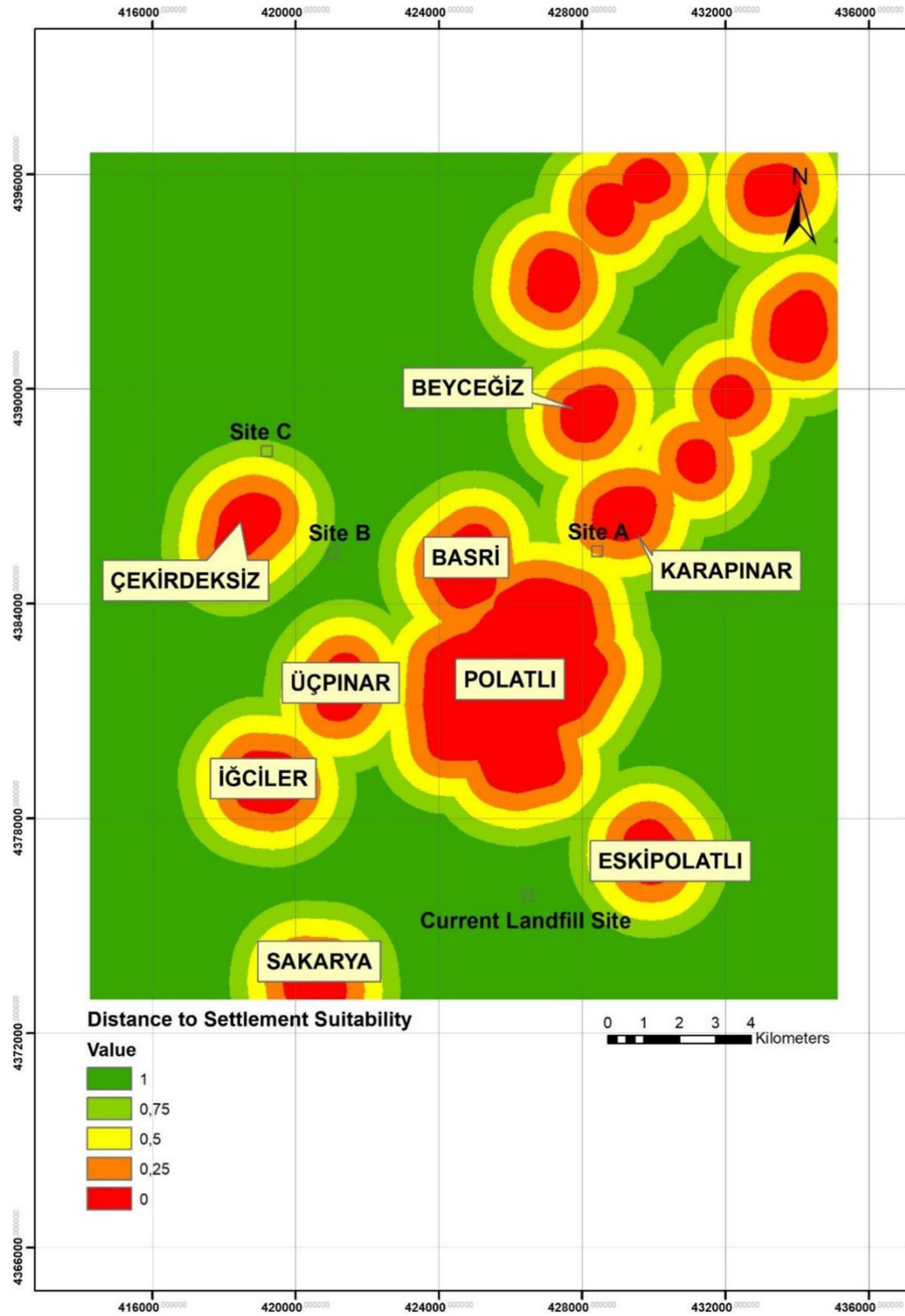

Fig. 5 Distance to settlement suitability map

Table 7 Suitability rankings based on distance to roads

Distance to roads (m)	Suitability rank
0–100	0.25
100–200	0.40
200–300	0.50
300–400	0.60
400–500	0.75
500+	1

Geology

The 1/100000 geological map acquired from The General Directorate of Mineral Research and Exploration was used for obtaining information on the geology of the area. The geological formations were digitized, and a vector map was generated utilizing the ArcGIS software. The lowest suitability rank was assigned to alluvium, slope debris and old alluvium formations since they possess the possibility

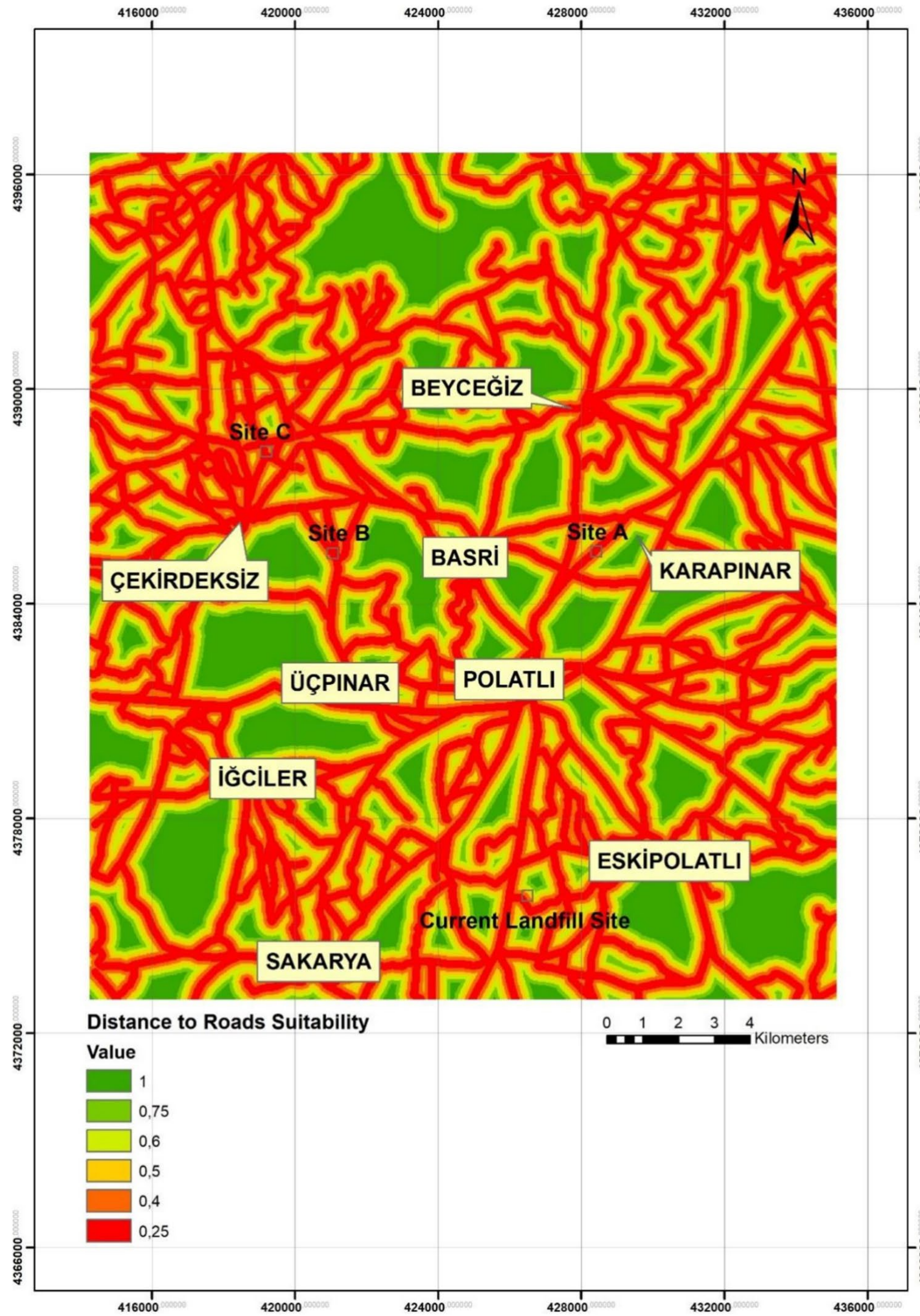

Fig. 6 Distance to roads suitability map

of a shallow groundwater level and possibility of flooding due to the presence of the uncemented gravel and sand units. The highest ranking, on the other hand was given to the Hançili Formation (Tmh) due to its high fine-grained soil content which makes it suitable for a landfill liner material. The other geological formations were assigned values between 0 and 1 with respect to their suitability as a landfill site material which is presented by Table 9 and Fig. 9. Site A and Site B have the highest suitability in geology with a score of 1, while Site C has the lowest suitability with a score of 0.

Distance to fault

Different researchers used different distance values for lineaments in their site selection studies. For example, in the study of Sener et al. (2010), all lineaments were buffered and weighed between 0 and 200 m. Sharifi et al.

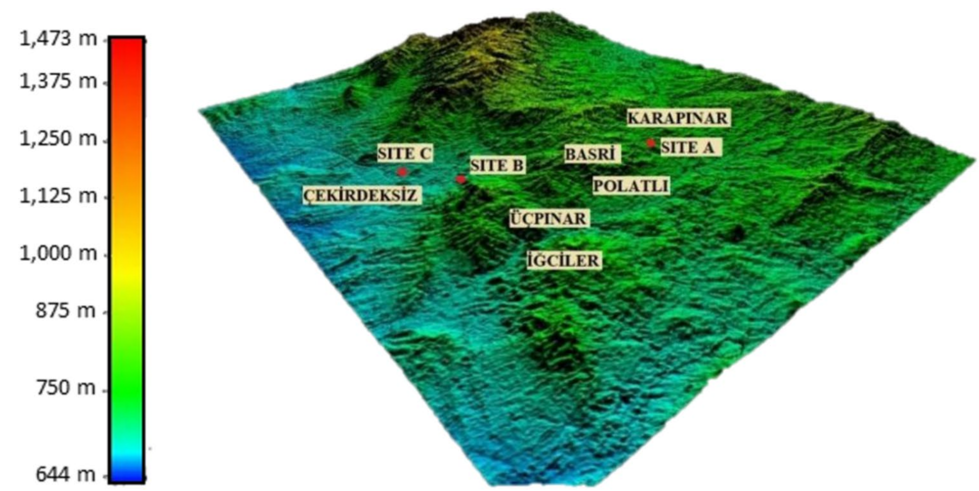

Fig. 7 Digital elevation model (DEM) of the study area

Table 8 Suitability rankings based on slope values

Slope (degree)	Suitability rank
0–5	0.25
5–10	1
10–15	0.75
15+	0

(2009) applied a buffer zone of 100 m. Akbari et al. (2008), used a buffer zone of 100 m around the faults. By considering this information, a total of five distance classes were specified and the corresponding rankings were assigned (Table 10). The faults in the study area were extracted from the 1/100000 scaled geological map of Ankara prepared by The General Directorate of Mineral Research and Exploration. The faults were digitized by using the ArcGIS software so that the resultant suitability map presented by Fig. 10 was obtained. Site A is the most suitable in terms of distance to faults with a score of 1, while Sites B and C both score 0.5, indicating moderate suitability.

Drainage

The drainage map was generated by the ArcGIS software based on the digital elevation model (DEM) of the study area. Afterwards, the generated drainage map was re-classified based on the distance to the flow lines and was assigned weights. The distance values suggested by Sharifi et al. (2009), were used prior to the analysis (Table 11). The resultant suitability map is presented by Fig. 11. Site A scores the highest in drainage suitability with 0.75, whereas Sites B and C have lower suitability scores of 0.25 each.

Land use

The land use map of the study area was acquired from the publicly available Corine Land Cover Map (Fig. 12). This map was digitized in an ArcGIS environment and re-classified according to the weights determined above. All of the unused areas, non- irrigated lands were considered to be suitable for a landfill site and a suitability rank of 1 was assigned to these areas. Areas that were utilized in the form of irrigated lands, settlements, factories, on the other hand were considered to be unsuitable and were assigned a suitability rank of 0 (Table 12). Figure 13 presents the land use suitability map of the project site. All three sites A, B, and C are equally suitable for land use, each scoring 1.

Erosion

Areas which are prone to high levels of erosion should be avoided when constructing a landfill site due to the vulnerability caused by erosion. Based on this information, the erosion map was re-classified into four different classes and assigned suitability rankings (Table 13). Figure 14 presents the erosion suitability map of the study area. All three sites A, B, and C are highly suitable regarding erosion, each scoring 1.

Distance to epicenters

According to the U.S. Environmental Protection Agency (USEPA), new sanitary landfill sites should not be located in seismic impact zones and should be designed to resist the maximum horizontal acceleration in lithified earth material. A seismic impact zone implies an area with a

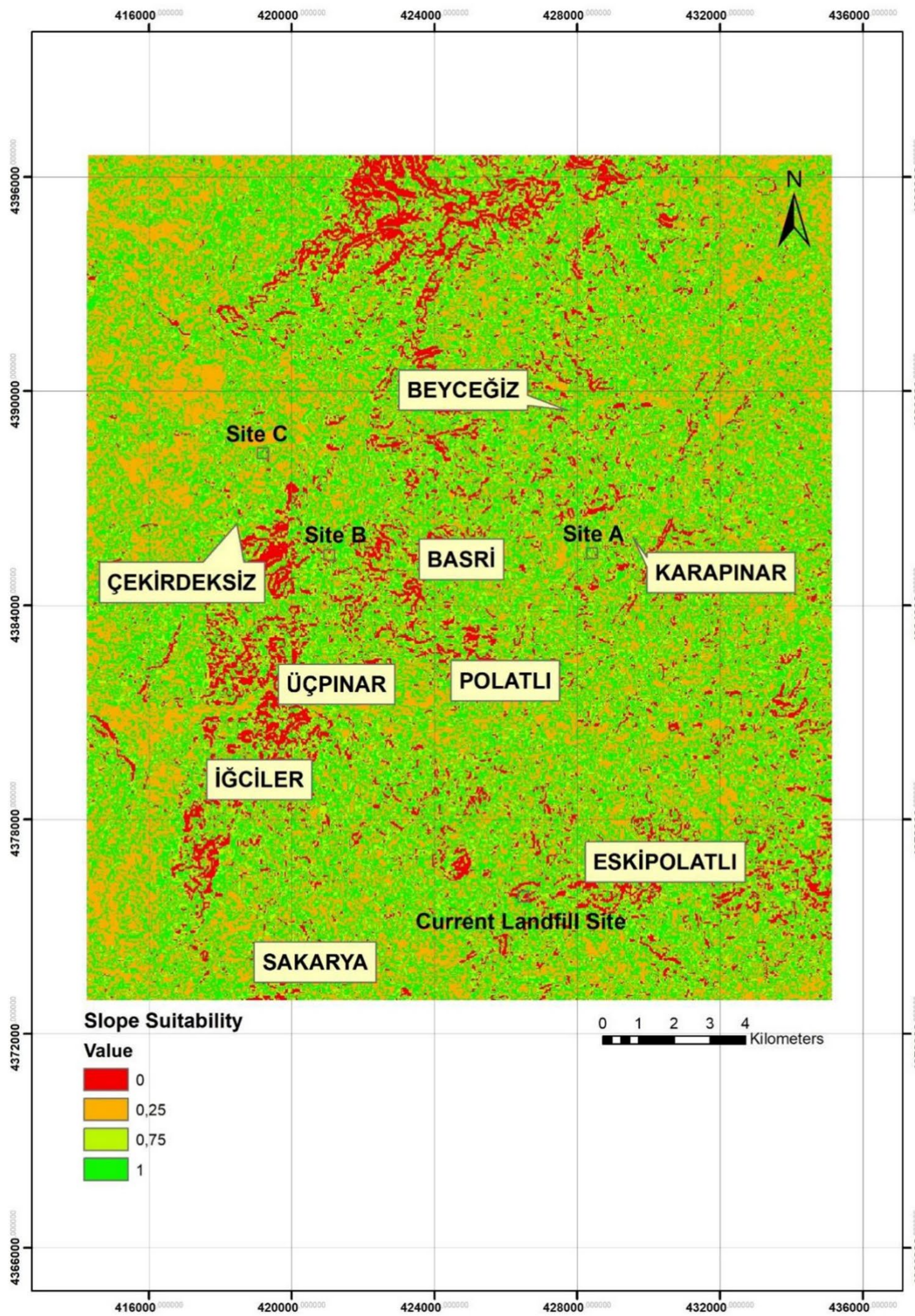

Fig. 8 Slope suitability map of the study area

Table 9 Suitability rankings based on geological formations

Formation	Suitability rank
Tmh	1
Teb, Tmsg, Tmplag, Tmhb, Tmsy	0.75
Tpek, Tpk, Tmplay, Tee, Tpei	0.25
Qal, Qeal, Qym	0

10% or greater probability that the maximum horizontal acceleration in lithified earth material, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 250 years.

In this study, earthquakes that have occurred in the past 100 years were gathered from the Kandilli Observatory and Earthquake Research Institute (KOERI 2024), and then imported to a GIS environment. A 60-meter-wide

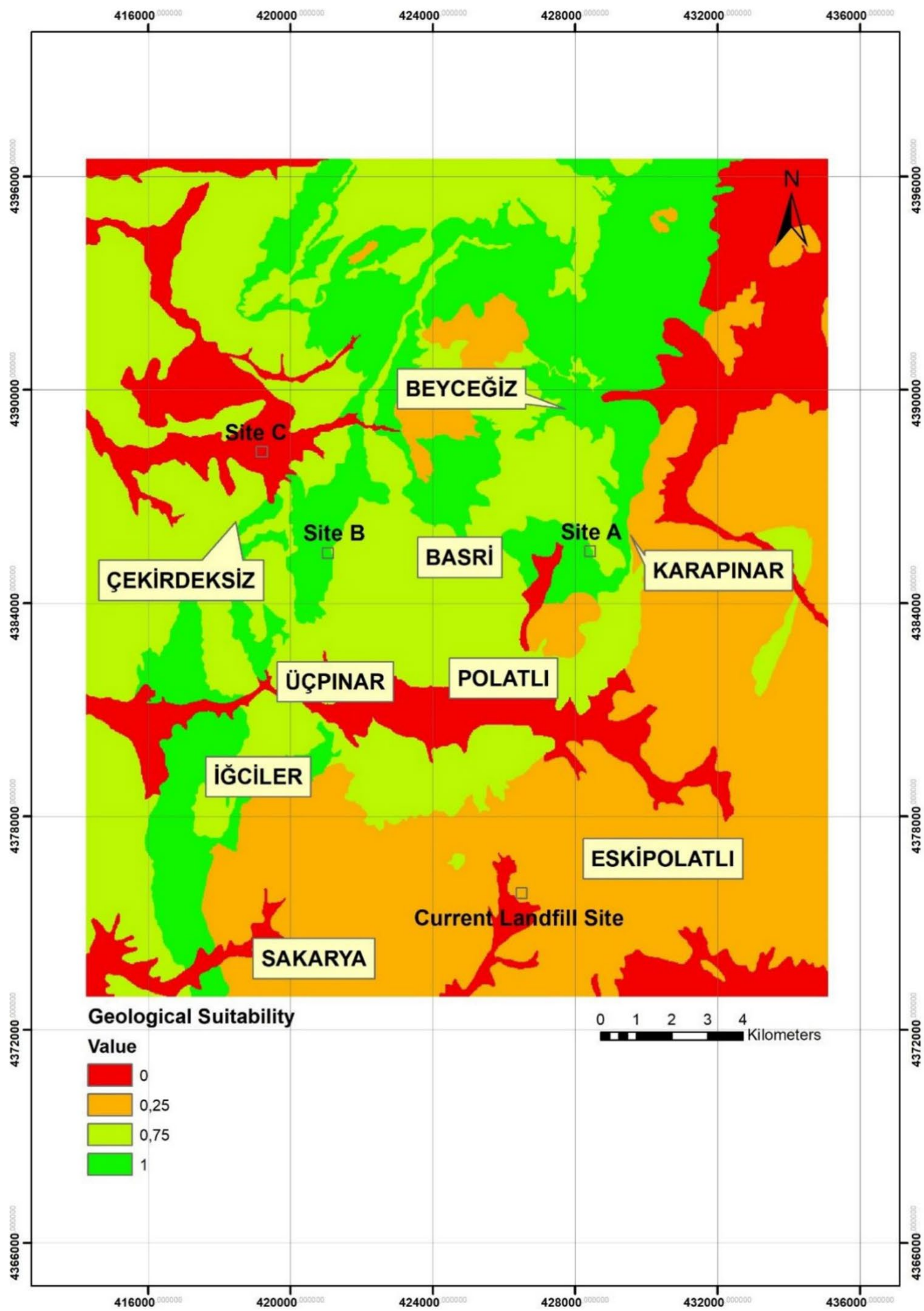

Fig. 9 Geological suitability map of the study area

Table 10 Suitability rankings based on the distance to fault (Sharifi et al. 2009)

Distance to fault (m)	Suitability rank
0–100	0
100–400	0.25
400–1500	0.5
1500–5000	0.75
1500+	1

buffer zone was applied and the suitability of the alternative site was increased linearly away from the earthquake epicenters. It is not very common in the literature to use earthquake epicenters as a criterion in landfill site selection. However, based on the definition of a seismic impact zone, epicenters were considered as a restricted criterion in this study. In Table 14, the suitability rankings have been assigned relative to the distance from the epicenters. The resultant suitability map is presented by Fig. 15. Site

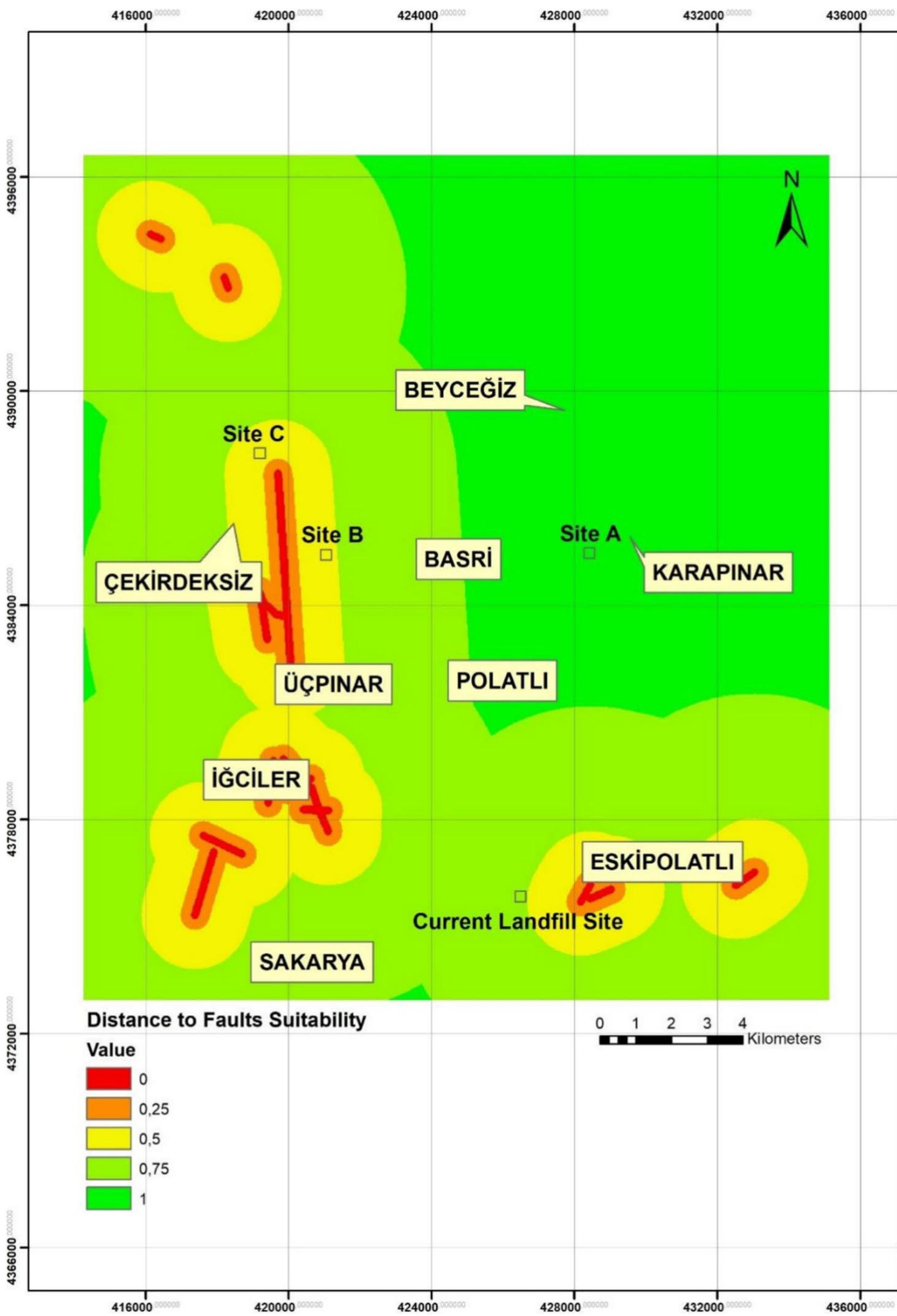

Fig. 10 Distance to fault suitability map

Table 11 Suitability rankings based on the distance to the flow line (modified from Sharifi et al. 2009)

Distance to flow line (m)	Suitability rank
0 –100	0
100–400	0.25
400–1000	0.75
1000+	1

B and Site C score the highest in distance to epicenters with a suitability score of 1, whereas Site A has a slightly lower score of 0.75.

Other criteria: air traffic safety

According to Baghci (1994), landfills should not be constructed within 3048 m (10000 ft) of an airport. EPA

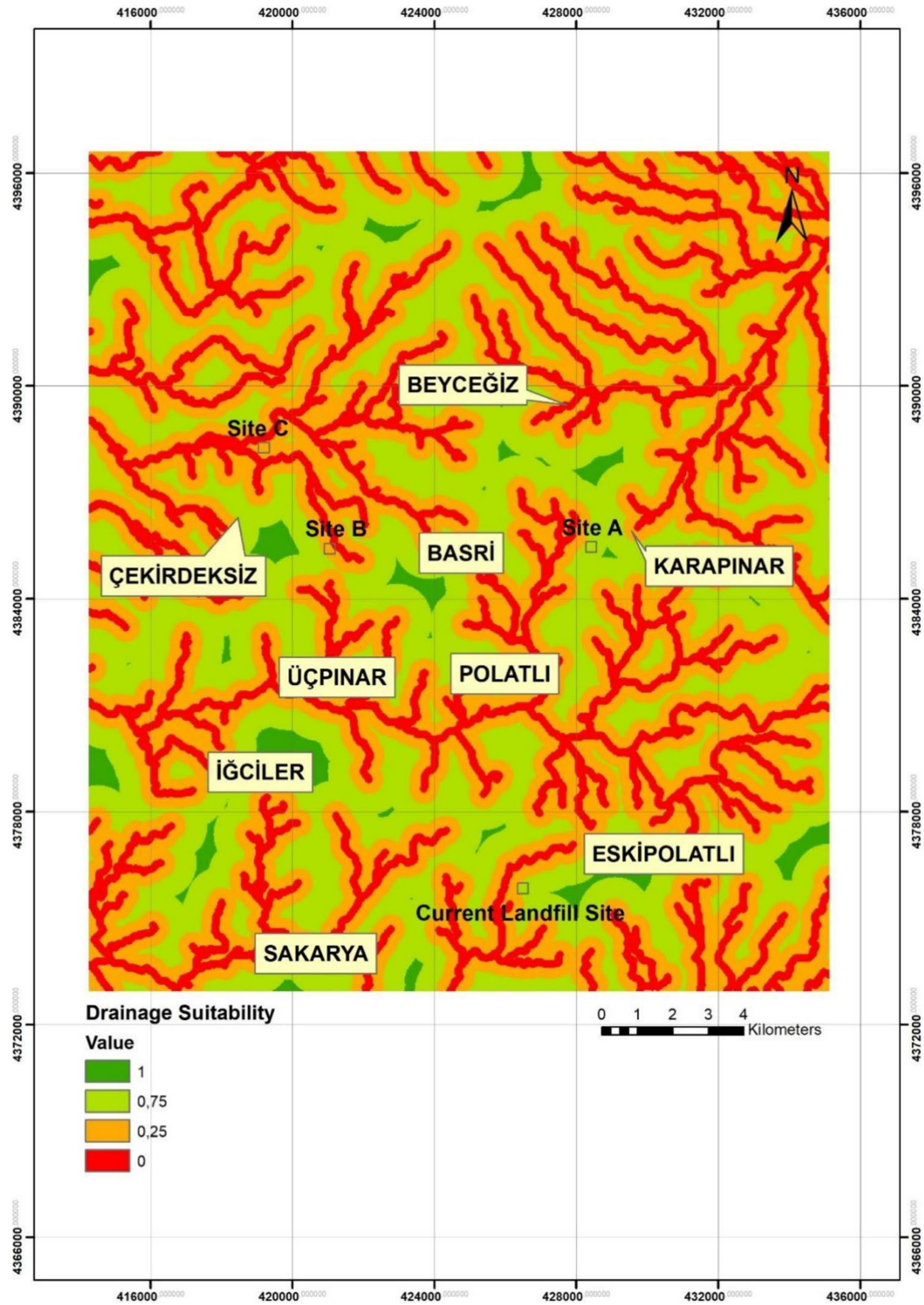

Fig. 11 Drainage suitability map of the study area

(2010), also suggests the same distance value. By considering the suggested values, the safe distance for an airport was determined to be 1500 m in the study of Yesilnacar et al. (2012). Since the closest airport (i.e., Temelli Airport) and its runway are located approximately 25 km from the center of Polatlı municipality, the effect of airports has not been considered as a restriction criterion (Fig. 1).

Discussion on the suitability of each site based on the criteria

Based on the suitability rankings, Site A scores the highest in geology, slope, erosion, drainage, and distance to faults, indicating favorable geological stability, terrain, and reduced seismic risks. However, Site A is moderately less suitable in terms of proximity to settlements and epicenters, which may

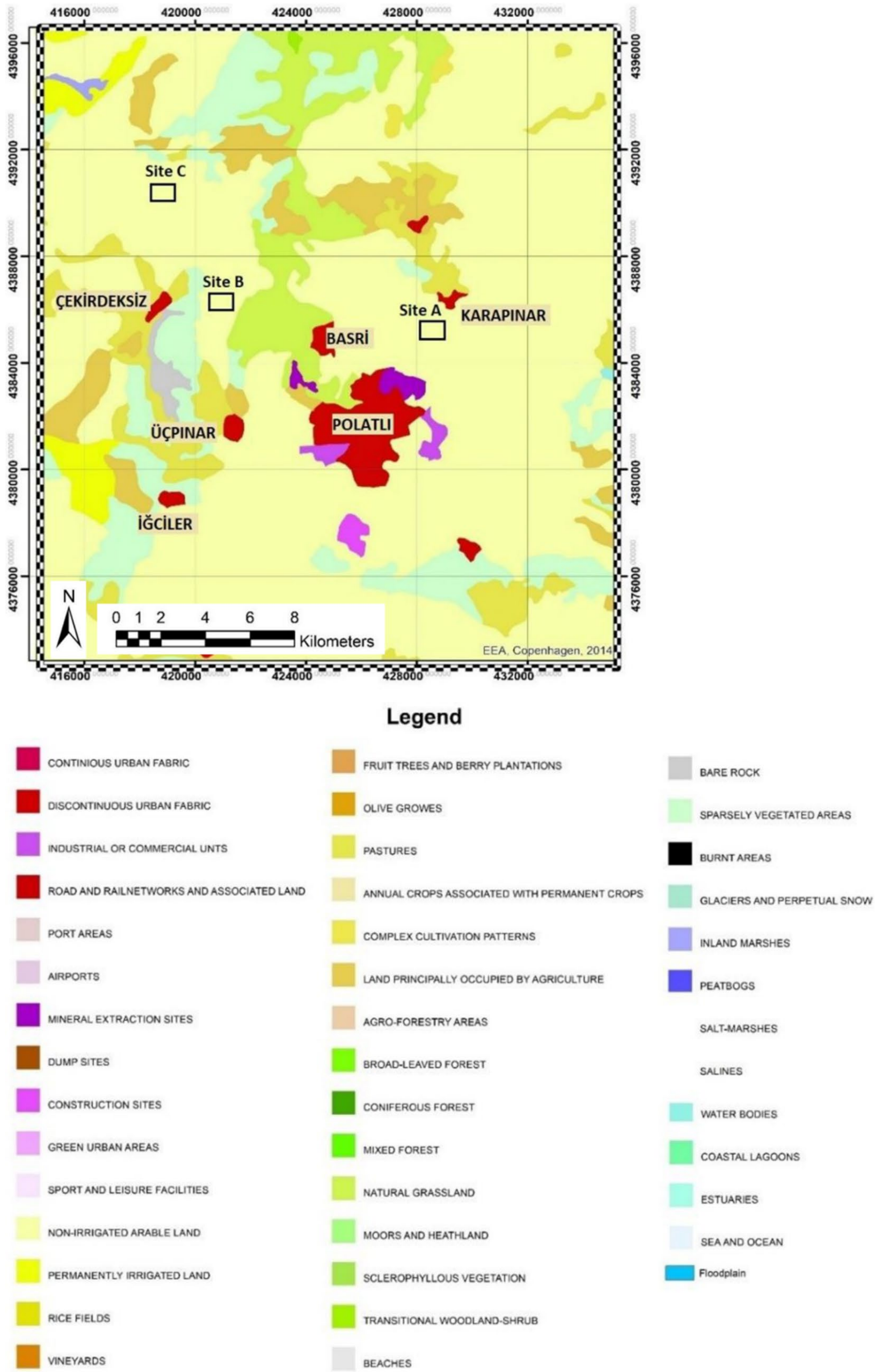

Fig. 12 Land use map of the study area (EEA 2018)

Table 12 Land use suitability rankings (Yal and Akgün 2013)

Land use	Suitability rank
Non-irrigated lands, dry fields, unused areas	1
Irrigated lands, forests, settlements, occupied areas	0

pose challenges related to human impact and seismic activity. Site B, on the other hand, is highly suitable in terms of distance to settlements and epicenters, making it less prone to risks associated with human activity and seismic events. However, it has moderate limitations in slope and drainage, which may affect terrain stability and water flow. Site C presents a mixed performance; while it is less favorable in geology and erosion, it scores well in land use, slope, and distance to epicenters. This suggests that Site C may have

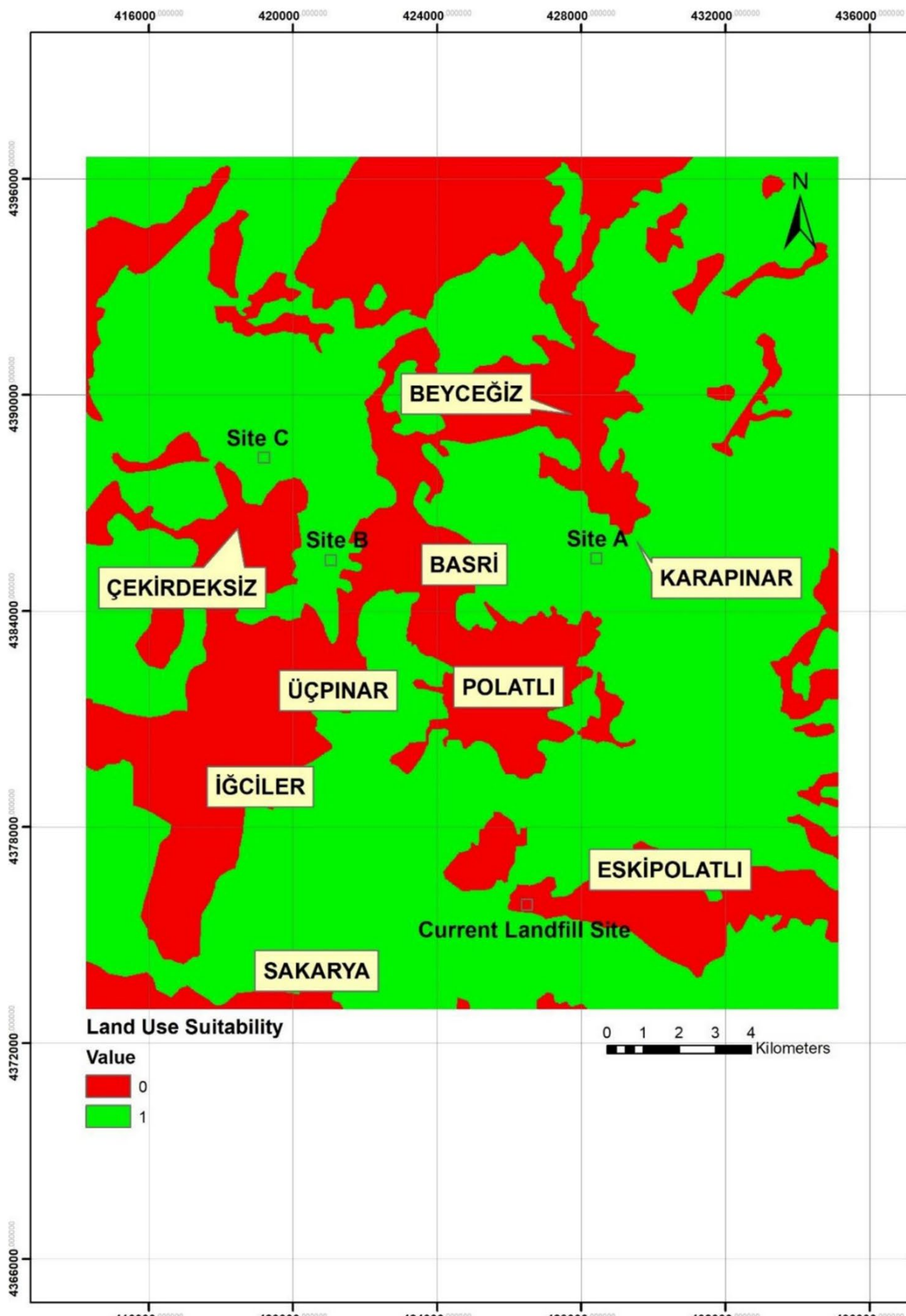

Fig. 13 Land use suitability map of the study area

Table 13 Erosion suitability rankings (modified from Yal and Akgün 2013)

Erosion risk	Suitability rank
Low potential	1
Moderate potential	0.75
High potential	0.5
Very high potential	0

specific advantages for certain applications but is generally less favorable overall (Table 15).

TOPSIS analysis

All of the attribute layers were digitized and prepared prior to TOPSIS analysis. Initially, the layers have been standardized since it was not possible to compare them without standardization. After that, all the layers were re-classified in

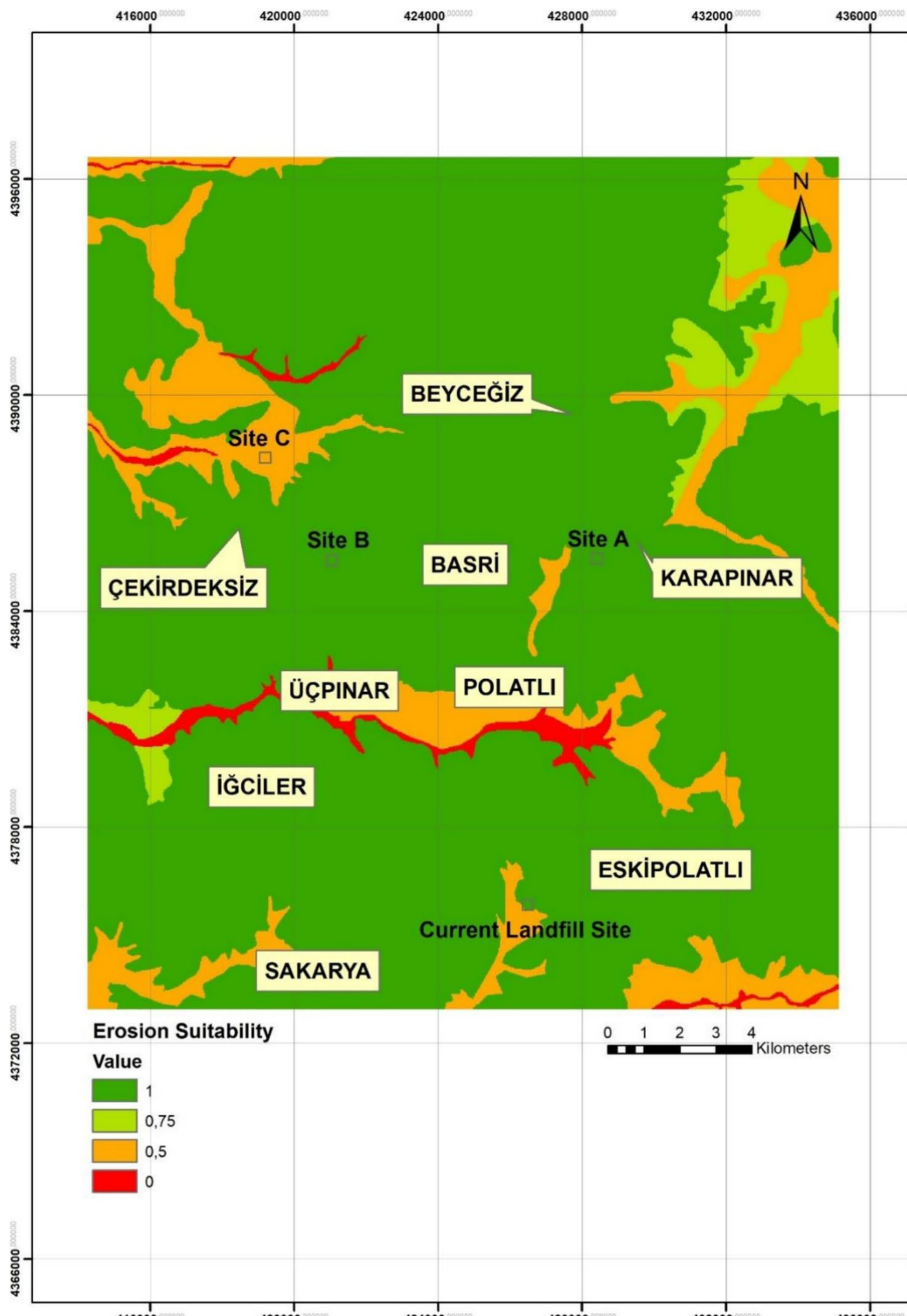

Fig. 14 Erosion suitability map of the study area

Table 14 Suitability rankings based on distance to epicenters (modified from Yal and Akgün 2013)

Distance to epicenters (m)	Suitability rank
0–60	0
60–200	0.25
200–500	0.50
500–1000	0.75
> 1000	1

conjunction with the assigned weight values. Finally, TOPSIS analysis was performed by utilizing the ArcGIS modal builder tool to obtain the final suitability map presented by Fig. 16. The final suitability map was also re-classified into four different classes, namely, not suitable, fairly suitable, suitable and very suitable. Approximately 15% of the study area was determined to be not suitable, 17.5% fairly suitable, 34.5% suitable and 33% very suitable. According to this map, it should be noted that the current open dump site

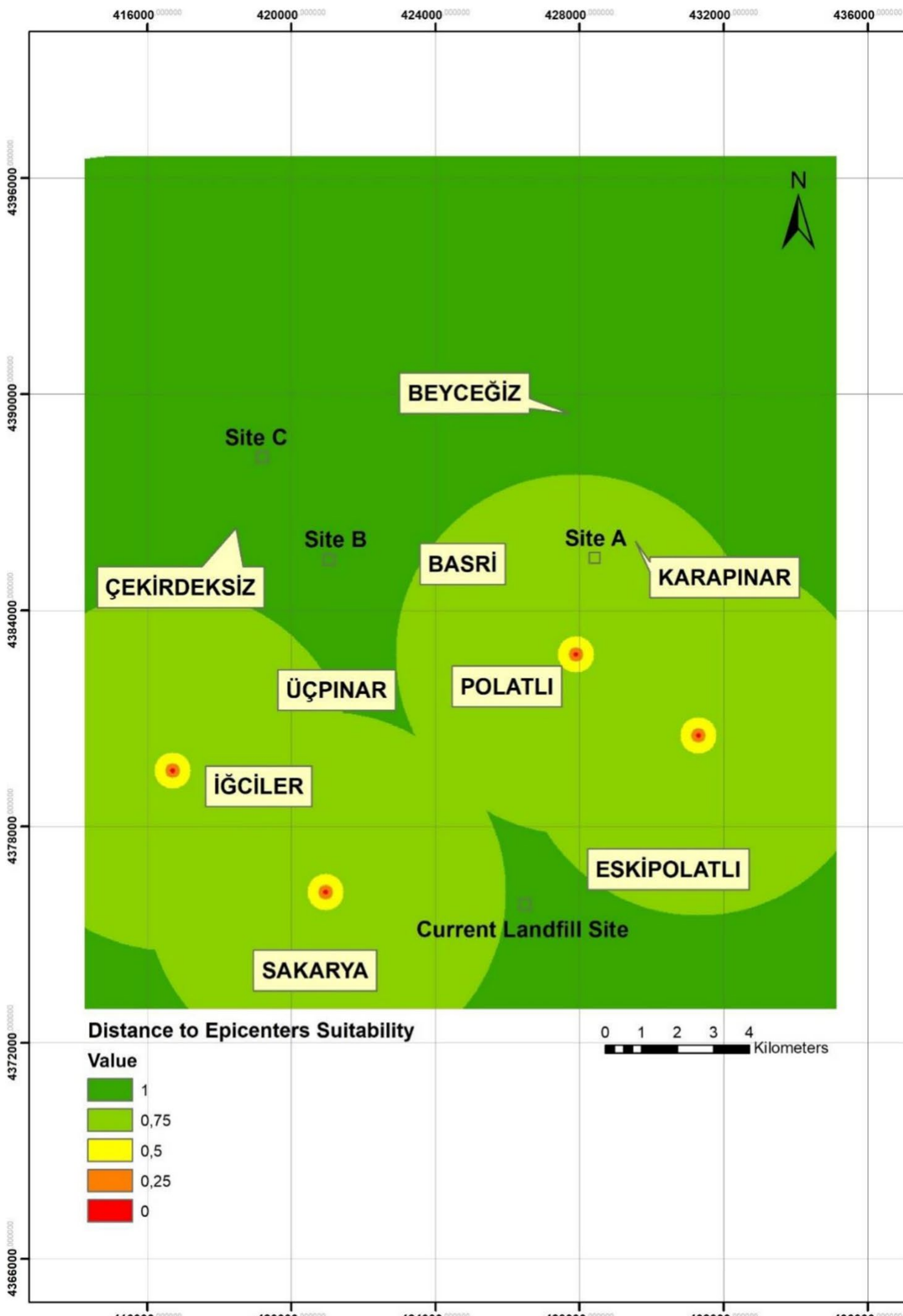

Fig. 15 Distance to epicenters suitability map of the study area

Table 15 Suitability rankings for each criterion corresponding to each site

Site	Geology	Land use	Distance to settlement	Distance to roads	Drainage	Slope	Erosion	Distance to faults	Distance to epicenters
A	1	1	0.25	0.25	0.75	1	1	1	0.75
B	1	1	1	0.25	0.25	0.75	1	0.5	1
C	0	1	0.75	0.25	0.25	1	0.5	0.5	1

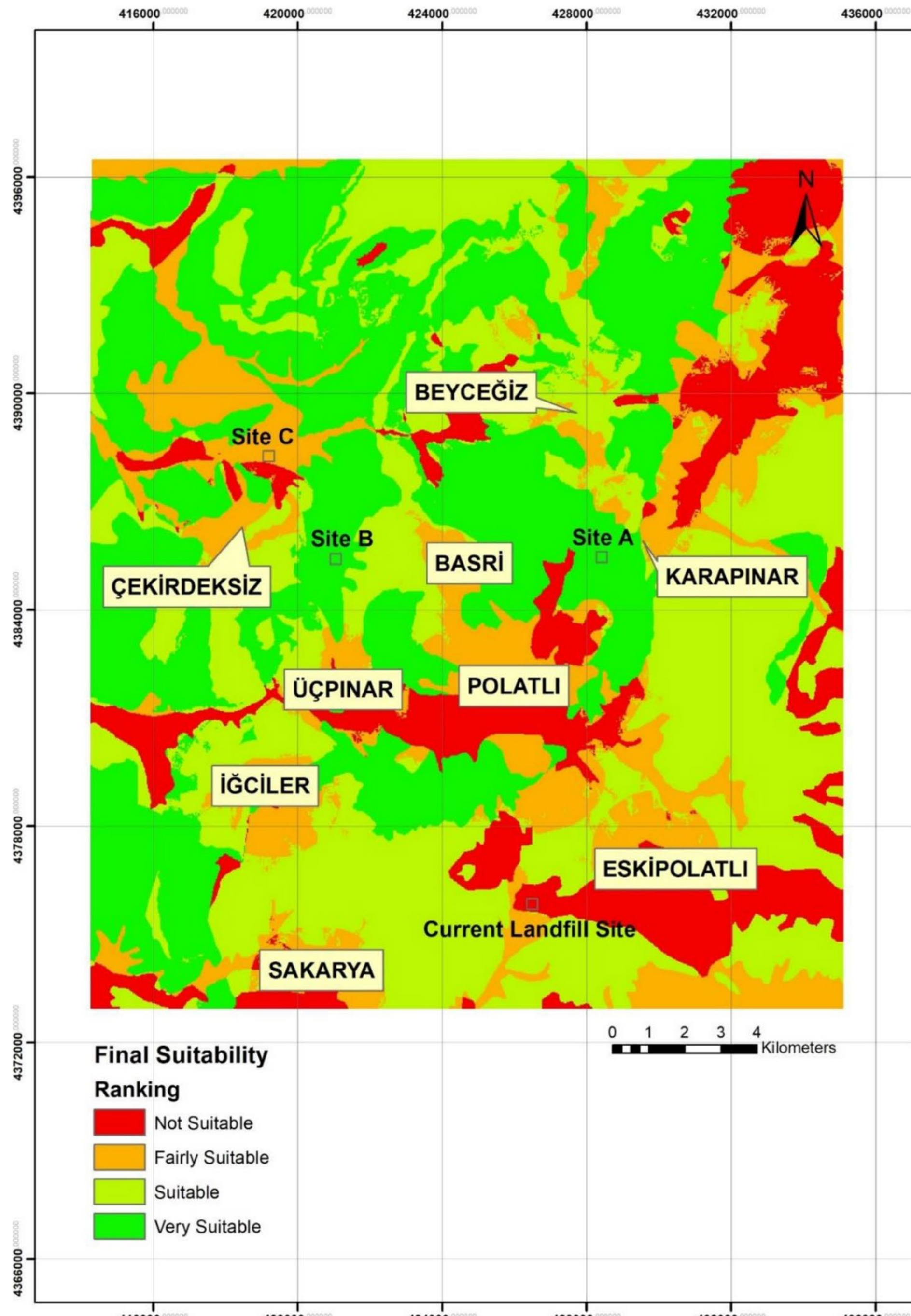

Fig. 16 Final landfill site suitability map

is situated in an area which is not suitable to construct a landfill. When alternative sites A, B and C are considered, it could be concluded that Site C lies in a fairly suitable area whereas Sites A and B are located in a very suitable part of the study area. These findings show that the best locations to construct a landfill are Site A or Site B.

Sensitivity analysis and discussion

Sensitivity analysis may be performed in various forms such as changing the weight values of the criterion layers, changing the buffer zones of the layers and excluding one layer at a time and repeating the analysis to observe its effect on the final resultant map (Yal and Akgün 2013). A sensitivity analysis was performed in this study to find out the individual effects of each layer on the final suitability map. The analysis was performed and repeated by excluding one layer at a time.

One of the layers was excluded in each analysis and a total of nine suitability maps were generated. Each layer was reclassified into four classes from 1 to 4 where 1 was the least suitable and 4 was the most suitable. The number of cells that corresponded to each suitability class was calculated. Figure 17 presents the number of cells corresponding to the suitability class 4. The red bar shows the analysis where each criterion is included. The blue bar, on the other hand, represents the analysis with one layer excluded. The difference between the red and blue bars indicates the effect of that particular layer. The most variation was observed in the geology layer which indicated the importance of the geology of the area for the analysis. The land use and distance to settlement criteria also seemed to lead to a noticeable difference in the analysis where all the layers were included. Thus, the sensitivity analysis highlighted the importance of these layers.

The number of cells corresponding to the suitability class 1 (least suitable) is presented in Fig. 18. When the number of cells which correspond to class 1 for the map where a layer is excluded is less than the complete analysis, it indicates a problem. This situation was observed mainly in the distance to settlement and distance to roads layers. According to many studies and regulations, municipal landfills should be located at least 250 m away from settlements. In the study area, since all three alternative landfill sites are located more than 1000 m away from the nearest settlement, it seems that this criterion has been satisfied. When utilizing the distance to roads layer for the TOPSIS analysis, distance values presented by Table 7 were used. In order to be more precautious, a more conservative approach may be followed by locating the alternative landfill sites farther away from the existing roads. However, since the study area is relatively small in extent, there is not enough space to site a landfill that far away from the existing roads. Hence, distance to existing roads values used in this study (Table 7) may be considered to be fairly reasonable. Consequently, the sensitivity analysis showed the importance of the geological characteristics of the study area. Additionally, a more

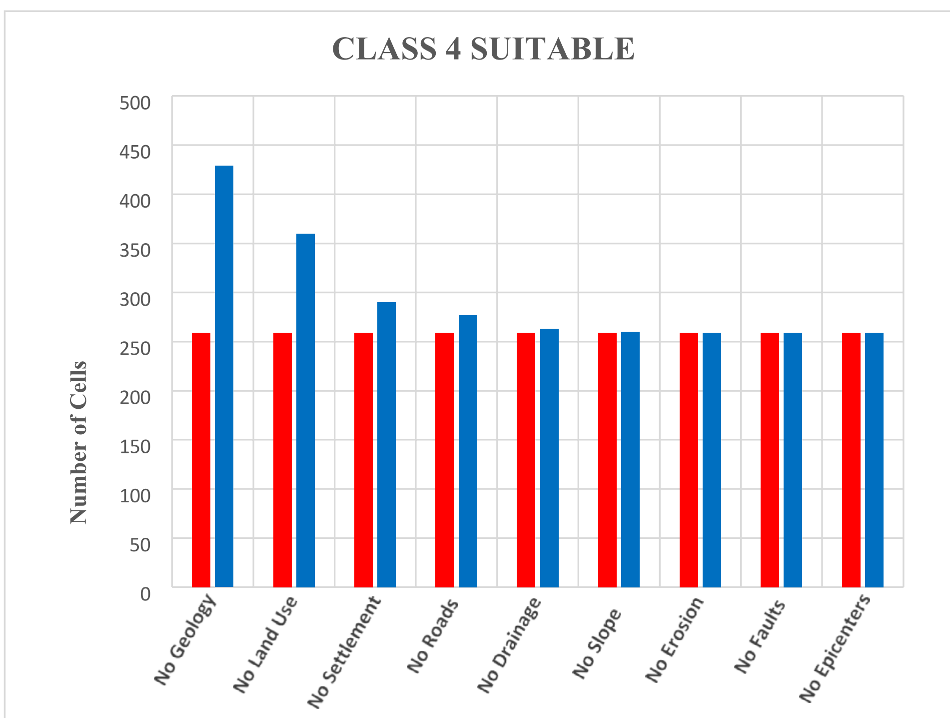

Fig. 17 The number of cells corresponding to suitability class 4 (most suitable)

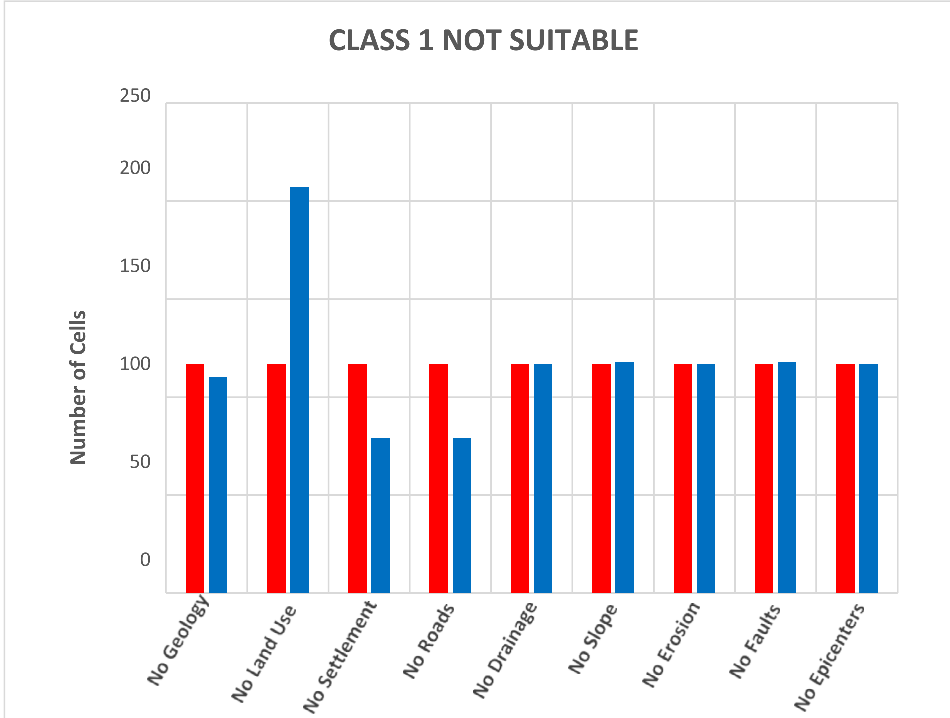

Fig. 18 The number of cells corresponding to suitability class 1 (least suitable)

conservative approach may be followed for the distance to roads criterion.

Landfill liner and cover system design aspects

After selecting the best alternative landfill site for Polatlı, the next step shall be the evaluation of the hydrological, geotechnical and mineralogical characteristics of the subsoils for designing the landfill lining and cover system at the selected landfill site, more specifically at Site A or Site B. Information on the effects of the hydrological aspects of the landfill site such as surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, temperature and precipitation, evaporative zone depth, maximum leaf area index, annual average wind speed, average quarterly relative humidity, dates starting and ending the growing season and leakage through soil, geomembrane or composite liners are required to determine the leachate head acting on the landfill profile. Different types of final cover systems (e.g., capillary barrier effect, three-layer landfill cover systems) can be utilized based on rainfall conditions to reduce rainfall infiltration (e.g., Ng et al. 2023, 2024b; Guo et al. 2024). In addition, geotechnical information on the fine soil levels of the Hançili formation shall be needed to accurately simulate the hydrologic processes and to geotechnically design the landfill lining and cover systems. Geotechnical laboratory tests required are specific gravity, Atterberg limit tests, Standard Proctor Compaction and falling head permeability tests. In addition, mineralogical tests, namely, X-ray diffraction (XRD), methylene blue and Scanning Electron Microscopy (SEM) tests need to be performed to better understand the nature and clay content of the fine soil levels (Akgün et al. 2017, 2018; Öner 2019).

Summary and conclusions

The aim of this study was to find a suitable landfill site location for the Polatlı municipality. To find the best location possible, criteria such as distance to roads, distance to settlement, geology, hydrogeology, distance to faults were used and then gathered in a GIS environment. The TOPSIS methodology was utilized as a multi-criteria decision making (MCDM) analysis since it is widely used to select the best alternative out of many possibilities. By combining GIS and TOPSIS, a final suitability map of the study area was generated. After comprehensive site selection studies, amongst the three alternative landfill sites A, B and C, the best locations to construct a landfill were chosen to be Site A or Site B that are situated north northeast (NNE) and north northwest (NNW) of Polatlı, respectively.

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Author contributions Gökalp Öner: prepared the material, collected data and performed the analysis. Haluk Akgün: Aided in conception, design of the study and in preparation of the first draft of the manuscript. Gökalp Öner, Mustafa Kerem Koçkar and Arzu Arslan Kelam: Developed the methodology of the study. Gökalp Öner and Arzu Arslan Kelam: Aided in the visualization of the study. Mustafa Kerem Koçkar: Reviewed and edited the manuscript. Gökalp Öner, Haluk Akgün, Mustafa Kerem Koçkar and Arzu Arslan Kelam: read and approved the final version of the manuscript.

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Data availability Datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akbari V, Rajabi MA, Chavoshi SH, Shams R (2008) Landfill site selection by combining GIS and fuzzy multi criteria decision analysis, case study: Bandar Abbas, Iran. World Appl Sci J 3:39–47

Akgün H, Türkmenoğlu AG, Arslan Kelam A, Yousefi-Bavil K, Öner G, Koçkar M (2018) Assessment of the effect of mineralogy on the geotechnical parameters of clayey soils: a case study for the Orta County, Çankırı, Turkey. Appl Clay Sci 64:44–53. https://doi.org/10.1016/j.clay.2017.08.029

Akgün H, Türkmenoğlu AG, Met İ, Yal GP, Koçkar M (2017) The use of Ankara clay as a compacted clay liner for landfill sites. Clay Miner 52:391–412

Akyurek B, Bilginer E, Catal E, Dager Z, Soysal Y, Sunu O (1980) Eldivan- Şabanözü (Çankırı) Hasayaz-Çandır (Kalecik-Ankara) dolayının jeolojisi. General directorate of mineral research and exploration. Ankara, Report No. 6741 (in Turkish)

Baban SJ, Flannagan J (1998) Developing and implementing GIS-assisted constraints criteria for planning landfill sites in the UK. Plann Pract Res 13(2):139–151. https://doi.org/10.1080/02697459816157

Bagchi A (1994) Design, construction and monitoring of landfills, 2nd edn. John Wiley & Sons Inc, New York

Bahrani S, Ebadi T, Ehsani H, Yousefi H, Maknoon R (2016) Modeling landfill site selection by multi-criteria decision making and fuzzy functions in GIS, case study: Shabestar, Iran. Environ Earth Sci 75:337

Beskese A, Demir HH, Ozcan HK, Okten HE (2015) Landfill site selection using fuzzy AHP and fuzzy TOPSIS: a case study for Istanbul. Environ Earth Sci 73:3513–3521

Bilgin AZ, Uğuz MF, Sevin M, Parlak O, Pekgöz M, Elibol H, Erdem Y, Özden UA (2009) Ayaş-Temelli-Polatlı (Ankara) dolayının jeolojisi. General directorate of mineral research and exploration. Ankara, Report No. 11215 (in Turkish)

Cambazoğlu S, Yal GP, Eker AM, Şen O, Akgün H (2019) Geothermal resource assessment of the Gediz Graben utilizing TOPSIS methodology. Geothermics 80:92–102. https://doi.org/10.1016/j.geothermics.2019.01.005

Cao L, Cheng Y, Zhang J, Zhou X, Lian C (2006) Application of grey situation decision-making theory in site selection of a waste sanitary landfill. Int J Min Sci Technol 16:393–398

Chou J-R (2013) A weighted linear combination ranking technique for multi-criteria decision analysis. South Afr J Economic Manage Sci 16(5):28–41

Donevska KR, Gorsevski PV, Jovanovski M, Pesevski I (2012) Regional non-hazardous landfill site selection by integrating fuzzy logic, AHP and geographic information systems. Environ Earth Sci 67(1):121–131

EEA (2018) The European Environment Agency – Data and Maps. CORINE Land Cover classes. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018. Accessed on 01 Nov

El Baba M, Kayastha P, De Smedt F (2014) Landfill site selection using multi-criteria evaluation in the GIS interface: a case study from the Gaza Strip, Palestine. Arab J Geosci 8:7499–7513

Eskandari M, Homaee M, Falamaki A, Pazira E (2013) Integrating GIS and AHP for municipal solid waste landfill site selection. Int J Sci Basic Appl Res 3:588–595

Gbanie SP, Tengbe PB, Momoh JS, Medo J, Kabba VTS (2013) Modelling landfill location using geographic information systems (GIS) and multi-criteria decision analysis (MCDA): case study Bo, Southern Sierra Leone. Appl Geogr 36:3–12

Guiqin W, Li Q, Guoxue L, Lijun C (2009) Landfill site selection using spatial information technologies and AHP: a case study in Beijing, China. J Environ Manage 90:2414–2421

Guo H, Ng CWW, Zhang Q, Qu C, Hu L (2024) Modelling the water diversion of a sustainable cover system under humid climates. J Rock Mech Geotech Eng 16(7):2429–2440. https://doi.org/10.1016/j.jrmge.2023.10.017

Hanine M, Boutkhoum O, Tikniouine A, Agouti T (2016) Comparison of fuzzy AHP and fuzzy TODIM methods for landfill location selection. Springerplus 5:501

Hwang CL, Yoon K (1981) Multiple attribute decision making methods and applications. Springer, New York

Kandilli Observatory and Earthquake Research Institute (KOERI) (2024) http://www.koeri.boun.edu.tr/sismo/2/deprem-verileri/deprem-katalogu/. Accessed 02 Feb 2024

Kang YO, Yabar H, Mizunoya T, Higano Y (2024) Optimal landfill site selection using ArcGIS Multi-criteria decision-making (MCDM) and Analytic Hierarchy process (AHP) for Kinshasa City. Environ Challenges 14:100826

Khamehchiyan M, Nikoudel MR, Boroumandi M (2011) Identification of hazardous waste landfill site: a case study from Zanjan province, Iran. Environ Earth Sci 64(7):1763–1776

Khan D, Samadder SR (2015) A simplified multi-criteria evaluation model for landfill site ranking and selection based on AHP and GIS. J Environ Eng Landsc 23:267–278

Khorram A, Yousefi M, Alavi SA, Farsi J (2015) Convenient landfill site selection by using fuzzy logic and Geographic Information Systems: a case study in Bardaskan, East of Iran. Health Scope 4:1–10

Malczewski J (1997) Propagation of errors in multicriteria location analysis: a case study. In: Fandel G, Gal T (eds) Multiple criteria decision making:154-155, vol 448. Lecture Notes in Economics and Mathematical Systems (LNE), Springer, Berlin

Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, Canada

MGM (2024) Meteorological data of Polatlı Station. State Meteorological Works of Türkiye (MGM). Ankara (unpublished)

Nas B, Cay T, Iscan F, Berktay A (2008) Selection of MSW landfill site for Konya, Turkey using GIS and multi-criteria evaluation. Environ Monit Assess 160(1–4):491–500

Nazari A, Salarirad MM, Bazzazi AA (2012) Landfill site selection by decision-making-tools based on fuzzy multi-attribute decision making method. Environ Earth Sci 65(6):1631–1642

Ng CWW, Guo H, Ni J, Chen R, Xue Q, Zhang Y, Feng Y, Chen Z, Feng S, Zhang Q (2024) Long-term field performance of non-vegetated and vegetated three-layer landfill cover systems using construction waste without geomembrane. Géotechnique 74(2):155–173. https://doi.org/10.1680/jgeot.21.00238

Ng CWW, Guo H, Ni J, Zhang Q, Chen R, Zhang Y (2023) Effects of plant-biochar interaction on the performance of a landfill cover system: field monitoring and numerical modelling. Can Geotech J 60(11):1663–1680. https://doi.org/10.1139/cgj-2022-0310

Ng CWW, Qu C, Guo H, Chen R, Xue Q (2024) Probabilistic analysis of a sustainable landfill cover considering stress-dependent water retention model and copula-based random fields. Eng Geol 332:18. https://doi.org/10.1016/j.enggeo.2024

Öner G (2019) Landfill site selection and landfill liner design for Polatlı, Ankara. Msc. thesis, Middle East Technical University, Department of Geological Engineering

Rathore S, Ahmad SR, Shirazi SA (2016) Use of the suitability model to identify landfill sites in Lahore-Pakistan. Int J Basic Appl Sci 12:103–108

Rezaeisabzevar Y, Bazargan A, Zohourian B (2020) Landfill site selection using multi criteria decision making: influential factors for comparing locations. J Environ Sci 93:170–184

Rigo de Righi M, Cortesini A (1959) Regional studies central anatolian basin, progress report 1. Turkish Gulf Oil Com, Ankara

Saaty TL (1991) Multicriteria decision making - the analytical hierarchy process. RWS, Pittsburgh

Sahnoun H, Serbaji MN, Karray B, Medhioub K (2012) GIS and multicriteria analysis to select potential sites of agro-industrial complex. Environ Earth Sci 8(66):2477–2489

Sener B (2004) Landfill site selection by using geographic information systems. Msc. thesis, Middle East Technical University, Department of Geological Engineering

Sener S, Sener E, Nas B, Karagüzel R (2010) Combining AHP with GIS for landfill site selection: a case study in the Lake Beyşehir catchment area (Konya, Turkey). Waste Manag 30(11):2037–2046. https://doi.org/10.1016/j.wasman.2010.05.024

Sharifi M, Hadidi M, Vessa E, Mosstafakhani P, Taheri K, Shahoie S (2009) Integrating multi-criteria decision analysis for a GIS based hazardous waste landfill siting in Kurdistan Province, Western Iran. Waste Manag 29:2740–2758

Tavares G, Zsigraiová Z, Semiao V (2011) Multi-criteria GIS-based siting of an incineration plant for municipal solid waste. Waste Manag 31:1960–1972

TSWCR (2010) Solid waste control regulation. Ministry of Environment and Forestry of Turkey, Resmi Gazete (Official Gazette) No. 27533, Ankara, Türkiye (in Turkish)

TurkStat (2023) The results of address-based population registration system (ABPRS). Turkish Statistical Institute. https://data.tuik.gov.tr/Bulten/Index?p=The-Results-of-Address-Based-Population-Registration-System-2023-49684. Accessed 31 July 2024

Ünalan G, Yuksel V, Tekeli T, Gonenc O, Seyirt Z, Huseyin S (1976) The stratigraphy and paleogeographical evolution of the upper cretaceous-lower tertiary sediments in the Haymana-Polatli region (SW of Ankara). Bull Geol Soc Turk 19:159–176

Uyan M (2014) MSW landfill site selection by combining AHP with GIS for Konya, Turkey. Environ Earth Sci 71:1629–1639

Yal GP, Akgün H (2013) Landfill site selection and landfill liner design for Ankara, Turkey. Environ Earth Sci 70:2729–2752

Yal GP, Akgün H (2014) Landfill site selection utilizing TOPSIS methodology and clay liner geotechnical characterization: a case study for Ankara, Turkey. Bull Eng Geol Environ 73(2):369–388

Yeşilnacar MI, Suzen ML, Kaya SB, Doyuran V (2012) Municipal solid waste landfill site selection for the city of Sanliurfa-Turkey: an example using MCDA integrated with GIS. Int J Digit Earth 5:147–164

Yoon KP, Hwang C-L (1995) Multiple attribute decision making: an introduction. In: Quantitative applications in the social sciences, vol 104. Sage Publications, Thousand Oaks, CA