



Data-driven landfill suitability mapping in Lagos State using GIS-based multi-criteria decision making

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Abstract

Careful selection of landfill sites is essential because improper dumping of wastes can negatively impact health and degrade the environment. Therefore, this research presents a Geographic Information System based—Fuzzy Analytic Hierarchy Process multicriteria decision-making approach for landfill zonation in Lagos State, Nigeria. Due to the rapid urbanisation leading to urban expansion and conversion of the landfills to built-up areas in Lagos State, the functioning landfills have been reduced. After a comprehensive literature review, this study considers nine factors: slope, elevation, land use and land cover, lithology, soil type, Normalised Difference Vegetation Index, the distances to roads, distance to settlements, and distance to water bodies. From the decision matrix, the distance to water bodies, distance to roads, distance to settlements, and land use and land (LULC) cover were ranked with percentage weights of 22%, 19%, 17% and 11%, respectively. Afterwards, potential landfill sites were mapped and classified into five classes: very low (626.48 km², 16.66%), low (1277.56 km², 33.97%), moderate (1227.97 km², 32.65%), high (500.52 km², 13.31%), and very high (128.13 km², 3.41%). The low and moderate suitability classes have the highest areal coverage due to the state's increased population and urbanisation. A large percentage of the high to very high suitability classes are located in Epe, Ikorodu, and Ibeju-Lekki local government areas (LGAs) which have lower urbanisation levels compared to most of the other LGAs. Therefore, governments and stakeholders should explore these areas for siting of landfills.

Keywords Landfill · Africa · Urbanization · Fuzzy AHP · Environmental pollution

Introduction

Solid waste management, an integral part of the Sustainable Development Goals, is a major concern for most African nations. Burdened by numerous health, environmental and

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economic challenges, waste management (and disposal) in Africa has not been effective (Bui et al. 2020). In 2012, the World Bank estimated that the global yearly municipal solid waste (MSW) would be approximately 2.6 million tonnes for urban regions by the end of 2025 (Das et al. 2019). This projected increase in environmental pollution can be detrimental to human health and the environment (Tella et al. 2021b).

In Nigeria, over 80 million kg of waste is generated daily (Babalola and Busu 2011), which is more than 50% of the total generated in Sub-Saharan Africa (Ike et al. 2018). The increasing population leading to urbanisation and industrialisation, poorly planned settlements, and public perceptions of social services have exacerbated the waste disposal problem. One of the effects of this phenomenon is the collection of waste below the amount generated and the inadequacy and overutilisation of dumpsites and landfills. These acts pose several risks for individuals and the society, such as environmental unsightliness, foul smells, environmental degradation, and groundwater pollution (Arogundade 2019; Das et al. 2019).

Though solid waste management is a local government function in Nigeria, state governments have taken up the task through various legislative enactments. Lagos State handles waste management, including generation, treatment, and final disposal, through the Lagos Waste Management Authority (LAWMA), which began as the Lagos State Waste Disposal Board in the 1970s. LAWMA is saddled with the task of managing the burden of over 9000 metric tonnes of waste per day for disposal at three major landfills, which have exceeded their capacities. Moreover, public apathy relating to payment for waste disposal services, and the problem of management efficiency became overwhelming, making Lagos the dirtiest city in South–West Nigeria in 2010 (Ike et al. 2018).

The challenge of managing solid waste in Lagos State is enormous, as the capacity for management is less than the

generation rate, which was estimated at 0.5–0.7% in 2013 (Anestina et al. 2014). The collection and disposal capacity is far from what is expected in a megacity, thus creating an environmental problem. In 2017, official records showed a wide gap between the waste collection target and the amount collected, a target of 4,892,301.48 metric tonnes was made while 1,349,010.17 metric tonnes were collected (Lawma 2020). With all of the landfill sites nearing the end of their usefulness and holding capacity in an already congested city, conservation as a technique for sustainable development becomes highly significant. The geographical location of landfill sites is also a pertinent question, given the rapid rate of urbanisation.

There is a stark disparity in waste management practices in Lagos, and other highly developed and industrialised societies. According to the United States Environmental Protection Agency in 2012, 250 million tonnes of waste was generated in the United States of America, of which 85 million tonnes of this material were recycled (EPA 2014). Also, over 80% of the waste generated in Malaysia are landfilled, while only 5% is recycled (Aja and Al-Kayiem 2014). In 2016, over 1.7 million tonnes of waste were dumped at landfills in Lagos State (Fig. 1), with organic waste (43%) taking the highest share of the material composition of the 0.44 kg per capita generation (Lawma 2020). Due to the state government's efforts, the amount of waste disposed at the dumpsite has reduced compared with previous figures, such as 3.8 million tonnes in 2009, the highest so far (Lawma 2020).

A landfill is known as the most common and widely used waste disposal method worldwide (Hussin et al. 2010). Landfills which are facilities for waste disposal on the earth's surface (Kamalan et al. 2011) are of two forms—sanitary and natural attenuation landfills constructed to reduce the negative effects of waste on the people and the environment (Nomohanran 2015). Advantages of landfills include energy generation, employment generation and a time lag for waste

Fig. 1 Aerial view of Olusosun landfill and surrounding communities (Source: Google Earth; Imagery date: 10 March, 2024)



disposal, while its disadvantages include contamination of surface and groundwater, wind-borne odours, reduction in land value (Nomohanran 2015), loss of vegetation and reduced soil quality (Yazdani et al. 2015). Given the aforementioned, this landfill suitability study is very crucial for environmental sustainability.

According to Yazdani et al. (2015), the first step in improving municipal solid waste management is to evaluate the state and site suitability of current landfills. In siting a landfill, several factors are considered, which have environmental and health implications (Muttiah et al. 1996). Among the guidelines for site selection of landfills are the Minnesota Pollution Control Agency (MCPA) guidelines, which identify six determinants, seven conditional factors, and regional screening guidelines, which recognise three critical factors (Yazdani et al. 2015). Determining the appropriate site for a landfill is thus an enormous task that can lead to land degradation through improper land use if not properly handled. Perhaps the difference between the developed and developing nations in waste management is linked to the extent of deliberateness in the connected processes (Ogwueleka 2009), of which disposal site selection is essential. The connected processes refer to the processes of reduction, reuse, recycling, sorting, collection, transportation, treatment, and final disposal, which are interconnected, and the deliberate concern for environmental sustainability.

Considering the necessity to integrate different factors for landfill suitability, the conventional methods seem difficult. In contrast, Geographical Information System (GIS) has been established globally (Mortazavi Chamchali and Ghazifard 2019; Rahimi et al. 2020) as an effective technique for the determination of the degree of suitability of landfills. In recent times, the integration of multicriteria decision-making (MCDM) and GIS has aided the decision-making process in providing practical solutions to environmental problems (Tella and Balogun 2020). Notably, the Analytical Hierarchy Process (AHP) has been frequently used for multiple criteria decision-making. Several studies (Güler and Yomralıoğlu 2017; Sisay et al. 2021; Rahmat et al. 2017) have shown the capability of AHP for landfill site selection. What the AHP does is to quantify the importance of the criteria in ranks based on expert advice for decision making. However, despite the usefulness of AHP, it is attributed to biases and inconsistencies, thereby leading to uncertainties in decisions (Tella and Balogun 2020).

To overcome this limitation, some studies used a hybrid system of AHP with fuzzy logic, otherwise known as Fuzzy AHP (Pasalari et al. 2019). Some other studies

improved the AHP method for better and more accurate criteria weighting and alternatives by employing FTOPSIS (Ali et al. 2021), fuzzy logic (Zarin et al. 2021), Analytic Network Process (ANP) (Aliani and Goleji 2018), and AHP—ANP (Lokhande et al. 2020). For instance, Ali et al. (2021) integrated GIS with Analytical Hierarchy Process (AHP) and FTOPSIS to select sanitary landfill sites in India's Memari Municipality. Through expert ranking and the inclusion of environmental and socioeconomic factors, the research was able to produce three landfill sites.

In the African continent, insufficient research exists in this crucial area of waste management. Undoubtedly, one of the major environmental problems is the improper management and disposal of waste. This is especially true for Lagos State, with a rapid population and an average waste generation capacity of 0.5 kg per capita per day (Chukwuone et al., 2022). Unfortunately, most of these wastes wind up in the road, drainage channels, canals, waterways, lagoons, and the ocean, given a coastal city with insufficient waste management infrastructure and poor garbage management. Hence, to properly ensure waste disposal management, this study assesses landfill suitability using GIS and MCDM. This is early research in Nigeria, especially in Lagos State, because there is limited research on landfill suitability utilising the integration of GIS and MCDM. Thus, this research aims to close this knowledge gap using Fuzzy AHP to determine the suitability of sites for landfills in Lagos State, to aid the policy framework for better solid waste management.

Study area

Lagos is one of the most urbanised and major commercial cities in Nigeria and the second-largest city in Africa. It is the second largest metropolitan city in Africa after Cairo. Lagos has a population of over 15 million people as of 2022, and it is expected to rise to over 24 million by 2035 (World Population Review, 2022). It is situated between latitude 6° 20' 00"N to 6° 40' 00"N, and longitude 2° 50' 0"E to 4° 20' 00"E (Fig. 2) and is one of the fastest-growing cities globally, with 20 local government areas and 37 Local Council Development Areas (LCDAs). Considering the rapid urbanization with a waste generation rate of 0.5kg per person per day, waste management is a serious problem in Lagos State. In the southern part of Lagos, there is a coastline stretch of about 175 km bordering the Atlantic Ocean, Ogun State in the northern and eastern parts, while the Republic of Benin is at the western part of the Lagos boundary.





Fig. 2 A map showing the study area

Geographically, Lagos consists of the Mainland and the Island. The mainland is a non-island region and is connected to other states through the land. The mainland comprises a large population of inhabitants, industries and commercial activities. On the contrary, the island is the water region of the state. The land is surrounded by water, mainly from the Atlantic Ocean. The mainland and island are connected through a bridge. The city has flat topography in most regions, with elevations ranging from 0 to 79 m above sea level.

Geologically, Lagos is composed of two major sediments: the Tertiary (comprised of sandstones, mudstones and sandy-clay soil) and the Quaternary (comprised of coastal alluvium, mangrove swamps, and deltaic sands) (Ikuemonisan et al. 2020). Notably, Lagos is mainly underlain by shales, sands and limestones. Lagos State exhibits a tropical savanna climate with high rainfall season between April and October, and a dry season between November and March.

The average mean temperature in the city ranges from 21.8 °C to 32.9 °C. The Lagos State drainage system comprises waterways and lagoons, which cover over 785 sq. km of the total landmass of 3577 km² of the city (Ikuemonisan et al. 2020). The main water bodies of the state are the Ogun River, Yewa River, and Lagos and Lekki Lagoons (Nwambuonwo and Mughele 2012).

Since the beginning of the current political era in 1999, subsequent administrations in Lagos State have steadily built essential infrastructure and made significant moves to improve the business environment. These progressive advancements ensure continuous attractiveness to investors, professionals, and people looking for better opportunities. The adverse effects of all of these include the burden placed on public facilities and the increasing difficulty in handling municipal solid waste due to the state's massive home, commercial, and industrial operations. Therefore, Lagos State, which has experienced rapid urbanisation, industrialisation, and infrastructural development, is a victim of its success. The two main sources of waste in Lagos State



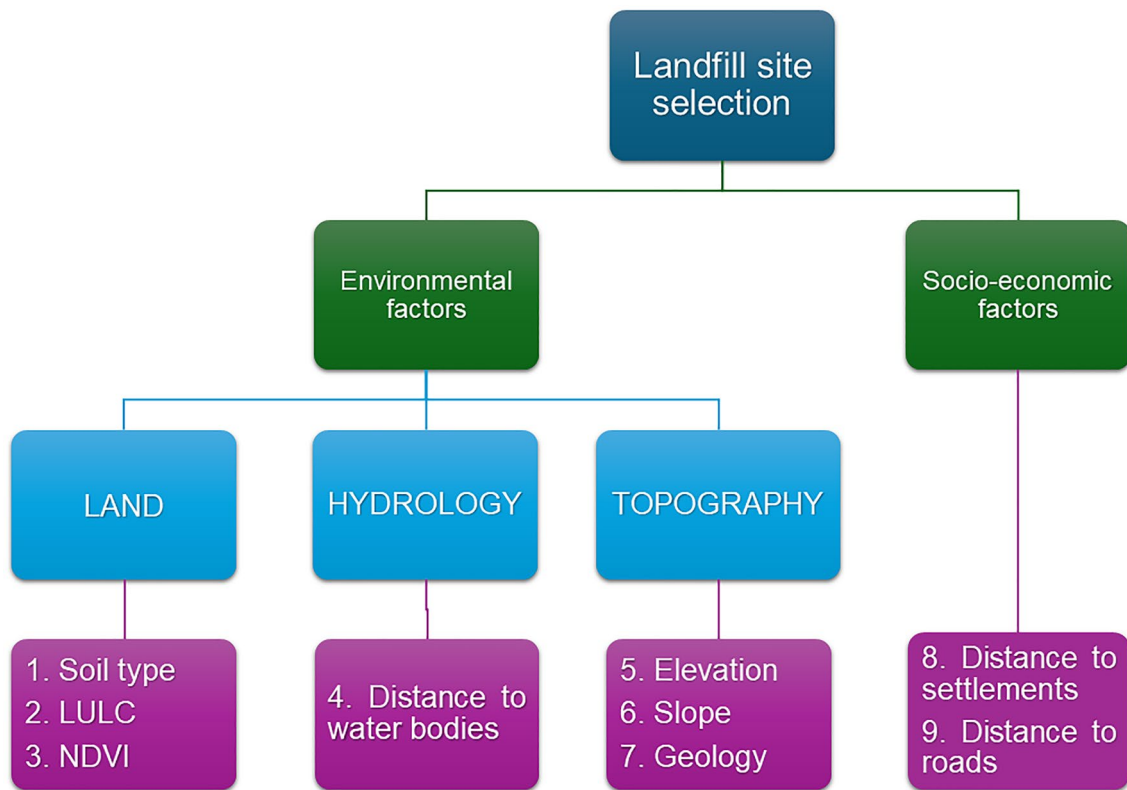


Fig. 3 Decision process hierarchical scheme for landfill suitability mapping

are municipal waste and e-waste. Improper waste management and disposal is a serious issue in Nigeria because only 20 to 30% of 32 million tonnes of waste generated are collected annually (Ogundele et al., 2018). Most of these over 0.5kg per capita disposals generated in Lagos are eventually

disposed of in canals, waterways, lagoons, and the ocean (Chukwuone et al., 2022). The majority of the solid waste generated by commercial land use categories is made up of plastics (29%), organic garbage (22%), and paper and textiles (14% each). As a result of small-scale production and

Table 1 Data sources and characteristics

No	Datasets	Data type	Spatial resolution	Source	Criteria map
1	Landsat 8 imagery—Operational Land Imager (OLI) sensor	Raster	30 m	United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov/)	Land use, NDVI
2	Shuttle Radar Topography Mission (SRTM) DEM	Raster	30 m	USGS Earth Explorer (https://earthexplorer.usgs.gov/)	Elevation, slope, distance to water bodies
3	Settlement layer	Vector	–	Office of the Surveyor General of the Federation (OSGOF)	Distance to settlements
4	Road network layer	Vector	–	OpenStreetMap (OSM) (https://www.openstreetmap.org/)	Distance to roads
5	Soil layer	Vector	–	Federal Department of Agricultural Land Resources (FDALR) https://fmard.gov.ng	Soil type map
6	Geology layer	Vector	–	Federal Department of Agricultural Land Resources (FDALR) https://fmard.gov.ng	Geology map

product unwrapping, there may have been a fall in domestic and business activity-based wastes, which could cause a rise in plastics and a decline in organics (Ojowuro et al., 2019).

Materials and methods

To create an appropriate landfill suitability map, geospatial analysis tools in GIS were utilised to generate nine criteria as thematic layers encompassing the study area. The following phases were considered for this study to determine the optimum landfill sites. These phases include:

- i. Defining the objectives
- ii. Selection of landfill decision criteria
- iii. Formulation of a questionnaire for expert advice (five experts)
- iv. Pairwise comparison and utilisation of the MCDM approach
- v. Determination of criteria weights and generation of landfill map
- vi. Identification of most suitable sites

In order to arrive at the final stage of this study, both environmental and economic factors were considered, as shown in Fig. 3. After a comprehensive review, nine criteria were adopted for this study.

Data acquisition

Nine criteria were used for this study. The datasets used for generating the criteria thematic maps were obtained from government sources, United States Geological Survey (USGS) Earth Explorer and OpenStreetMap. The elevation, slope, and water body maps were generated from the Shuttle Radar Topography Mission (SRTM) DEM with spatial resolution of 30 m. The Normalised Difference Vegetation Index (NDVI), and the land use and land cover maps were produced using Landsat 8 imagery—Operational Land Imager (OLI) sensor with spatial resolution of 30 m. Other criteria such as the road, settlement, soil and geology maps were generated from the vector datasets obtained from open access platforms such as OpenStreetMap (OSM), and government institutes. The sources of the datasets used for this study are summarised in Table 1.

Selection and evaluation of conditioning factors

Identifying the optimal location for siting a landfill requires a rigorous assessment of multiple criteria. Still, several studies have been conducted in the past to understand what criteria are significant in landfill selection. The existing literature has identified multiple selection criteria such as elevation, slope, land use, geology, soil and topography, proximity to development, and transportation facilities (Kharat et al. 2016; Alkaradaghi et al. 2019; Tercan et al. 2020). Ultimately, selecting a combination of these criteria is done to choose the optimal location for a landfill that is environmentally sustainable, economically viable, and that minimises hazards to public health (Kharat et al. 2016).

Moreover, there is a need to subject the conditioning factors to prioritisation according to the considerations of environmentalists and local indigenes of the study area. This order of precedence is crucial for landfill suitability analysis. Therefore, the criteria used for this study are based on the advice of experts, local indigenes, and environmentalists. The conditioning factors used for this study are the distance to roads, elevation, distance to water bodies, NDVI, geology, distance to settlements, soil type, slope, and LULC. These factors are discussed in detail in the following section:

Distance to roads: this is an important factor to consider for landfill suitability. Notably, several researchers (Alkaradaghi et al. 2019; Güler and Yomraloğlu 2017), have opined that landfills should be close to the road to reduce transportation costs. However, it is not always advisable for landfill sites to be close to the roads. Considering that urban settlements are in close proximity to the roads in Lagos State, this study carried out buffering of roads in the state. According to Ali et al. (2021), areas closer to the road are ranked low. Also, landfill sites should be located far enough from transportation facilities such that public visibility is hardly possible. Thus, the longer the visible distance of a site from a road, the better it is for a landfill. The road layer was downloaded from OpenStreetMap and a minimum buffer of 500m was implemented.

Elevation: another critical factor to consider in selecting landfill sites is the land elevation. The elevation is the basic surface from which first order topographic attributes such as slope are derived. The elevation is one of determinants of slope and related terrain attributes. Areas with low-lying land and flat terrain are ideal and technically suitable for the construction of landfills (Kharat et al. 2016). Low-lying regions are usually more stable and less vulnerable



to landslides (Kharat et al. 2016). Also, higher elevation increases the cost of transportation and excavation.

Slope: The slope is an essential criterion for soil erosion, subsurface flow, soil water content and drainage. Therefore, a steep slope affects drainage and influences the rise of downstream water pollution and landslide disasters (Rezaei-sabzevar et al. 2020). More so, flat terrain with a gentle slope has little risk of runoff (Chang et al. 2008). Contrarily, a steep slope aids runoff and has a high risk of contamination. The slope was generated from the SRTM DEM in ArcGIS 10.8.

Land Use and Land Cover (LULC): an important environmental consideration in landfill selection is the land use and land cover (LULC) of the area. Critical habitats, sensitive ecosystems and areas with biophysical elements like wetlands and large upstream hydrological basins are not suitable for landfill location (Chang et al. 2008; Ding et al. 2018). Cultivated lands and rocky terrain are moderately suitable, while non-cultivated land and pasture are optimal (Kharat et al. 2016). Areas covered with vegetation are not suitable for landfill sites because these are potential agricultural sites that may be dangerous to health and productivity if contaminated. The LULC map was generated from the Landsat 8 OLI using supervised classification in ArcGIS 10.8.

The proximity of the land to an urban area: this is an important social, environmental and health consideration. It is recommended to situate landfills significantly away from urban areas due to public concerns, decreased property value, and health issues (Chang et al. 2008; Alkaradaghi et al. 2019). Generally, the closer the area to residential, industrial, and tourist centres, the less suitable the landfill location (Kontos et al. 2005; Ding et al. 2018). The buffering was carried out from the settlement with a minimum distance of 2000 m from the city.

Geology: The optimal lithological units in landfill selection are massive rocks with no cracks, which usually do not contain groundwater (Simsek et al. 2006). There are six lithological types in Lagos State. The geological data was imported to ArcGIS 10.8 as a shapefile for further processing.

Soil classes: highly porous alluvial soils with sand and gravel are good aquifers, thus least preferable for landfill locations because of the high potential of groundwater contamination, while impervious soils are one of the ideal materials (Simsek et al. 2006). As a rule of thumb, landfill

sites should be located at sites with a low vulnerability to groundwater contamination (Alkaradaghi et al. 2019). There are two major soil classes in Lagos State, namely, sandy and clay soil. The data was also imported into the ArcGIS software environment as a shapefile.

Proximity to water bodies: this is a major consideration in landfill selection. Landfill sites should not be close to rivers, springs, wells or other bodies of water (Kharat et al. 2016; Alkaradaghi et al. 2019) to prevent the contamination of the water from solid waste leakages (Alam et al. 2020), which is a common phenomenon in developing countries like Nigeria. The stream layer was generated with ArcGIS Spatial Analyst tools using Strahler stream order, and a buffer of a minimum of 1000m from the streams was carried out.

Normalised Difference Vegetation Index (NDVI): in epidemiological research aimed at evaluating the health impact of green space in urban environments, the normalised difference vegetation index (NDVI) is commonly used as a measure of environmental green space (Gascon et al. 2016). Landfills should not be situated in forested regions or agricultural land due to their negative impacts on the environment (Qureshi et al. 2021). The NDVI for this study was generated from near-infrared (NIR) and red (R) bands of landsat 8 OLI imagery. Equation 1 was used in ArcGIS10.8 via raster calculator to derive the NDVI map (Tella et al. 2021a).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

The buffer distances used for some criteria were sourced from the literature, as shown in Table 2.

The thematic maps for the landfill suitability zonation are shown in Fig. 4.

Fuzzy set theory

In multicriteria decision making, fuzzy set theory is a technique for modelling sophisticated systems that are difficult to represent in crisp numbers (Zadeh et al. 1996). The fuzzy set theory is mostly used for simulating vague and imprecise judgements based on the priorities of the decision-makers. The fuzzy set theory allows the extraction of exact conclusions from ambiguities and uncertainties in a remarkably simple approach (Mallick 2021). The crisp number can be between 0 and 1, representing the degree of membership

Table 2 Buffer distances used in this study and the references

Causative factors	Buffer distance	References
Distance to water bodies	Minimum of 1 km from water	(Feyzi et al. 2019)
Distance to roads	Minimum of 0.5 km from main road	(Ali et al. 2021; Spigolon et al. 2018)
Distance to settlements	Minimum of 2 km from the city	(Rahmat et al. 2017; Saatsaz et al. 2018)



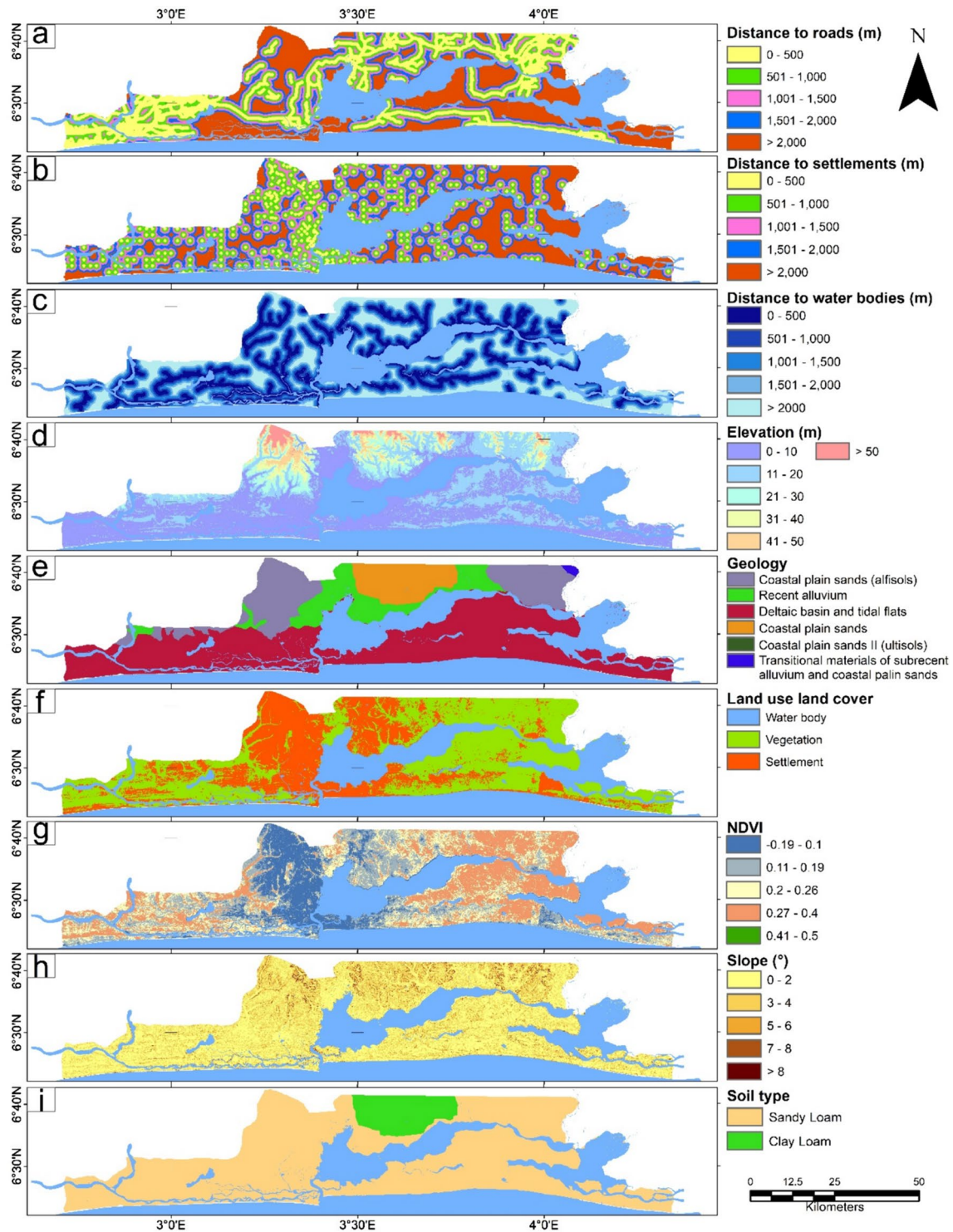


Fig. 4 The landfill thematic criteria maps **a** distance to road **b** distance to settlement **c** distance to water bodies **d** elevation **e** geology **f** LULC **g** NDVI **h** slope **i** soil classes

function. A triangular fuzzy number (TFN) is characterised by M , which is expressed as (l, m, u) , meaning lowest, middle, and highest possible number, as shown in Fig. 5, and Eq. 2

is the linear representation of its membership term in both right and left sides (Mallick 2021).



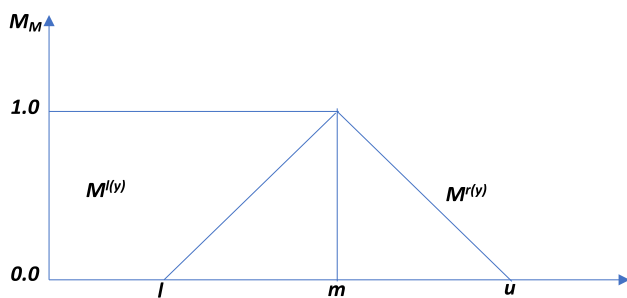


Fig. 5 A triangular fuzzy number

$$\mu(x \setminus \tilde{M}) = \begin{cases} 0, & x < l, \\ (x - l)/(m - l), & l \leq x \leq m \\ (u - x)/(u - m), & m \leq x \leq u \\ 0, & x > u \end{cases} \quad (2)$$

Weight assessment of the conditioning factors

To define the weights of the landfill conditioning factors, the AHP method was used. AHP is known to be capable of handling qualitative and quantitative data. Moreover, the consistency of the experts can be checked using the consistency ratio. Summarily, AHP gives a hierarchical representation of the factors. However, despite the usefulness of AHP, it cannot express the human mindset since it does not take into account fuzziness or subjectivity (Ekmekcioğlu et al. 2021). Also, it is affected by biases and uncertainty, making the result less reliable. As a result, conventional AHP is regularly faulted for its failure to accurately handle the problem of uncertainties and vagueness during the pairwise comparison process (Tella and Balogun 2020). Fuzzy AHP was introduced to improve the original AHP’s weighting of criteria and selection of alternatives (Ayhan 2013). Instead of utilising actual numbers to calculate, the Fuzzy AHP technique uses fuzzy numbers (triangular) to determine the criteria weights. The phases followed to get the conditioning weights are:

Derivation of triangular fuzzy number from AHP decision matrix

The triangular fuzzy number (TFN) is characterised by M, which is expressed as (l,m,u), where l stands for lower, m stands for middle, and u stands for upper numbers. Before

proceeding to the fuzzy AHP model, the pairwise comparison matrix was validated using a consistency ratio to check the consistency in the experts’ decisions. Equations 3, 4 and Table 3 were used to derive the consistency ratio:

$$CR = \frac{CI}{RI} \quad (3)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

where: RI is the random index, λ_{max} is the principal eigenvalue of matrix, CI is the consistency index, CR is the consistency ratio, and n is the number of total components in the matrix. A consistency ratio less than or equal to 10% is satisfactory, and this ascertains consistency in the decision matrix (Saaty 1988). Therefore, the consistency ratio was validated before proceeding with the triangular fuzzification of the AHP pairwise comparison matrix.

We also considered the consensus and agreement between the experts’ decisions which is represented by S* whose degree of consensus extends from 0% (no conformity) to 100% (high conformity) (Roccati et al. 2021). To fuzzify the AHP pairwise comparison matrix, the Fuzzy AHP scales shown in Table 4 were used for this study.

Calculation of geometric mean and fuzzy weights

Table 4 was used to formulate the Fuzzy AHP pairwise comparison matrix. Buckley’s geometric mean approach was used

Table 4 The Fuzzy AHP scale

Linguistic terms	AHP Scale	Fuzzy numbers (l,m,u)	Reciprocal fuzzy numbers ($\frac{1}{u}, \frac{1}{m}, \frac{1}{l}$)
Equal Importance	1	(1,1,1)	($\frac{1}{1}, \frac{1}{1}, \frac{1}{1}$)
Intermediate value	2	(1,2,3)	($\frac{1}{3}, \frac{1}{2}, \frac{1}{1}$)
Weak importance	3	(2,3,4)	($\frac{1}{4}, \frac{1}{3}, \frac{1}{2}$)
Intermediate value	4	(3,4,5)	($\frac{1}{5}, \frac{1}{4}, \frac{1}{3}$)
Fair importance	5	(4,5,6)	($\frac{1}{6}, \frac{1}{5}, \frac{1}{4}$)
Intermediate value	6	(5,6,7)	($\frac{1}{7}, \frac{1}{6}, \frac{1}{5}$)
Strong importance	7	(6,7,8)	($\frac{1}{8}, \frac{1}{7}, \frac{1}{6}$)
Intermediate value	8	(7,8,9)	($\frac{1}{9}, \frac{1}{8}, \frac{1}{7}$)
Very strong importance	9	(9,9,9)	($\frac{1}{9}, \frac{1}{9}, \frac{1}{9}$)

Table 3 Random consistency index

n	1	2	3	4	5	6	7	8	9	10
R	0	0	0.58	0.9	1.21	1.24	1.34	1.41	1.45	1.49

Table 5 Fuzzy AHP pairwise comparison matrix of the conditioning factors

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1,1,1	1,2,3	2,3,4	2,3,4	2,3,4	4,5,6	3,4,5	2,3,4	1,1,1
C2	0.33,0.5,1	1,1,1	2,3,4	2,3,4	2,3,4	4,5,6	2,3,4	1,2,3	1,1,1
C3	0.25,0.33,0.5	0.25,0.33,0.5	1,1,1	2,3,4	2,3,4	2,3,4	1,2,3	1,2,3	0.25,0.33,0.5
C4	0.25,0.33,0.5	0.25,0.33,0.5	0.25,0.33,0.5	1,1,1	3,4,5	1,2,3	1,2,3	1,2,3	0.17,0.2,0.25
C5	0.25,0.33,0.5	0.25,0.33,0.5	0.25,0.33,0.5	0.2,0.25,0.33	1,1,1	0.25,0.33,0.5	2,3,4	0.25,0.33,0.5	0.17,0.2,0.25
C6	0.17,0.2,0.25	0.17,0.2,0.25	0.25,0.33,0.5	0.33,0.5,1	2,3,4	1,1,1	1,2,3	0.25,0.33,0.5	0.25,0.33,0.5
C7	0.2,0.25,0.33	0.25,0.33,0.5	0.33,0.5,1	0.33,0.5,1	0.25,0.33,0.5	0.33,0.5,1	1,1,1	0.25,0.33,0.5	0.25,0.33,0.5
C8	0.25,0.33,0.5	0.33,0.5,1	0.33,0.5,1	0.33,0.5,1	2,3,4	2,3,4	2,3,4	1,1,1	0.25,0.33,0.5
C9	1,1,1	1,1,1	2,3,4	4,5,6	4,5,6	2,3,4	2,3,4	2,3,4	1,1,1

Table 6 Geometric mean and fuzzy weight of the criteria

Factors	Geometric mean			Fuzzy weight			M_i	N_i	Weight(%)	Ranking
	l	m	u	l	m	u				
C1	1.79	2.46	3.05	0.12	0.23	0.40	0.25	0.22	22	1
C2	1.40	1.95	2.55	0.09	0.18	0.33	0.2	0.17	17	3
C3	0.79	1.16	1.74	0.05	0.11	0.23	0.13	0.11	11	4
C4	0.58	0.85	1.27	0.04	0.08	0.16	0.09	0.08	8	6
C5	0.34	0.44	0.65	0.02	0.04	0.08	0.05	0.04	4	8
C6	0.41	0.55	0.90	0.03	0.05	0.12	0.07	0.06	6	7
C7	0.31	0.42	0.73	0.02	0.04	0.1	0.05	0.04	4	8
C8	0.64	0.89	1.47	0.04	0.08	0.19	0.1	0.09	9	5
C9	1.71	2.20	2.64	0.11	0.2	0.34	0.22	0.19	19	2
Total	7.99	10.91	15.00				1.16	1	100	
Inverse	0.13	0.092	0.067							
Increasing order	0.067	0.092	0.12							

to define the fuzzy geometric mean and weighting for the criteria with respect to Eqs. 5 and 6.

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{-n} \tag{5}$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_i \otimes \dots \otimes \tilde{r}_n)^{-1} \tag{6}$$

where \tilde{r}_i is the geometric mean of the fuzzy comparison for criterion i , \tilde{a}_{in} is the fuzzy comparison value for each criterion i , \tilde{w}_i is the fuzzy weight of the i th criterion. The triangular fuzzy number of the weighting (\tilde{w}_i) can be represented as lw_i, mw_i, uw_i . After getting the criteria weights, the landfill suitability was assessed within the GIS environment.

Landfill suitability map (LSM)

Nine landfill site selection criteria were considered for this study. Fuzzy AHP was used to calculate the weights of each criterion. Each criterion's raster layer was given a weight based on its significance in the landfill site selection process. The Landfill Suitability Map (LSM) was generated by integrating the criteria weights generated from the Fuzzy AHP model with the thematic maps in ArcGIS 10.8 using the weighted overlay tool within the Spatial Analyst extension. Equation 7 explains the formula used for calculating the LSM:

$$S = \sum_{N=1}^a \sum_{m=1}^n (N_i \times T_m) \tag{7}$$

where N_i is the normalised weight, T_m is the thematic map(s) of the criteria, S is the site suitability for landfill, n is the total number of suitability layers in a theme, and a is the number of themes.

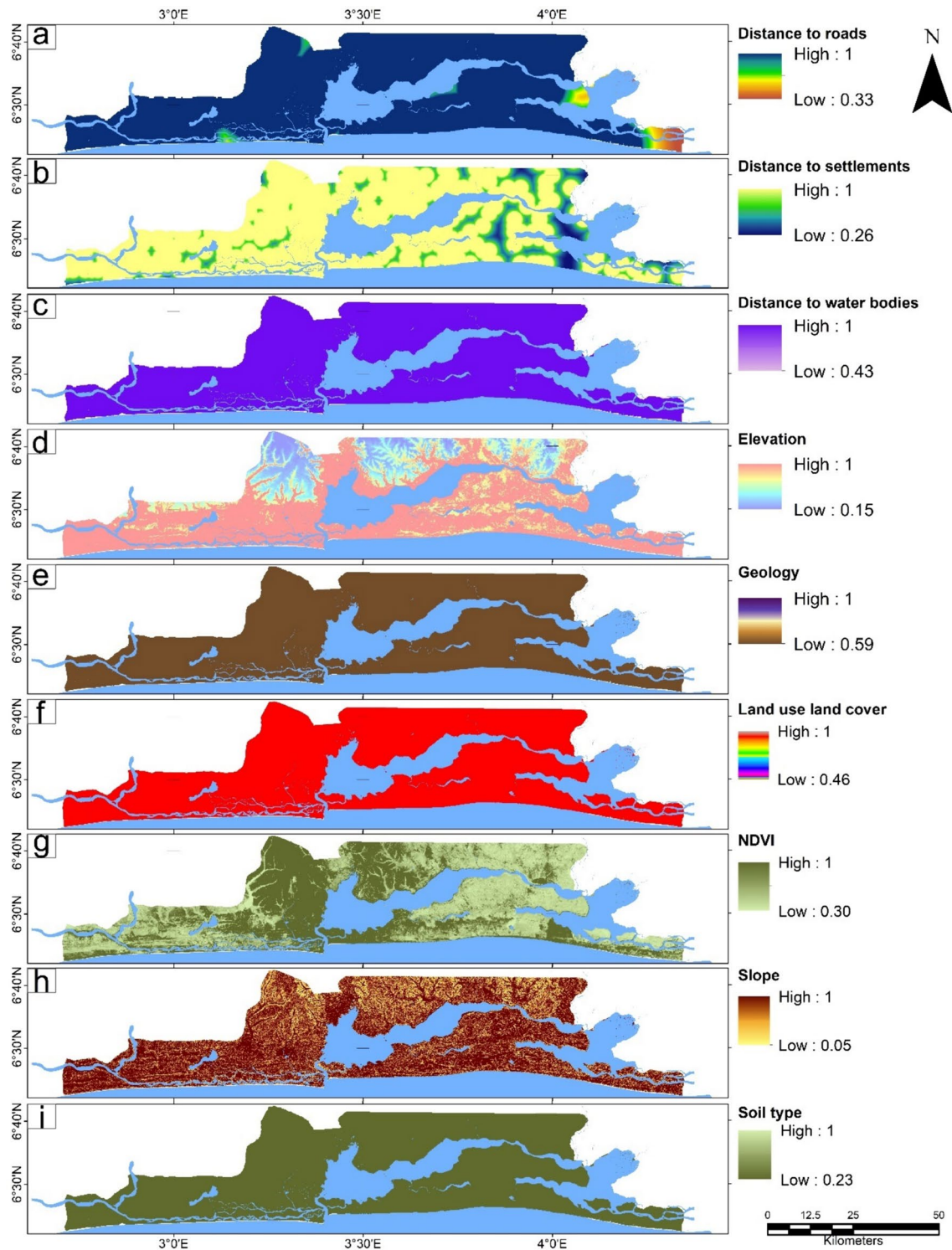


Fig. 6 Fuzzified thematic maps; **a** distance to roads **b** distance to settlements **c** distance to water bodies **d** elevation **e** geology **f** LULC **g** NDVI **h** slope **i** soil

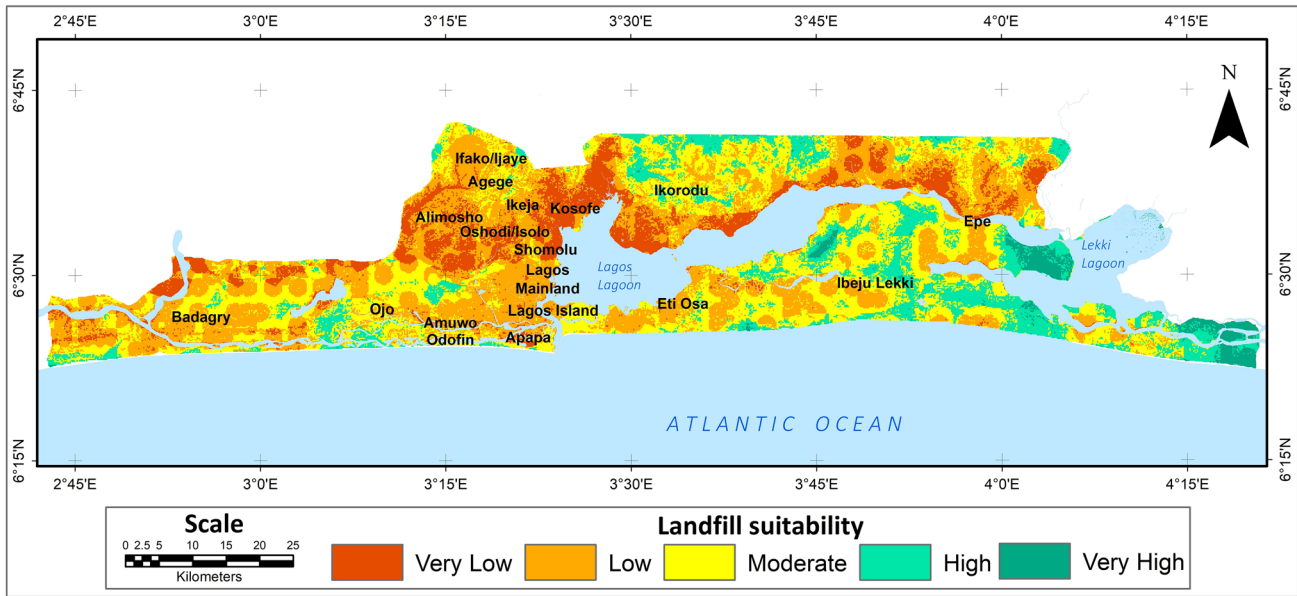


Fig. 7 Landfill suitability map of Lagos State

Table 7 Comparison of the areal coverage of the landfill suitability classes

Landfill suitability classes	Area (km ²)	Area (%)
Very low	626.48	16.66
Low	1277.56	33.97
Moderate	1227.97	32.65
High	500.52	13.31
Very high	128.13	3.41

Results and discussion

Weighting of the criteria

The Fuzzy AHP model was employed to get the weight of each criterion. In assigning the relevancy of each criterion to landfill, steps such as literature review, consulting experts’ decisions, and familiarisation with the terrain of the study area were carried out. The fuzzy pairwise comparison matrix, the geometric mean, and the fuzzy weight of the criteria are shown in Tables 5 and 6.

*C1—distance to water bodies; C2—distance to settlements; C3—land use and land cover (LULC); C4—elevation; C5—slope; C6—geology; C7—NDVI; C8—soil type; C9—distance to roads .

*C1—distance to water bodies; C2—distance to settlements; C3—land use and land cover (LULC); C4—elevation; C5—slope; C6—geology; C7—NDVI; C8—soil type; C9—distance to roads.

The experts’ decision has a consistency ratio of 4.5%, which is less than 10%. Therefore, it can be said that there is consistency in the experts’ decisions. Also, there is 97.3% consensus among the decision-makers, meaning there is an agreement on criteria ranking by them.

Landfill suitability zonation

Given the daily increase in waste and the decreasing land availability for waste disposal in Lagos State, it is crucial to determine suitable zones for waste disposal to ensure proper management of the excessive waste generation in the city. This study assesses the suitability of sites for landfills using GIS-based Fuzzy AHP, an effective method for mapping landfill zones. Therefore, the thematic maps are fuzzified, ranging between 0 and 1, as shown in Fig. 6.

The fuzzified thematic maps were used to derive the final landfill map shown in Fig. 7, and the area covered by the suitability classes is shown in Table 7. The present and past landfill sites and non-landfill sites are overlaid on the landfill map.

The distribution of the landfill suitability classes is as follows: very low (626.48 km², 16.66%), low (1277.56 km², 33.97%), moderate (1227.97 km², 32.65%), high (500.52 km², 13.31%), and very high (128.13 km², 3.41%). All the landfill inventory data fall across moderate to very high susceptibility.

Discussion

Lagos State's waste problem is exacerbated by rapid population growth, urbanization, industrialization, poorly planned settlements, and degraded infrastructure. As a result, waste collection rates are lower than production rates, and dumpsites and landfills are inefficient and overused, leading to environmental pollution, foul odours, and groundwater contamination. Despite generating 13,000 metric tonnes of waste per day, only 7,000 metric tonnes are disposed of by LAWMA at its landfill sites, and only 10% of the city's waste is collected (Imouokhome 2022). With the amount of waste generated exceeding the capacity of available landfill sites, there is a pressing need to expand or locate new sites. This research addresses this issue by identifying potential landfill sites using GIS, which is an effective tool for project planning and site selection studies.

Fuzzy AHP was used to weigh criteria due to AHP's limitations, including uncertainties, restricted judgment scale, fuzziness, and lack of transitivity. AHP was initially used to assign weights based on experts' decisions, with a CR of 4.5% and an S* of 97.3%, indicating a strong agreement. The fuzzified AHP approach, using linguistic variable weight, was employed for a more accurate assessment of landfill sites' suitability.

The study considered nine landfill conditioning factors based on a literature review of previous studies on landfill susceptibility mapping. The four most important factors, which were distance to water bodies, distance to roads, distance to settlements, and land use and land cover with percentage weights of 22%, 19%, 17% and 11%, respectively, accounted for 69% of the total weight. These factors are crucial when expanding an existing landfill or creating a new one. The study recommends that these factors be given priority in landfill site management and zoning. These findings align with previous studies in Iran (Pasalari et al. 2019) and Saudi Arabia (Mallick 2021), which also highlighted the importance of distance to roads, settlements, and land use and land cover. Therefore, the study recommends prioritizing the four highest-ranking criteria in landfill site selection:

- Landfills release leachates, solid and liquid pollutants that pose a risk to water bodies, and plastic pollution is a significant global threat (Worm et al. 2017; Rosevelt et al. 2013). To address this, governments and stakeholders should consider a reasonable distance between landfill sites or extensions and water bodies.
- Distance to settlements, distance to roads, and LULC are essential factors to consider when expanding or proposing a new landfill site to avoid potential environmental dangers and odour. Landfills should be far from settlements but not too far from accessible roads to reduce transportation costs. However, a considerable distance from the road should be maintained to avoid unexpected impacts on built-up areas. Economic factors should also be considered, and a balance must be struck between distance from important roads and the expense of building new access roads (Rezaeisabzevar et al. 2020).

After combining enormous volumes of spatial and quantitative data, GIS presents the final output in a comprehensible and graphical format that is understandable to both the general public and professionals. The landfill map for the study area was classified into five classes: very low (626.48 km², 16.66%), low (1277.56 km², 33.97%), moderate (1227.97 km², 32.65%), high (500.52 km², 13.31%), and very high (128.13 km², 3.41%). There are limited suitable spaces for landfill sites, as shown in Fig. 7 and Table 7. This is basically due to the increased population caused by urbanisation. Lagos State attracts many inhabitants, which could explain the low availability of spaces. For instance, there was a high decrease in cultivated land and the conversion of rural areas into urbanised settlements between 2000 and 2010 due to rapid urbanisation (Onilude and Vaz 2020). For example, Obiefuna et al. (2021) established that there were 55.1% vegetated areas in Lagos in 1984 which had reduced to 27.7% in 2015.

Moreover, the built-up areas rose from 8.1% to 54.2% between 1984 and 2015. Also, according to Akinluyi et al. (2018), between 1984 and 2016, there was an approximately 23% increase in built-up areas and 18% decrease in vegetated areas. According to Kasim et al. (2021), the land use in Lagos State is covered by built-up areas, which claimed 50% of the state's land use and land cover in 2019. Based on the foregoing, there is a probability of increased population and land encroachment in Lagos State.

There are suitable areas for landfill sites in Epe, Ikorodu, and Ibeju-Lekki local government areas of Lagos State, as indicated by this study. The government could explore these



areas or expand the capacity of existing landfills, such as the one in Epe (Arogundade 2020). However, it is important to note that GIS and multi-criteria-based studies have highlighted potential challenges with certain areas, and further field investigations are necessary to select final landfill sites (Ali et al. 2021; Mallick 2021). Despite this limitation, the study provides valuable contributions: (i) the identification of landfill variables for locating municipal landfill sites and creating awareness for the public; (ii) sensitisation of the public of the danger and threat of having water bodies and settlements close to landfill sites; (iii) this study proposes some local governments such as Epe, Ibeju/Lekki and Ikorodu that the stakeholders can explore for creating new or expanding existing landfills.

Conclusion

Lagos State has experienced rapid urbanisation and population growth in the last few decades, leading to increased waste generation and land encroachment. Despite the increased population leading to increased waste generation, there are only three landfills in the state. Previous landfills have been converted to built-up areas due to urbanisation. Thus, there is a need to select new landfill sites because if these wastes are not properly managed, they can affect the people, climate, aquatic organisms, contaminate groundwater and increase plastic pollution. A review of previous studies revealed that no significant study of the optimal location of the waste disposal sites in Lagos State had been conducted. Therefore, this study carried out a landfill site suitability analysis using GIS-based Fuzzy AHP. Nine (9) landfill influencing factors were considered, and four (4) of these factors were ranked high by the experts. These factors are distance to water bodies, distance to settlements, distance to roads, land use and land cover with percentage weights of 22%, 19%, 17% and 11%, respectively. Potential landfill sites were discovered and classified into five classes: very low (626.48 km², 16.66%), low (1277.56 km², 33.97%), moderate (1227.97 km², 32.65%), high (500.52 km², 13.31%), and very high (128.13 km², 3.41%). The landfill suitability map shows that there is limited available land suitable for landfills. Most of the highly suitable sites fall in three local governments: Epe, Ikorodu and Ibeju-Lekki. The main reason is the reduced effects of urban sprawl in these areas compared to other regions in Lagos State. Besides the utilisation of landfills, this study suggests the recycling of waste

products to facilitate the state's economic growth and reduce environmental pollution.

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Declarations

Conflict of interest This manuscript has not been published or presented elsewhere in part or entirety and is not under consideration by another journal. There are no conflicts of interest to declare.

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Consent for Publication Not applicable.

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