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Site Selection and Design for Sanitary Landfill in Harar Town, Eastern Ethiopia

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Abstract

Solid waste management is a critical environmental and public health concern in different countries of the world and a significant issue in developing countries like Ethiopia. Open dumping is a widespread practice in most Ethiopian towns and not different in Harar town. This study aimed to select a suitable landfill site using a geographic information system and analytical hierarchy process for Harar town. Related studies conducted did not mention site selection concerning population growth and waste generation, this study considered these facts and calculated the area required for landfilling over the proposed landfill age. Secondary data from different sources were used in this study. Landfill area, road accessibility, distance from Well water, distance from residence, land use and land cover, elevation, slope, and direction of wind were used in the analysis of the landfill site. An analytical hierarchy process was used to rank and weight these criteria using Eigenvector and standardized matrix. Out of the most suitable areas identified (125 hectare, ha), three potential sites in the eastern part of the town had a total area (11.2ha, 13.6ha, and 16 ha). Depending on the projected waste generation rate (195,457.5 tons) in 10 years, no area in Harar town satisfied the area requirements for landfilling. So, the town should be aware of this and deal with the neighboring towns.

Keywords: Landfill; Design; Suitability; Geographic Information System; Analytical Hierarchy Process; Waste Generation

Introduction

Rapid population growth, urbanization, change in consumption patterns, and inadequate or negligible recycling and reuse practices increased municipal solid waste generation [1,2,3]. Globally, there is a rise in solid waste generation rates accounted for a footprint of 0.75kg per person per day in 2016. With rapid population growth and urbanization, annual solid waste generation is expected to increase by 70% from 2016 to 2050 [4].

Open dumping and improperly built sanitary landfills are the most common disposal sites in most developing countries. This, in turn, results in generating toxic leachates and significant greenhouse gas emissions that contribute to global warming and environmental degradation [5,6,7]. Like most, solid waste management is a critical problem in Ethiopia. Despite rapid urbanization and an increasing per capita waste generation, most cities and towns did not have an integrated solid waste management program [3,8].

Harar city, which is one of the most ancient cities in the country is one of the cities practicing open dumping. A study in 2008 showed that the daily waste generation of the city is estimated to be around 38.8 tons or 14, 162 tons per year. Less than half of the generated waste was collected and dumped openly in the Kile area, at the outskirt of the city. Although the Kile area was considered a potential landfill site a decade ago, the landfill construction has never been materialized and used as only as an open dumping site [9].

Kile open dumping site is located 11km from the center of Harar town and surrounded by rural residents and farmlands. The Leachate from the dumping site is released and entered into farmlands without any treatment and the site becomes a source of nuisance for the surrounding community. Open burning is also practiced in the area and causes air pollution in the area. The site is also an area where high voltage electric lines pass through [9]. The above-mentioned issues need to be addressed by identifying a landfill site that considers the economic, social, public health, and environmental guidelines. This study aimed to determine a suitable landfill site for Harar town. A Geographic information system (GIS) integrated with analytical hierarchy process (AHP) multi-criteria decision making was applied to determine a suitable landfill site through minimizing conflicting criteria.

Methods and Materials

Description of the study area

Harar town, located at 9^0 18' 43" N latitude and $42^0$7' 23" E longitude, is a historical and oldest city found in eastern Ethiopia, 525Km from the capital, Addis Ababa. The town 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 1,885 meters above sea level. Harar town population in 2021 is 153,000 according to the projection made depending on the 2007 Census [10]. The region has a mean annual temperature between 10-26°C and a mean annual rainfall of 804.7 mm.

Data acquisition and pre-processing

Secondary data acquired from the internet, reports, books, journals, governmental institutions, and other documents were used in this study. Spatial vector and raster data were acquired from various websites and Harar city municipality, Harari urban development, and construction bureau (HUDCB). Study area map, road networks, well points, and dumpsite location were acquired from the municipality. Additional raster data such as satellite imageries (Landsat 8 images and Digital Elevation - Shuttle Radar Topography Mission (SRTM)) obtained from USGS EROS Archive (https://www.usgs.gov/centers/eros/science/usgs-eros-archive).

Image processing was done using ArcGIS 10.4 (https://support.esri.com/en/products/desktop/arcgis-desktop/arcmap/10-4-1) and QGIS 3.2 (http://qgis.osgeo.org/). Pre-processing operations like digitization, geo-referencing, and pan-sharpening were done using QGIS 3.2. Digitization was done for Well points, built-up areas, and road networks which were obtained in AutoCAD format from HUDCB. Geo-referencing was done for the town boundary obtained in shape format from HUDCB with ground control points. Pan sharpening and image merging were done in raster preprocessing.

Determining Siting Criteria

Eight criteria were selected for evaluating landfill site selection for Harar town. Factors such as distance to roads, distance from Well water points, distance from residence, land use and land cover, elevation, slope, landfill size, and direction of wind were considered for this analysis after reviewing works of literature [6,11-19].

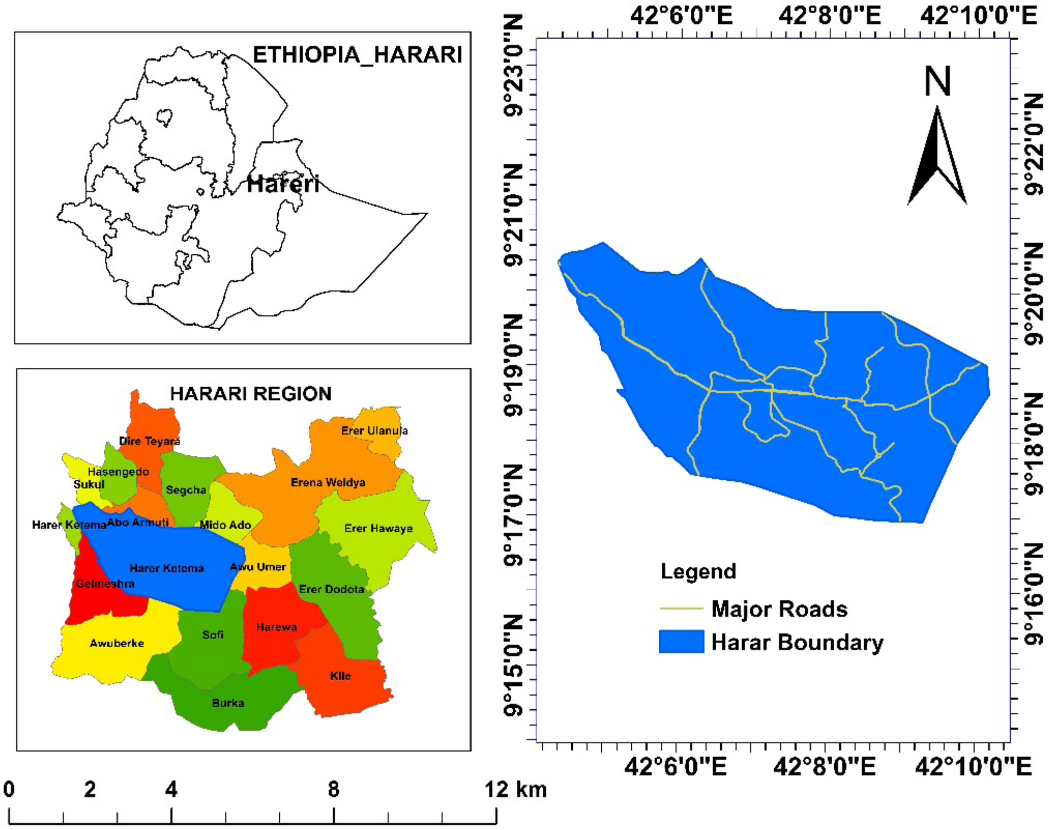

Figure 1: Map of the study area

Criteria	Limit/ Suitability
Road	100m buffer
Built-up	1000m away
Land use/ land cover	Urban space, green area, agricultural land
Well points	300m buffer
Slope	< 10%
Altitude	>1500
Direction of wind	Depend on the dominant wind in the study area
Land size area	186 ha

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

Landfill sites should be located away from water sources and the buffer zone could differ from case to case [20-22]. In this study, a 300m buffer zone was defined for all well water sources as used in the previous study [23]. To exclude the productive land areas that have significant socio-economic values including agricultural lands, grasslands, and forest zones, Land use, and land cover were used. Although numerous studies suggested exclusion of several Land uses urban spaces, green area, and agricultural land use were not considered suitable for this study [24,25,26]

Easy access to a landfill site can avoid extra costs, so we selected road accessibility as one factor. Locating a landfill within a proximate distance to roads could cause nuisance, bad smells, and related problems [27,28]. Therefore, a reasonable distance should be considered by taking the factors mentioned into account, an area less than 100m for this study is unsuitable (Ohri and Singh, 2013; Balew *et al.*, 2020; James, 2020). Also, we considered an area greater than 2km from residence as a landfill site should be far from a residential area, commercial buildings, urban green space, service area, and industries [6,27,28].

A flat area is favorable for a landfill site to reduce construction costs and the risk of pollution [32,33]. According to [19,32,33] we considered a slope less than 10^0 as highly suitable for a landfill site. To minimize the bad odor generated from a landfill site that affects near residents, it is important to consider the direction of the wind [34]. Since North West wind type is dominant in the study area it is unsuitable.

Landfill size determination

Landfills should be able to accommodate waste disposal for a minimum of 5 years of operation [35]. 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, and density of the compressed landfill material were considered [26,29,36,37].

To calculate the volume of the landfill, 3m landfill height was chosen because of the high groundwater table in the area. The following factors and values were considered to calculate the size of the landfill area in each year: 0.35 kg/capita/day waste generation, Compacted specific weight of solid waste in landfill (350kg), 15 cm soil cover on top and sides for lift height of 1.5 to 2 m, 1.5m thick liner system with leachate collection layer and 1.0 m thick cover system including gas collection layer. All calculations were performed using the following formulas:

$$Vw = total\ waste\ generation\ in\ n\ years\ (tons)/rate\ of\ compaction\ (kg/m3),\ where;\ Vw\ is\ total\ volume\ of\ waste\ (m^3/year) \quad (1)$$

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

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

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

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

$$Wi = 1\frac{1}{n}\sum_{j=1}^{n} aij/\sum_{i}^{n} aij\ , i, j = 1,2, \ldots n \quad (6)$$

$$CR = CI/RI\ , where\ CI\ is\ consistency\ index\ and\ RI\ is\ random\ index \quad (7)$$

$$CI = \lambda max - n/(n-1)\ , \lambda\ max\ is\ pricipal\ eigen\ value\ and\ n\ is\ number\ of\ factors \quad (8)$$

Criteria ranking

Expert opinion was used to rank these criteria. By using the AHP method appropriate weight was given for each criterion. Each criterion is then sub-classified into five sub-criteria groups as unsuitable, least suitable, moderately suitable, suitable, and highly suitable. We have considered 8 criteria that are adequate for land suitability analysis to the siting of a landfill site following previous studies.

The calculation involves the Computation of the sum of values in each column of the pairwise matrix, the normalization of the matrix by dividing each element by its column total, and the computation of the mean of the elements in each row of the normalized matrix. Generally, AHP consists of three main principles, including hierarchy framework, priority analysis, and consistency verification [38].

Pairwise comparison and standardized matrix

We compared each criterion by using the relative scale pairwise comparison as shown in Table (2). To calculate the vectors of priorities, the average normalized column method is used. In this, the elements of each column are divided by the sum of the column and then the elements in each resulting row are added and this sum is divided by the number of elements in the row (n). Mathematically this was expressed as equation (6) below. 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 (7) below.

In the final stage, the influence of each criterion compared to the other for landfill site selection was assigned a weight. 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 below.

$$S = \sum_{i=1}^{n} WiXi \text{ , where } S \text{ suitability, } Wi \text{ weight of factor and } Xi \text{ criterion score of factor } i \quad (9)$$

2.5. Land Suitability Assessment

To identify the most suitable site for a landfill in the study area, weighted information generated using AHP multicriteria was integrated with layers in the GIS interface by using the weighted overlay spatial analyst tool. The Suitability index was calculated as equation (10). Then results were further analyzed depending on landfill capacity and landfill area calculated above.

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

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 direction of wind criterion, and EL is elevation criterion. All the reclassified factor layers done by the Euclidean distance tool were used in weighted overlay analysis and the final landfill site for solid waste disposal for Harar town was produced.

Result

Landfill area determination

A landfill area with a capacity of holding generated waste in Harar town for consecutive ten years was determined (Table 4). Following the formulas mentioned earlier, solid waste generation is expected to increase and a total of 195,457.5 tons will be generated in the next ten 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 5m to compensate for high groundwater table is 128 ha.

The total area needed in 10 years for Harar town landfill was

$$T10 = 153{,}000 \; x \; 0.35 \; kg/\; capita/day \; x \; (365 \; x10) \; x \; 10^{3}$$

$$kg/ton = 195{,}457.5 \; tons$$

$$V10 = 195{,}457.5 tons \; x1000 kg/tons/350 \; kg/m3 = 558{,}450 \; m3$$

$$Area = 558{,}450 m3/5m \; x \; 1000 m2/ha = 112 \; ha$$

$$Total \; area = 1.15 Area = 128 \; ha$$

Criteria	LU/LC	Road	Well	Slope	Built Up	Aspect	Elevation
LU/LC	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	½	1

Table 2: Pair-wise comparison of criteria for landfill site selection of Harar town

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%

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

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total pop.	153,000	157,000	162,000	166,000	171,000	175,000	180,000	185,000	189,000	194,000
Waste/yr. (tons)	53.55	54.95	56.7	58.1	59.85	61.25	63	64.75	66.15	67.9
Volume/yr. (m^3/yr.)	153	157	162	166	171	175	180	185	189	194
Capacity (m^3/day)	206.55	211.95	218.7	224.1	230.85	236.25	243	249.75	255.15	261.9
Cover soil(m^3/day)	15.3	15.7	16.2	16.6	17.1	17.5	18	18.5	18.9	19.4
Total area (ha)	15	15.5	16	16.4	16.8	17.2	17.7	18.2	18.6	19.1

Table 4: projected waste generation, volume, planned cell height and area needed each year

Siting Criteria suitability

Road suitability

As shown in Table 5, 21.58% of the area was unsuitable related to road suitability criteria. The rest 1.05 %, 6.45%, 7.10%, 63.82%, and 63.82% were classified as less suitable, moderately suitable, suitable, and highly suitable respectively for the landfill site (figure2).

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.

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 5). The remaining 9.66 % of the study area was highly suitable based on land-use/land-cover suitability (figure 4).

Slope suitability

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

Residential or built-up area suitability

There were no suitable and highly suitable areas observed because all the study area was within 2km of distance from built-up (Figure6). 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 town (Table 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 town. Three potential areas were identified with an area greater than 10 ha from the most suitable sites by using the spatial tool "Con tool" From the previous calculation, 128ha is required

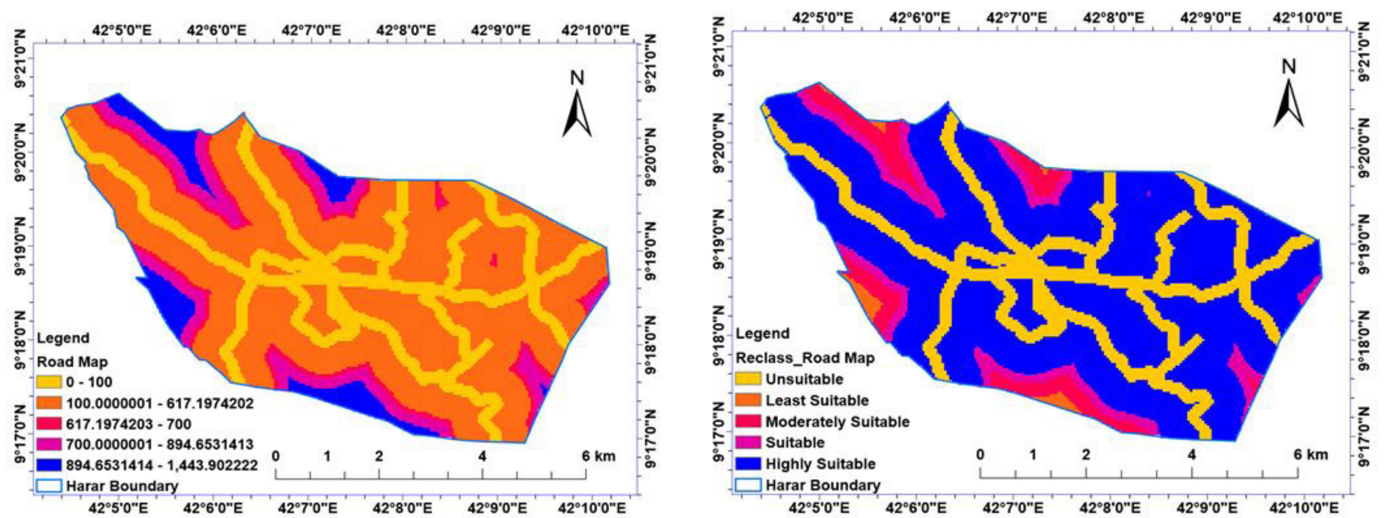

Figure 2: Original and Reclassified ranked suitability map of the road network.

Factors	Parameter	Suitability Classes	Rank	Weight	Area, ha	Percentage, %
Well	0-300	*Unsuitable*	1		99	2.37
	301-600	*Least Suitable*	2		258	6.18
	601-1200	*Moderate Suitable*	3	15.9%	770	18.45
	1201-2000	*Suitable*	4		999	23.94
	>2000	*Highly Suitable*	5		2047	49.05
Road	0-100, > 5000	*Unsuitable*	1		900	21.58
	101-700	*Highly suitable*	5		2662	63.82
	701-1500	*Suitable*	4	23.7%	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		3698.63	88.62
	701-1500	*Least Suitable*	2		474.55	11.37
	1501-2200	*Moderately Suitable*	3	7%	0.35	0.01
	2201-3000	*Suitable*	4		0	0
	> 3001	*Highly suitable*	5		0	0
Land use/ land cover	Settlements	*Unsuitable*	1		834	20
	Cropland	*Least suitable*	2		1734	41.54
	Forest	*Moderately suitable*	3	35%	635	15.22
	Shrub/bush	*Suitable*	4		567	13.59
	Grassland/ barren land	*Highly suitable*	5		403	9.66
Aspect	North west	*Unsuitable*	1		695	16.68
	west	*Least suitable*	2		706	16.94
	South west/south	*Moderately suitable*	3	4.6%	884	21.21
	East	*Suitable*	4		956	22.94
	Flat, northeast	*Highly suitable*	5		926	22.22
Slope	$>23^0$	*Unsuitable*	1		41	0.98
	$12\text{-}20^0$	*Least suitable*	2		225	5.40
	$0\text{-}5^0$	*Moderately suitable*	4	10.6%	1383	33.17
	$7\text{-}12^0$	*Suitable*	5		690	16.55
	$5\text{-}7^0$	*Highly suitable*			1830	43.9
Elevation	2033-2158	*Unsuitable*	1		430	10.31
	1962-2032	*Least suitable*	2		1109	26.59
	1883-1961	*Moderate suitable*	3	3.2%	876	21
	1790-1882	*Suitable*	4		841	20.16
	1680-1889	*Highly suitable*	5		915	21.94

Table 5: Criteria for landfill site suitability and their rank.

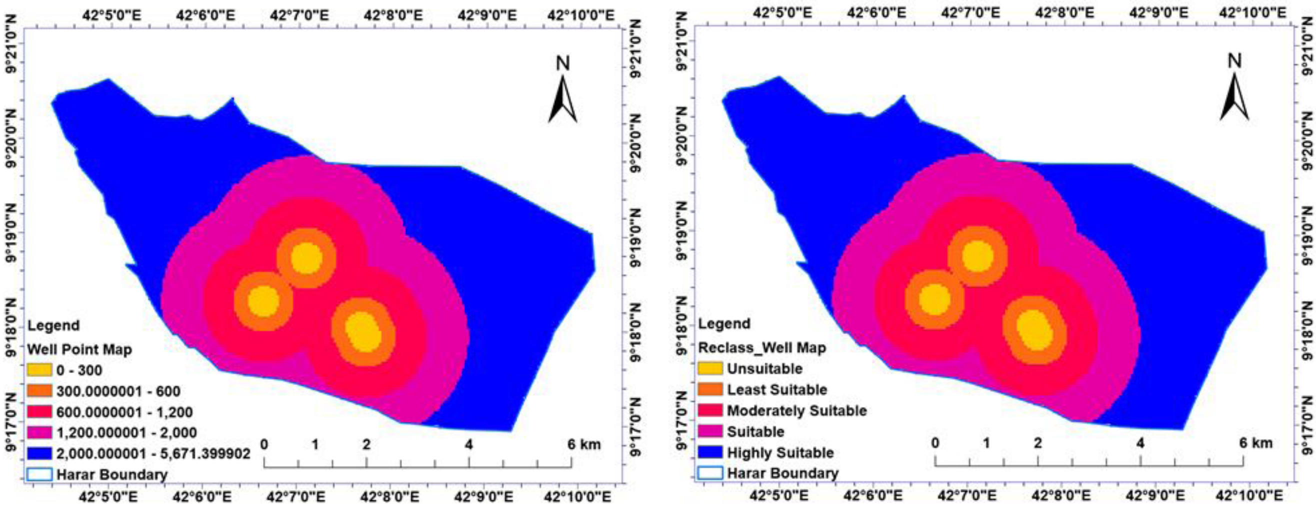

Figure 3: Original and Reclassified ranked suitability map of Well points.

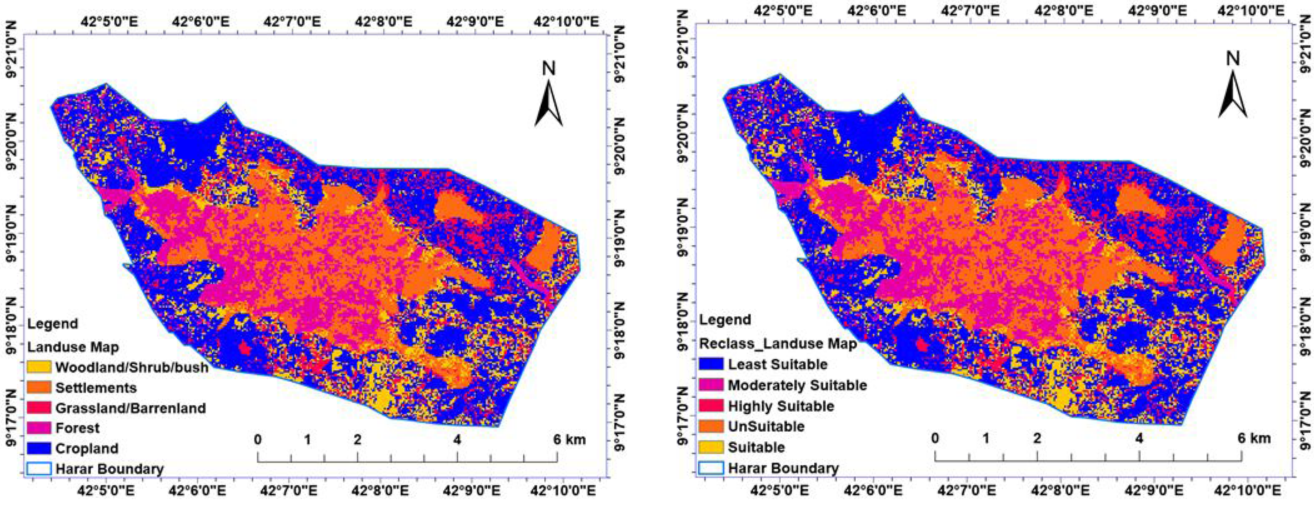

Figure 4: Original and reclassified ranked suitability map of land use/land cover

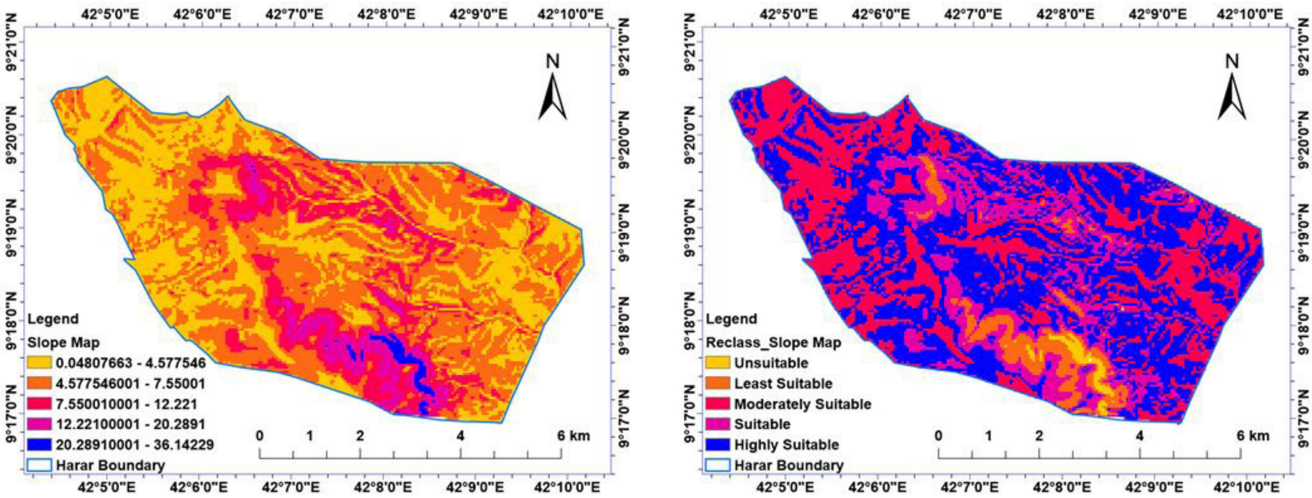

Figure 5: Original and Reclassified ranked suitability map of study area slope.

for a landfill site with current generation rate and estimated population growth for the town. So, no area satisfies the required landfill area for a landfill.

Discussion

Out of the total study area, about 3% fall under highly suitable and satisfy environmental, social, and economic criteria included in this study. These areas were in the eastern part of the town. 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 town (Figure7).

Except for few studies, none considered the generation rate and area needed for landfill sites selection in integration with techniques widely used such as GIS and MCDM (36,39). Among the techniques, GIS and AHP are being widely applied in the recent past for analysis of landfill site selection studies (22,23,29,30,40–42). In Ethiopia, it is also widely used for disposal site selection (2,16,17,19,27,31,43,44).

Although landfills are considered as the simplest and most cost-effective methods for solid waste disposal, it has a significant impact on the environment unless designed through careful planning and site selection (45–50). In this study, we considered eight criteria for the selection of a landfill. These criteria may not necessarily have equal preferences and we used multicriteria decision-making AHP to rank these criteria. The landfill area was selected because all the suitable sites identified may not necessarily be capable of landfilling depending on the generation rate. Surface water was not considered in this study because of the seasonality of rivers in the study area. Drainage of the town was not considered because of a lack of data.

The use of GIS in this study was to identify a landfill site depending on screening criteria of suitability for Harar town.

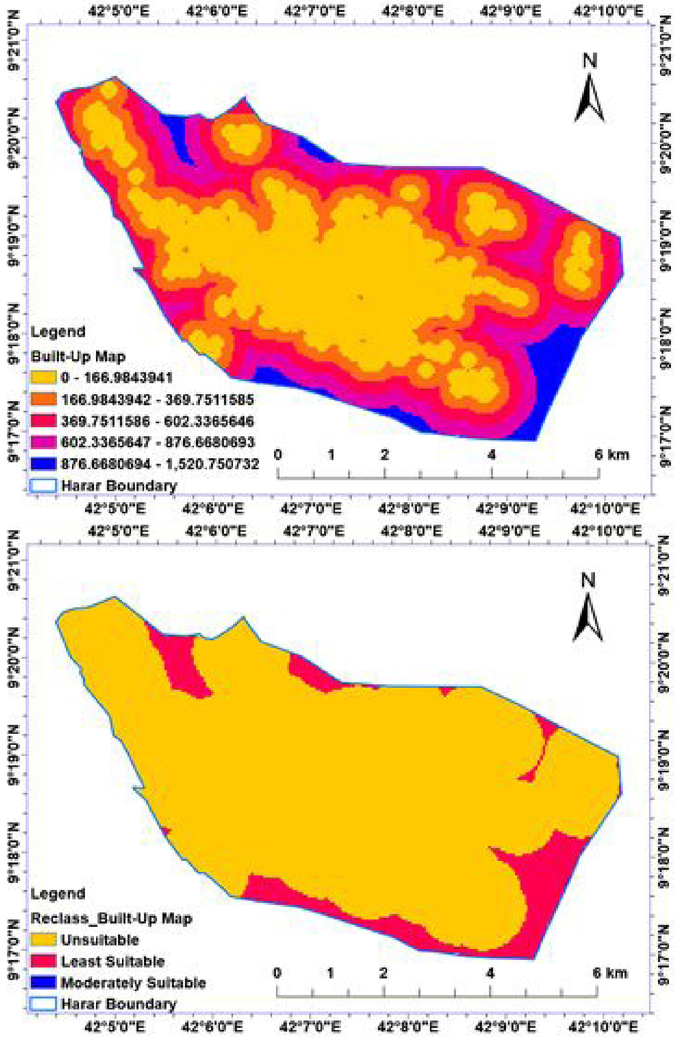

Figure 6: Original and reclassified ranked suitability map of built-up area.

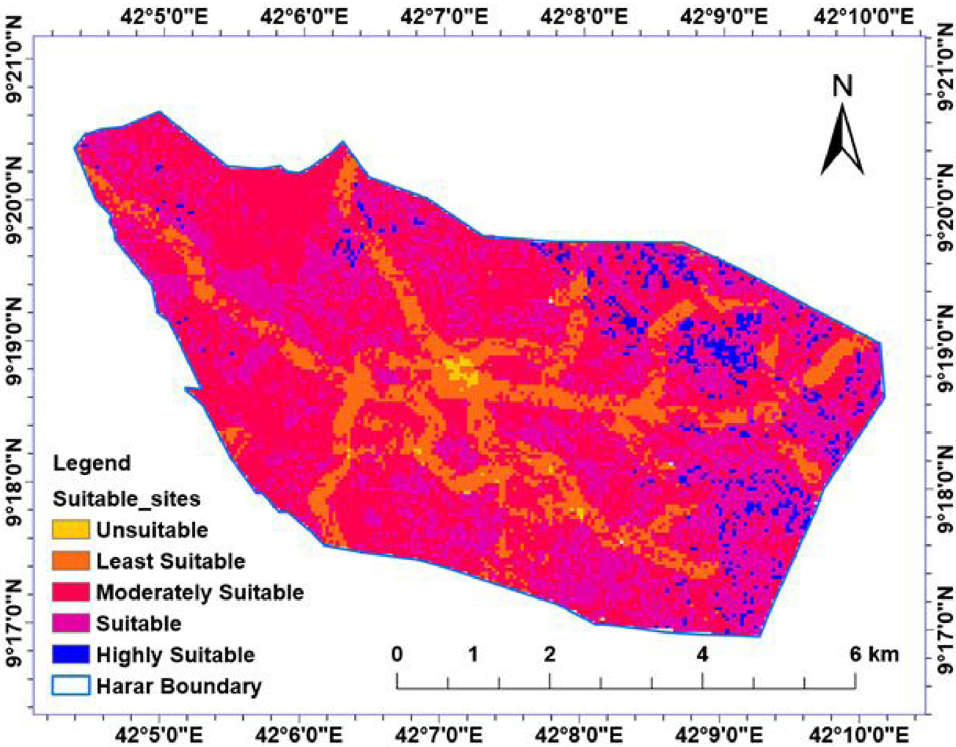

Figure 7: overall landfill suitability analysis for Harar town.

This was done through spatial analyst tools such as Euclidean, reclassification, weight overlay, and select feature. The identified potential landfill sites were field checked, these sites were flat, no residents were around, found within 200m road access, and found on open spaces but from the south of one of the sites, there were farmlands. The area of these sites ranges between 11.2, 13.6, and 16 hectares. But these sites could not hold the projected waste generation of the town in the coming 10 years (128 ha).

Conclusion

This study used GIS in integration with AHP for better decision making to analyze a suitable landfill site for the study area and proved that GIS is an efficient and effective tool in figuring out suitable sites for solid the waste disposal system. But this technique alone cannot guarantee the proposed site is a suitable site for landfill that is why this study calculated the area needed for a landfill site. The result showed suitable landfill sites, but the sites were not fit the projected waste generation rate for the study area. Because of this Harar town will be forced to look out for a landfill site in the neighboring region which is Oromia regional state.

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