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Authors: Asefa, Elsai Mati, Damtew, Yohannes Tefera, and Barasa, Kefelegn Bayu

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Elsai Mati Asefa, Yohannes Tefera Damtew and Kefelegn Bayu Barasa

Department of Environmental Health, College of Health and Medical Science, Haramaya University, Harar, Ethiopia.

ABSTRACT: Solid waste disposal is one of the challenging components in integrated solid waste management. Particularly the problem is prominent in cities with rapid population growth and waste generation. Harar, a capital city of Harari regional state located in the eastern part of Ethiopia, covers an area of 19.5 km^2 and has a total population of 270 000. Despite the fastest population growth of the city, it doesn't have a landfill site to accommodate the waste generated and open dumping is in full practice. As an integral part of a solid waste management plan, the construction of a landfill has been suggested by the city municipality. However, the multi-dimensional and conflicting aspect of landfill sitting, which involves environmental, social, technical, and economic considerations, challenges the location of a suitable landfill site. In the current study, we have applied geographic information system (GIS) and analytical hierarchy process (AHP) multi-criteria decision analysis to select a landfill site through minimizing conflicting interests. Environmental and socio-economic factors including well water, distance from residence, land use and land cover, elevation, slope, and wind direction were weighted to develop a suitability index for landfill siting. Experts' opinion was obtained to rank the aforementioned factors. The required landfill size was determined based on population growth, waste generation rate, and waste volume/year. Accordingly, the suitability index resulted in 3% of the area as highly suitable, and the rest 0.29%, 14.18%, 52.75%, and 29.8% classified as unsuitable, least suitable, moderately suitable, and suitable, respectively. Considering the future trend of waste generation, 16 ha of land located in the eastern part of the city was selected as a candidate landfill site with all the required suitability. The results of this study can be used as an input for decision making in siting landfill for Harar city.

KEYWORDS: Harar, Ethiopia, landfill site, geographic information system, analytical hierarchy process, waste generation rate

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CORRESPONDING AUTHOR: Elsai Mati Asefa, Department of Environmental Health, College of Health and Medical Science, Haramaya University, P.O. Box: 235, Harar, Ethiopia. Emails: elsyyymati@gmail.com; Elsai.mati@haramaya.edu.et

Introduction

Rapid population growth, unplanned urbanization, change in consumption patterns, and insufficient or negligible recycling and reuse practices all to an increase municipal solid waste generation.[1-3] Globally, there is a rise in solid waste generation rates that accounts for a footprint of 0.75 kg/person/day in 2016. With rapid population growth and urbanization, annual solid waste generation is expected to increase by 70% from 2016 to 2050.[4] Managing such a high volume of waste requires an integrated approach.[5,6] As the main component of integrated solid waste management, disposal of waste is one of the most challenging aspects.[7] Even countries with a high rate of reuse and recycling face a challenge for disposal of the remaining waste, as a final disposal site is always scarce and debated.[5,8]

Previous incidents and current scenarios in several parts of the world have indicated the environmental and public health threats of poorly located solid waste disposal sites and improperly built sanitary landfills.[9,10] Soil and water pollution, fire accidents, and the risk of disease transmission related to poorly managed disposal sites have been mentioned in various studies.[11] Recent findings also showed open dumping sites as a potent greenhouse gas emission source.[12,13] Therefore, sitting sanitary landfills should consider various environmental, social, technical, and economic aspects to minimize the aforementioned potential impacts.[14,15]

Identifying a potential candidate location for a landfill is one of the most challenging tasks faced by most municipalities and urban planning authorities.[16] Minimizing the impact without compromising social, economic, environmental, and technical aspects requires multiple decisions at a time.[17,18] The use of multi-criteria decision analysis (MCDA) approaches to tackle complicated decision-making situations, such as landfill site selection, is common.[19] The use of multi-criteria decision approaches (MCDA), which combine geographic information systems (GIS), and multicriteria evaluation techniques such as the analytical hierarchy process (AHP), is currently considered as a better approach. GIS-based MCDA converts available spatial and non-spatial data into useful important information with extra judgment from decision-makers,[20-22] and AHP is the most extensively used MCDA technique for weighting the criteria and ranking the alternatives.[23]

GIS is a powerful tool due to its ability to manage and analyze a large volume of spatially distributed data from a variety of sources.[24,25] The availability of a large set of free and commercial spatial data makes the use of GIS methods an alternative option in landfill site selection. AHP, which is a multi-criteria decision-making approach, was developed by Saaty[26] and it is widely used to unify multiple criteria in the process of decision-making. The method is a better technique to model complex decision problems in a wide variety of

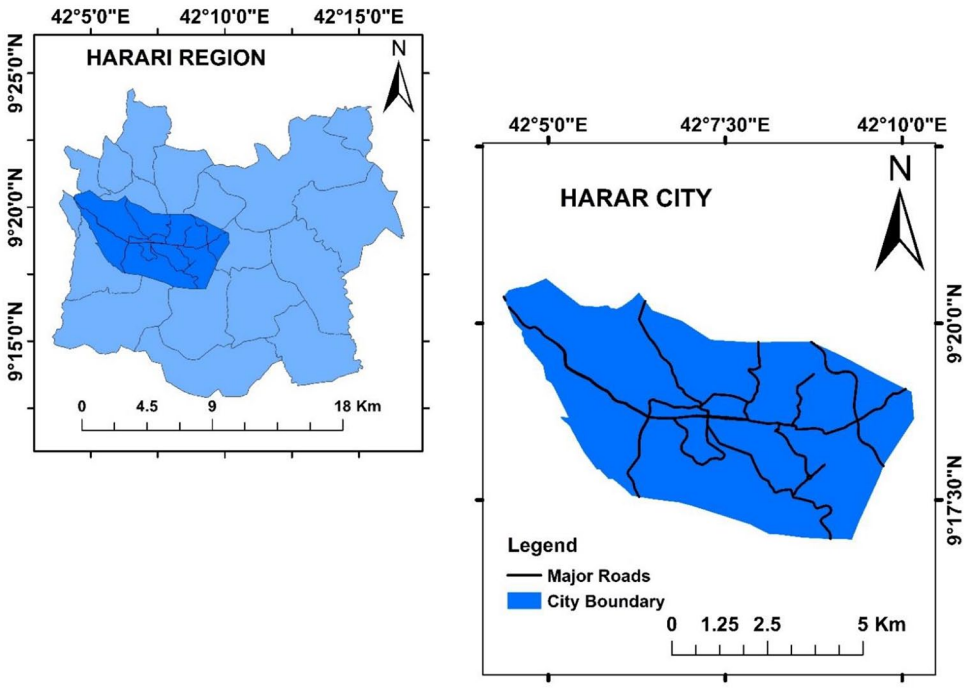

Figure 1. Map of the study area.

fields.[27] Several studies used a multi-criteria decision approach by combining GIS and AHP in landfill site selection. Therefore, based on the previous results and the ease of applicability of the method, the present study focused on the selection of a sanitary landfill for Harar city based on the geographic information system and the analytical hierarchy process.

Materials and Methods

Description of the study area

Harar city, located at 9°18′43″N latitude and 42°7′23″E longitude, is the historical and oldest city found in eastern Ethiopia, 525 km from the capital, Addis Ababa as shown in Figure 1, study area map. The city is the commercial and administrative capital of the Harari regional state and covers a total area of 19.5 km^2 and is located at an elevation of 1885 m above sea level. Harar city's population in 2021 is 153 000, according to the projection made based on the 2007 Ethiopian census.[28] The region has a mean annual temperature between 10°C and 26°C and a mean annual rainfall of 804.7 mm.

A study conducted in 2008 showed that the daily waste generation of Harar city was estimated to be around 38.8 tons, or 14 162 tons/year, of which less than half of the generated waste was collected and dumped openly at the Kile site, on the outskirts of the city.[29] This site was considered a potential standardized landfill site a decade ago, but its construction has never materialized and it is currently serving as an open dumping site. Open burning, leachate release, and nuisance from Kile's open dumping site posed greater risks for the environment and public health sustainability.[30] Due to these factors, there is a dire need to be addressed by identifying a landfill site that fulfills the economic, social, and environmental guidelines. The current status of the Harar city dumpsite is presented in Figure A1.

Methodology

Selecting a suitable sanitary landfill site is tedious and complex work. It is well known that several criteria are incorporated to make a better decision in the selection of landfill sites. To manage this large amount of data efficiently and effectively, we used a geographic information system (GIS) based multi-criteria technique. Pre-processing operations such as digitization, clipping, geo-referencing, merging, and pan-sharpening were done using QGIS 3.2 (http://qgis.osgeo.org/). Further, ArcGIS 10.4.1 (https://support.esri.com/en/products/desktop/arcgis-desktop/arcmap/10-4-1) tools such as buffer, Euclidean distance, union, dissolve, select feature, and weighted overlay were used for GIS-based analysis. This study used primary and secondary data from different sources. Primary data included in this study were raw data obtained from USGS EROS Archive (https://www.usgs.gov/centers/eros/science/usgs-eros-archive), Harari urban development and construction bureau (HUDC), and Harari municipality. In addition, experts' opinions from three major sectors (Harar city municipality, Harari urban beatification bureau, and experts in Haramaya University) were included for ranking of the selected criteria. Secondary data is acquired from reports, books, and other works of literature. The current study is conducted in 4 stages and the detailed methodology of each stage is presented in the next sections. These stages are preprocessing, criteria setting, determining landfill size and application of AHP techniques, and assessment of suitable landfill sites. The hierarchical

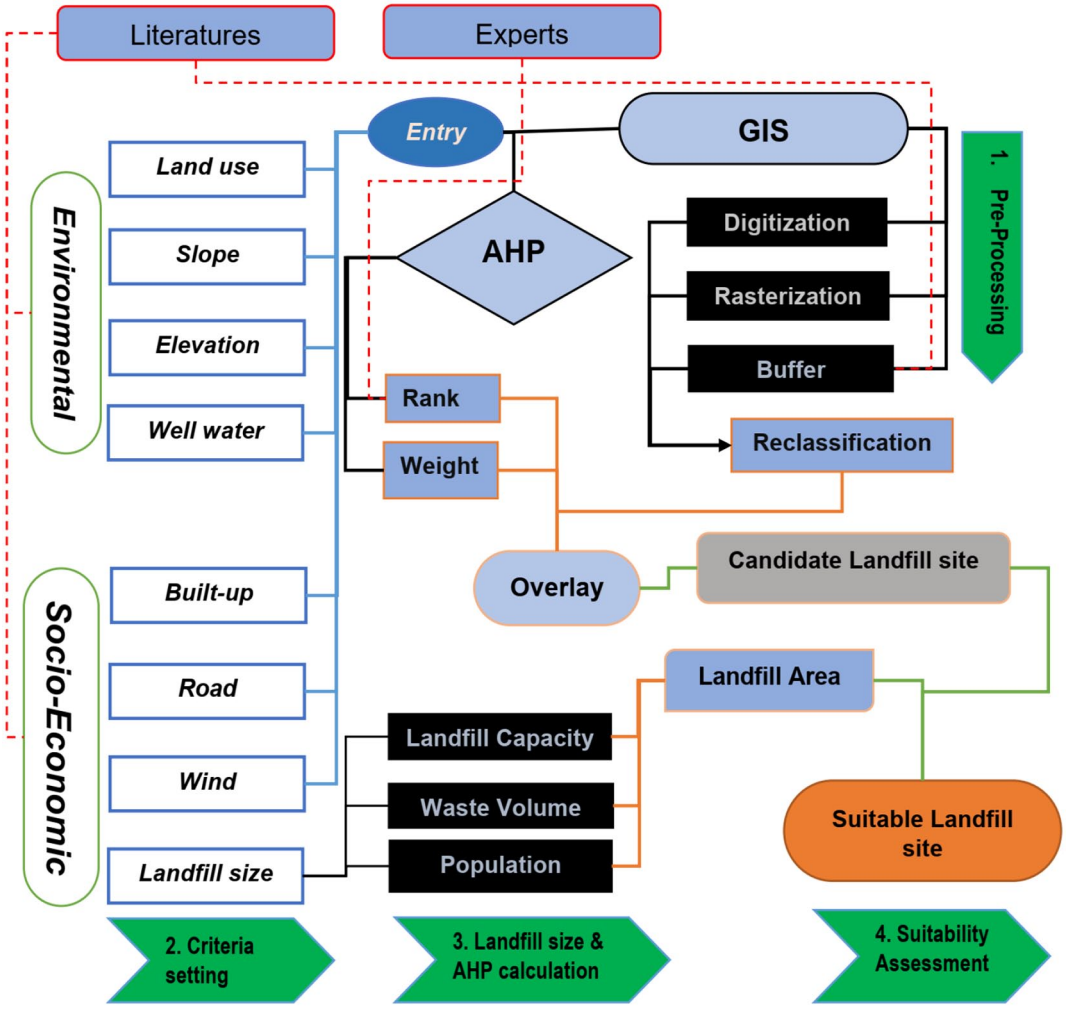

Figure 2. Framework of the study to select a suitable sanitary landfill site for Harar city.

framework, the stages of this study, and methodology flow are presented in Figure 2.

Data preprocessing. In the preprocessing stage, raw data obtained was arranged and edited to meet the purpose of this study. Preprocessing was done in 3 stages; in the first stage, vector preprocessing, which included digitization of the study area map, road networks, and well points acquired from HUDC and Harari municipality, was done. In the second stage, raster preprocessing, which included pan sharpening, clipping, and image merging of Landsat 8 imagery and shuttle radar topography map (SRTM) obtained from the USGS EROS Archive, was done. In the final stage, geo-referencing was done for the city boundary obtained in shape format from HUDCB in Adindan UTM zone 38 N with a marginal error of 0.342. Pre-processing was done using QGIS 3.2 software. This software is selected for this purpose because of the capability it has in managing raw data. QGIS is fast, effective in geoprocessing, and has significant performance in operations like clipping compared to Esri ArcGIS. But in spatial analytic capacities like hill shading, overlays, map algebra, surface approximation, and network analysis, ArcGIS is more effective (https://www.gislounge.com/qgis-versus-arcgis/accessed on August 20, 2021). For this purpose, Esri ArcGIS is used in the final overlay analysis of landfill site selection.

Determining siting criteria. There are numerous environmental, social, and economic criteria to consider while choosing a landfill site.[19] Resource availability, physical environment, and natural events have a determinant role in determining criteria for landfill site selection. While constructing a landfill site, it is necessary to consider the required land size, transportation access, physical environment, topography, climate conditions, environmental protection, and hydrogeological conditions.[31] Based on data availability and significance, factors such as distance to roads, distance from well water, distance from residence, land use and land cover, elevation, slope, landfill size, and wind direction were considered in this study for the analysis of a suitable landfill site. After reviewing works of literature, the criteria selected were presented with fixed suitable buffers in Table 1.[13,32-40]

Table 1. Selected criteria for suitability analysis of landfill with criteria limit.

CRITERIA	LIMIT/SUITABILITY
Road	100 m buffer
Built-up	1000 m away
Land use/land cover	Open space, green area, agricultural land
Well points	300 m buffer
Slope	<10%
Altitude	>1500
Wind direction	The prevailing wind in the study area
Land size area	12.8 ha

Landfill size determination. Ethiopia is one of the developing countries with rapid population growth and an emerging economy. The projected Ethiopian population steadily increased from 83.7 million in 2012 to 133.5 million in 2032.[41] For the estimation of landfill size, secondary data from the central statistics agency and Harari regional survey reports were used to extract estimated population and per-capita waste generation. Further, works of literature have been reviewed for the assumption of compacted specific weight of solid waste and other landfill size calculation specifications. Landfills should be able to accommodate disposed waste for a minimum of 5 years of operation.[42]

This study proposed a 10-year landfill life span by considering cost-effectiveness, political acceptability, and land availability. To calculate the area required for a landfill, factors such as waste generation rate, population growth, and density of the compressed landfill material were considered.[43-46] To calculate the volume of the landfill, 5 m landfill height was chosen because of the high groundwater table in the area. In doing so, the landfill area was calculated with the assumption; 0.35 kg/capita/day waste generation, compacted specific weight of solid waste in landfill (350 kg), 15 cm soil cover on top and sides for lift height of 1.5 to 2 m, 1.5 m thick liner system with leachate collection layer and 1.0 m thick cover system including gas collection layer. All calculations were performed using equations (1) to (5).

$$Vw = total\ waste\ generation\ in\ n\ years(tons) / rate\ of\ compaction(kg/m^3), where; Vw\ is\ total\ volume\ of\ waste(m^3/year) \quad (1)$$

$$Vdc = 0.1Vw, where\ Vdc\ is\ total\ volume\ of\ daily\ cover\ and\ Vw\ is\ total\ volume\ of\ waste \quad (2)$$

$$Vc = 0.25Vw, where\ Vc\ is\ total\ volume\ for\ linear\ and\ final\ cover\ and\ Vw\ is\ total\ volume\ of\ waste \quad (3)$$

$$Ci = Vw + Vdc + Vc, where\ Ci\ is\ Landfill\ capacity(m^3/year) \quad (4)$$

$$A_i = Ci / Hi, Ai\ is\ landfill\ area(ha), Ci\ is\ landfill\ capacity\left(\frac{m^3}{yr}\right) and\ Hi\ is\ landfill\ height(m) \quad (5)$$

Criteria ranking using analytical hierarchy process. The Analytic Hierarchy Process was conceived by Thomas Saaty in 1980. AHP can simplify preference ratings among decision criteria using pair-wise comparisons.[47] It is used for addressing complex decision-making processes and supports the decision-maker to give the best conclusion about the subject matter. Also, it reduces complex decisions to a series of pairwise comparisons to give the results.[25,48]

In this study, the criteria selected (Table 1) was ranked using expert opinion relative to its importance with other values from a set {1, 2, 3, 4, 5, 6, 7, 8, 9}.[47] Only experts having a minimum of 2 years of experience in the area were included and asked to rank each criterion on the level of importance for landfill site selection (Supplementary Material II). The result of 12 experts (6 from Harar municipality, 2 from Harar urban beatification bureau, and 4 from Haramaya University) was included for criteria ranking. Accordingly, land use was ranked twice more important than road access and 9 times more important than elevation and the slope had 1/3 influence on land use, road access, and groundwater points. Most of the study areas are flat (<10°) therefore; the probability that slope criteria influence landfill site selection is minimum. Then, appropriate weight was given to each criterion after experts' ranking by the AHP method and sub-criteria were determined. Each criterion was sub-classified into 5 sub-criteria groups as unsuitable, least suitable, moderately suitable, suitable, and highly suitable.

Land suitability assessment. The results from the preprocessing, landfill area calculation, and analytical hierarchy process were analyzed in Esri ArcGIS 10.4.1. Each criterion was reclassified as unsuitable, least suitable, moderately suitable, suitable, and highly suitable by the Euclidean distance and reclassify spatial tool. The Suitability index for landfill sites was determined by equation (6). Then, the reclassified criteria were overlaid by a weighted overlay spatial tool to produce a potential landfill site for solid waste disposal in Harar city. Further, the highly suitable classes were analyzed for the capacity to hold waste generated in the coming 10 years. Field visits were also conducted to validate the final site selected landfill (result) obtained using the methodology used in this study.

$$S = \sum_{i=1}^{n} WiCi * \prod_{j=1}^{m} rj \quad (6)$$

where S is the suitability for a waste disposal site, Wi is the weight of factor i, CI is the criterion for suitability of factor i, rj is the criterion for suitability of constraint j and Π is the product.

Description of input data

In this section, the production of a thematic map for each of the selected criteria was presented. We covered the criteria used, buffers used, and how the criteria map was developed in this section. For each criteria, the thematic map produced is presented in Figure A2. In addition, the thematic map and suitability class map for landfill site selection in Harar city are presented in Supplementary Material I.

Distance from well water sources. Landfill sites should be located away from water sources and the buffer zone could differ from case to case.[49-51] There are 3 well water sources identified in this study which were obtained from Harari urban development and construction bureau and a 300 m buffer zone was defined for all well water sources as used in the previous study.[52] The closer the distance to well water sources, the lower the suitability of a landfill site.

Land use and land cover. This criterion is used to exclude productive land areas that have significant socio-economic values, including agricultural lands, grasslands, and forest zones. Landsat imagery obtained from the USGS EROS Archive with nine classes such as settlements, cropland, wetland, forest, woodland, shrubs, bush, grassland, and barren land was used. Although numerous studies suggested the exclusion of several land uses, urban spaces, green areas, and agricultural land were not considered suitable in this study.[13,38,53-56] Accordingly, land use and land cover in the study area were reclassified as unsuitable for residential areas and highly suitable for grassland and barren land.

Road accessibility. Easy access to a landfill site can avoid extra costs and locating a landfill within a proximate distance to roads could cause nuisance, bad smells, and related problems.[53,54] Therefore, a reasonable distance should be considered by taking the factors mentioned into account. An area of <100 m for this study is unsuitable.[44,57,58] The digitized road network in this study includes only major roads obtained from Harar municipality. These roads were updated using the Open Street map in ArcGIS.

Built-up and residential area. Locating a landfill near residential areas may increase the risk of pollution and public concerns like air pollution, noise, nuisance, communicable diseases, and fires. A landfill site should be far from a residential area, commercial buildings, urban green space, service area, and industries.[13,53,54] In this study, we considered an area >2 km from residence as highly suitable. The base map for the built-up areas of Harar was obtained from the Harari urban development and construction bureau and digitized for every building in the study area using a vector editing polygon tool.

Slope. The topography of an area determines surface runoff and the flow of leachate velocity. Also, a steep slope increases the cost of construction. Therefore, a flat area is favorable for a landfill site to reduce these risks.[59,60] In this study, we considered a slope $<10^{\circ}$ as suitable for a landfill site.[40,59,60] A slope map of the study area was obtained from the SRTM digital elevation map (DEM) with 30 m resolution from USGS (United States Geological Survey) (https://www.usgs.gov). The slope of Harar city ranges from 0° to 36° and most of the study area has a gentle slope $<10^{\circ}$.

Elevation. Similar to the slope, areas with higher altitudes are not suitable for a landfill site. This is due to the difficulty of access, rising transportation costs, and easy leachate flows from higher to lower areas.[61] As the elevation of an area increases, the suitability of an area decreases. An elevation map of Harar was also obtained from SRTM DEM. The elevation of the study area ranges between 1680 m above mean sea level (MSL) and 2158 m above mean sea level. More than 40% of Harar is covered by an elevation of 1790 m above MSL and this area is considered suitable for a landfill site.

Prevailing wind direction. To minimize the bad odor generated from a landfill site that affects near residents, it is important to consider wind direction.[62] Northwest is the prevailing wind direction in the study area; therefore, this direction is unsuitable to locate a sanitary landfill. SRTM DEM was used to obtain prevailing wind types in the study area. Also, the hillside effect was used to visualize the direction and wind types in Harar.

Result

Multi-layer spatial analysis for the study area

Overlay analysis is used to superimpose multiple layers representing different themes together for the analysis. Multiple layer analysis is used to completely digitize the study area by placing the criteria map over one another in GIS. The suitability analysis of each criterion mapped was reclassified as unsuitable, least suitable, moderately suitable, suitable, and highly suitable, as shown in Figure 2. All the reclassified factor layers done were used in weighted overlay analysis and the final landfill site for solid waste disposal for Harar city was produced in Figure 3.

Pairwise comparison and standardized matrix (analytical hierarchy process)

Well water, distance from residence, land use and land cover, elevation, slope, and wind direction were compared with each other by the relative scale pairwise comparison based on the

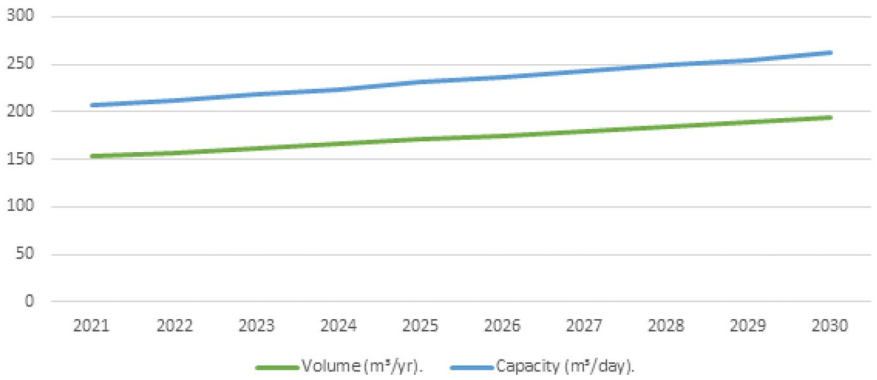

Figure 3. Projected waste generation volume and capacity for Harar city in 10 years.

Table 2. Pair-wise comparison of criteria for landfill site selection of Harar city.

CRITERIA	LAND USE	ROAD	WELL	SLOPE	BUILT-UP	ASPECT	ELEVATION
Land use	1						
Road	1/2	1					
Well	1/3	1	1				
Slope	1/3	1/3	1/3	1			
Built up	1/3	1	1/2	2	1		
Aspect	1/6	1/5	1/4	1/3	1/2	1	
Elevation	1/9	1/6	1/5	1/4	1/3	1/2	1

opinion of the experts included in Table 2. The average normalized column method was used to calculate the vectors of priorities. In this, the elements of each column are divided by the sum of the column and then the elements in each resulting row were added. Then, this sum is divided by the number of elements in the row (n). Mathematically, this is expressed in equation (7). To get rid of inconsistency that may result due to our opinion and judgment, we calculated the consistency ratio to be $0.031 < 0.1$ which is acceptable as equations (8) and (9).

$$Wi = 1\frac{1}{n}\sum_{j=1}^{n} aij \Big/ \sum_{i}^{n} aij, i, j = 1,2,\ldots n \tag{7}$$

$$CR = CI / RI, \text{ where } CI \text{ is consistency index and } RI \text{ is random index} \tag{8}$$

$$CI = \lambda max - n/(n-1), \lambda \max \text{ is pricipal eigen value and } n \text{ is number of factors} \tag{9}$$

In the final stage, the influence of each criterion compared to the other for landfill site selection was assigned a weight (Table 3). This was done using a standardized matrix which we used in the weighted overlay spatial analysis tool to produce a final suitable site. It was calculated mathematically as equation (10).

Table 3. Principal Eigenvector of the pair-wise comparison matrix.

CRITERIA	WEIGHT (%)
LU/LC	33.8
Road	18.7
Well	18.4
Slope	9.2
Built up	12.1
Aspect	4.8
Elevation	3.1

$$s_i = \sum_{i=1}^{7} 33.8LU + 18.7RD + 18.4WL + 9.2SL + 12.1BU + 4.8AS + 3.1EL \tag{10}$$

Where Si is the suitability index, LU is the land use criterion, RD is the road criterion, WL is the groundwater point criterion, SL is the slope criterion, BU is the residential area criterion, AS is the wind direction criterion, and EL is elevation criterion.

Landfill size determination

A landfill area with a capacity of holding generated waste in Harar city for consecutive 10 years was determined (Figure 3). Following the estimation, solid waste generation is expected to increase and a total of 195 457.5 tons will be generated in the next 10 years. Thus, the total area required in 10 years with the following assumptions; rectangular shape (2:1) with infrastructural facilities (1.15 of total area) and a maximum height of 5 m to compensate for high groundwater table is 12.8 ha.

The total area needed in 10 years for Harar city landfill was calculated as the following:

$$T10 = 153{,}000\,x\,0.35\,kg/capita/day\,x\,(365\,x\,10)\,x\,10^3\,kg/ton = 195{,}457.5\,tons$$

$$V10 = 195{,}457.5\,tons\,x\,1000\,kg/tons/350\,kg/m^3 = 558{,}450\,m^3$$

$$Area = 558{,}450\,m^3/5m\,x\,10{,}000\,m^2/ha = 11.2\,ha$$

$$Total\ area = 1.15\,Area = 12.8\,ha$$

Landfill site suitability analysis

Well water points suitability. Well water suitability analysis showed that 2.37%, 6.18%, 18.45%, 23.94%, and 49.05% of the total area are unsuitable, less suitable, moderately suitable, suitable, and highly suitable respectively for the study area landfill site (Table 4; Figure 4a).

Land use and land cover suitability. The largest part of the study area was least suitable (41.54%) while 20%, 15.22%, and 13.59% of the area were unsuitable, moderately suitable, and suitable respectively for land use and land cover suitability (Table 4). The remaining 9.66% of the study area was highly suitable based on land-use and land-cover suitability (Figure 4b).

Road suitability. As shown in Table 4, 21.58% of the area was unsuitable related to road suitability criteria. The remainder, 1.05%, 6.45%, 7.10%, and 63.82%, were categorized as less suitable, moderately suitable, suitable, and highly suitable for the landfill site, respectively (Figure 4c).

Slope suitability. The sloping topography of the study area ranges from 0° to 36°, from which 5° to 7° covers 43.9%, 0° to 5°covers 33.17%, and >20° covers only 0.98%. More of the study area (75%) is covered by the highly suitable area and 0.2%, 0.6%, 3.2%, and 21% for unsuitable, least suitable, marginally suitable, and moderately suitable areas, respectively (Figure 4e).

Residential or built-up area suitability. There were no suitable and highly suitable areas observed because all the study area was within 2 km of distance from built-up (Figure 3). As a result, 88.62% of the total area is unsuitable, while 11.37% is less suitable for a landfill site in the study area.

Aspect and elevation suitability. Each suitability class covered the study area nearly equal, 16.68%, 16.94%, 21.21%, 22.94%, and 22.22% for unsuitable, least suitable, moderately suitable, suitable, and highly suitable, respectively. Elevation suitability showed 21.94% highly suitable and 10.31 unsuitable areas for Harar city (Table 4; Figure 4f and g).

Out of the total study area, about 3% falls under highly suitable and satisfying environmental, social, and economic criteria included in this study. These areas were in the eastern part of the city. The suitable area covers an area of 29.8% (1237 ha), moderately suitable areas 52.75% (2191 ha), less suitable area 14.18% (589 ha), and the remaining 0.29% (12 ha) unsuitable for landfill site for Harar city (Figure 5).

After identifying the most suitable site for the study area, the result was further analyzed depending on the waste generation and area needed for the proposed landfill life. Only 124 ha was identified as a highly suitable area for a landfill site in Harar city. Three potential areas were identified with an area >10 ha from the most suitable sites by using the spatial tool "Con tool" From the previous calculation, 12.8 ha is required for a landfill site with the current generation rate and estimated population growth for the city.

Two areas satisfied landfill size requirements and these areas were analyzed by a field visit. Both areas were found in the eastern part of Harar city and they are open areas. Site 1 has a 13.6-ha area and site 2 has an area of 16 ha. Site 1 has met the landfill size requirement, but with the current population growth rate, waste generation is expected to increase rapidly; therefore, site 2 is preferred.

Discussion

The present study addressed the need for solid waste disposal site selection for Harar city by identifying a proper sanitary landfill site. To address the issue, a technology-based approach integrating a geographic information system (GIS) and analytical hierarchy process (AHP) was used. This tool is effective in landfill site selection because it can handle and manage a huge amount of data, making it effective for site selection research.[63,64] In recent years, this approach has been widely applied in site selection studies.[44,51,52,57,65-67] Nowadays, many researchers in Ethiopia are using this approach to select suitable solid waste disposal sites.[2,37,38,40,53,58,68,69]

Table 4. Criteria for landfill site suitability and their rank.

FACTORS	PARAMETER	SUITABILITY CLASSES	RANK	WEIGHT (%)	AREA (HA)	PERCENTAGE (%)
Well	0-300	Unsuitable	1	15.9	99	2.37
	301-600	Least suitable	2		258	6.18
	601-1200	Moderate suitable	3		770	18.45
	1201-2000	Suitable	4		999	23.94
	>2000	Highly suitable	5		2047	49.05
Road	>5000	Unsuitable	1	23.7	900	21.58
	101-700	Highly suitable	5		2662	63.82
	701-1500	Suitable	4		296	7.10
	1501-3000	Moderate suitable	3		269	6.45
	3001-5000	Least suitable	2		44	1.05
Built up	0-700	Unsuitable	1	7	3698.63	88.62
	701-1500	Least suitable	2		474.55	11.37
	1501-2200	Moderately suitable	3		0.35	0.01
	2201-3000	Suitable	4		0	0
	>3001	Highly suitable	5		0	0
Land use/ land cover	Settlements	Unsuitable	1	35	834	20
	Cropland	Least suitable	2		1734	41.54
	Forest	Moderately suitable	3		635	15.22
	Shrub/bush	Suitable	4		567	13.59
	Grassland/barren land	Highly suitable	5		403	9.66
Aspect	North west	Unsuitable	1	4.6	695	16.68
	West	Least suitable	2		706	16.94
	South west/south	Moderately suitable	3		884	21.21
	East	Suitable	4		956	22.94
	Flat, northeast	Highly suitable	5		926	22.22
Slope	>23°	Unsuitable	1	10.6	41	0.98
	12°-20°	Least suitable	2		225	5.40
	0°-5°	Moderately suitable	4		1383	33.17
	7°-12°	Suitable	5		690	16.55
	5°-7°	Highly suitable			1830	43.9
Elevation	2033-2158	Unsuitable	1	3.2	430	10.31
	1962-2032	Least suitable	2		1109	26.59
	1883-1961	Moderate suitable	3		876	21
	1790-1882	Suitable	4		841	20.16
	1680-1889	Highly suitable	5		915	21.94

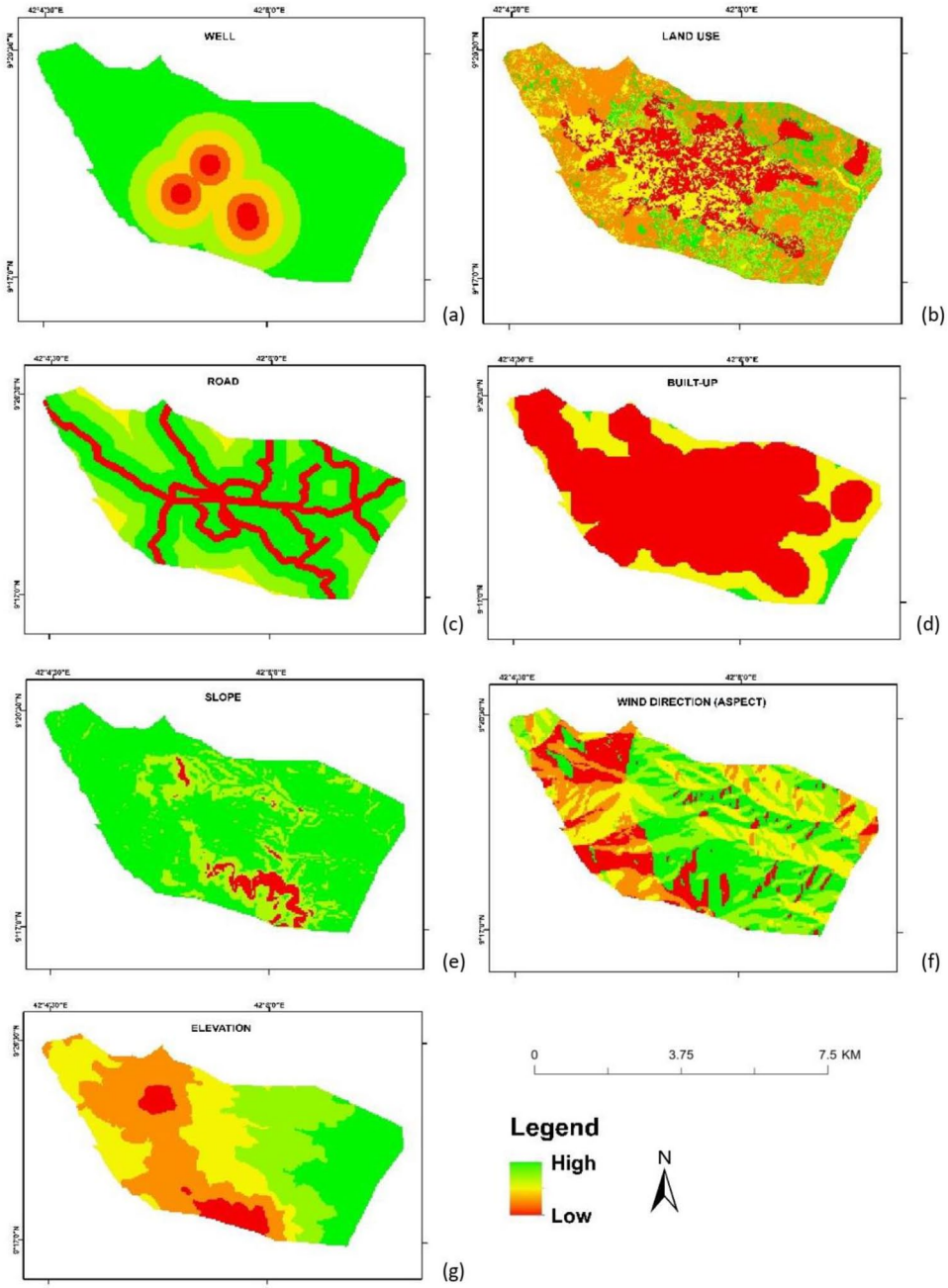

Figure 4. Suitability class-map for landfill site selection in Harar city: (a) well water suitability map, (b) land use land cover suitability map, (c) road suitability map, (d) built-up suitability map, (e) slope suitability map, (f) wind direction suitability map, and (g) elevation suitability map.

Selecting a suitable landfill site is a challenging process that requires consideration of a number of factors. The top factors for selecting landfill sites, according to Rezaeisabzevar et al[70] are groundwater, surface water, slope, soil permeability, land use, and nearby settlements. After reviewing 106 studies in GIS-based MCDM modeling for landfill site suitability between 2005 and 2019,[23] found that surface and groundwater, geology, land use, distance to the fault zone, distance to urban areas, and distance to road and slope are the most commonly used criteria groups in siting suitable landfills, among others. The study conducted in Iraq considered 13 criteria such as; groundwater, slope, elevation, slope, geology, villages, rivers, soil, geology, road, oil and gas, power lines, land use, archeology, land use, and urban area for solid waste site selection.[71] We considered factors such as distance to roads, distance from Well water points, distance from residence, land use and land cover, elevation, slope, landfill size, and wind direction were considered in this study based on the data availability and significance of these criteria for Harar city landfill siting.

The result of this study showed that more than half of Harar is covered by moderately suitable areas (52.75%), followed by

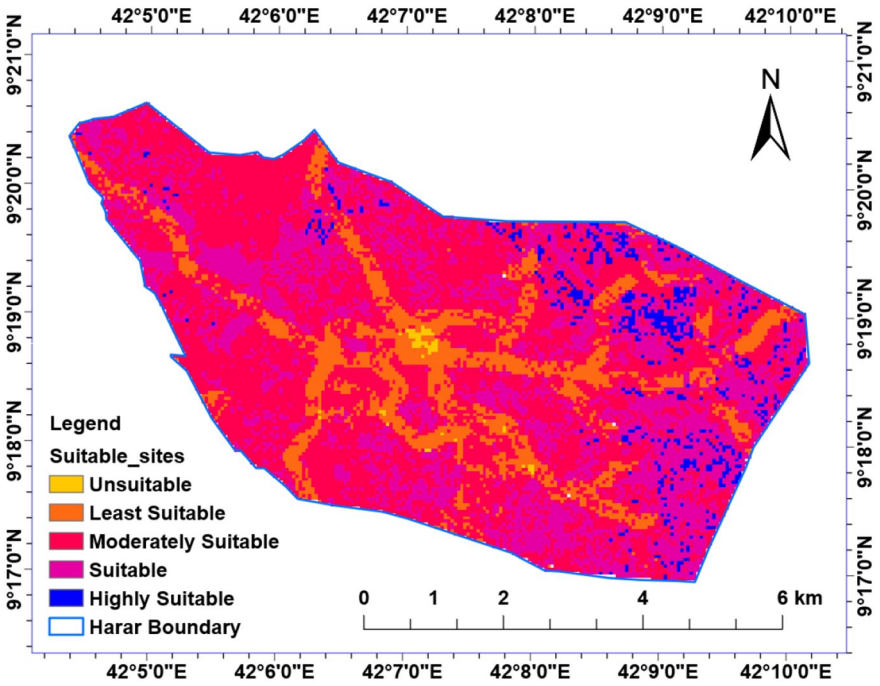

Figure 5. Overall landfill suitability analysis for Harar city.

suitable areas (29.8%), less suitable areas (14.18%), highly suitable areas (3%), and unsuitable areas (0.29%). Compared to similar studies conducted near Harar, where the largest area is covered by unsuitable area (94.3%) followed by moderately suitable (3.8%), highly suitable (1%), and least suitable (0.9%), the study area has wider suitability which satisfies environmental, social, and economic criteria included.[72]

Like Ekmekçioğlu et al[73] states, leachate released from the disposal site is a major contaminant of both surface and groundwater sources. There are 3 identified groundwater sources in this study and about half of the study area is highly suitable for groundwater criteria. According to Moeinaddini et al[52] a limiting buffer zone of at least 300 m was defined for well water sources. Mussa and Suryabhagavan[40] clearly stated, landfill sites should not be located within 500 m of groundwater sources, and a 300 m buffer is used in this study. Also, a landfill site selected based on the factor sets should easily be accessible by roads according to Olusina and Shyllon.[74] A minimum distance of 700 m buffer should be maintained for road accessibility, according to a study conducted in Zimbabwe.[75] In our result, 21.58% of an area is within a 100 m buffer, which was considered unsuitable according to the criteria limit set, which is smaller than that of other studies. This is because the road network of Harar will not allow accessibility as it goes from major roads.

When selecting a landfill site, consider a region that is less prone to floods. According to the EPA, flat terrain and mild slopes are the most typical sites to consider for landfill siting.[25,76] Harar's slope topology was flat in 75% of the city, making it ideal for landfill site selection, according to previous studies.[40,48,53] In this study, a landfill site within 1 km of an urban residential area was limited due to the possible future expansion of the study area. A study in Iraq used a buffer of 5 km for urban residential areas and 1 km for villages because[77] this buffer is too close to the distance limit for transfer stations, which is required when the source of waste generation is 6 km from the final disposal site,[78] so we used a 1 km buffer for Harar city.

While determining the size of a landfill site, the amount of solid waste generated in Harar should be calculated. Predicting the amount of waste generated, according to Hai and Ali,[79] necessitates estimating future population and per-capita waste generation rates. Similarly, the Bangladesh Center for Advanced Studies (BCAS) forecasted waste generation from 1998 to 2021 based on GDP growth and per capita waste generation.[80] Enayetullah and Sinha[81] determined the required landfill area based on waste generation, assuming a 6 m height and 1.1 ton/m^3 compaction density. Additionally, Ambat[82] used 600 kg/m^3 for heights of 8, 12, 16, 20, and 24 m. However, none of these studies utilized this factor into account as an independent factor while selecting on a landfill site.

In this study, solid waste generation is estimated to be 195 457.5 tons in 10 years. A study conducted in Nigeria also estimated solid waste generation for 5 years with an increment from 85 to 226.4 tons/day[83]; similarly, for Harar, there will be an increment from 206.55 to 230.85 tons/day in the coming 5 years. A study conducted in Bangladesh,[84] concluded based on their estimation in the year 2020 solid waste generation rate may exceed 30 000 tons/day for Dhaka city, which in turn requires 81 ha/year and this is because of rapid population growth. Similarly, we estimated the total area required for landfill site with estimated population and per-capita waste

generation rate to be 12.8 ha over 10-year landfill age and sited potential landfill site for Harar city.

Conclusion

The use of geographic information systems in landfill site selection is an effective tool, and it is widely used in every corner of the world. A geographic information system can handle huge data from diverse sources, allowing using them in an organized way with a better visualization. Its application becomes easy and quick at low cost when integrated multicriteria evaluation such as analytical hierarchy process developed by Thomas Saaty in 1980.

Harar city, the study area, suffered a lot in the management of solid waste as the city has witnessed a high waste generation rate resulting from rapid population growth. The open disposal site of Harar city is deteriorating the environment and worsening public health. Also, it will not be able to cope with the amount of waste it generates. Overlaid Suitability analysis for landfill site selection for Harar city showed only 3%, or 125 ha, of Harar city is highly suitable for a landfill site. Further, based on the landfill size required to cope with the increasing amount of waste generation, an area found in the eastern part of the city with a total area of 16 ha was selected. This site is selected based on its capacity, low risk of pollution, and easy access after field validation.

Overall, this study proved that GIS is an effective tool in selecting healthy and environment-friendly landfill sites. The introduction of the estimation of waste volume and landfill size calculation as an independent factor for landfill site selection makes this study unique. This study used the opinions of experienced experts to rank each criterion, which is the most important but neglected part of many published landfill siting studies. Moreover, the results of this study can be used as an input for decision making in siting landfill for Harar city. The future trend of waste generation calculated in this study can be used as a baseline by policymakers. Thematic maps of Harar city generated during can also be used as base maps to study the related problems and the methodology used can be adopted to solve sanitary landfill siting problems in other areas.

Limitations and Future Scope

This study considered 8 criteria for selecting a landfill site, but more parameters should be used to make a better decision. Surface water was not considered in this study due to the seasonality of rivers in the study area. Geologic properties, drainage systems, groundwater depth, and soil types were not included because of authentic data availability. In the future, more factors and others should be taken into account and the result can be compared with the current study. The current dumpsite's impact on the environment and community has not yet been studied, so these issues can be addressed in the future.

Author Contributions

Conceptualization: EMA and YTD. Methodology: EMA and YTD. Data collection: EMA. Formal analysis: EMA and YTD. Writing—original draft, Review final manuscript: EMA, YTD, and KBB. All authors read and agreed on the manuscript.

ORCID iDs

Elsai Mati Asefa https://orcid.org/0000-0001-7864-8382
Yohannes Tefera Damtew https://orcid.org/0000-0003-2936-2462
Kefelegn Bayu Barasa https://orcid.org/0000-0002-0669-2947

Supplemental Material

Supplemental material for this article is available online.

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Appendix 1

Figure A1. Harar city, Kile dumpsite, problematic and unscientific waste disposal site.

Appendix 2

Thematic map produced each criterion selected for suitability analysis of Harar landfill site (section 2.3).

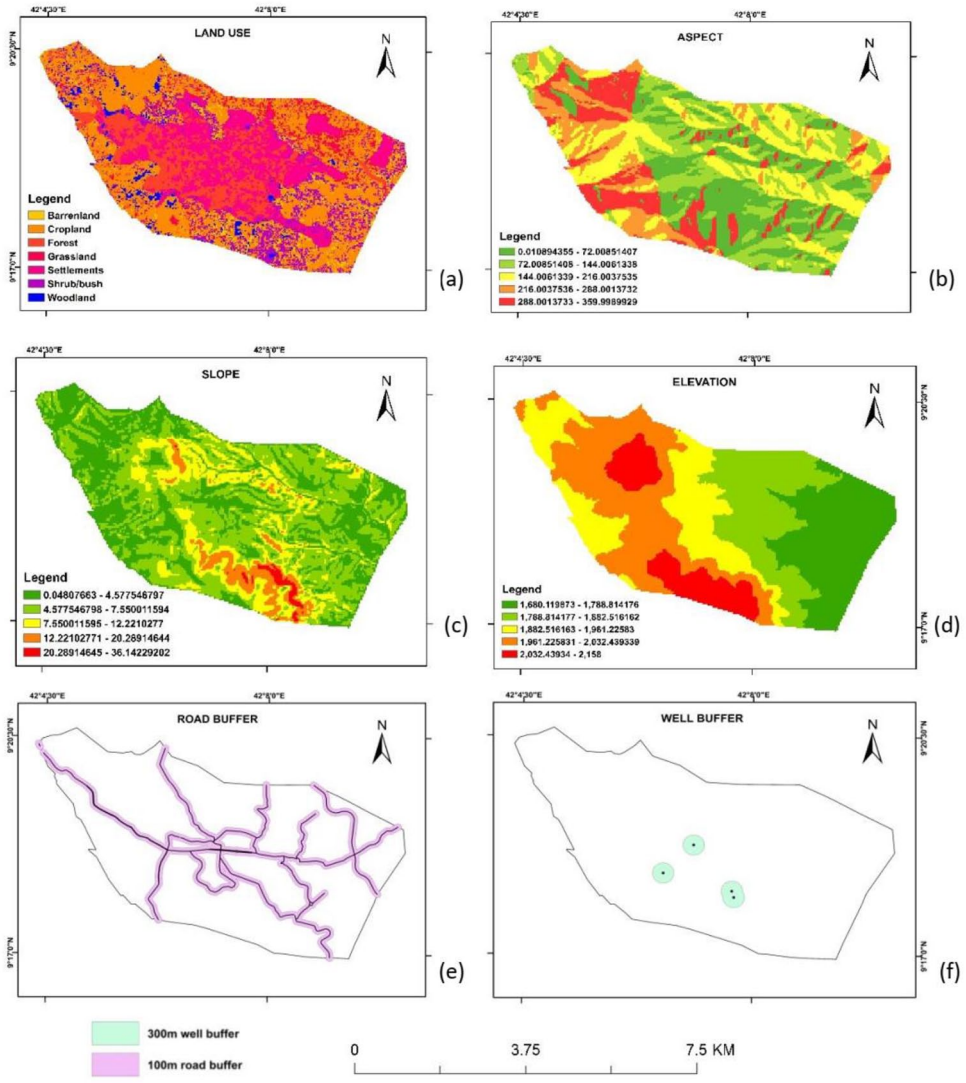

Figure A2. Thematic map produced: (a) land use map, (b) wind direction, (c) slope map, (d) elevation map, (e) road map, and (f) well water map.