

A MULTI-CRITERIA GIS MODEL FOR SUITABILITY ANALYSIS OF LOCATIONS FOR DUMPSITES IN LILONGWE CITY.

HILLARY MAZIBUKO

Thyolo, Malawi

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DECLARATION

I, Hillary Mazibuko declare that this research project represents my work and that it has never been submitted to this institution or any other institution for any academic purpose. All sources of information have been appropriately acknowledged.

Signature: 

Date: 29th May, 2025.

DISSERTATION APPROVED BY:

SUPERVISOR:

Dr. Jabulani Nyengere Signature: 

ASSESSOR:

Name: Signature:

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ABSTRACT

The rapid urbanization of Lilongwe City, Malawi, has exacerbated solid waste management issues, as the existing dumpsite in Area 38 (Mtaya) is insufficient to accommodate the growing population. This study employs multi-criteria decision analysis (MCDA) utilizing Geographic Information Systems (GIS) to identify optimal dumpsite locations that ensure environmental sustainability and safeguard public health. The assessment involved key criteria including proximity to airports (1,000 m buffer), boreholes and waterways (500 m buffer), railways and roads (400 m buffer), slope gradients, soil characteristics (surface loamy sand and subsurface sandy clay loam), and land use/land cover (LULC). This was achieved through the integration of spatial datasets and the application of Analytic Hierarchy Process (AHP) weighting. The results indicate that 11% (45.88 km²) of Lilongwe's land is suitable for landfill sites, primarily located in the northern, southwestern, and southeastern regions. The designated areas adhere to international landfill placement regulations, characterized by non-productive barren terrain comprising 25 percent of the city and mild slopes of less than 5°, thereby minimizing the risk of leachate discharge. Soil types with restricted permeability safeguard groundwater, while proximity buffers reduce the likelihood of water source contamination and decrease transportation costs. The finding that only 11% of these results are suitable underscores the necessity of transitioning to constructed landfills equipped with leachate treatment systems, as recommended by Malawi's Environmental Affairs Department. The research demonstrates that data-driven spatial planning, utilizing GIS and remote sensing, can significantly mitigate environmental and health risks. Recommendations include on-site verification of proposed locations, community engagement in waste management initiatives, and additional studies that integrate climate resilience factors such as flood vulnerability. This study presents a replicable framework for sustainable waste management in rapidly urbanizing regions, emphasizing the need to balance ecological preservation with infrastructure development

Keywords: GIS, multi-criteria decision analysis (MCDA), waste management, Lilongwe city, landfill site selection, urbanization.

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ACRONYMS/ABBREVIATIONS

AHP:	Analytic Hierarchy Process
DEM:	Digital Elevation Model
ESRI:	Environmental Systems Research Institute
FAO:	Food and Agriculture Organization (United Nations)
GCS:	Geographic Coordinate System
GEE:	Google Earth Engine
GIS:	Geographic Information Systems
HOTOSM:	Humanitarian OpenStreetMap Team
LULC:	Land Use/Land Cover
MCDA:	Multi-Criteria Decision Analysis
USGS:	United States Geological Survey
UTM:	Universal Transverse Mercator (Coordinate System)

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CHAPTER 1: Introduction

1.1. Background

Waste disposal involves the collection, removal, and relocation of waste to designated areas for storage or recycling. The waste comprises diverse materials, including leaves, food remnants, paper, textiles, bones, and deceased animals (Banda, 2014). Global waste production is projected to increase to 2.8 billion metric tons by the year 2050. The increase imposes significant cost constraints on collection, landfills, and recycling, with the Sub-Saharan Africa region generating approximately 62 million tons of waste each year (Nkhoma, 2023). The rapid growth of urban populations has led to city expansion, increased consumption rates, and the formation of squatter settlements. Additionally, the industrial revolution has resulted in heightened production, consequently generating more waste (Abubakar Aminu Usman, 2015).

In previous years, residences in the city generated minimal solid waste, and backyard pits served as the most convenient method for waste disposal. Some households continue to utilize backyard pits for the disposal of household and agricultural waste (Logistics Cluster, 2025). The large dumpsites were utilized for the disposal and burial of metals and certain construction residuals, with many of these sites remaining active to the present day. The majority of dumpsites present a health risk to the community, as many are situated in proximity to residential areas due to population growth and urbanization (Rebecca Zagozewski, 2011).

Malawi, similar to other developing nations, encounters significant challenges due to reliance on a single dump site. This situation adversely affects the well-being of residents in adjacent areas, highlighting the urgent need for appropriate solid waste disposal sites (Ndala, 2021). The Environmental Affairs Department in Malawi has advised the Lilongwe City Council against closing the dumping site at Area 38 (Mtaya). They argue that immediate closure will not provide a sustainable solution to the sanitation challenges faced by residents. Instead, they recommend the establishment of an engineered landfill site where waste can be recycled for the production of items such as fertilizer, plastic pumps, and chairs (Zinazi, 2023).

The Lilongwe City Council has recently determined that the dumpsite will be relocated from the city to facilitate the use of the area for commercial activities. The identified recommended area is in proximity to Salima Road.

1.2. Problem Statement

Lilongwe city is the capital city in Malawi, for this reason it is going through very rapid urbanization, thereby increasing the number of wastes from industries, schools and households. In most neighbourhoods, people dump wastes without considering the health hazards, for instance, some dump the wastes in water sources whilst some dump their wastes in open dessert lands which poses high risks of vector borne and water borne diseases in the community. The current dumpsite that is located in area 38 by the name Mtaya is inadequate to cater for growing population and expansion of the city (Tembo, 2023). Therefore, this study aims at identifying the alternative sites for disposing the wastes within the Lilongwe City accompanied with the promotion of healthier, more sustainable living conditions for all residents, mitigating the impacts of inadequate dumpsites on public health, the environment, and social equity (Sam Zulu, 2017).

1.3. Main Objective

- To examine optimal sites for waste disposal in Lilongwe city.

1.4. Specific Objectives

- To perform a proximity analysis of airport, boreholes, waterways, railways and roads.
- To evaluate the appropriate slope and type of soil for optimal waste site
- To analyse the land use of Lilongwe city for locating the suitable dump site.

Research questions

- What are the key factors to consider when selecting a suitable site?
- How does the slope affect the selection of a suitable site for the dumpsite?
- What are the possible health and environmental impacts of the dumpsite?
- How can GIS, Remote Sensing and GEE be used to determine the suitable site for the dumpsite?

1.5. Significance of Study

This study is critical for identifying alternative, scientifically validated dumpsite locations that prioritize community well-being, environmental sustainability, and compliance with Malawi's waste management policies. The study directly addresses the pressing need to mitigate groundwater contamination, reduce pollution from leachate runoff, and prevent disease outbreaks by incorporating spatial criteria like safe distances from critical infrastructure (airports, boreholes, and waterways), ideal slope gradients, and appropriate soil types. In accordance with Malawi's Environmental Affairs Department's guidelines and guaranteeing long-term environmental preservation, the findings will direct policymakers in their shift from open dumping to controlled engineered landfills.

CHAPTER 2: Literature Review

2.1. Proximity Analysis of Airport, Boreholes, Waterways, Railways, and Roads

Proximity analysis is critical in landfill site selection to mitigate environmental and public health risks while ensuring logistical efficiency. Ravindra Jaybhaye et al. (2014) established a 1,000-meter buffer around airports to mitigate hazards such as bird strikes and aesthetic conflicts, a guideline adopted in this study. Their analysis in Pune, India, showed that dumpsites near airports compromise tourism and aviation safety, reinforcing the need for spatial exclusion zones. The selection of landfill sites requires careful consideration of proximity to critical infrastructure and natural features to balance public health, environmental safety, and logistical efficiency.

Similarly, Gizachew Kabite et al. (2012) and Dereje Biru et al. (2023) stress the importance of separating dumpsites from groundwater sources and boreholes. A 500-meter buffer decreased the probability of groundwater contamination by 60% in Bonga Town, Ethiopia, according to Biru's analysis; this threshold is applied here to Lilongwe's borehole-dense communities. Emmanuel Kazuva et al. (2019) point out that rapid urbanization in Dar es Salaam, Tanzania, frequently forces smaller buffers (500 meters) due to spatial constraints, while Nitin Mundhe et al. (2014) advocate for 2,500-meter buffers to prevent surface runoff pollution in Pune. Waterway proximity is still controversial. This analysis acknowledges trade-offs between ideal environmental standards and actual land use by adopting a 500-meter buffer for Lilongwe's rivers.

Accessibility and community health must be balanced when it comes to transportation infrastructure closeness. Roads and railroads between 400–1,200 meters maximize garbage transit efficiency while reducing noise and air pollution, according to OE Demesouka et al. (2014). This is supported by Iftikhar Ali et al. (2023) in Peshawar, Pakistan, where a 400-meter buffer decreased transportation expenses by 30% without exposing more homes. Mojtaba Barzehkar et al. (2019) warn that Iran's overemphasis on road access resulted in the encroachment of dumpsites on agricultural land, highlighting the necessity of multi-criteria balancing. When taken as a whole, these studies support buffer distances but also emphasize contextual flexibility, which calls for practical adjustments in Lilongwe's quickly urbanizing environment.

2.2. Determining Appropriate Slope and Soil Type

Slope and soil properties are critical for minimizing leachate runoff and preventing groundwater contamination. Bauer (2024) defines slopes less than 5° as optimal for landfills due to the erosion and pollutant migration associated with steeper gradients. This guideline is utilized internationally, as evidenced by the research conducted in Gondar Town by Getahun Sisay et al. (2020).

Mohammad Ali Alanbari et al. (2014) highlight the significance of soil permeability, particularly in sandy clay loam (subsurface) and loamy sand (surface) soils, due to their effective contaminant retention and low permeability characteristics. According to studies conducted in the Al-Mahaweelqadaa region of Iraq, these soils decreased leachate infiltration by 75%. The findings were corroborated in the Al-Naja City investigation conducted by Sabreen Kareem et al. (2021). The suitability of Lilongwe is evidenced by local data from Munthali (2024), indicating that 94.87% of the subsurface soil consists of sandy clay loam, while 25.49% of the surface soil is classified as loamy sand. This aligns with the findings of Tamrat Mekuria et al. (2019) in Ethiopia, where sustainable landfill siting was facilitated by similar soil compositions.

Munthali (2024) asserts that soil compaction cannot replace engineered liners in areas with high rainfall, a gap this study seeks to address by promoting transitional landfill designs. The results emphasize the importance of combining global standards with localized soil mapping, especially in areas such as Lilongwe, where the advantages of natural soil must align with engineering measures to achieve long-term sustainability objectives.

2.3. Land Use Analysis for Suitable Dump Site Location

Non-productive lands are prioritized in land use/land cover (LULC) analysis to avoid displacing areas that hold agricultural or environmental value. This study replicates Saikia's (2020) research on Guwahati, which determined that barren areas are optimal for landfills based on AHP-weighted land use and land cover criteria. This strategy is additionally corroborated by the findings of Otoniel Buenrostro Delgado et al. (2007)

and Getahun Sisay et al. (2020), which indicate that bare ground or degraded grasslands reduce land-use conflicts.

A remote sensing study in Lilongwe by Sam Zulu et al. (2017) identified that 25% of the land was bare, indicating numerous potential locations. Urbanization pressures complicate the prioritization of land use and land cover (LULC). Tembo (2023) indicates that residential developments are encroaching upon pre-designated dumpsites, such as Area 38, due to the rapid urbanization of Lilongwe. Nkhoma (2023) advocates for community involvement in the upkeep of unproductive areas through the emphasis on Malawi's National Clean-Up Day initiatives. To mitigate urban sprawl, Zinazi (2023) outlines the policy context by highlighting the Environmental Affairs Department's support for the establishment of landfills on peri-urban barren land.

Active zoning and community engagement are essential for effective urban expansion, despite the successful identification of suitable locations through LULC analysis. Research conducted in Saskatchewan by Zagozewski et al. (2011) highlights the significance of community engagement, often overlooked in purely technical studies. Lilongwe's 25% bare ground provides immediate solutions; however, long-term sustainability requires the incorporation of climate resilience strategies, such as flood susceptibility mapping (Munthali, 2024), alongside policy enforcement to reconcile environmental preservation with infrastructural needs.

The reviewed literature highlights significant gaps while affirming the methodology and criteria employed in this study. The AHP framework established by Goepel (2013) provides a dependable weighting mechanism for multi-criteria evaluations; however, regional discrepancies in buffer distances for waterways continue to exist. The waste management challenges in Lilongwe are outlined in Logistics Cluster (2025); however, it does not provide technical methodologies, which this dissertation addresses through GIS-driven spatial modeling. This study prioritizes high-confidence datasets, such as USGS slope maps, to ensure reliability, despite the applicability of Mehmet Ekmekçioğlu's (2010) fuzzy logic technique in addressing data uncertainty.

CHAPTER 3: Methodology

3.1. Research Design

The research design of the study illustrated in figure 1 outlines the workflow of identifying the suitable place for placing the dumpsite. It starts with collecting the spatial data which includes DEM file to calculate slope, Lithology data(Subsurface and surface soil), hydrological factors(rivers and boreholes), social economic factors (Railway, Roads and Airport) and land cover land use data. The Hydrological and socio-economic factors were further analysed using Euclidean distance whilst Lithology was rasterized. Then all the data was reclassified according to their criteria. Using AHP, weights were assigned to all the variables according to the level of importance. The weights were then input to the Weighted Overlay analysis model in the Google Earth Engine to create a suitability map.

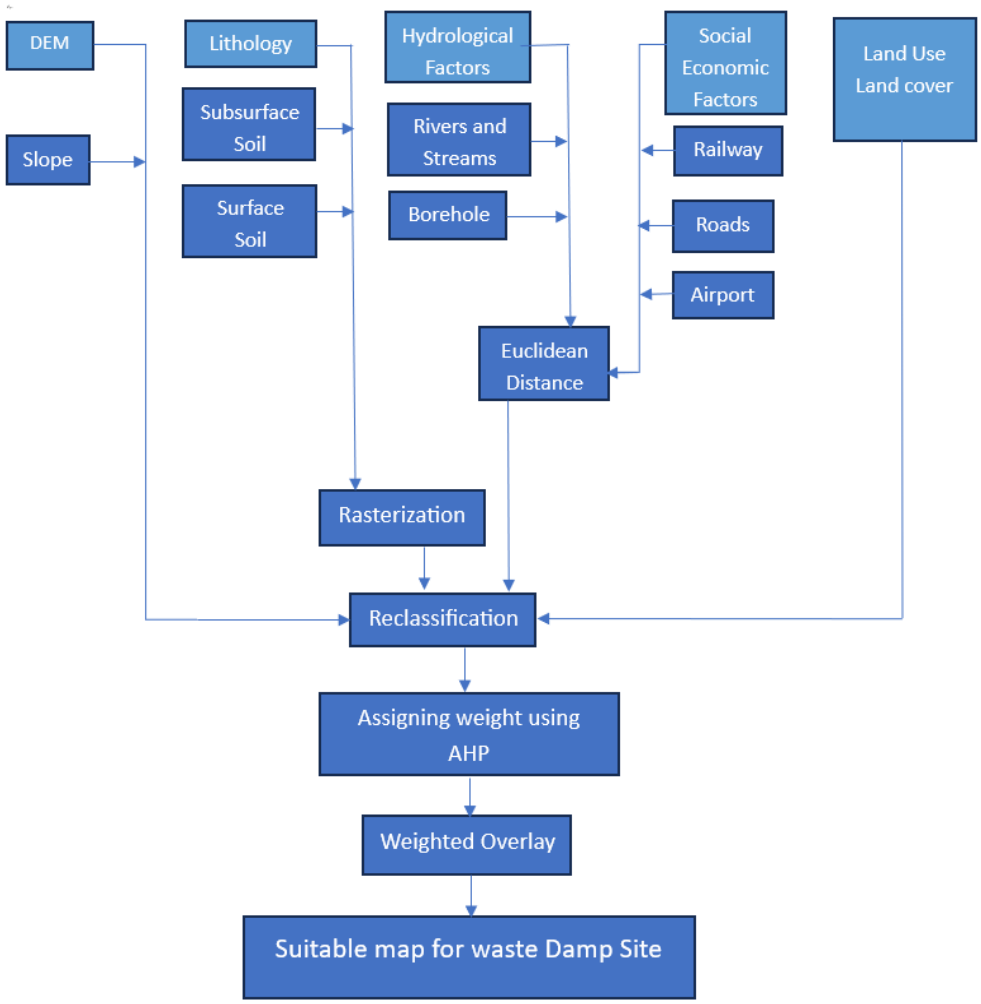


Figure 1 Research Design

3.2. Materials and Methods

3.3. Study Area

Lilongwe city of Malawi is located in the central region of Malawi at the latitude of 13.8500°S to 14.1000 and longitude of 33.6500°E to 33.9000°E precisely located within the Lilongwe district. It is the capital city of Malawi and the area is known for its high urbanization, high population and an increase in solid wastes which opts for a large and efficient disposal site. It has an elevation ranging from 983 meters to 1259meters and it is mainly comprised of flat plains with a total area of 403.343Km^2.

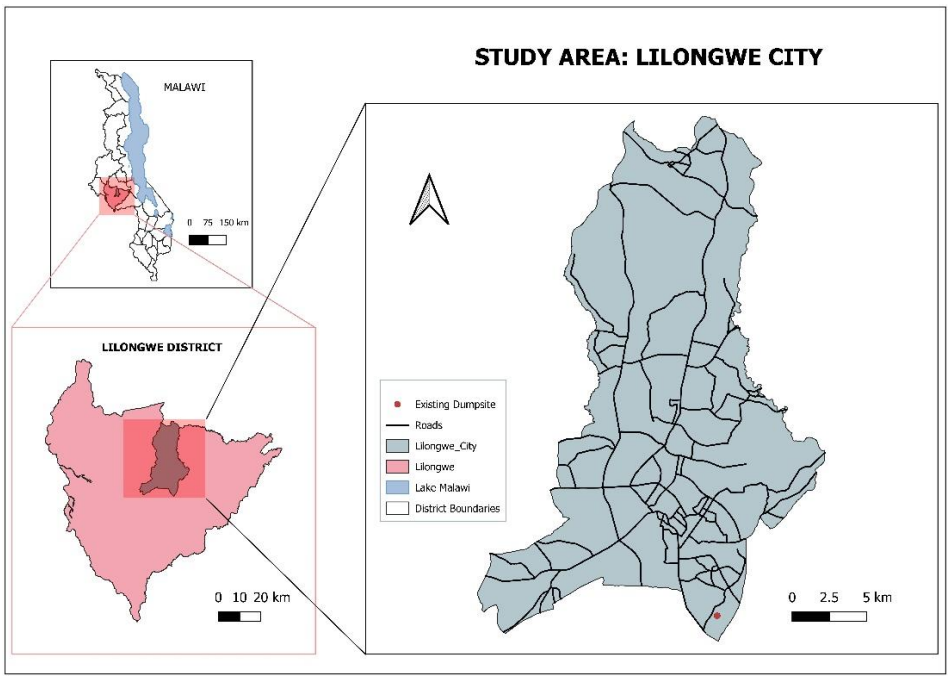


Figure 2 Study Area Map

3.3.1. Data used

Data that was used in this project was sourced from multiple sources; of which most of the data that was used was vector data and a few raster data. Literature was studied and most researches mainly emphasized on the following datasets for the selection of a suitable dumpsite:

Table 1 Shows sources and description of Data

Dataset	Description	Data source
Airport	It is a polygon vector dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S	Humanitarian Data Exchange
Boreholes	It is a point vector dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S	Humanitarian Data Exchange
Waterways	It is a line vector dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S	Humanitarian Data Exchange
Railway	It is a line vector dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S	HOTOSM
Roads	It is a line vector dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S	Lilongwe City Council
Slope	It is a raster dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S With a resolution of 30.4716 by 30.4716m	USGS
Surface	It is a polygon vector dataset with a geographic coordinate system of GCS_Arc_1950 and a projected Coordinate System of Arc_1950_UTM_Zone_36S	FAO
Subsurface Soil	It is a polygon vector dataset with a geographic coordinate system of GCS_Arc_1950 and a projected Coordinate System of Arc_1950_UTM_Zone_36S	FAO
Land Use Land Cover	It is a 2024 Raster dataset with a geographic coordinate system of GCS_WGS_1984 and a projected Coordinate System of WGS_1984_UTM_Zone_36S with a resolution of 10m by 10m	ESRI Land Cover Explorer

3.3.2. Data Processing

Airport

Using ArcGIS Desktop, the vector data was converted into raster that is essential for the analysis and this is done using the Euclidean distance tool (Anil Kumar Joshi, 2023). The Euclidean Distance tool was then used to assign the appropriate distances from the airport to a buffer distance of 1000m. The result from the Euclidean distance, was then used as an input in the reclassification of the data into 4 classes showing the suitability (Ravindra Jaybhaye N. M., 2014). The lowest class distance is ranked as 1(unsuitable) and the highest class is ranked as 4(Most suitable).

Boreholes

The vector data of the borehole points was converted into raster that is essential for the analysis and this is done using the Euclidean distance tool (Anil Kumar Joshi, 2023). The Euclidean Distance tool was then used to assign the appropriate distances from the boreholes to a buffer distance of 500m (Dereje Biru, 2023). The result from the Euclidean distance, was then used as an input in the reclassification of the data into 4 classes showing the suitability. This is to ensure that the community has safe water that is not contaminated from the boreholes (Gizachew Kabite, 2012).

Waterways

The waterways vector data was converted into raster that is essential for the analysis and this is done using the Euclidean distance tool (Anil Kumar Joshi, 2023). The Euclidean Distance tool was then used to assign the appropriate distances from the waterways to a buffer distance of 500m (Dereje Biru, 2023). The result from the Euclidean distance, was then used as an input in the reclassification of the data into 4 classes showing the suitability. Solid waste disposal site must not be located near river and stream this is to ensure that the community has safe water that is not contaminated that can be used for consumption and irrigation. (Nitin Mundhe, 2014, p. \)

Railways and Roads

The railways and roads vector data were converted into raster that is essential for the analysis and this was done using the Euclidean distance tool. The Euclidean Distance tool was then used to assign the appropriate distances from the roads and the railway to a buffer distance of 400m (Iftikhar Ali1, 2023). The result from the Euclidean distance, was then used as an input in the reclassification of the data into 4 classes showing the suitability. The presence of the primary and secondary roads helps to enable that the costs of transporting the wastes and the accessibility of the dumpsite is friendly while moving them away from the main roads (OE Demesouka, 2014).

Slope

Slope is the rate at which the elevation changes on a certain location (Bauer, 2024). To determine the slope of Lilongwe city, the slope tool was used to calculate the slop of the DEM file. The most suitable slope angle was a slop of <5 and the unsuitable angle was >20. It is known that places with high slope have a high risk of pollution because the wastes can easily run downstream. (Ravindra Jaybhaye N. M., 2014)

Surface soil

The surface soil type played a huge part since the dumpsite is supposed to be located in an area where the infiltration will not be that drastic (Mohammad Ali Alanbari N. A.-A., 2014). The data was converted from vector to raster then reclassified into the two soil types that are present within the study area and most recommended surface soil type to place the dumpsite was Loamy sand soil with its compactness unlike the sandy loam soil (Sabreen L. Kareem, 2021).

Subsurface

The subsurface soil type is the soil that lays beneath the surface soil and it played a huge part since the dumpsite is supposed to be located in an area where the permeability is very low. (Mohammad Ali Alanbari N. A.-A., 2014) The data was converted from vector to raster then reclassified into the two soil types that are present within the study area and most recommended subsurface soil type to place the dumpsite was sand clay loam soil with its compactness unlike the sandy loam soil. (Munthali S. M., 2024) Then the output was reclassified as input for the weighted overlay analysis.

Land Use Land Cover

This data is used to show how the land was used up in terms of built-up areas, vegetation, rivers, agricultural land and bare land (Saikia, 2020). To come up with an output, Centinel 2 data in Google Earth Engine and supervised classification was used in which training samples were collected to represent the above-mentioned classes to produce a complete land use land cover map which was exported to the Google drive. From the analysis, the bare land are the most suitable places to put the dumpsites and followed by the crop lands. (Gizachew Kabite, 2012)

Table 2 Summary of variables for the Suitability analysis

Variable	Parameters	Suitability	Rank
1. Airport	0-1000m	Unsuitable	1
	1000 – 2000m	Less Suitable	2
	2000 – 3000m	Suitable	3
	3000 – 4000 m	Highly Suitable	4
2. Boreholes	0 – 500m	Unsuitable	1
	500 – 1000m	Less Suitable	2
	1000 – 1500m	Suitable	3
	1500 – 2000m	Highly Suitable	4
3. Waterways	0 – 500m	Unsuitable	1
	500 – 1000m	Less Suitable	2
	1000 – 1500m	Suitable	3
	1500 – 2000m	Highly Suitable	4
4. Railway	0 – 400m	Unsuitable	1
	400 – 800m	Less Suitable	2
	800 – 1200m	Suitable	3
	1200 – 1500m	Highly Suitable	4
5. Roads	0 – 400m	Unsuitable	1
	400 – 800m	Less Suitable	2
	800 – 1200m	Suitable	3
	1200 – 1500m	Highly Suitable	4
6. Slope	0 – 5 °	Highly Suitable	4
	5 – 10°	Suitable	3
	10 – 15°	Less Suitable	2
	>15°	Not Suitable	1
7. Surface Soil	Loamy Sand	Highly Suitable	2
	Sandy Loam	Unsuitable	1
8. Subsurface Soil	Sand Clay Loam	Highly Suitable	2
	Sandy Loam	Unsuitable	1

9. Land Use Land Cover	Water	Unsuitable	1
	Vegetation	Unsuitable	1
	Crops	Less Suitable	3
	Built-Up	Unsuitable	1
	Bare Ground	Highly Suitable	4

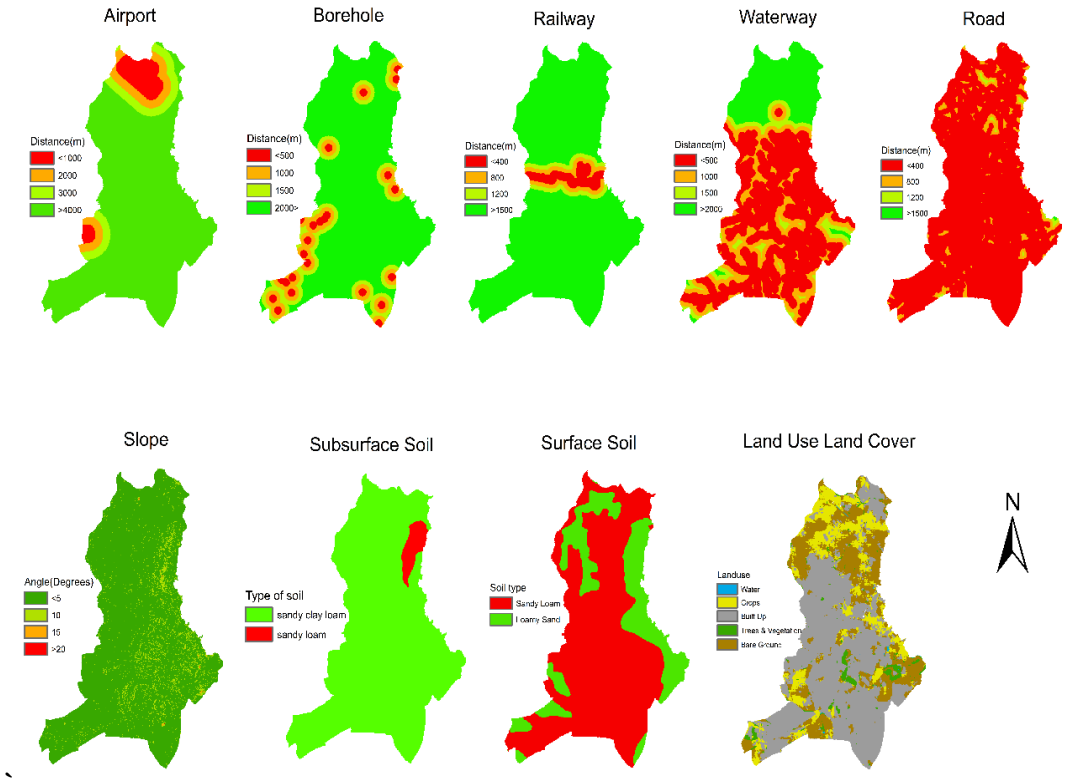


Figure 3 Showing all variables to be used in the analysis

3.3.3. Weighted Overlay Analysis

Using all the criteria mentioned in Figure *3*, they were uploaded to GEE under the assets where the were imported into the code. The classified criteria were then overlayed by assigning weights which were generated using the AHP to each criterion according to the impact and importance of the criteria in a relation to find the suitable places for placing the dumpsites (Goepel Klaus, 2013). The result was then exported to google drive which went through reclassification in ArcGIS desktop. After reclassification, the dataset was converted into polygon data whereby areas of each class in km^2 were calculated.

CHAPTER 4: Results and Discussion

4.1. Determining the Appropriate slope of the Area

4.1.1. Slope

The slope significantly influences underground water quality regarding contamination and the financial implications of managing the dumpsite. The slope of Lilongwe was categorized into four classes: 0-5°, 5-10°, 10-15°, and greater than 20°, with the 0-5° class identified as the most suitable for dumpsite allocation. The findings of Sisay et al. (2020) indicate that the suitable area is distant from settlement and is covered by grasslands. Crop lands, bare land, and grassland exhibited slopes ranging from 0% to 10%. Therefore, utilizing GIS and remote sensing technology for the precise identification of suitable solid waste merchandising sites can reduce environmental risks and health concerns. Getahun Sisay (2020) Bare ground, comprising 25% of Lilongwe city according to the land use land cover classification, indicates that the land is unused, rendering it appropriate for a dumpsite.

4.2. Evaluating the distance from topographic features

4.2.1. Distance from Airport

The airport, as a site of tourist attraction, requires careful consideration regarding the placement of the dumpsite. Each airport was assigned a buffer zone, with a minimum distance of 1000 meters established for the placement of the dumpsite. In Figure *3* shows that Lilongwe city, 6% of the total area (25.21 km²) is classified as unsuitable, another 6% (23.05 km²) as less suitable, 7% (2.47 km²) as moderately suitable, and 81% (328.53 km²) as highly suitable.

4.2.2. Distance from Boreholes

Many squatter settlements rely on wells and boreholes, which must be managed properly to prevent significant health issues. Each borehole was assigned a buffer zone, with a minimum distance of 500 meters established for the placement of the dumpsite. In Figure *3* it shows that Lilongwe city, 4% (17.33 km²) of the total area is classified as

unsuitable, 9% (38.47 km²) as less suitable, 11% (42.89 km²) as moderately suitable, and 76% (304.84 km²) as highly suitable. Mehmet Ekmekçioğlu (2010) identifies groundwater contamination as a significant issue primarily resulting from the leaching of dumpsites. To address this issue, it is recommended to position the dumpsite at a sufficient distance beyond the minimum buffer zone to reduce contamination risks.

4.2.3. Distance from waterways

Heavy rainfall subject dumpsites to surface runoff, significantly increasing the risk of contamination to water bodies such as rivers and streams. Each waterway was assigned a buffer zone, with a minimum distance of 500 meters established for the placement of dumpsites. Figure *3* shows that in Lilongwe city, 55% of the total area (221.67 km²) is classified as unsuitable, 18% (72.23 km²) as less suitable, 6% (24.30 km²) as moderately suitable, and 21% (85.13 km²) as highly suitable. Delgado et al. (2008) indicate that land situated at a distance from waterways is preferred, with a recommended buffer of at least 2,500 meters measured in a straight line.

4.2.4. Distance from railway and Roads

The primary considerations were public health implications during the transportation of waste from various sources to the dumpsite, as well as the associated transportation costs. The railways were buffered and reclassified to a minimum class of 0-400 meters using Euclidean distance. Figure *3* shows that in Lilongwe city, 4% of the total area (16.99 km²) is classified as unsuitable, 3% (13 km²) as less suitable, 3% (12.18 km²) as moderately suitable, and 90% (361.21 km²) as highly suitable (in figure 3).

The Euclidean distance was employed to buffer and reclassify the roads, establishing a minimum classification range of 0-400 meters. In Lilongwe city, 94% of the total area (377.78 km²) is classified as unsuitable, 6% (22.38 km²) as less suitable, 1% (2.95 km²) as moderately suitable, and less than 1% (0.189 km²) as highly suitable. The application of the aforementioned criteria may contribute to a reduction in transport costs. Barzehkar et al. (2019), Kazuva and Zhang (2019), and Mekuria et al. (2019) indicate that selecting an appropriate site for solid waste disposal can enhance transportation efficiency and lower transport costs.

4.3. Determining the appropriate type of soil

Surface Soil and Subsurface

The study area contains two types of surface soil: loamy sand and sandy loam. Among these, loamy sand is deemed more suitable due to its compactness, which minimizes the infiltration of contaminated water that could impact underground water sources. The sandy loam comprises approximately 293.55 km², accounting for 72.8% of Lilongwe, while the loamy sand covers about 102.769 km², representing 25.49% of the total area of Lilongwe city.

The subsurface soil types identified in the study area include sandy clay loam and sandy loam. Sandy clay loam is preferable because its clay content reduces the infiltration of contaminated water, thereby protecting underground water sources. The sandy clay loam encompasses approximately 382.59 km², representing 94.87% of the Lilongwe area, while the sandy loam accounts for about 13.74 km², or 3.41% of the total area of Lilongwe city (Figure *3*). Mohammad Ali et al. (2014) demonstrated that soil characteristics such as low porosity, low permeability, high retention of hazardous solutes, and workability are critical factors in the siting of landfill facilities. The loam in the surface soil and the clay component in the subsurface soil are essential for retention and permeability. (Alanbari, M. A. N. A.-A., 2014)

4.4. Land use land cover

The land use in the study area is categorized as follows: water constitutes approximately 1% (2.48 km²), vegetation accounts for about 3% (12.04 km²), cropland covers around 16% (63.82 km²), built-up areas represent approximately 55% (223.36 km²), and bare ground comprises about 25% (101.52 km²). Otonil Buenrostro Delgado et al. (2007) argue that the highly suitable areas are found in four municipalities characterized by low hilly terrain, rain-fed agricultural land, shrublands, and bare lands. Consistent with the findings of Sisay et al. (2020), the suitable area was distant from settlement and covered by grasslands. The analysis demonstrates that the bare land is appropriate for the placement of the dumpsite.

4.5. Weighted Overlay Analysis for the Dumpsite

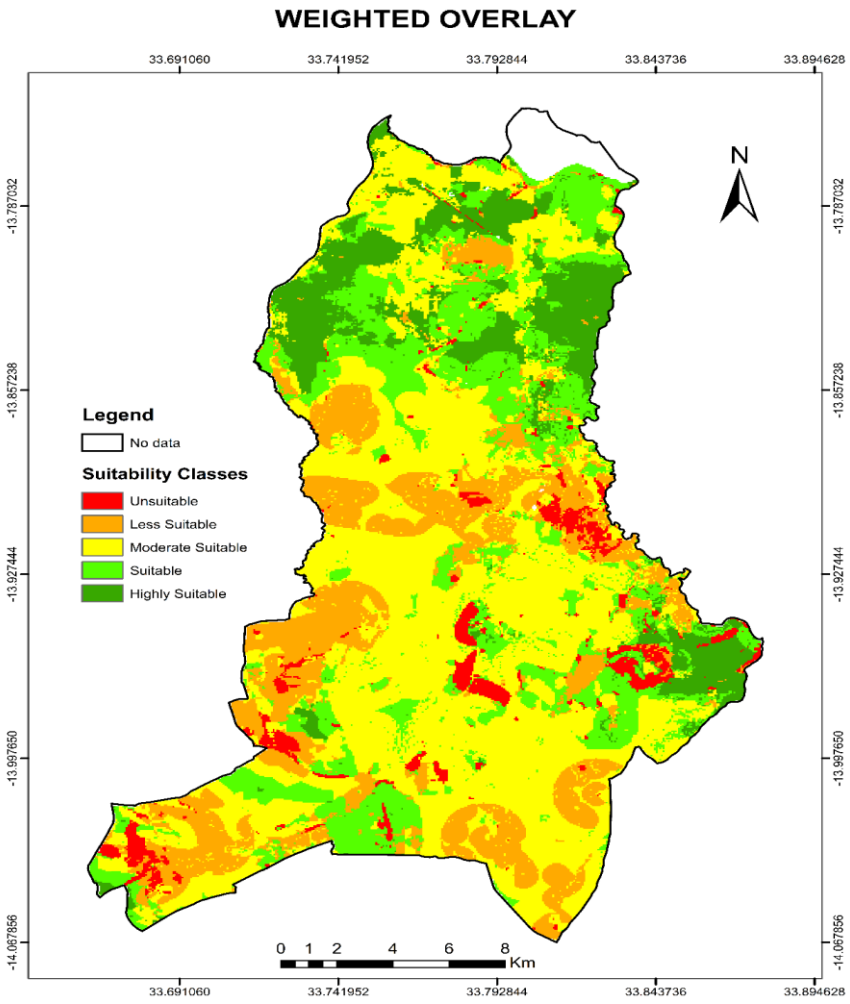


Figure 4 Map showing a weighted overlay of Lilongwe City

In table 3 below is an output from an overlay analysis that was focused on the identification of a suitable site for a dumpsite in Lilongwe city. To assign weights, AHP was used to and the criteria that were used are listed in table 2 . The output from the analysis in Figure *4* was classified into 5 classes namely: Unsuitable, less suitable, moderate suitable, suitable and highly suitable. After performing the analysis 16.52km^2 of the land is unsuitable amounting to 4% of the total land of Lilongwe city, 76.65 km^2 of the land is less suitable amounting to 19%, 172.76 km^2 of the land is moderate suitable amounting to 43%, 80.56 km^2 of the land is suitable amounting to 20%, 45.88 km^2 of the land is highly suitable amounting to 11% and 10.938933 km^2 of the land has no data amounting to 3%.

Table 3 Shows the suitability classes and the area they cover within Lilongwe City

Suitability Classes	AREA(Km^2)	Percentage (%)
Unsuitable	16.52	4
Less Suitable	76.65	19
Moderate Suitable	172.76	43
Suitable	80.56	20
Highly Suitable	45.88	11
No data	10.94	3

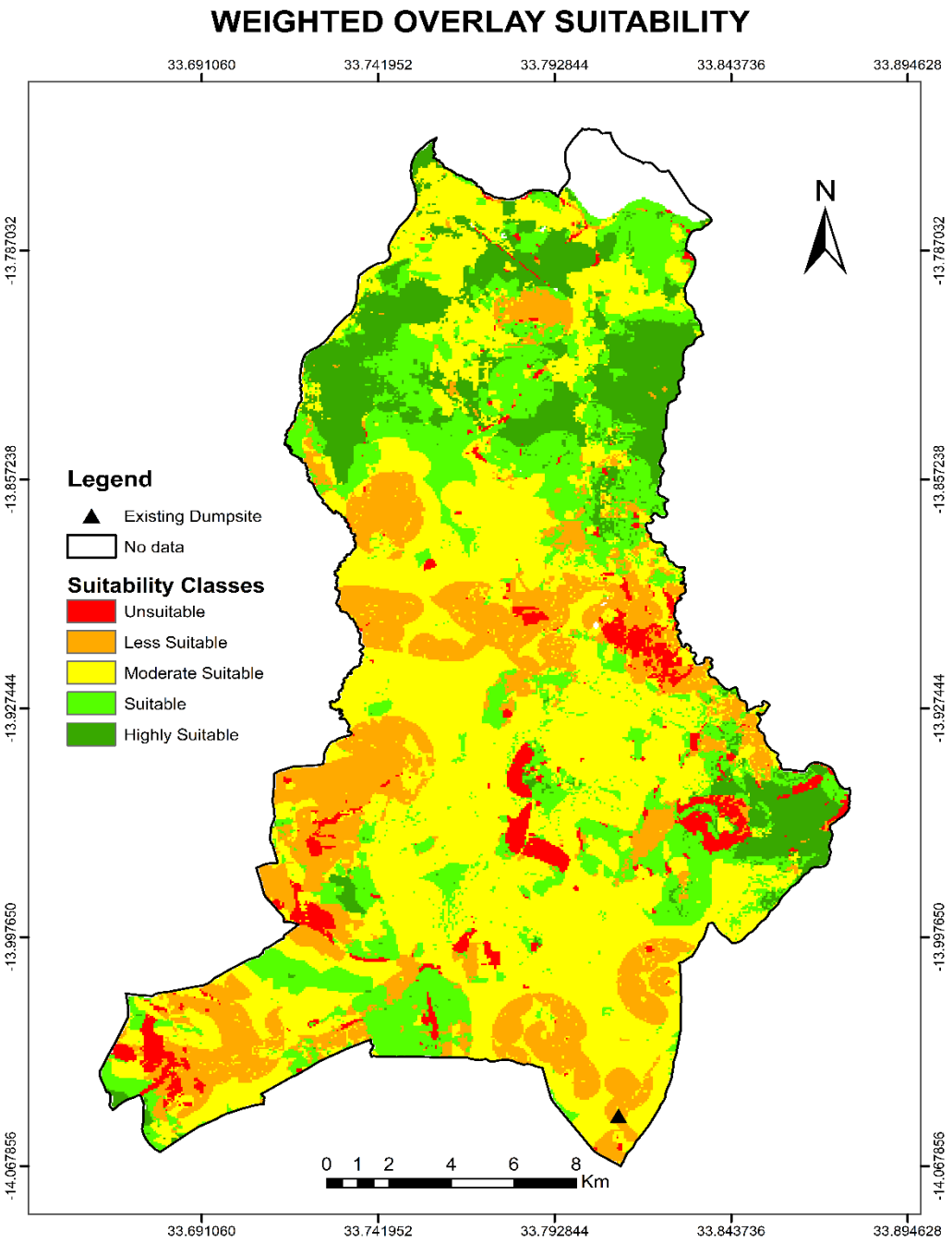


Figure 5 Map showing the classes and the location of the existing dumpsite in Lilongwe city

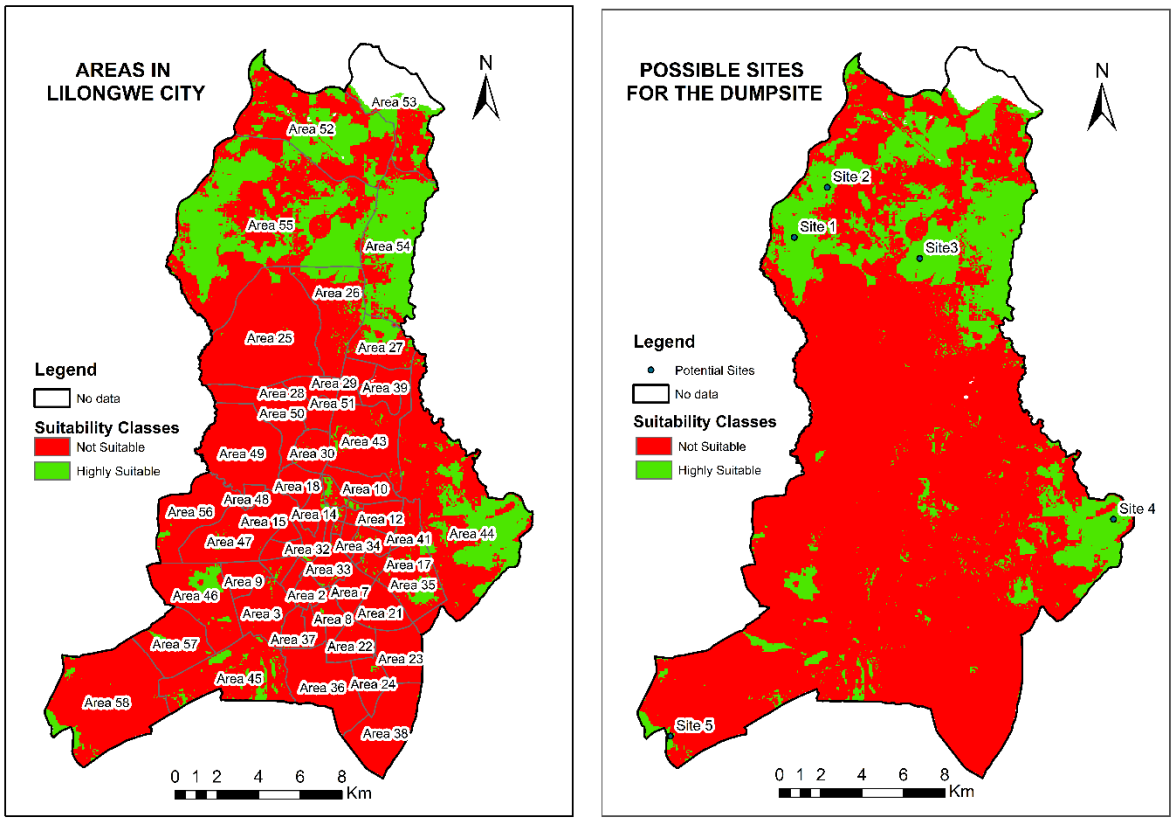


Figure 6 A map showing all the highly suitable class across Lilongwe city and the area names in which these suitable classes are located.

Results presented in Figure 6 shows that the highly suitable class across Lilongwe where a dumpsite might be located and the area names in which these suitable classes are located. On the other hand, the map also shows the potential sites on which the new dumpsites might be located considering all the criteria upon verification. After the analysis, it has been found that 89% of Lilongwe city covering about 357.46 km² is unsuitable and only 11% of Lilongwe city covering about 45.88 km² is highly suitable for placing the dumpsites mostly on the south eastern and south western side of the city and the northern side. These areas were found after the alignment of the criteria that was given into the model and the result was mainly influenced by criteria such as the gentle slope of <5°, the loamy sand soil and the few overlaps of the boreholes and the rivers within the city. Crop lands, bare land and grassland had 0%–10% slope. Hence, the capability to use GIS and remote sensing technology for the effective identification of appropriate solid waste merchandising site can minimise the environmental risk and health issues. On the other hand, bare ground which covers 25% of Lilongwe city from

the land use land cover class shows that the land is unproductive making it suitable for the dumpsite.

Table 4 Shows the coordinates of potential sites of the dumpsites

Name	Latitude	Longitude	Altitude
Site 1	-13.8326	33.72992	1167
Site 2	-13.8108	33.74431	1186
Site3	-13.8418	33.7846	1168
Site 4	-13.9553	33.869	1013
Site 5	-14.0496	33.67601	1098

From Figure *6*, Area 55, 44 and 58 have been chosen to have the potential sites of the dumpsites listed in Table *4* but as of the others areas that show suitability have been excluded, this is because most of the criteria in those areas were suitable just that one criterion wasn't met that's why it is not suitable. For example, in Area 52 where the airport is located shows most of the area to be suitable because almost all the criteria shows that the area is suitable except for the airport suitability so the weighted analysis has prioritized the other criteria.

CHAPTER 5: Conclusion and Recommendations

5.1. Conclusion

This research utilized a GIS-based multi-criteria decision analysis (MCDA) to determine optimal dumpsite locations in Lilongwe City, responding to the necessity for sustainable waste management amid rapid urbanization. The integration of spatial datasets concerning proximity to infrastructure (airports, boreholes, waterways, roads, and railways), slope, soil characteristics, and land use/land cover (LULC) indicated that around 11% (45.88 km²) of the city's area, predominantly in the southeastern, southwestern, and northern regions, is highly suitable for dumpsites. The identified regions met the defined criteria, characterized by gentle slopes (<5°) to reduce leachate runoff (Sisay et al., 2020), loamy sand surface soil and sandy clay loam subsurface soil with low permeability to protect groundwater, and compliance with buffer distances (1,000 m from airports, 500 m from boreholes and waterways) to minimize public health risks.

Bare ground, comprising 25% of the city, was identified as the most suitable land use/land cover (LULC) class, aligning with global standards that prioritize non-productive lands (Delgado et al., 2008). The study demonstrates the effectiveness of GIS and remote sensing in addressing environmental and health risks. However, the limited availability of highly suitable land (11%) indicates the need for a transition to engineered landfills and the enhancement of recycling initiatives to support spatial planning and ensure long-term sustainability.

5.2. Recommendations

On-site validation of potential landfill suitability sites is crucial, as a series of ground-based tests must be conducted to protect the environment, the communities and ground and surface water sources. Transitioning from open dumping to engineered landfills with liners and leachate collection and treatment systems is recommended to prevent groundwater contamination. Construction of facilities that can be used to recycle some of the materials like plastics to produce other plastic products like containers or chairs and another department that would work in the production of organic fertilizer from decomposing materials. Due to urban expansion, the demand for land for settlement

and construction of commercial structures is increasing so the dumpsite might as well be place out of the city boundaries that are friendly transport wise. Finally, incorporating temporal and dynamic aspects, including wind direction, city expansion, and land use changes, into the model is essential for enhancing sustainability and facilitating long-term planning in future studies.

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Appendices

Weighted Overlay analysis and TIF download Google Earth Engine Code

```
// Loading datasets from the assets of the project
var landUseSuitability = ee.Image("projects/ee-gis-016-20/assets/LULC");
var slopeSuitability = ee.Image("projects/ee-gis-016-20/assets/Slope");
var surfaceSoilSuitability = ee.Image("projects/ee-gis-016-20/assets/SurfaceSoil");
var subsurface = ee.Image("projects/ee-gis-016-20/assets/subsurface");
var waterBuffer = ee.Image("projects/ee-gis-016 20/assets/WaterwaysSuitabilityClasses1");
var roadBuffer = ee.Image("projects/ee-gis-016-20/assets/RoadsSuitabilityClasses1");
var railwayBuffer = ee.Image("projects/ee-gis-016-20/assets/RailwaySuitabilityClasses");
var boreholeBuffer = ee.Image("projects/ee-gis-016-20/assets/BoreholesSuitabilityClasses1");
var airportBuffer = ee.Image("projects/ee-gis-016-20/assets/AirportSuitabilityClasses1");

// Assigning the study area
var lilongweBoundary = ee.FeatureCollection("FAO/GAUL/2015/level2")
  .filter(ee.Filter.eq('ADM2_NAME', 'Lilongwe'));

// Weighted overlay analysis using reclassified datasets
var suitabilityMap = landUseSuitability.multiply(0.24)
  .add(slopeSuitability.multiply(0.13))
  .add(waterBuffer.multiply(0.165))
  .add(surfaceSoilSuitability.multiply(0.092))
  .add(subsurface.multiply(0.05))
  .add(railwayBuffer.multiply(0.055))
  .add(boreholeBuffer.multiply(0.115))
  .add(airportBuffer.multiply(0.089))
  .add(roadBuffer.multiply(0.064));

// Display results
Map.centerObject(lilongweBoundary, 10);
Map.addLayer(suitabilityMap, {min: 1, max: 5, palette: ['red', 'orange', 'yellow', 'lightgreen',
'green']}, 'Dumpsite Suitability');

// Exportig the weighted result to Google drive folder
Export.image.toDrive({
  image: suitabilityMap,
  description: 'Dumpsite_Suitability_Lilongwe',
  scale: 30,
  region: lilongweBoundary.geometry().bounds(),
  maxPixels: 1e13
});
```