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Integration of Multicriteria Decision Analysis and GIS for Evaluating the Site Suitability for the Landfill in Hargeisa City and Its Environs, Somaliland

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Abstract: Poor waste management and illegal waste shipments adversely affect the environment and public health, resulting in environmental degradation. Indeed, environmental degradation is one of the most visible problems in Hargeisa. Currently, solid waste is disposed of at two dumping sites within the city limits, causing problematic and unsanitary conditions. Moreover, the existing dumpsites are on the verge of closure, highlighting an important need that must be addressed. This research aimed to integrate multicriteria decision analysis and GIS to evaluate the site suitability for landfill in Hargeisa, Somaliland. For this purpose, eleven significant parameters were selected: proximity to built-up areas, surface water, groundwater well points, sensitive sites (airports), land use/land cover, geology, soil type, elevation, slopes, roads, and separation from existing dumpsites. Next, these were combined via an analytical hierarchy technique. Subsequently, restriction buffer analysis was performed on the seven parameters to obtain better and more accurate results, and restricted zones were omitted. Furthermore, the pair-wise comparison used to obtain priorities between the selected criteria showed that the LULC is the most significant criterion in the model, with a relative weight of 0.1829, followed by habitations, with 0.1506. The overall result reveals that approximately 68.96% (21,060.9 ha) of the study area is unsuitable, while 24.36% (7441.53 ha) and 6.68% were considered less and highly appropriate zones, respectively. As a result, this study reveals that despite the vast extent of the study area, the areas ideal for landfill remain severely limited. Therefore, in light of the findings of this study, the municipal council of Hargeisa must reevaluate dumpsite locations and waste management practices to address the issues in the region in a timely manner. Furthermore, this systematic research approach will assist regional and global researchers, policymakers, and municipal governments.

Keywords: analytic hierarchy process; GIS; landfill site; multicriteria decision analysis; solid waste

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1. Introduction

Solid waste management is a global concern, particularly in developing nations, where the availability of sanitary landfill is poor due to rapid population growth and urbanization [1]. Because of urbanization and rapid growth, the generation of solid waste has also increased dramatically [2]. Similarly, in the Hargeisa study region, the population and economic growth due to urbanization have increased the amount of municipal waste [3]. Nonetheless, the estimated number of people residing in Hargeisa is approximately one million, with an average annual population growth rate of 3.1% [4]. This means that the city has doubled its inhabitants in the past ten years. Accordingly, the city has expanded remarkably in all directions, and many new areas are emerging. Despite having the city's fastest rate of population increase, it lacks a landfill system to handle the solid waste produced, and open dumping is widely practiced.

In African countries, roughly 95% of the solid waste produced from different sources is discarded at the peripheries of cities or in open dumpsites [5]. In the context of Hargeisa, the city municipal council (CMC) has not allotted any land for solid waste processing, and, so far, no such facility has been created. Additionally, the city produces more solid waste than its current disposal sites can handle, underscoring the need for a new sanitary landfill system. Moreover, the existing dumpsite (south dumping site—one) is so close to the airport (4.6 km) that it reduces aircraft visibility. Thus, the airport authorities are highly concerned about this threat and have requested that the municipal authority close or shift this site. Therefore, to accommodate the generated solid waste from the municipality, it is crucial to propose a new, reliable solid waste landfill site for the city by considering ecological, environmental, and socio-economic aspects.

Recent studies [6,7], from various African nations have found that the continent's solid waste management is frequently weak due to poor planning, poor governance, outdated technology, a lack of enforcement of current laws, and a lack of financial and economic incentives to encourage environmentally sound development. This situation is much worse with regard to low-income nations [8]. In brief, both developed and developing countries have faced serious and inevitable problems related to solid waste generation [9]. The city's growing population and economic activities produce much solid waste in Somaliland. In addition, solid waste generation in the study area is observed at an increasing rate compared to the management response.

Moreover, the city's per capita solid waste generation rate is 0.4 kg/capita/day [10]. This figure is expected to rise because of population growth. In addition, only roughly half of the generated solid waste is collected and dumped at the open dumpsites on the city's outskirts.

In contrast, good solid waste disposal design and site practices can greatly reduce the danger of environmental pollution and public health issues posed by an inefficient system, which is common in poor countries [2,10,11]. However, creating a secure place for solid waste disposal is not an easy task; it is time-consuming, costly, and necessitates numerous difficult steps. This, moreover, necessitates understanding from a variety of fields, including geology, environmental science, urban planning, soil science, and hydrology [1,12].

On the other hand, various techniques and approaches have been employed by numerous scholars to identify ideal locations for landfills, particularly in major cities around the globe. Among them are the Ratio Scale Weighting (RSW) method [13]; the integration of the fuzzy MCDM method, i.e., fuzzy analytic hierarchy process (FAHP) [14]; the decision-making trial and evaluation laboratory (DEMATEL) method [12]; and the fuzzy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method [15]. A recent study used a GIS-based analysis for sanitary landfill sites in Abuja, Nigeria [11]. However, the aforementioned study did not consider multicriteria decision analysis when using the GIS technique. In addition, [16] studied landfill location by fuzzy TOPSIS for Istanbul. In contrast, [17] reported that the conventional TOPSIS model has several drawbacks, such as an inability to generate a strong correlation between criteria. Moreover, this may result in uncertainty in obtaining weights. Because of this, accurate results might be found through the integration of GIS with AHP techniques [18].

As a result, one of the most recently emerged multicriteria decision analysis (MCDA) methodologies, the analytic hierarchy process (AHP), has been used in selecting potential landfill sites to identify an ideal location with low socio-economic and environmental repercussions [19]. In the previous two decades, it has become increasingly popular for this purpose. Furthermore, the versatility of the GIS-based multicriteria evaluation (MCE) technique in managing large amounts of geographical data from many sources makes it an ideal tool for such studies [20]. However, the experts' opinions on the weighting scale might produce different results [21]. Nonetheless, so far, because of its simplicity in pair-wise comparisons, consistency in evaluation, and adaptability, the AHP is chosen as the best method from a selection of possible techniques and provides the decision makers with an accurate solution [22]. Besides its many advantages, recent studies have reported the usefulness of integrated AHP and GIS techniques [22–24]

Various studies on solid waste management have been conducted throughout the country, including [3] on sustainable waste management in the construction industry and [25] on constraints for solid waste management in Somaliland. However, this current study is novel for the municipal area of Hargeisa, as this is the first of its kind using advanced GIS techniques with the integration of AHP, restriction analysis, and selection criteria. With this purpose, the current study aims to integrate multicriteria decision analysis and GIS to evaluate site suitability for landfill in Hargeisa City and its environs, Somaliland. As a result, it will reduce the related costs, time, and environmental and socio-economic impacts, leading to the sustainable management of solid waste as part of the sustainable development goals (SDG).

2. Materials and Methods

2.1. Description of the Study Site

Hargeisa is situated in a valley in the Galgodon (Ogo) highlands and sits at an elevation of 1334 m above sea level (4377 ft.). Figure 1 depicts the latitude and longitude of the city at 9°34′ N and 44°4′ E, respectively. The area of the city totals 56 sq. km and it encompasses eight districts within its administrative boundaries. It represents the capital of Somaliland and its main gateways with trading centers to all regions in Somaliland and neighboring countries. Additionally, the climate of the study region is warm and dry, with semiarid conditions. From the historical temperature records, the average maximum and minimum temperatures of the area can be determined. Accordingly, the maximum and minimum annual average temperature of the study area are 25.9 °C and 23.9 °C, respectively. Moreover, Somaliland has a bimodal rainfall distribution with average annual rainfall levels of 400 to 500 mm.

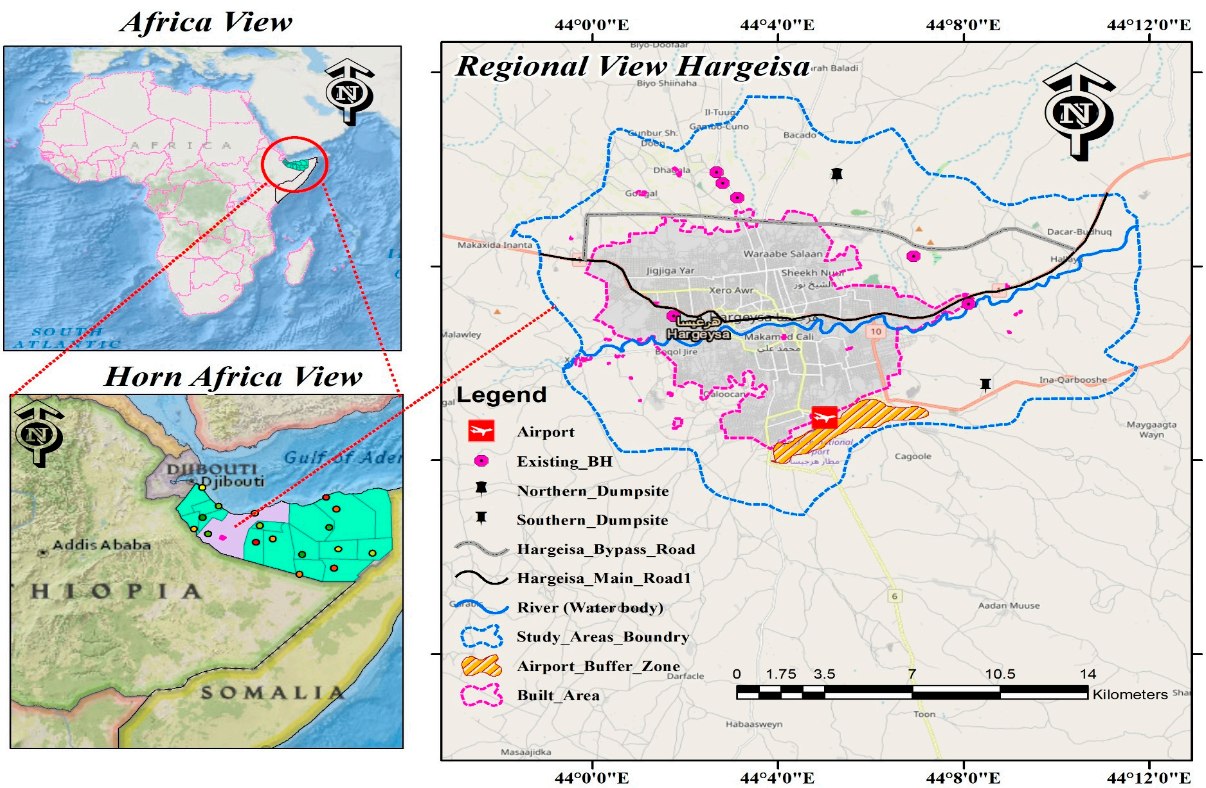

Figure 1. Map of the study area.

Furthermore, there are fewer weather-related hazards in Hargeisa City; there has not been any recent seismic activity. However, flooding occurs during periods of rainfall due to a shortage of storm drains, caused by inadequate urban infrastructure and blocked drains due to haphazardly dumped waste. Therefore, it is crucial to identify new landfill locations for the City of Hargeisa in order to properly dispose of municipal solid waste (MSW) while taking into account pertinent environmental, social, and economic considerations.

2.2. Current Status of Municipal Solid Waste Management in Hargeisa

The effects of solid waste on the environment, human health, society, and the economy are becoming a major threat, particularly in low-income nations [6,26]. A similar problem was encountered in the study area, where medical waste is mixed with municipal waste, posing a serious threat to the health and environment of the workforce, rag pickers, and the general public.

Solid waste management is a principal function of the municipal council. However, the municipal authority, primarily responsible for managing solid waste, lacks in-house capabilities and adequate finances to manage solid waste effectively. As a result, the citizens generally dispose of their solid waste on the streets and open spaces around them, creating unhygienic conditions. Moreover, plastic bags are seen littered all around and stuck on trees and bushes. Likewise, street sweepers only operate around commercial areas and on main streets. However, municipal solid waste management by-laws [27] made it mandatory not to leave solid waste on the streets and to separate solid waste at the source into biodegradable and non-biodegradable solid waste. Thus far, for various reasons, the municipal authority has not been able to implement these by-laws. As a result, even the solid waste that has been collected and transferred officially is dumped at unregulated open dumpsites. As a result of environmental pollution and other aesthetic effects, it is also challenging to fulfil the minimum criteria set by environmental protection agencies.

On the other hand, existing dumpsites were not given scientific appraisal when introduced. Moreover, in [10], a feasibility study noted the imminent need for a sanitary landfill, as well as the closure of current dumpsites. Thus, the insufficient solid waste service is anticipated to impact this city's productivity and economic growth negatively. Therefore, it is essential to introduce new, appropriately evaluated, alternative disposal sites to meet the exponentially growing population's solid waste disposal needs.

Inadequate storage of solid waste at the source, a lack of separation of recyclable solid waste, a lack of primary collection of solid waste from households, irregular street sweeping, inappropriate and unhygienic secondary storage of solid waste, irregular transport of solid waste in open vehicles, a lack of treatment of solid waste, and unhygienic solid waste disposal are only a few of the obvious deficiencies in the city's solid waste management [10].

Therefore, to identify sustainable solutions to these general problems in Hargeisa, it is vital to research and suggest appropriate landfill locations. Thus, this study contributes to the provision of pertinent information necessary for the selection of suitable solid waste management sites.

2.3. Current Status of Municipal Solid Waste Disposal Sites in the Studied Area

The entirety of the solid waste of the city is disposed of at dumping grounds and untreated. Valuable resources are often burnt. The city municipal council has adopted crude dumping as a method of solid waste disposal. Municipal solid waste is disposed of in only two dumpsites within the city limits, resulting in problematic and unsanitary conditions (Figure 2).

Figure 2. Open dumping and burning of solid waste, including medical waste, at the dumpsites: (**a**) north dumping site—two (**b**) south dumping site—one.

South dumping site—one:

Generally, the solid waste disposal sites, including the roadways, are poorly managed. Solid waste is haphazardly dumped in open spaces. Additionally, the solid waste is neither spread nor covered. The site is occupied by birds and baboons. Smoke is seen emanating from the heaps of solid waste, posing a serious threat to human health, the environment, and the safety of aircraft. Burning of solid waste is used to reduce the solid waste's volume, resulting in air pollution by releasing pollutants such as dioxins. There is no segregation of solid waste. The solid waste contains a great deal of plastic, tin, metals, and glass, which can be recycled [10].

The dumpsite is located only 4.6 km from the airport, significantly impacting aircraft movement. The airport authorities are greatly concerned about this threat and have requested that the municipal authority close or shift this site. Moreover, the site is located on the hillside; the leachate/contaminated water flows down the slope and contaminates the downstream region. Furthermore, the strong winds transport plastic bags around the area, significantly affecting the activities and health of the surrounding community [10].

North dumping site—two:

This is the largest dumpsite in the city. Previously, it was located far from habitation, but plots for housing have been implemented very close to the site. At both municipal solid waste disposal sites, there has been no digging of pits/holes. Solid waste is being directly dumped and burnt. The solid waste disposed of at the earlier site (old disposal site) near the present site has not been capped. Citizens are required to dispose of it at the new disposal site, which is not far away. The same procedure of burning solid waste is adopted at the new location. Once the fire is extinguished, the ashes are moved aside so that new solid waste can be dumped and burned. In addition, since both the old and the new solid waste disposal sites are located on a hilltop, the flow of the contaminated water during rainfall travels down the valley towards the streams and drinking water sources/wells near the area [10].

Moreover, although some scavenging is done at the site by rag pickers, tin, glass, and plastic bags are still not picked up. In addition, during strong winds, plastic bags are transported over long distances and suspended around the community. Therefore, the sustainability of the environment and public health is more seriously threatened by open burning, leachate leakage, and disturbances from the north open dumping site [10].

Considering all the aspects mentioned above, this study was designed to identify the best future solid waste landfill sites for the City of Hargeisa, using GIS-based analytical hierarchy processes.

2.4. Simulation Model Design

Figure 3 displays the developed methodology applied in this study. Eleven determinant factors were used in the current study, including proximity to existing dumpsites, surface water and river access, boreholes (distance to water wells), distance from airport and main roads, land use/land cover (LULC), geology, soil type, elevation, and slope.

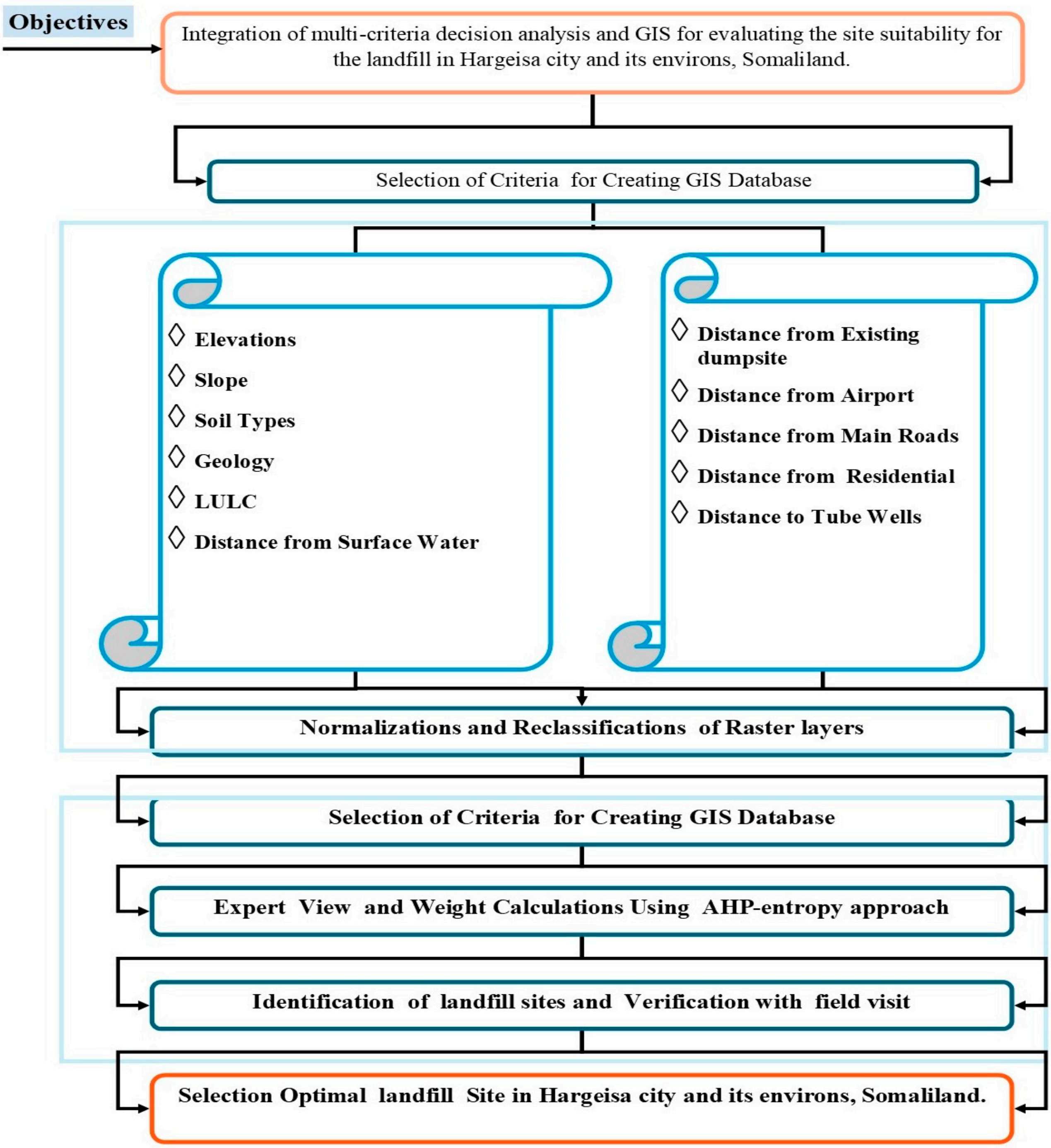

Figure 3. The methodological framework used in the study.

2.5. Data Collection and Processing

To successfully investigate the entire region and assess the level of suitability for the area, technical and social data were also collected using both primary and secondary sources. Additionally, information was gathered from a variety of sources, including the most recent multispectral satellite pictures, cloudless Landsat geo-referenced data, DEM, and professional opinions (Table 1). Several software programs, including ERDAS Image 2015 and ArcGIS 10.3, were used to do this. According to [28], one of the most accurate types of elevation data that is currently freely available is derived from the Shuttle Radar Topographic Mission (SRTM), a digital elevation model (DEM) dataset with a 12.5 m spatial resolution. From the Open Street Map website (https://www.openstreetmap.org), (Accessed on 10 December 2022) road data were downloaded. A portable global positioning system (GPS) was used to gather data on airports and existing dumpsites in the research area. The geology and soil of the research region were retrieved from the geological and soil datasets that were obtained from Somalia Water and Land Information Management (SWALIM) (https://faoswalim.org) (accessed on 5 January 2023). First, using the ArcGIS 10.3 software, all criteria utilized in this study were geo-referenced and transformed into raster format in order to be ready for categorization and standardization. Thus, all criteria were then geo-referenced to zone 38 N of the UTM projection system. The spatial resolution of 12.5 m was achieved by rasterizing and resampling the vector datasets. Secondly, using the spatial analyst tool in the ArcGIS 10.3 software, all input datasets were reclassified, ranked, and then standardized into unsuitable, less suitable, suitable, moderately suitable, and very suitable zones, with their given weights ranging from 1 to 5. By using the AHP technique, where the consistency ratio was assessed, weights were assigned to each thematic dataset. Following the integration of these datasets using the weighted linear combination (WLC) method, a map of the suitability of solid waste landfill sites was created. Finally, using the predetermined eleven influencing parameters, very suitable sites in the study area were identified.

Table 1. Datasets used in the study.

No.	Map Layer	Data Source
1	Base map	Map of the area (1:50,000), satellite images from Landsat-8 (12.5 m)
2	Dumpsite locations	GPS handheld data collection with Google Earth verification
3	Well data	SWALIM https://faoswalim.org (accessed on 5 January 2023).
4	LULC	Landsat-8 satellite imagery (12.5) with Google Earth verification
5	Road map	Open Street Map
6	Slope map	ASTER-DEM (12.5) http://earthexplorer.usgs.gov/ (accessed on 25 December 2022)
7	Elevation	ASTER-DEM (12.5) http://earthexplorer.usgs.gov/ (accessed on 25 December 2022)
8	River	Google Earth pro
9	Airport	GPS handheld data collection with Google Earth verification
10	Geological structure	SWALIM https://faoswalim.org (accessed on 5 January 2023).
13	Soil information	FAO-SWALIM Organization funded by EU https://faoswalim.org (accessed on 5 January 2023).

2.6. Application of GIS-Based Multicriteria Decision Analysis in Landfill Site Selection

2.6.1. Analytic Hierarchy Process

Using Equations (1)–(7), the AHP was performed. The multicriteria decision analysis (MCDA) technique known as AHP was developed in [29,30]. In this study, the AHP–entropy technique was employed to analyze data from a questionnaire survey. Therefore, specialists with in-depth knowledge and experience in choosing solid waste dumpsites were invited to take part in the survey. Additionally, after normalizing the matrix value total and dividing it by numerous criteria, the weights for each criterion were determined. Due to the ability to statistically evaluate the judgment's accuracy, this technique is more dependable [28].

Moreover, the fundamental steps in applying the AHP approach are as follows [31].

Step 1—Compare the factors: With nine levels of intensity, using the scale in Appendix A Table A1, the pair-wise matrix was constructed using the perspectives of the experts [16], which are shown in Appendix A Table A2. In addition, the pair-wise comparison matrix was calculated using the following equation:

$$comparison\ matrix = \begin{bmatrix} C11 & C12 & C13 \\ C21 & C22 & C23 \\ C31 & C32 & C33 \end{bmatrix} \quad (1)$$

where C_{11} represents the *i*th row's (first row) and jth column's (first column's) respective values in this comparison matrix.

Step 2—Complete the matrix: The matrix's values were added independently for each column [32]. Additionally, the column sums of the pair-wise matrices are given by the following equation:

$$\mathrm{Cij} = \sum_{i=1}^{n} Cij \quad (2)$$

Step 3—Matrix normalization: The normalization for each column value could then be expressed using the following equations, as shown in Appendix A Table A3.

$$\mathrm{Xij} = \frac{Cij}{\sum_{i=1}^{n} Cij} = \begin{bmatrix} X11 & X12 & X13 \\ X21 & X22 & X23 \\ X31 & X32 & X33 \end{bmatrix} \quad (3)$$

Step 4—Weight determination: After normalization, the row sum in the normalization matrix was divided by the total number of criteria [14]. The following shows how the priority vector's criteria weights were calculated:

$$\mathrm{Wij} = \frac{\sum_{j=1}^{n} Xij}{n} = \begin{bmatrix} W11 \\ W12 \\ W13 \end{bmatrix} \quad (4)$$

Step 5—Calculate the consistency ratio (C.R.): Only the consistency ratio (C.R.) value may be used to evaluate the judgment value's trustworthiness. As a result, when the C.R. value was less than 0.10 (10%), the comparison matrix was consistent, as indicated by [29].

Step 5A—*Lambda* (λ) max: The average value of each consistency vector was used to calculate the principal eigenvector (λmax). The following is the equation that was used to obtain the principal eigenvalue (λmax) [18].

$$\lambda_{\max} = \sum_{i}^{n} CVij \quad (5)$$

Step 5B—The consistency index (CI): This was chosen to assess the degree of a matrix's departure from consistency. The value of λmax was highlighted as being necessary for the discussion of the consistency ratio calculation [33]. The consistency index (CI) was calculated as follows:

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - n}{n - 1} \quad (6)$$

where λmax is the maximum eigenvalue and n represents the number of criteria.

Step 5C—Random index (R.I.): The only factor affecting the random index was how many elements were compared. Table 2 displays the random index values for the consistency index.

Table 2. Random index values for the consistency index [29].

n *	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.51	1.54	1.56	1.57	1.58

* n = order of the matrix.

Step 5D—Consistency ratio (C.R): Comparing the CI with the random index resulted in the development of the final consistency ratio [29], as shown in Appendix A Table A4.

$$C.R = \frac{CI}{CR} \quad (7)$$

The current study's C.R is 0.05 and is less than 0.10. If the obtained C.R is higher than this threshold, the judicial response in the pair-wise comparison matrix is regarded as inconsistent, and the process needs to be re-performed [28]. It, therefore, suggests that the weights assigned were appropriate. Additionally, the model accurately reflected the degree of reality present in the research area, demonstrating the method's efficacy in locating and mapping suitable landfill locations.

2.6.2. Applications in GIS

Normalization of Selected Criteria

The datasets had distinct categorization units and needed to be rasterized before they could be combined into a single measuring unit for further analysis. Moreover, the weighted criteria were divided into sub-classes and listed on a common preference scale from 1 (least liked) to 5 (most favored) [34]. In order to normalize the datasets, an integer value between 1 and 5 was assigned to each, utilizing the reclassifying tool in the ArcGIS10.3 program. This is a helpful tool for spatial decision making (Table 3).

Table 3. Suitability score [34].

Score	Suitability
1	Unsuitable
2	Less Suitable
3	Suitable
4	Moderately Suitable
5	Highly Suitable

However, the solution of landfill selection issues has been made easier with the incorporation of GIS and the AHP approach [35].

Criteria Restriction Mapping

In order to create a binary mask layer with the values 0 and 1, all gathered restricted layers were merged using a raster calculator tool in the spatial analysis [36]. As a result, a value of 0 for the unsuitable regions and a value of 1 for the suitable areas was assigned to the restricted and non-restricted areas, as illustrated in Figure 4**.** The exclusionary regions for waste disposal sites that were not included in the suitability mapping are shown in Table 4.

2.7. Criteria Used

2.7.1. Distance from Rivers and Surface Water

Solid waste dumped near rivers causes environmental, agricultural, and public health issues. Because of this, municipal solid waste disposal (MSWD) sites should not be located close to surface waters [37]. The proximity map was reclassified. As a result, the region surrounding these water bodies is judged inappropriate for solid waste storage because doing so could harm humans and the environment [38]. A 250 m protective barrier was erected around rivers and surface waters in the study zone to ensure that the water bodies were not contaminated, and this area was omitted from the solid waste model. These scenarios were taken into account when creating the site map for the solid waste dumpsite (Table 5 and Figure 5a). Accordingly, 5.0% of the area was unsuitable, 4.48% was less suitable, 4.19% was suitable, 4.06% was moderately suitable, and 82.25% was highly suitable for solid waste disposal in Hargeisa.

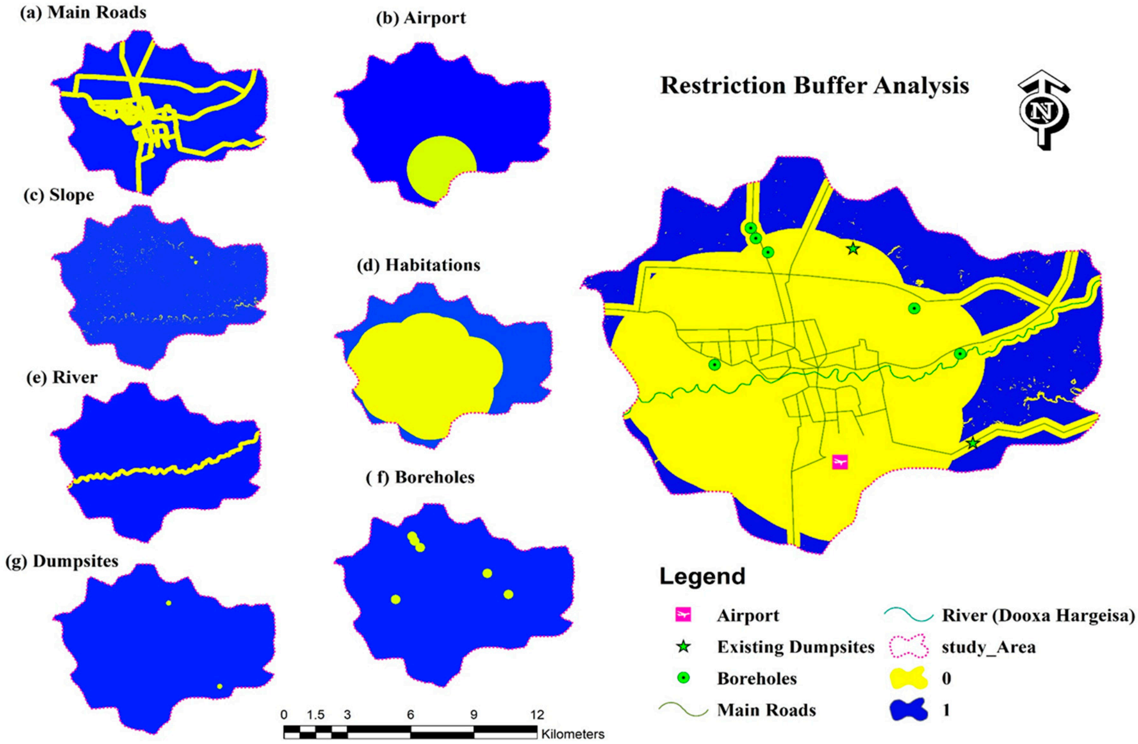

Figure 4. Restriction buffer analysis used for (**a**) roads, (**b**) airport, (**c**) slope, (**d**) habitation, (**e**) rivers, (**f**) boreholes, and (**g**) dumpsites.

Table 4. Exclusionary criteria for landfill sites in the study area.

Criterion	Parameter *	Suitability Score	Rank	Area in Hectares
Slope	0–30% >30%	Suitable Unsuitable	1 0	30,240.7 301.547
Habitation	0–3000 >3000	Unsuitable Suitable	0 1	18,824.8 11,732
Water bodies	0–250 >250	Unsuitable Suitable	0 1	1530.23 29,026.6
Airport	0–4000 >4000	Unsuitable Suitable	0 1	4226.44 26,328.4
Existing dumpsites	0–500 >500	Unsuitable Suitable	0 1	56.0313 30,500.8
Roads	0–300 >300	Unsuitable Suitable	0 1	7536.2 23,020.6
Wells	0–500 >500	Unsuitable Suitable	0 1	444.469 30,112.3

* All parameters are in meters, except slope in %.

Table 5. Description of criteria and sub-criteria of the input layer.

Criterion	Sub-Criterion	Ranking	Area		Level Suitability	Reference
			(Hectares)	Percentage (%)		
Elevation	<1195	5	1728.94	5.65	Highly Suitable	[39]
	1195–1245	4	7152.09	23.40	Moderately Suitable	
	1245–1295	3	10,336.80	33.82	Suitable	
	1295–1345	2	8537.31	27.93	Less Suitable	
	>1345	1	2800.88	9.16	Unsuitable	
Distance from water bodies	<250	1	1530.23	5.0	Unsuitable	[17,40]
	250–550	2	1369.28	4.48	Less Suitable	
	550–750	3	1281.84	4.19	Suitable	
	750–1000	4	1242.2	4.06	Moderately Suitable	
	>1000	5	25,133.2	82.25	Highly Suitable	
Distance from the built-up area	<3000	1	18,824.8	61.60	Unsuitable	[40]
	3000–4000	2	3735.34	12.22	Less Suitable	
	4000–5000	3	2917.48	9.54	Suitable	
	5000–6000	4	2185.16	7.15	Moderately Suitable	
	>6000	5	2894.06	9.47	Highly Suitable	
Slope	<20	5	29,077.1	95.20	Highly Suitable	[38]
	21–30	4	1163.59	3.80	Moderately Suitable	
	31–40	3	234.422	0.76	Suitable	
	41–51	2	56.5	0.18	Less Suitable	
	>51	1	10.625	0.03	Unsuitable	
LULC	Water bodies	1	6.09375	0.01	Unsuitable	[39]
	Built-up areas	2	4412.47	14.44	Less Suitable	
	Agricultural areas	3	324.34	1.21	Suitable	
	Shrubs	4	5349.94	17.51	Moderately Suitable	
	Bare land	5	20,432.5	66.89	Highly Suitable	
Geology	Auradu Limestone (Ea)	1	273.797	0.89	Unsuitable	[1]
	Sands, silt, and gravels (Q)	5	19,672	64.37	Highly Suitable	
	Yesomma sandstones (Ky)	3	10,611	34.72	Suitable	
Distance from an existing dumping ground	<500	1	157.03	0.51	Unsuitable	[28]
	500–1000	2	470.50	1.53	Less Suitable	
	1000–1500	3	779.23	2.55	Suitable	
	1500–2000	4	928.57	3.03	Moderately Suitable	
	>2000	5	28,221.5	92.35	Highly Suitable	
Distance from main road	<750	5	14,456	47.30	Highly Suitable	[9]
	750–1500	4	7884.61	25.80	Moderately Suitable	
	1500–2250	3	4077.53	13.34	Suitable	
	2250–3000	2	2096.19	6.85	Less Suitable	
	>3000	1	2042.5	6.68	Unsuitable	
Distance from wells (GW protections)	<500	1	444.46	1.45	Unsuitable	[1]
	500–1000	2	1099.91	3.59	Less Suitable	
	1000–1500	3	1723.19	5.63	Suitable	
	1500–4500	4	16,640.1	54.45	Moderately Suitable	
	>4500	5	10,649.1	34.85	Highly Suitable	
Soil type	Calcaric Camisoles	3	26,746	87.52	Suitable	[1]
	Chronic Cambisols	3	107.047	0.35	Suitable	
	Eutric Leptosols	1	3703.78	12.12	Unsuitable	
Distance from airport	<4000	1	4229.7	32.31	Unsuitable	[40]
	4000–5000	2	2030.78	15.51	Less Suitable	
	5000–6000	3	2080.31	15.89	Suitable	
	6000–7000	4	2234	17.07	Moderately Suitable	
	>7000	5	2511.34	19.19	Highly Suitable	

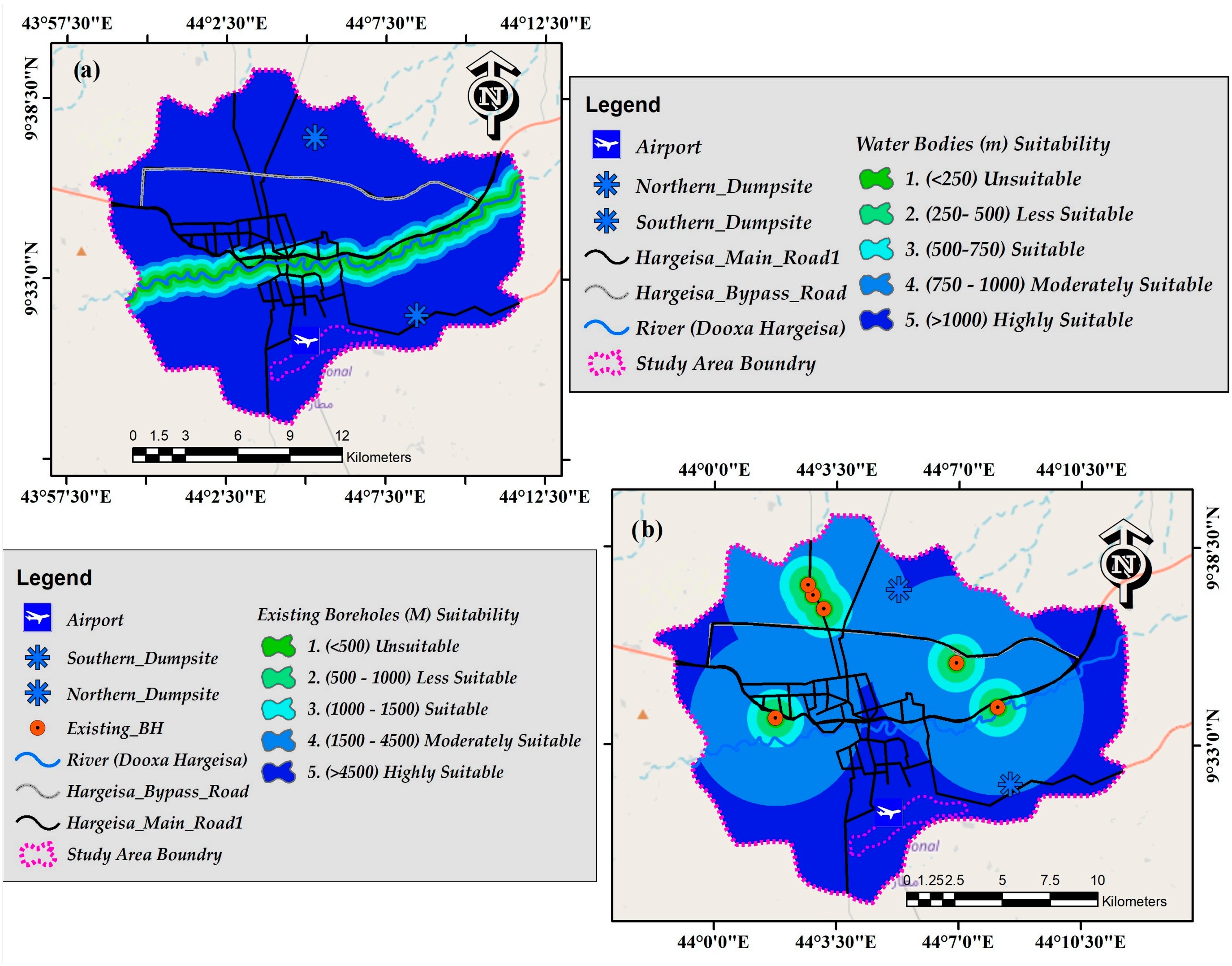

Figure 5. Landfill site suitability criteria for (**a**) water bodies, (**b**) distance from boreholes.

2.7.2. Distance from Groundwater Discharge Points (Boreholes)

Numerous studies show that landfill sites should not be located within 500 m of deep or shallow boreholes [17]. A distance of less than 500 m was deemed undesirable in the current study, 500–1000 m was designated less suitable, 1000–1500 m was deemed suitable, 1500–4500 m was perceived to be suitable, and beyond 4500 m was considered highly suitable (Table 5 and Figure 5b). According to the analysis, the overall research area has 34.85% highly suitable, 54.45% suitable, 5.63% moderately suitable, and 3.59% and 1.45% less suitable and unsuitable areas, respectively (Table 5 and Figure 5b).

2.7.3. Distance from Urban Areas

When municipal solid waste disposal facilities are constructed close to residential areas, many environmental problems may arise [18]. Therefore, in this study, regions within 3000 m of residential areas were eliminated from the analysis. Thus, the remaining areas were divided into five distinct groups by taking into account all the recommended safe distances in the literature and local data on the rate of city growth. Minimum distances from the settlement areas in the study area were determined as follows: at least 3 km for urban centers was considered unsuitable, 3000–4000 m was less suitable, 4000–5000 m was moderately suitable, 5000–6000 m was suitable, and above 6000 m was highly suitable (Table 5). Figure 6a displays the spatial findings of the distance from urban regions. Overall, 61.60% and 12.22% of the research area are inappropriate and less suitable, respectively.

Meanwhile, 9.47%, 7.15%, and 9.54% of the region are, respectively, very, moderately, and highly suitable for waste disposal locations.

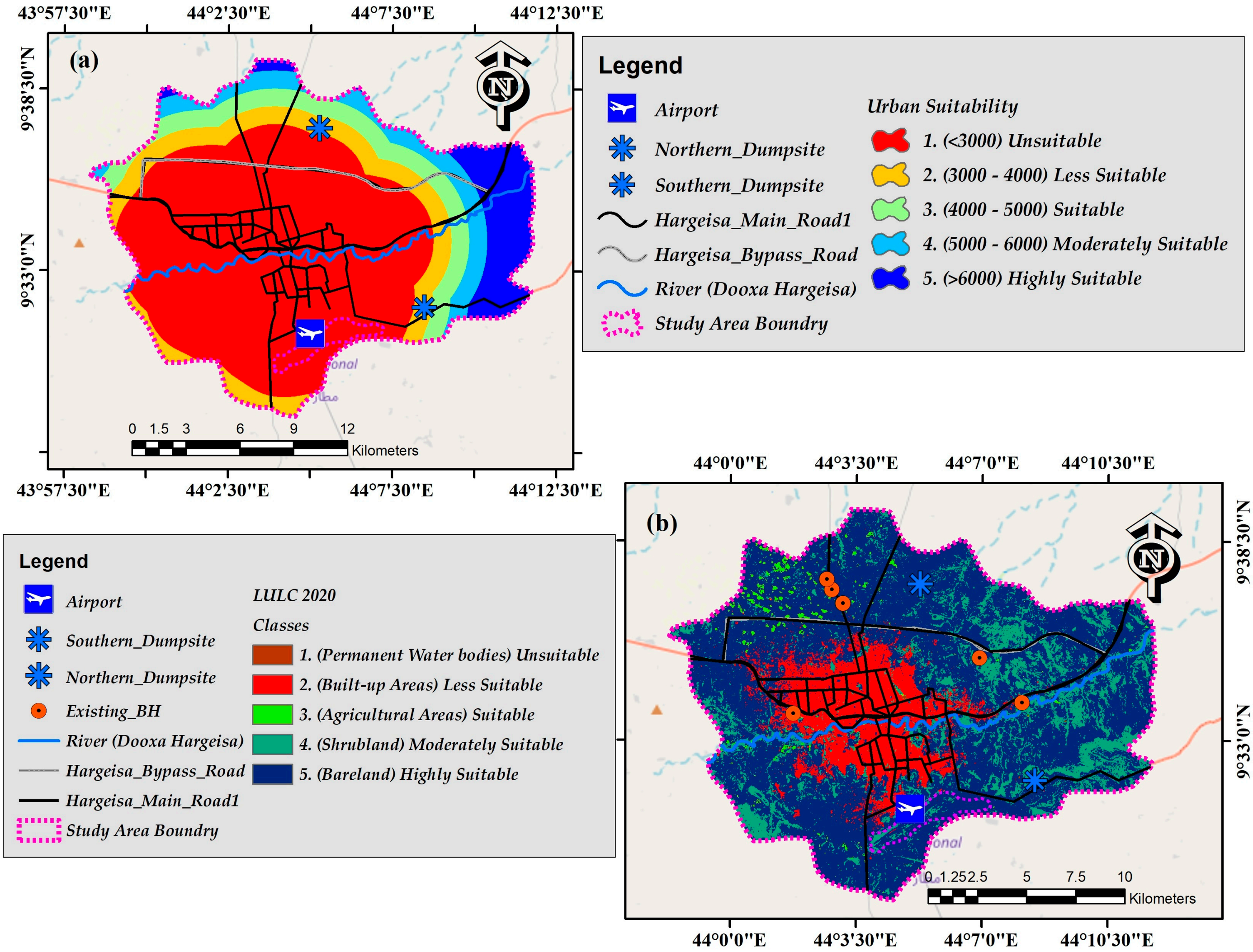

Figure 6. Landfill site suitability criteria for (**a**) urban areas, (**b**) LULC.

2.7.4. Land Use Land Cover

People seek out free space by moving to the city's peripheries due to the large population increase. Based on this, LULC suggests where potential additional landfill sites might be placed [30]. As a result, on 16 November 2022, the research area's raw satellite data were obtained utilizing the website (https://scihub.copernicus.eu) (accessed on 5 January 2023). To construct a mosaic raster of the research region, six bands of the raw data were joined; the pre-processed mosaicked image improved the raw data's image quality. Spectral signatures gathered from training samples (polygons that represent separate sample areas of the various land cover types to be categorized) were used to perform supervised classification on the satellite data. The maximum likelihood classifier subsequently applied labels to every image pixel in accordance with the training parameters to produce a land cover map of the research area after creating the signature file. The study area's land use/land cover map was then created using Google Earth verification. These methods of classification allowed for the division of a region's land use/land cover into five main groups: agricultural areas, bare land, water bodies, settlements, and shrub land. The distribution of land use is shown in Table 5, and it shows that approximately 1.21% of the study area is used for agricultural purposes. According to the land use and land cover map, bare land + shrub land represent around 84.4% of the total area. According to Figure 6b, urban areas and aquatic bodies constitute around 14.45% of the total area.

2.7.5. Geology (Lithology) of the Study Area

The geomorphic map of the study region was received from FAO-SWALIM (https://faoswalim.org) (accessed on 5 January 2023), and the geological map of the study area was created by digitizing and converting it into a grid map (12.5 × 12.5 m resolution). Thus, over a sufficiently thick, impermeable basis, a landfill can be constructed [20] by preventing contaminant movement and landfill leakage, which could pollute groundwater [41]. The produced map has been classified into four rock types: sand, silt with gravel, Auradu limestone, and Yesomma sandstone.

As stated in [42], the following explanation for the variation in lithological units can be applied in the examined area. Regarding gravel, sand, and silt, a heterogeneous mixture of boulders, gravel, sand, and silt constituted this unit. In comparison to gravel and sand, silt has lower permeability and a higher rate of self-purification because of its small grain sizes, platy structure, and electrostatic forces. Therefore, it is advisable to establish a landfill where there are silty particles between sand and gravel particles. These deposits received the highest weight value because they are thought to indicate the ideal location for a landfill [40]. The Auradu limestone rocks of the limestone formation exhibit significant karstic permeability and resistant qualities at the following level. These regions had lower weight values because they were determined to indicate more inappropriate units.

On the other hand, semipermeable rocks (such as the Yesomma sandstone) were given a moderate suitability rating. As a result, the map below displays the geospatial distribution and area coverage of this suitability modeling. Approximately 64.370% (19,672 ha) of the study area is highly suitable for a landfill disposal site. Meanwhile, areas considered suitable (10,611 ha) and unsuitable (273.797 ha) for landfill amount to approximately 34.72% and 0.897%, respectively (Table 5 and Figure 7a).

2.7.6. Distance from Main Roads

A municipal solid waste disposal site near the main roads may result in aesthetic concerns that impede the region's economic growth in tourism or residential regions [41]. On the other hand, it is not economically feasible to carry waste over longer distances [43]. Therefore, exclusion zones were chosen to be 300 m away from roads. However, municipal solid waste disposal facilities should not be located too far away from the existing road system, so as to reduce costs during the planning and construction phases. The remaining areas were classified into five categories after the exclusion zones were established. Those greater than 3000 m were given less weight since they would not be suitable in terms of the transit time or cost. Areas less than 750 m were given the highest weight. Figure 7b displays the predicted distances for the adequacy of the road network. In the study area, 1.45% and 6.68% of the areas were unsuitable and less suitable, respectively; based on the spatial map, the identified areas were located mainly on the outskirts of the city, where the road networks are not advanced, while 47.3%, 25.804%, and 13.34.1% of the area were highly suitable, moderately suitable, and suitable, respectively, for waste disposal sites.

2.7.7. Distance from the Airport

The location of landfills is influenced by the distance between the airport and the disposal site, as birds and dust flow through the air, posing a risk to air traffic [43]. As a result, to avoid risks to aircraft, different studies [22,40] have established various minimum separation distances between airports and waste disposal sites. Thus, to choose a landfill site, a distance of less than 4000 m (32.31%) was deemed unsuitable, and distances of 4000–5000 m (15.51%), 5000–6000 m (15.89%), 6000–7000 m (17.07%), and greater than 7000 m (19.19%) were categorized as less suitable, moderately suitable, suitable, and extremely suitable, respectively (Figure 8a).

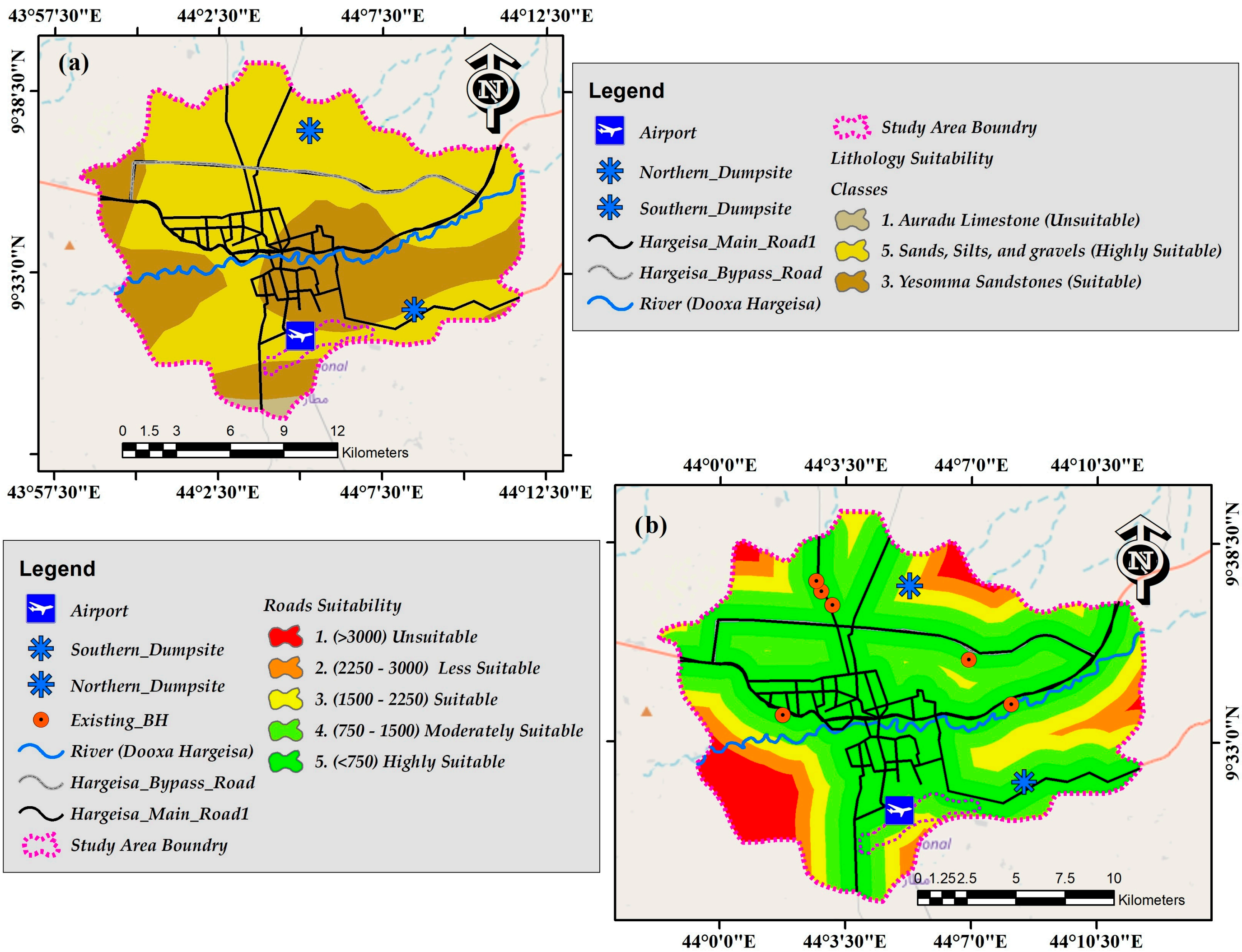

Figure 7. Landfill site suitability criteria for (**a**) lithology, (**b**) main roads.

2.7.8. Soil Type

The process of infiltration is significantly influenced by the composition of the soil. Therefore, ideal candidates are soils with little permeability [28]. Thus, infiltration and leaching into the subsurface are less likely [44]. On the other hand, very permeable soils are inappropriate because they may cause waste to release pollutants into the groundwater [9]. Hence, soil types with a lower infiltration rate were given a greater AHP weight.

From FAO-SWALIM (https://faoswalim.org) (accessed on 5 January 2023), the city's digital soil map was retrieved. Calcaric cambisols, chronic cambisols, and eutric leptosols are the three sub-soil units that represent the two main soil formations that constitute the research area.

Leptosols represent the majority of the soils of Somaliland, covering roughly 29% of the area (49,014 km^2). The mountains (Golis and Karkaar) and the distinct plateaus are where they are typically found [42]. However, as indicated in Table 5 and Figure 8b, this soil class only accounts for around 12.12% of the land (43,703.78 ha) in Hargeisa (the research region). These soils are extremely shallow over continuous rocks, but they are also exceedingly gravelly or stony. As a result, these qualities render these soils unfit for disposal in landfills [44]. Contrarily, the soil texture of cambisols belongs to the loamy group. As a result, these soils, which represent approximately 87.88% of the total area (26,853.047 ha), are moderately acceptable for dumpsites.

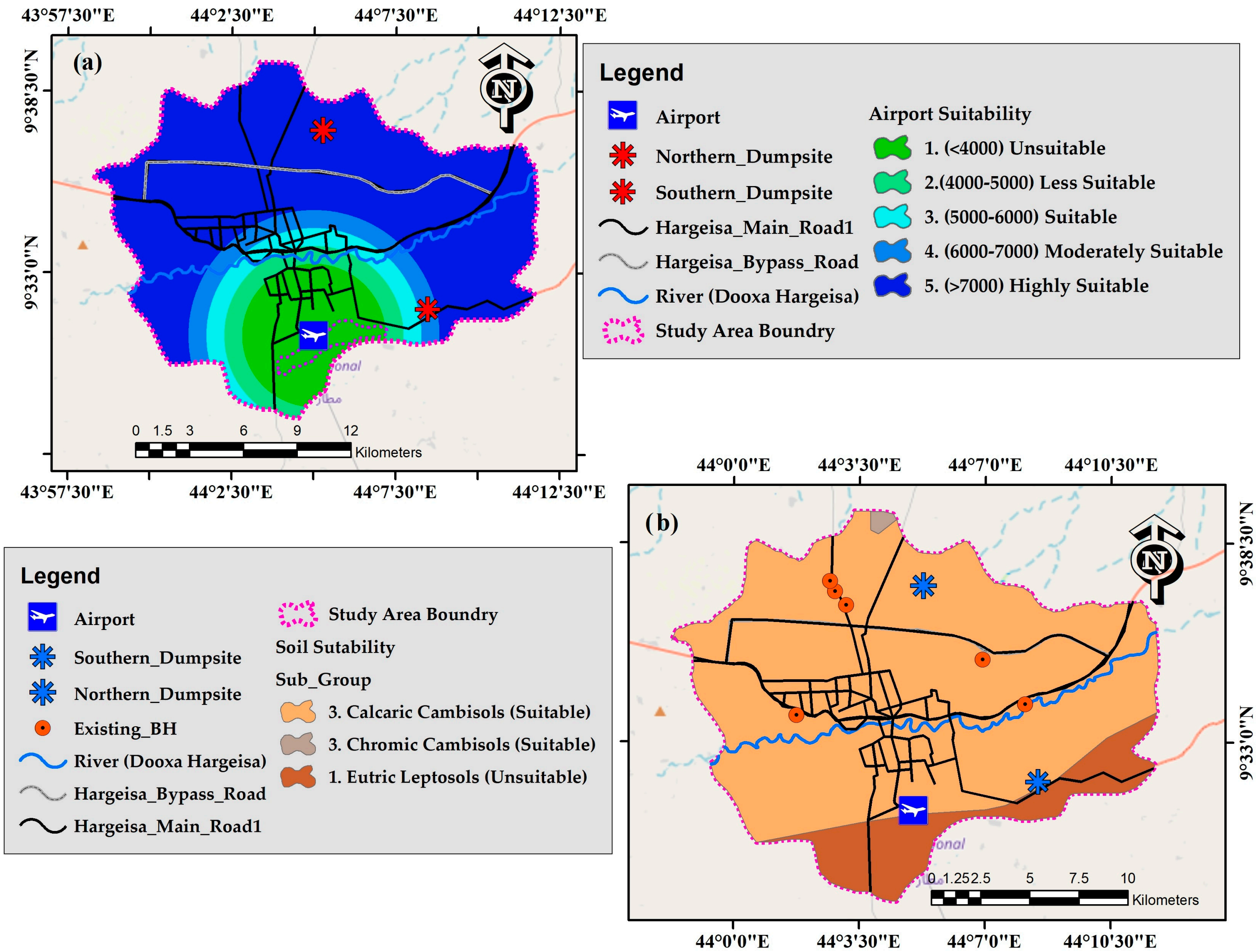

Figure 8. Landfill site suitability criteria for (**a**) airport, (**b**) soil type.

2.7.9. Elevation

Less elevated ground is preferable for waste disposal based on appropriateness level preferences [28]. Therefore, more elevated locations are not preferable for the placement of landfills as they increase construction costs. This criterion has been utilized in several investigations around the world [1,8]. The research area's elevation in this investigation spans from 1145 to 1399 m above the mean sea level (a.m.s.l). As shown in Table 5, the distances were separated into five classes (1145–1195 m, 1195–1245 m, 1245–1295 m, 1295–1345 m, and 1345–1399 m), and rated as extremely suitable, suitable, moderately suitable, less suitable, and unsuitable, respectively.

The research area's northern and northeastern regions, with low elevation (altitudes below 1245 m above sea level), are the best locations for solid waste disposal sites, as indicated in Appendix A Figure A1. In contrast, the central parts of the city, which are located between the southeast and northwestern and western regions (at a height between 1246 and 1399 m above sea level), have less and are not suitable as dumpsites. While 27.93% and 9.16% of the study area are less suitable and unsuitable for waste disposal, respectively, 5.65%, 23.40%, and 33.82% are highly suitable, moderately suitable, and suitable, respectively.

2.7.10. Distance from an Existing Dumping Ground

A landfill should be placed sufficiently far away from another dumpsite to ensure a secure gap between them [45]. In this study, weights were assigned in accordance with appropriateness, and buffer zones such as 0–500, 500–1000, 1000–1500, 1500–2000, and >2000 m were established (Table 5). Additionally, Appendix A Figure A1's map includes a full examination of these criteria.

2.7.11. Slope

The study area's slope map was created using a 12.5 m resolution slope percentage. Areas with steep slopes carry the risk of erosion and expensive construction. In addition, the building of landfills is economically unviable [18]. Thus, a higher degree of slope is technically unfavorable for landfill establishment since the migration of the leachate in a region with a steep slope is thought to contribute to water and soil contamination [41].

According to the reclassified slope map (Appendix A Figure A2), the study area's slope values ranged from 0° to 81°. As a result, the slope was categorized into five classes. The study area has a slope of less than 20 degrees, which is extremely suitable for landfill in the area under investigation. It is also the dominant slope, as it represents 95.20 percent (29,077.1 hectares) of the entire study area. Similarly, [43] highlighted very high landfill suitability for slopes under 20%. Approximately 3.80% (1163.59 ha) and 0.76% (234.422 ha) of the study area is characterized as moderately suitable (21–30%) and suitable (31–41%) for a landfill disposal site, respectively. Areas of low (41%–51%) and very low (>51%) landfill suitability represent approximately 0.18% and 0.03%, respectively (Table 5). Thematic mapping revealed that the majority of the research area zones had flat terrain, making them ideal for dumpsites. However, sections of the study area's middle region have gently sloping terrain along the main river, which runs from the eastern to the western borders.

3. Results and Discussion

Evaluating Candidates for Landfill Site

The selection of appropriate locations for the disposal of solid waste should be based on several factors that represent economic, social-cultural, and environmental aspects [20]. As a result, various sources were used to determine the planned landfill (Table 1).

Using the defined eleven criteria—distance to residential areas, airport, geology (lithology), distance to major roads, distance to surface water, distance to groundwater, land use, land cover, distance to existing dumpsites, elevation, and slope—suitable landfill areas within the study area were first identified. Though this research was carefully designed, there were some limitations. For example, some other factors, such as permeability, aspect (wind), and land values, can also affect the site selection for solid waste landfill [11]. However, this study did not examine these variables, as the source data were unavailable. Nonetheless, these points should be considered within future studies in other regions. Moreover, the main justification in utilizing these standards is their regular and sufficient use in determining whether or not a location is suitable for landfilling [28]. According to the classification presented by [11], the buffers for each criterion were constructed.

Therefore, because of the detrimental effects of landfill on specific locations, the constraint map typically excludes those sites where dumpsites cannot be created or are not allowed, as these locations are deemed undesirable for landfill. In this study, restricted regions that are undesirable for landfill sites, such as metropolitan areas, surface water, groundwater discharge points, existing dumpsites, key roadways, and airports, were avoided based on several criteria and sources [28]. In order to create a binary mask layer with the values 0 and 1, all of the resulting restricted maps were combined. A raster calculator was used to integrate it into the ArcGIS spatial analyst tool. The restricted and unrestricted zones each had a value that ranged from 0 to 1. To create the overall restriction map of Hargeisa City and its surroundings, as shown in Figure 4, a restricted map of specific areas was incorporated into the ArcGIS environment.

Table 6 shows that 31.04% (9479.66 ha) of the study area could be taken into consideration, whereas 68.96% (21,060.9 ha) of the study area was deemed unsuitable (restricted areas). The analysis demonstrates that the northern–eastern, northern, and the majority of the western portions of the study area are excellent locations for landfills. As a result, the remaining components were excluded from further examination since they did not satisfy the environmental, social, economic, and technological requirements [46]. Indeed, with rapid population growth, people are moving towards the city's peripheries for open space. Based on this, we suggest that the most significant constraints reducing the viability of dumpsites are metropolitan areas and dispersed habitation.

Table 6. Landfill susceptibility, area coverage, and percentage of the study area.

Suitability Class	AHP (Area)	
	ha	Percentage
Constrained Area/Zone	21,061	68.96
Less Suitable	7441.5	24.36
Highly Suitable	2038.1	6.68

In the second stage, after removing locations deemed inappropriate for landfilling by the restricted method, the analysis only concerned the remaining suitable zones to identify potential landfill sites. The weights and consistency ratios (C.R.) produced from the AHP technique, used to compare the weights of each main criterion and the weights of sub-criteria within each criterion, are shown in Appendix A Table A4. All comparisons' C.R. values were 0.05, indicating that the weights found were reliable.

The analysis of the pair-wise comparison in Appendix A Table A2, used to determine the priorities between the criteria, revealed that the LULC was the most significant one, with a relative weight of 18%, followed by the criteria for habitation and water bodies, and then the airport criterion, with weights of 15 and 11%, respectively (Appendix A Tables A2 and A3). On the other hand, for the soil type criterion, distance to boreholes, and existing dumpsites, the lowest weights of 2, 3, and 4%, respectively, were determined in terms of environmental considerations.

Weighted overlay analysis in the ArcGIS environment was used to overlay the thematic maps to produce the suitability map seen in Figure 9**.** Weighted overlay analysis was utilized in conjunction with the restricted layer to obtain the outcome, namely prospective landfill locations. Different sites that were suitable for landfilling were identified on the final suitability map (Figure 9). The research region was found to be unsuitable for landfilling in approximately 68.96% (21,060.9 ha), while approximately 24.36% (7441.53 ha) had less suitability, and approximately 6.68% had high suitability for landfill sites (Table 6). In actuality, fewer than 7% of the total regions were ideally suited for landfill disposal. This shows that despite the study area's large size, the number of areas suitable for landfills is still very small.

To lessen the risk to the environment and public health, potential landfill candidate sites are chosen based on their size and distance from residential areas [47]. Finally, based on their high suitability for landfill siting areas, three sites, namely sites one, two, and three, were proposed, which are the most suitable locations for Hargeisa City and its environs (Table 7).

The first landfill site, which is north of the research area, is seen to be the most suitable since it might minimize the negative environmental and socio-environmental effects. In the current study, landfill sites three and two are located closer to major roads than disposal site one; as a result, they are economically very suitable concerning transportation costs for municipal solid waste. Nevertheless, to prevent harm to people and the environment, landfills should not be located close to highways [2]. Thus, from the distance-based perspective of residential and road proximity, landfill site one is highly suitable compared to the others as it is far from residential areas [26]. Moreover, before the building of a landfill, local communities should be consulted, and a thorough feasibility assessment should be conducted on the site to avoid disputes between land users and reduce potential contamination issues. As a result, the outcomes of the current approach can help decision makers to rank and identify appropriate disposal locations.

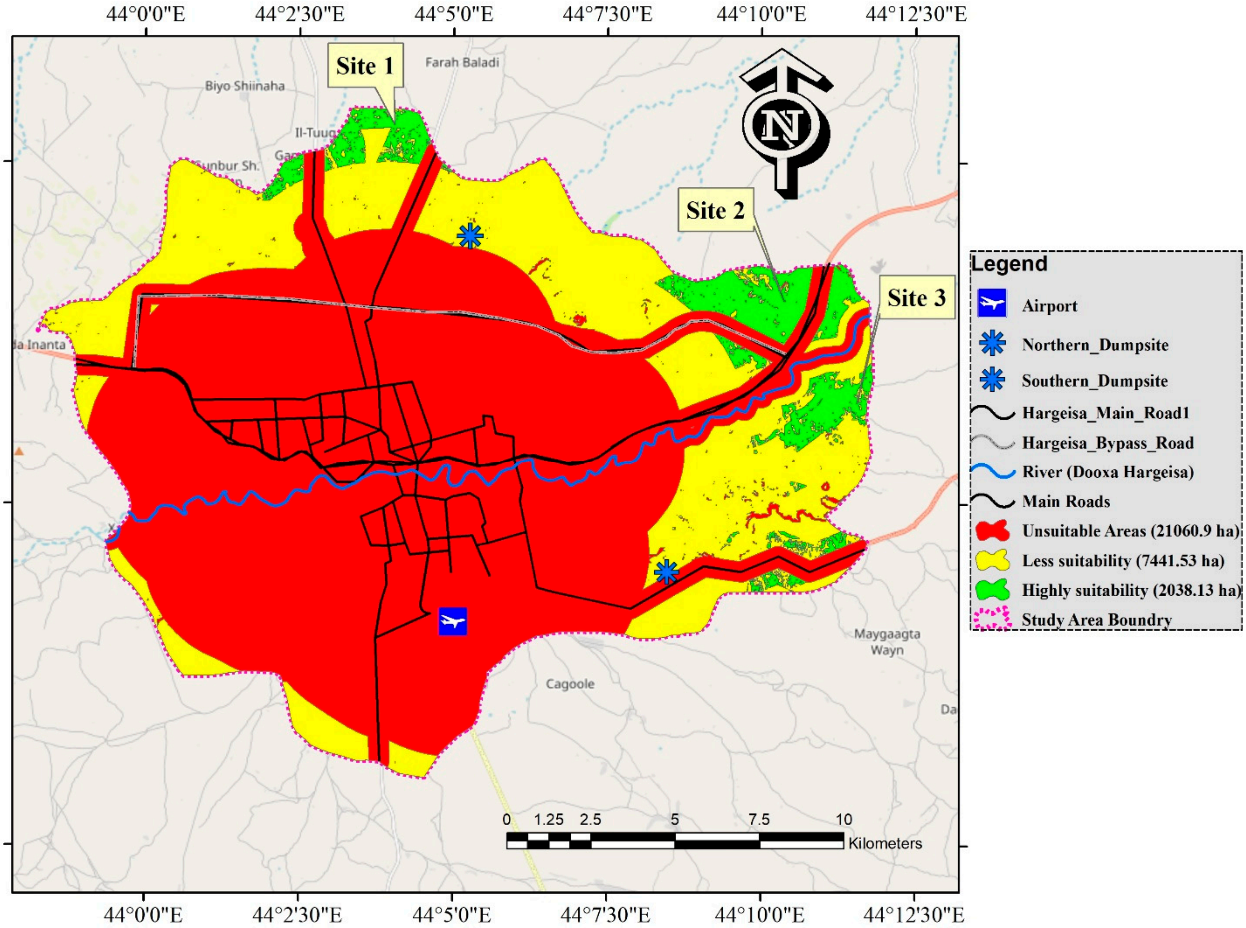

Figure 9. Landfill site suitability (LSS) map along with the three preferred candidate sites identified.

Table 7. Locations of the selected sites.

Sites Number	Rank *	Latitude	Longitude
1	1	9°38′36.98″ N	44°4′29.59″ E
2	2	9°36′35.18″ N	44°8′28.65″ E
3	3	9°34′27.71″ N	44°11′36.74″ E

* Rank: 1—most suitable, 2—moderately suitable, 3—less suitable.

4. Conclusions

The weighting of all criteria was assessed using a developed analytical hierarchy process (AHP) with a consistency ratio of 0.05. Additionally, the model accurately reflected the degree of reality present in the research area, demonstrating the method's efficacy in locating and mapping suitable landfill locations. The study determined the viability of three potential landfill locations in the wasteland.

Furthermore, the land use and land cover (LULC) criterion is the most significant one, with a relative weight of 0.1829, followed by habitation, with a relative weight of 0.1506. This was shown by the pair-wise comparison used to determine the priorities between the criteria that were chosen. The research region is unsuitable for landfilling in around 68.96% (21,060.9 ha), but only 24.36% (7441.53 ha) had low suitability and approximately 6.68% had high suitability. In this context, the government, local authorities, and city planners might refer to and follow the findings of this site selection analysis for subsequent development. However, in this study, there were certain constraints. Due to the absence of source data, this research study did not consider permeability and land value, which might also impact the selection of solid waste landfill sites. Nevertheless, when conducting further research in other areas, these points should be taken into account. Moreover, the approaches used in this study can make an important contribution to the scientific community working on the study and design of solid waste disposal facilities in Somaliland and elsewhere.

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Conflicts of Interest: The authors declare no conflict of interest/competing.

Appendix A

Table A1. The nine-point weighting scale for pair-wise comparisons [29].

Intensity of Importance	Description	Suitability Class
1	Equal importance	Low suitability
2	Equal to moderate importance	Very low suitability
3	Moderate importance	Low suitability
4	Moderate to strong importance	Moderately low suitability
5	Strong importance	Moderately suitability
6	Strong to very strong importance	Moderate high suitability
7	Very strong importance	High suitability
8	Very to extremely strong importance	Very high suitability
9	Extreme importance	Highest suitability

Table A2. Pair-wise comparison matrix for selected landfill controlling factors.

Factors	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)	(C10)	(C11)
LULC (C1)	1	2	2	2	3	3	3	2	3	4	4
Habitation (C2)	0.50	1	1	3	2	3	3	1	4	5	5
Water bodies (C3)	0.50	1.00	1	2	2	3	3	2	4	4	6
Airport (C4)	0.50	0.33	0.50	1	2	2	3	2	3	4	5
Elevation (C5)	0.33	0.50	0.50	0.50	1	2	3	3	4	4	4
Roads (C6)	0.33	0.33	0.33	0.50	0.50	1	2	2	3	4	5
Slope (C7)	0.33	0.33	0.33	0.33	0.33	0.50	1	1	2	3	4
Lithology (C8)	0.50	1.00	0.50	0.50	0.33	0.50	1.00	1	2	3	4
Soil types (C9)	0.33	0.25	0.25	0.33	0.25	0.33	0.50	0.50	1	2	3
Boreholes (C10)	0.25	0.20	0.25	0.25	0.25	0.25	0.33	0.33	0.5	1	2
Existing dumpsites (C11)	0.25	0.25	0.16	0.20	0.25	0.20	0.25	0.25	0.33	0.50	1
Sum	4.83	7.15	6.83	10.6	11.9	15.8	20.1	15.1	27	34.5	43

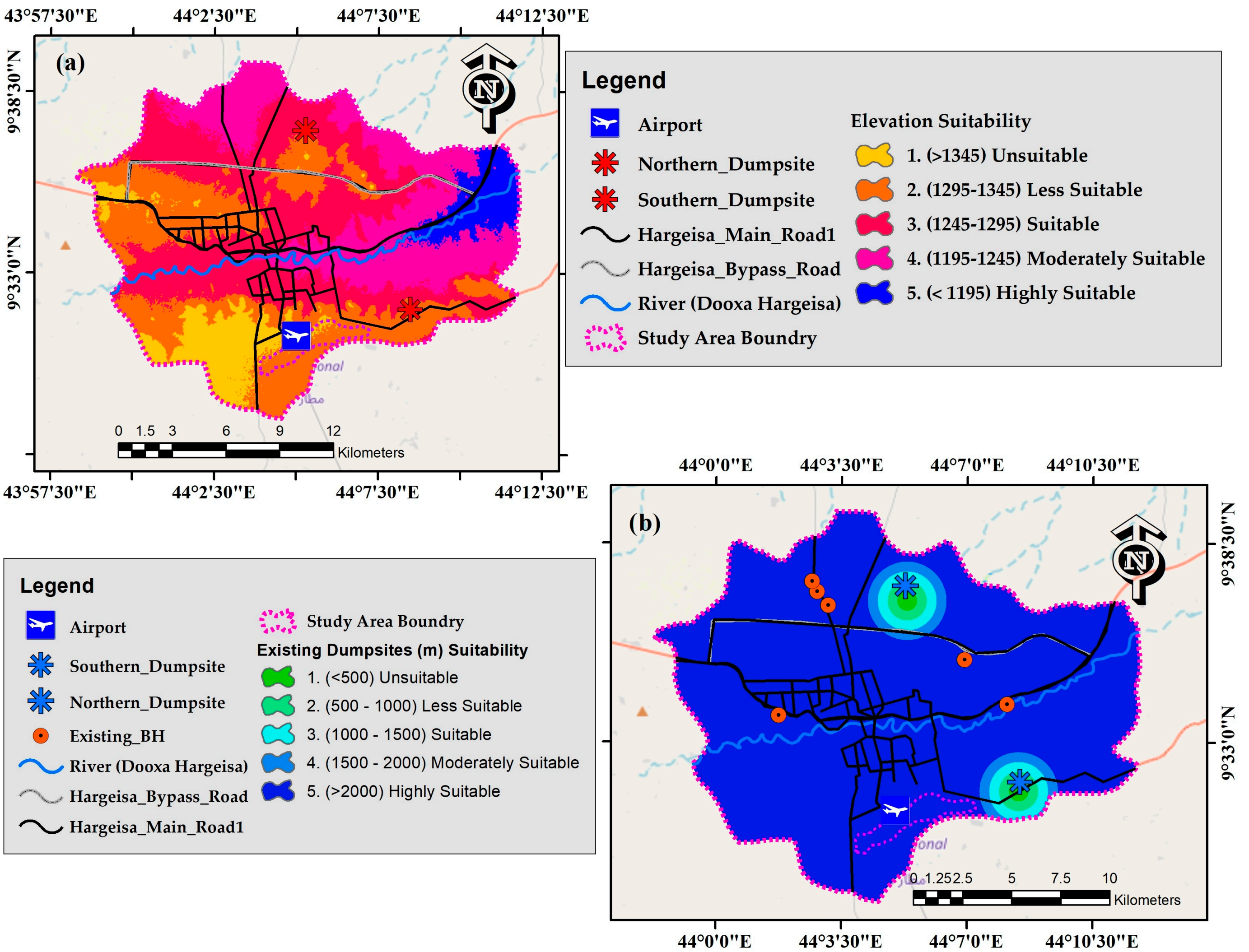

Figure A1. Landfill site suitability criteria for (**a**) elevation, (**b**) distance from an existing dumping ground.

Table A3. Normalized pair-wise comparison matrix and calculated criteria weights for each parameter.

Factor	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)	(C10)	(C11)	Sum	Criteria Weight	Criteria Weight (%)
(C1)	0.21	0.28	0.29	0.19	0.25	0.19	0.15	0.13	0.11	0.11	0.09	2.01	0.18	18
(C2)	0.10	0.14	0.15	0.28	0.17	0.19	0.15	0.07	0.15	0.14	0.12	1.66	0.15	15
(C3)	0.10	0.14	0.15	0.19	0.17	0.19	0.15	0.13	0.15	0.12	0.12	1.62	0.15	15
(C4)	0.10	0.05	0.07	0.09	0.17	0.13	0.15	0.13	0.15	0.12	0.12	1.24	0.11	11
(C5)	0.07	0.07	0.07	0.05	0.08	0.13	0.15	0.20	0.15	0.12	0.09	1.18	0.11	11
(C6)	0.07	0.05	0.05	0.05	0.04	0.06	0.10	0.13	0.11	0.12	0.12	0.89	0.08	8
(C7)	0.07	0.05	0.05	0.03	0.03	0.03	0.05	0.07	0.07	0.09	0.09	0.63	0.06	6
(C8)	0.10	0.14	0.07	0.05	0.03	0.03	0.05	0.07	0.07	0.09	0.09	0.79	0.07	7
(C9)	0.07	0.04	0.04	0.03	0.02	0.02	0.03	0.03	0.04	0.06	0.02	0.44	0.04	4
(C10)	0.05	0.03	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.05	0.31	0.03	3
(C11)	0.05	0.03	0.02	0.02	0.02	0.01	0.01	0.07	0.01	0.01	0.02	0.22	0.02	2
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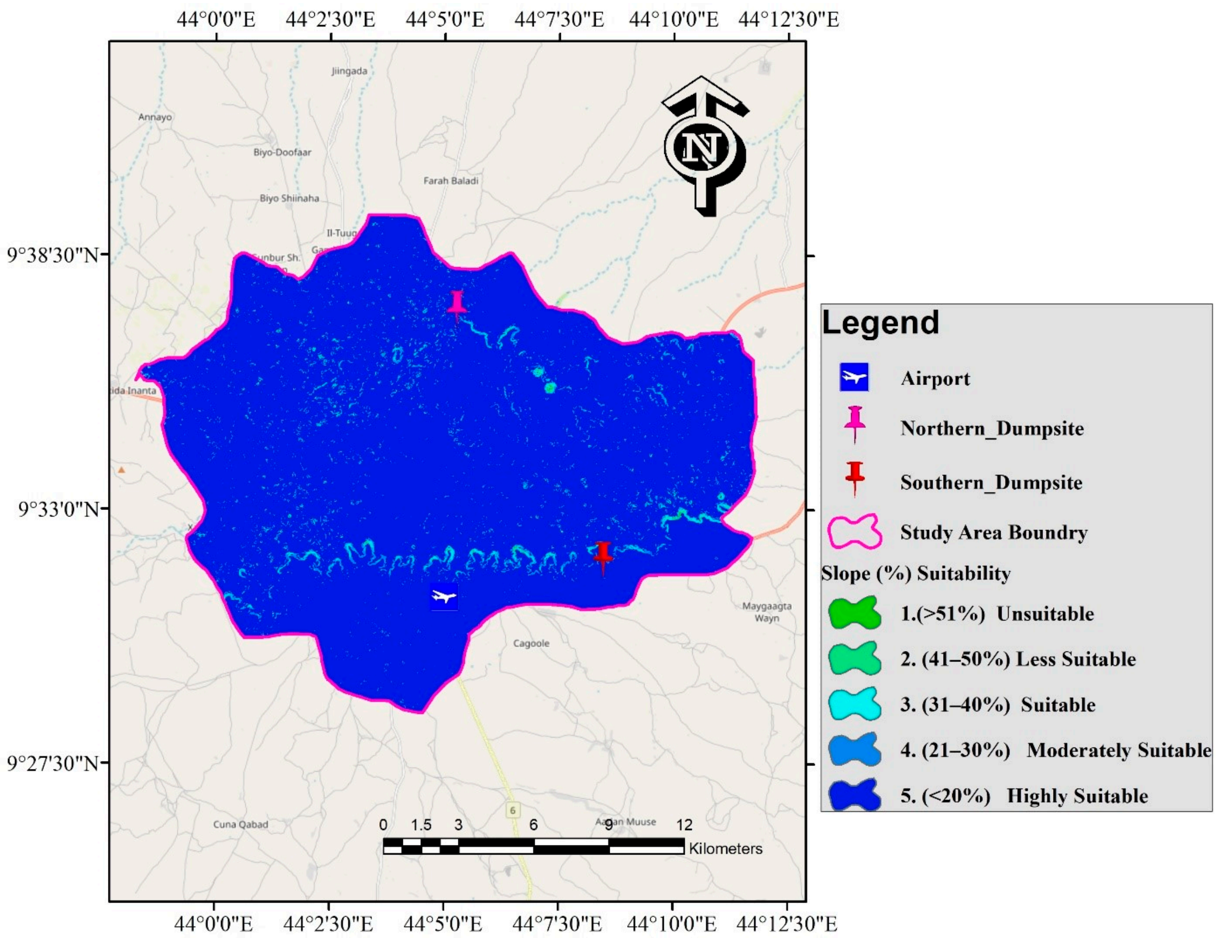

Figure A2. Landfill site suitability criteria for slope (%).

Table A4. Calculation of the consistency of pair-wise comparison (C.R. = 0.05).

Factor	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)	(C10)	(C11)
(C1)	0.18	0.30	0.30	0.22	0.32	0.24	0.17	0.14	0.12	0.11	0.09
(C2)	0.09	0.15	0.15	0.34	0.21	0.24	0.17	0.07	0.12	0.14	0.11
(C3)	0.09	0.15	0.15	0.23	0.21	0.24	0.17	0.14	0.12	0.11	0.13
(C4)	0.09	0.05	0.07	0.11	0.21	0.16	0.17	0.14	0.12	0.11	0.11
(C5)	0.06	0.08	0.07	0.06	0.11	0.16	0.17	0.22	0.12	0.11	0.08
(C6)	0.06	0.05	0.04	0.06	0.05	0.08	0.11	0.14	0.12	0.11	0.11
(C7)	0.06	0.05	0.04	0.04	0.04	0.04	0.06	0.07	0.02	0.08	0.09
(C8)	0.09	0.15	0.07	0.06	0.04	0.04	0.06	0.07	0.02	0.08	0.09
(C9)	0.06	0.04	0.03	0.04	0.03	0.03	0.03	0.04	0.04	0.06	0.06
(C10)	0.05	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.04
(C11)	0.05	0.03	0.02	0.02	0.03	0.02	0.01	0.02	0.01	0.01	0.02

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