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Combination of Geographic Information Systems and Multicriteria Analysis for Waste Landfill Site Selection – A Case Study of Kenitra Province, Morocco

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ABSTRACT

In the last decade, Morocco has experienced increased population, urban expansion, and improper environmental management, leading to a significant rise in waste production. This situation has exacerbated waste landfill issues, particularly in coastal areas such as Kenitra province, in the north-western part of Morocco. In this region, landfills have been responsible for the degradation and pollution of air, soil, and water resources. Therefore, identifying suitable sites for waste landfills is essential for achieving sustainable environmental management in the study area. The objective of this study was to provide, for the first time, a map of suitable waste landfill sites in Kenitra province. To achieve this objective, a database consisting of nine parameters was collected from environmental and socio-economic sources. The data was gathered and spatialized using various techniques. Subsequently, the analytical hierarchy process (AHP) and geographic information system (GIS) were employed to generate the final map of suitable waste landfill sites. The results indicate that the study area can be classified into four categories: 78% of the area is not suitable for landfill development, while areas classified as less suitable, moderately suitable, and highly suitable constitute 1%, 17%, and 4% of the surface, respectively. On the basis of these findings, three potential landfill locations that meet stringent environmental, social, and technical criteria have been proposed. This work represents the first attempt at improving landfill management in Kenitra province. The combination of AHP and GIS techniques offers a novel approach to landfill site selection. However, additional studies could be conducted, taking into account the results of this study, other parameters, and new data that may become available in the future. The map of suitable landfill sites provides a scientific foundation and could aid in developing the management strategies to mitigate pollution and guide territorial planning in the study area.

Keywords: analytical hierarchy process, geographic information system, landfill site.

INTRODUCTION

In Morocco, waste management represents a significant challenge due to the rapid population growth and improved living standards, which have led to a substantial increase in municipal solid waste (MSW) production. This rise, coupled with inefficient waste management practices at landfill sites, contributes to severe pollution of air, soil, and water, adversely affecting public health and quality of life (Alam and Ahmade, 2013). Although initiatives for recycling and waste reduction at the source exist, disposal and landfilling remain the critical components of waste management.

Morocco generates over 6 million tonnes of solid waste annually, posing major management challenges not only in terms of collection but also in selecting and managing landfill sites (Barakat et al,. 2017). These sites are often chosen using traditional methods without adhering to current environmental standards or critical scientific criteria necessary for environmental preservation. The city of Kenitra exemplifies these issues, with problematic sites including the Ouled Berjal landfill near the Sebou River, which threatens groundwater and potable water supplies, and the Mehdia dumpsite located in a former quarry, which is geologically impermeable and situated near a beach as well as a protected ecological area. Other landfills, such as those at Moulay Bousalham and Souk El Arbaa, are poorly located near forests, residential areas, or on permeable soils without adequate protective measures, posing risks to both the environment and public health (Environment Department of the Urban Commune of Kénitra).

The integration of GIS and multi-criteria analysis (MCA), particularly the AHP, is recognized as an effective approach for selecting optimal landfill sites that comply with regulatory constraints. Various international and national studies have demonstrated the effectiveness of this approach, including cases in Nigeria, Iraq, Ethiopia, Turkey, and Morocco (regions such as Tangier-Asilah, Khénifra, and Fez).

For instance, in Nigeria, Adewumi et al. (2019) utilized a GIS and AHP-based approach for siting MSW landfills in Lokoja. In Iraq, Alkaradaghi et al. (2020) applied GIS and AHP methods, combined with the simple additive weighting (SAW) method, for landfill site selection in the Sulaymaniyah Governorate. In Ethiopia, Desta et al. (2023) assessed landfill site suitability using GIS, remote sensing, and multicriteria decision-making approaches (AHP). In Turkey, Şener et al. (2010) combined AHP and GIS for landfill site selection in the Lake Beyşehir watershed (Konya).

On a national level in Morocco, several studies have adopted this approach for landfill site selection. In the Tangier-Asilah province, Hmamou et al. (2023) conducted a geospatial analysis using AHP and GIS to evaluate landfill site suitability for solid waste disposal. In Khénifra, Elhamdouni et al. (2017) used a GIS-AHP approach to select appropriate municipal landfill sites. In Azza et al. (2018) evaluated landfill site selection using AHP and GIS. In Fez, a geographical analysis of landfill site suitability was also conducted using these tools.

Compared to previous studies, the novelty of the presented work lies in its innovative approach, which derives several criteria from remote sensing, such as lineaments and morphological parameters. Moreover, this study is distinguished by being the first to specifically focus on the Kenitra province, a region with limited in-depth research in this field. Unlike traditional methods, the adopted approach integrates environmental, geological, and social criteria, aligned with Moroccan standards, to ensure sustainable landfill site management as well as mitigate environmental and health risks from the initial phase of solid waste management in the province.

The objective of the study was to identify suitable landfill sites in the Kenitra province using a GIS and AHP-based methodology. It aims to locate potential sites for controlled public landfills by leveraging new geospatial technology and adopting regulatory selection criteria, such as proximity to surface waters, groundwater vulnerability, and infrastructure accessibility. This integrated approach seeks to ensure that landfills do not have adverse environmental impacts, such as water contamination or proximity to sensitive areas, from the initial waste management phase.

MATERIAL AND METHODS

Study area

The Kenitra province, is located in the northwest of Morocco and part of the Rabat-Salé-Kenitra region, covering a total area of 3.052 km². The province is geographically located at coordinates 34.27° north, 6.58° West.Its coastline extends 140 kilometers along the Atlantic Ocean (Fig. 1).

In 2014, the total population of the province of Kenitra reached approximately 1,061.435 inhabitants, representing 23.2% of the regional population (HCP, 2014). Projecting a demographic increase for the next decade, the estimated quantity of household and similar waste in the study area amounts to 380,288 tons per year.

The province of Kenitra enjoys a Mediterranean climate influenced by oceanic factors, characterized by two distinct seasons, from December to March, the weather is marked by high humidity and average temperatures around 13.1 °C. In contrast, from May to November, the region faces dry conditions and significant heat, with average temperatures reaching 28.1 °C.

The coastal strip is characterized by a predominantly oceanic climate, marked by frequent fog, particularly concentrated along the immediate coastline and in proximity to the Sebou River. The proximity of the region to the Atlantic Ocean results in significant precipitation, averaging around 500 mm annually based on

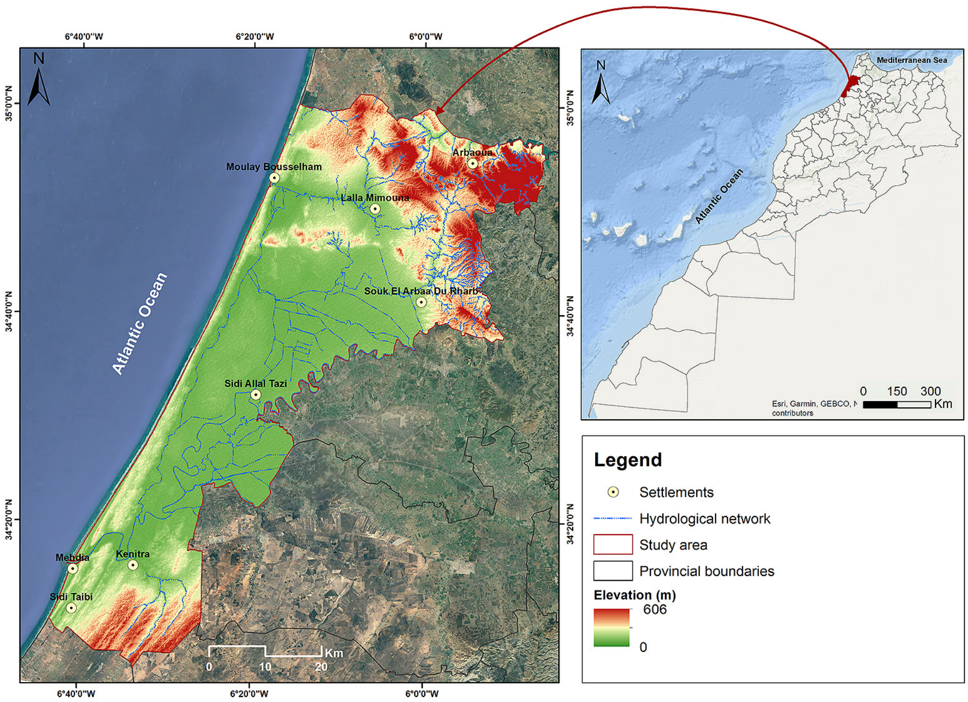

Figure 1. Geographic location of the study area

two decades of local meteorological data from local meteorological stations. This considerable amount of precipitation places the region significantly in national rankings for rainfall volume.

It is important to note that precipitation distribution is not uniform across the entire provincial territory, with a general decline from coastal to inland areas and from north to south.

The province is characterized by diverse terrain, with a vast plain in its center that belongs to the Gharb plain. To the north, it is bordered by the pre-Rifian zone, and to the west, by the coastal strip characterized by sand dunes. The dune cord effectively separates the coastal area from its hinterland. To the south, the province is surrounded by the Maamora forest.

Evaluation criteria

To achieve the study objectives, a comprehensive set of decision criteria was established through a rigorous literature review.

By leveraging the capabilities of GIS and their specialized analytical tools, a series of thematic layers encompassing nine critical factors were generated for the study area: distance to surface waters, groundwater table, land use, distance to natural areas, permeability, slope, distance to linear features, distance to built areas, and distance to roads). This methodology aimed to assess the suitability of potential landfill sites. The various data sources corresponding to these criteria are detailed in Table 1. By using GIS based

Table 1. Source of the criteria map

Data	Source	Generated information plan
Topography (DEM with a 30 m resolution)	https://earthexplorer.usgs.gov/ (SRTM)	Slope
		Hydrographic network
		Lineament
Lithology	Digitization of 1/100,000 geological maps for Rabat, Sidi Yahya du Rharb, Souk el Arba du Rharb, and Ouezzane	Permeability
Road network	OpenStreetMap, road network map of the province of Kenitra	Road network
Sentinel satellite image (resolution: 10 m, year 2022)	https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED	Land use
Piezometry	Sebou Hydraulic Basin Agency (Depth and piezometric level of 31 boreholes)	Piezometric map

data processing and standardization, these raw data were transformed into compatible formats to facilitate rigorous analysis and informed decision-making (Fig. 2). Some researchers categorize these criteria into different categories, notably hydrological/hydrogeological, environmental, social, and techno-economic criteria (Kontos et al., 2005).

Moeinaddini et al. (2010) further subdivided these into four main factors: terrain physical characteristics, buffer zones and distances, visibility, ecosystem sensitivity, land use, and vegetation cover.

Demesouka et al. (2009) and Barakat et al. (2017) organized these factors into three different categories: land availability, natural resource

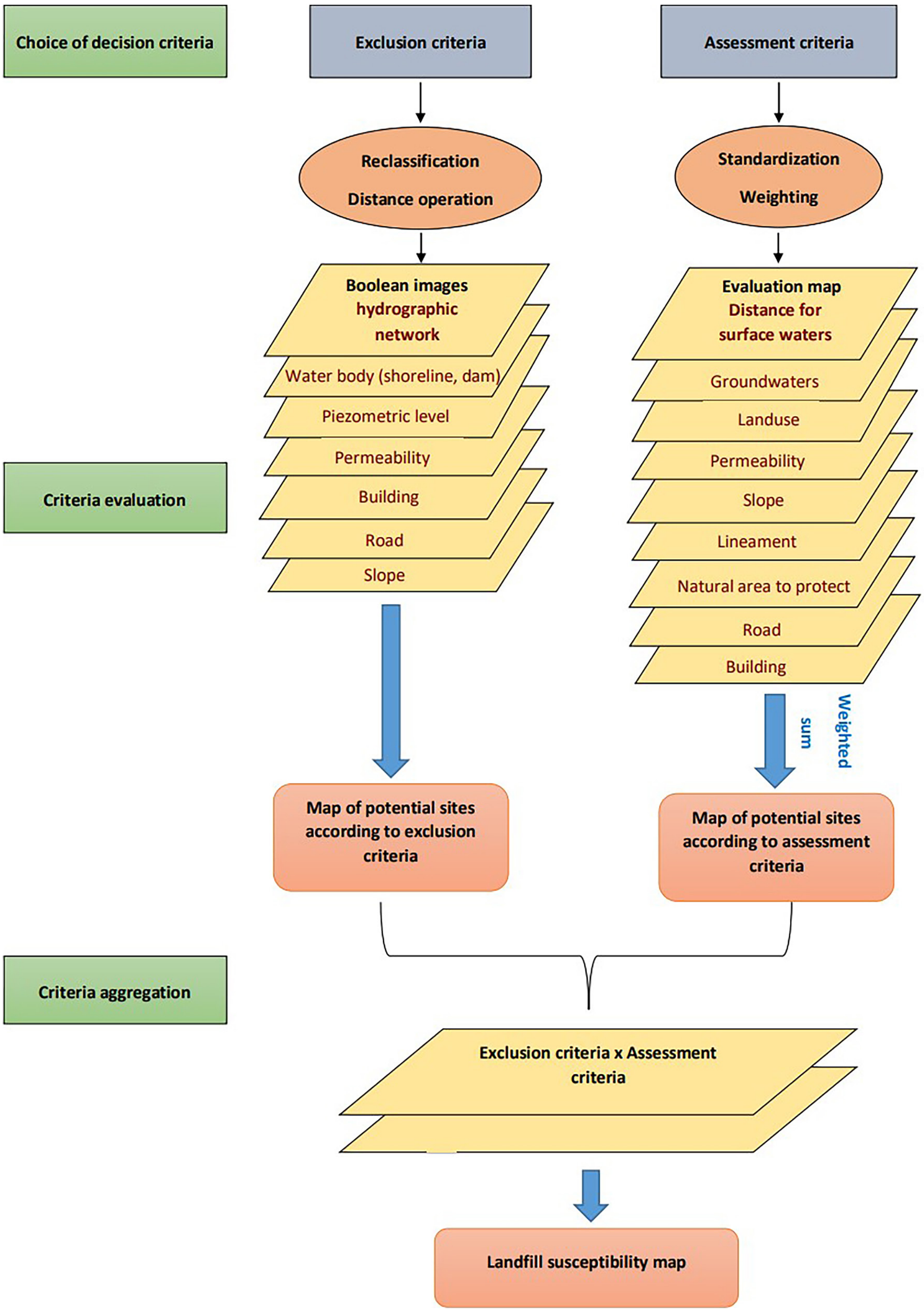

Figure 2. Criteria hierarchy for landfill site selection

conservation, and socio-economic criteria. Additionally, Chabuk et al. (2017), Alkaradaghi et al. (2019), and Sener et al. (2006) focused on environmental factors, including both natural and artificial influences.

Furthermore, some researchers have integrated economic and environmental criteria to assess potential sites. Sener et al. (2010), Wang et al. (2009), Karimi et al. (2019), and Hafezi Moghaddas and Hajizadeh Namaghi (2011), have included economic considerations, such as land prices alongside environmental factors.

This study exclusively focused on environmental criteria in the selection of a landfill site in Kenitra province, excluding economic considerations. Socio-economic aspects were also incorporated into a multidimensional approach involving a range of socio-economic factors, which was adopted to complement the environmental assessment of potential sites. This approach aligns with the work of Ajibade et al. (2019) and Arshad et al. (2023), who similarly underscore the importance of a thorough assessment of both environmental and socio-economic impacts.

ENVIRONMENTAL CRITERIA

Hydrological and hydrogeological criteria

Distance to surface waters

Landfill sites pose a potential risk to surface water resources due to leachate release and alteration of waste. To minimize these risks, landfill locations should be situated at a maximum distance from surface water bodies such as lakes, ponds, and rivers (Karimi et al., 2019; Demesouka et al., 2019).

According to Moroccan legislation, controlled landfills are not permitted to be located near sensitive areas, prohibition zones, and safeguard zones as stipulated by Law No. 10–95 on water and its implementing regulations.

A minimum buffer zone of 500 meters was rated as 0, a 1 – kilometer buffer zone was rated as 1, a 1.5 – kilometer buffer zone was rated as 2, a 2 – kilometer buffer zone was rated as 3, and buffer zones greater than 2 kilometers were rated as 4. The rating increased progressively with distance from the buffer zone. Figure 3a displays the classification map for distance to surface waters obtained in the GIS environment using the Euclidean distance module.

Groundwater table

Leachate characteristics, depth of buried waste, and landfill cover significantly impact groundwater resources quality (Karimi et al., 2019). To prevent groundwater pollution, it is crucial to avoid locating landfills on or near aquifers (Rahmat et al., 2017). Optimal landfill locations should be characterized by deep groundwater tables, minimal aquifer vulnerability. Moreover, the disposal site should not be chosen where the groundwater table has been less than 5 meters deep over the past 30 years (Rouhani et al., 2021).

A piezometric surface layer was generated within a GIS environment using “kriging” interpolation based on water level data collected from boreholes within the study area. This layer was subsequently classified into five depth intervals, each assigned a weight determined through AHP, as illustrated in Figure 1b.

Land criteria

- Land use – the province of Kénitra is primarily characterized by predominant agricultural land use, with various types of forests present in the region. To identify suitable locations for a landfill site, data from GIS databases and remote sensing were integrated. Land use was categorized into five types by combining these information sources: (1) unsuitable areas for a landfill site, including dense forests, agricultural lands, industrial zones, and built-up areas, which were given a score of 0; (2) areas suitable for future consideration, mainly consisting of unused lands, which were assigned a score of 4.
- Natural areas to protect (forest, vegetation, SIBE, and historical monument) – according to current regulations in Morocco, the establishment of controlled landfills near sensitive areas such as national parks, protected areas, tourist interest sites, biological and ecological interest sites, wetlands, and forests is strictly prohibited. This measure aims to preserve these valuable spaces and prevent any deterioration of their environment, in accordance with the established standards.

The province of Kenitra encompasses several biologically important areas, including wetlands listed within Ramsar sites. Given the classification of protectorates as sensitive environments requiring aesthetic preservation (Effat and Hegazy, 2012), along with the unsuitability of national

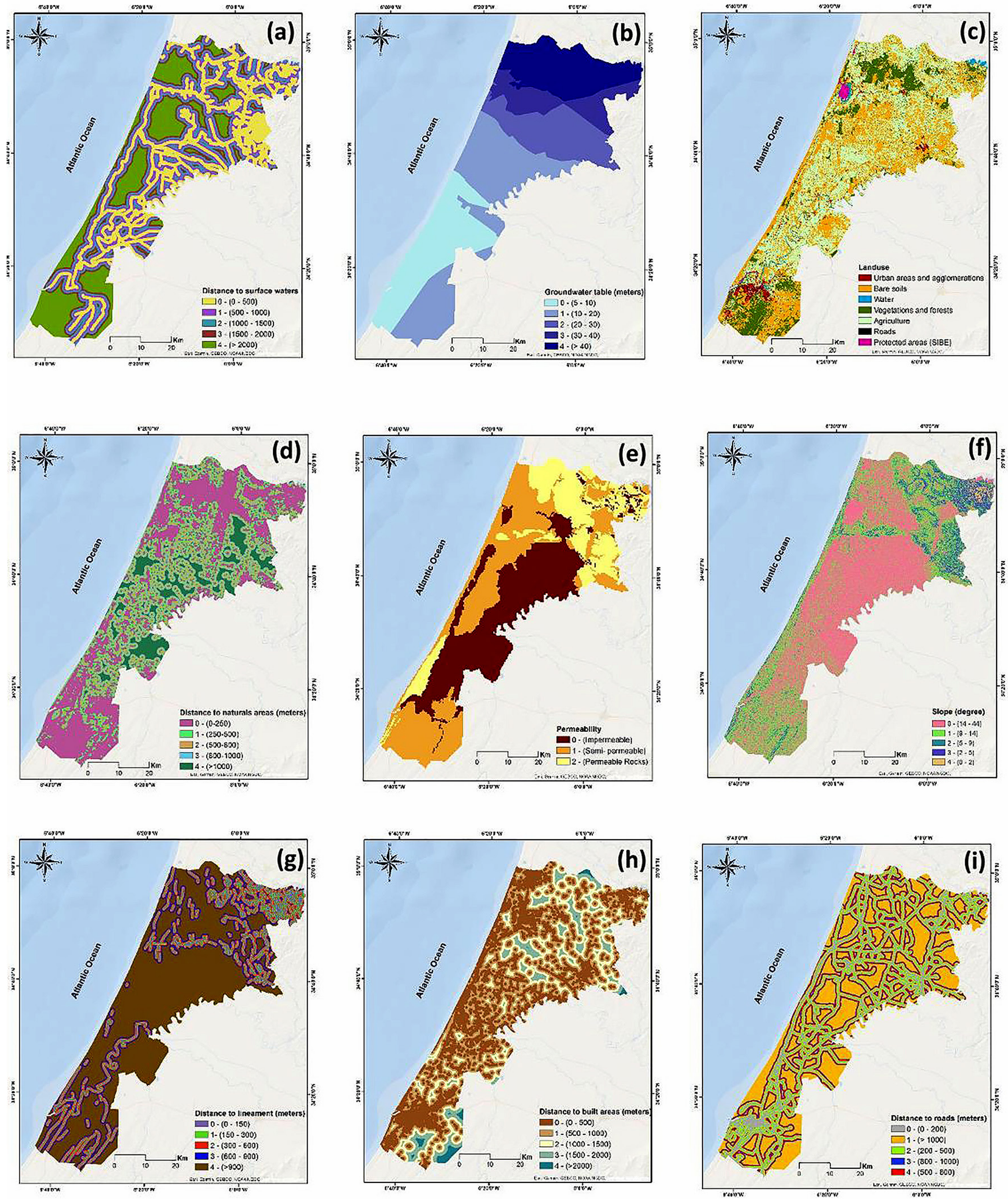

Figure 3. Criteria considered in the study: distance to surface waters (a), groundwater table (b), land use (c), distance to natural areas (d), permeability (e), slope (f), distance to linear features (g), built-up areas (h), and distance to roads (i)

parks and archaeological sites for landfill development (Şener et al., 2010)

In this study, the buffer zones surrounding sensitive areas were evaluated by assigning ratings based on their proximity. Buffer zones situated more than 1000 meters from these areas were assigned the highest rating of 4, while those within 250 meters received the lowest rating of 0, as detailed in Table 2. The assessment results are graphically represented in Figure 3d, offering essential insights for informed decision-making concerning the management of these sensitive zones

Lithological criteria

- Permeability – the selection of appropriate landfill sites necessitates careful consideration of geological factors, particularly lithological

Table 2. Scores for variable importance (Saaty, 1987, 1988, 1990)

Numeric value	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to Extremely strong importance
9	Extremely importance

characteristics, which significantly influence landfill performance and potential environmental impacts.

As highlighted by (Barakat et al., 2016), limestone and clay formations, characterized by extensive fracturing and high permeability, are generally unsuitable for landfill development. Conversely, metamorphic rocks may be considered potential options subject to their specific geological attributes

The study area features several lithological formations, classified into three permeability-based units: impermeable (clay, marl, shale), semi-permeable (sandy sedimentary rocks), and permeable (limestone, sands, silts); the latter two lithological classes (Permeable and semi-permeable) predominate in the region. Geological maps of the study area, compiled at a scale of 1:100,000 from the four maps of Rabat, Sidi Yahya du Rharb, Souk El Arba du Rharb, and Ouezzane, were digitized to develop a vector layer for lithology.

Each permeability class was evaluated and ranked using the analytical hierarchy process areas characterized by low permeability were deemed more suitable for landfill sites and consequently received higher scores compared to those with high permeability.

Topographic criteria

- Slope and elevation – Terrain topography plays a critical role in the design and management of landfill and waste disposal facilities. In the adopted methodology, site topography was evaluated based on slope measurements, expressed in degrees.Slope and elevation are fundamental parameters for landfill site construction (Kontos et al., 2005). Areas with high elevation or steep slopes are generally unsuitable for landfill sites (Sener et al., 2010). Optimal locations for waste disposal are typically found in areas with moderate elevation, surrounded by hills, and slopes not exceeding 20% (Akbari et al., 2008). Steep terrain poses economic challenges, as it is more costly to manage for landfill construction (Effat and Hegazy, 2012). Environmentally, slope influences water management, regulation of rainfall runoff, erosion potential, and leachate drainage during precipitation events. The slope was derived from the digital elevation model (DEM) of the study area with a resolution of 30 × 30 meters, as shown in Figure 3f. Slope values ranging from 0 to 44 degrees, were categorized on a scale of 0 to 4, where a score of 0 (indicating the least suitable) was assigned to slope values ranging from 14° to 44°, while a score of 4 (indicating the most suitable) was assigned to slope values ranging from 0 to 4°.
- Lineament – Lineaments, such as fractures, faults, ridges, streams, and folds, are distinct geological or topographical features that can indicate the presence of groundwater in a region. These features play a crucial role in the potential movement of contaminants, providing the pathways for solid waste leachates to flow towards groundwater (Ajibade et al., 2019). Faults, in particular, are geological structures that can restrict the selection of safe landfill sites due to their impact on rock permeability (Gemitzi et al., 2007). To mitigate environmental risks associated with landfill sites, it is crucial to maintain adequate distance from these linear features. Ideally, faults, fractures, joints, streams, lakes, and other shear zones should be located at least 100–200 meters from the landfill site. This distance helps to minimize the potential for groundwater contamination and reduces the risks associated with ground movement (Moeinaddini et al., 2010; Gorsevski et al., 2012; Basavarajappa et al., 2014).

SOCIO-ECONOMIC CRITERIA

Sociocultural criteria

Urban area and agglomeration

The proximity of waste disposal sites to urban and rural areas can have negative repercussions on both the population and the environment.

Previous research by Uyan, 2014, Tchobanoglous et al., 1993, and Zanjani et al., 2017 has identified a range of adverse effects associated with landfill operations, including odors, dust, and noise. These issues can lead to air and water pollution, noise pollution, odor emissions, presence of pests and insects, foul odors, as well as fire hazards (Barakat et al., 2017).

To mitigate these risks, the literature and previous studies on solid waste management recommend that no sanitary landfill should be situated within 500 meters of residential areas, consequently a buffer zone of 500 meters has been established for around current urban and rural residential areas. This buffer zone has been graded on a scale of 0 to 4 based on its distance from the landfill, ranging from 0 for a 500 m buffer zone to 4 for buffer zones exceeding 2 km. This measure aims to protect public health and the environment by limiting the proximity of landfills to inhabited areas.

Accessibility and infrastructure criteria

- Distance to roads – the Kenitra province occupies a strategically central location with respect to major consumption centers, benefiting from a dense road network that enhances regional connectivity. The significance of road accessibility in landfill site selection has been widely acknowledged in the literature. To minimize the infrastructure costs associated with new road construction, landfill sites should ideally be located in close proximity to existing road networks (Nas et al., 2010). Prioritization of main and secondary roads for landfill siting is essential to optimize operational efficiency and transportation costs (Rouhani et al., 2021).

Furthermore, it is essential to ensure that the vehicles used for landfill operations do not disrupt existing traffic flows (Guiqin et al., 2009) and meet accessibility criteria.

On the basis of these considerations, locations situated more than 200 meters but less than 1000 meters from roads are considered most suitable, while those more than 1000 meters away or less than 200 meters from existing roads are less favorable (Karimi, 2019). Locations farther from major roads and closer to established routes receive higher ratings.

A proximity-to-roads map was generated using the Euclidean distance function within a GIS environment (Figure 3i). This analysis quantified the distance between pixels and road networks, providing essential data for evaluating site suitability based on road accessibility criteria.

METHODOLOGY

This research employs a combined approach of geographic information systems and the analytic hierarchy process to identify optimal landfill sites in alignment with both national regulations and international literature. AHP, a prominent multi-criteria decision-making technique developed by Saaty in 1980, was utilized to determine the relative importance of various criteria (Sumathi et al., 2008).

The site selection process comprised two distinct stages. Initially, a Boolean approach was applied to exclude unsuitable areas based on predefined exclusion criteria. This method involved the creation of Boolean maps to delineate areas categorically unfit for waste disposal.

Subsequently, Boolean logic was employed, and parameter maps were segmented into suitable and unsuitable zones to define the areas deemed appropriate for waste disposal, based on constraint maps. It transforms the data from each raster map into a binary format, with true or false values represented by 1 and 0. The value 0 was assigned to the areas excluded from consideration, while 1 was assigned to other respective zones.

To further evaluate the results of Boolean logic, the second step involves pairwise comparisons based on AHP, followed by the calculation of weights for each factor. A comparison matrix was generated where each criterion is compared to others based on its importance in the hierarchical model. Criterion weights were calculated as AHP is an effective approach for determining the relative importance of identified criteria weights (Ampofo et al., 2023). The consistency ratio (CR) results from dividing the consistency index (CI) by the random index (RI), with its value ranging from 0 to 1. A CR of 0.1 or less indicates a reasonable level of consistency (Malczewski, 1999); a CR greater than 0.1 necessitates a reassessment of the decision matrix for any inconsistent factor ratings (Pourghasemi et al., 2012).

$$CI = \frac{\lambda max - n}{n-1} \tag{1}$$

where: λmax is the largest or principal eigenvalue of the matrix, which can be easily calculated from the matrix, and n is the order of the matrix

$$CR = \frac{CI}{RI} \quad (2)$$

where: the RI is the average CI, which depends on the order of the matrix as given by Saaty (1980).

The criteria comparison matrix and their weights are provided in Table 5. The summary of weight importance is given in Table 3. The calculated consistency ratio was 0.06, which is lower than the threshold value of 0.1. Therefore, the comparison was considered consistent (Table 4).

Ultimately, by overlaying raster maps of all elements in ArcGIS and performing a weighted overlay analysis, the overlay tool integrates map layers to create a composite suitability map. This map is based on the influence weights derived from the pairwise comparison matrix, resulting in the generation of a landfill suitability map.

RESULTS AND DISCUSSION

Two multicriteria analysis methods were applied to evaluate decision criteria: weighted linear combination, Boolean logic, and overlay.

The decision criteria selected for multicriteria analysis are categorized into two types: exclusion criteria and appreciation criteria. Some criteria play a dual role, serving both as appreciation and exclusion criteria depending on distance, for example. Proximity to roads serves as an exclusion criterion when the distance is less than 200 meters or greater than 1000 meters, while it becomes an appreciation criterion when the distance to the road is between 200 and 1000 meters.

The criteria that strictly exclude the establishment of a landfill site include distance to roads, surface waters, built-up areas, dams and oceans, presence of permeable layers, as well as forest cover and areas identified as Important Sites for Biodiversity and Ecology (SIBE).

Following reclassification into binary values of 0 and 1 (unsuitable and suitable), this analysis involves overlaying the information contained in Boolean layers that meet the previously stated exclusion criteria (Morjani et al., 2003), (Fig. 4).

This analysis produces a map showing excluded and suitable areas. The suitable areas underwent classification using Multicriteria and AHP analysis methods in the second stage of the analysis, based on all selected criteria. The weighted combination approach, widely adopted in multicriteria analysis, offers great flexibility by allowing criteria to be normalized on continuous scales. In this method, each factor is assigned a specific weight, enabling comparison within a relative range against each other (Karimi, 2019). At this stage of the study, a pairwise comparison matrix was constructed following the hierarchical model, determined the criteria weights, and evaluated the CR. CR was found to be less than 0.10 (0.06), indicating satisfactory consistency in the judgments used for comparisons. Subsequently, the various classified layers were overlaid in a GIS, using the overall importance weights derived from the pairwise comparison matrix. This step led to the creation of the final relevance map, shown in Figure 5.

Table 3. Random inconsistency indices for different values of (n) (Saaty 1980; Isalou et al., 2013; Alkaradaghi et al., 2020; Demeke Desta et al., 2023)

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56

Table 4. Comparison matrix

Criteria	A	B	C	D	E	F	G	H	I	Weights
a	1	1/2	1	2	2	2	2	1/3	3	0.12
b	2	1	2	2	1	2	1	1/2	3	0.14
c	1	1/2	1	1	1/2	2	2	1	1	0.11
d	1/2	1/2	1	1	2	2	2	1/2	3	0.11
e	1/2	1	2	1/2	1	2	1	1/3	3	0.10
f	1/2	1/2	1/2	1/2	1/2	1	2	1/3	3	0.07
g	1/2	1	1/2	1/2	1	1	1	1/3	3	0.08
h	3	2	1	2	3	3	3	1	5	0.22
i	1/3	1/3	1	1/3	1/3	1/3	1/3	1/5	1	0.04

Table 5. Buffer zone criteria

Main criteria	Criterion	Buffer zone (m)	Suitability class	Rank
Environmental criteria	Distance for surface waters	0-500	Unsuitable	0
		500–1000	Less suitable	1
		1000–1500	Moderately suitable	2
		1500–2000	Suitable	3
		>2000	Highly suitable	4
	Groundwater table	5	Unsuitable	0
		10	Less suitable	1
		20	Moderately suitable	2
		30	Suitable	3
		40	Highly suitable	4
	Landuse	Urban areas and agglomerations	Less suitable	1
		Bare soils	Highly suitable	4
		Water	Unsuitable	0
		Vegetations & forests	Suitable	3
		Agriculture	Less suitable	1
		Roads and infrastructure	Moderately suitable	2
		Protected areas (SIBE)	Unsuitable	0
	Natural area to protect (forest, vegetation, SIBE, and historical monument)”	0-250	Unsuitable	1
		250-500	Less suitable	2
		500-800	Moderately suitable	3
		800-1000	Suitable	4
		>1000	Highly suitable	5
	Permeability	Impermeable	Highly suitable	2
		Semi permeable	Moderately suitable	1
		Permeable	Unsuitable	0
	Slope (degree)	0–2	Unsuitable	4
		2–5	Less suitable	3
		5–9	Moderately suitable	2
		9–14	Suitable	1
		14–44	Highly suitable	0
	Lineament	0–150	Unsuitable	0
		150–300	Less suitable	1
		300–600	Moderately suitable	2
		600–900	Suitable	3
		>900	Highly suitable	4
Socio-Economic criteria	Distance from urban and rural areas	0–500	Unsuitable	0
		500–1000	Less suitable	1
		1000–1500	Moderately suitable	2
		1500–2000	Suitable	3
		>2000	Highly suitable	4
	Road	0–200	Unsuitable	0
		200–500	Moderately suitable	2
		500–800	Highly suitable	4
		800–1000	Suitable	3
		>1000	Less suitable	1

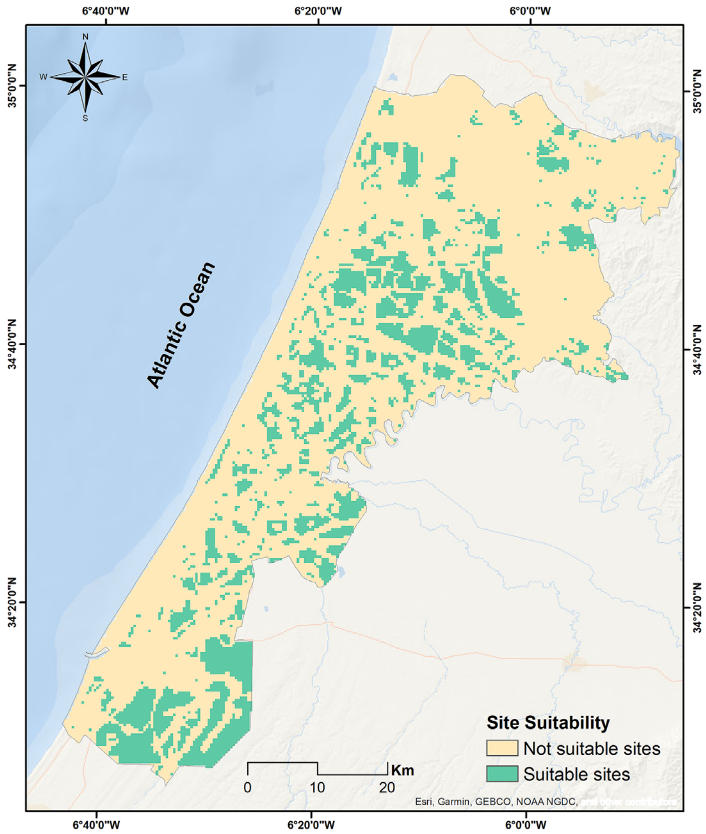

Figure 4. Map of potential zones from Boolean images of exclusion criteria

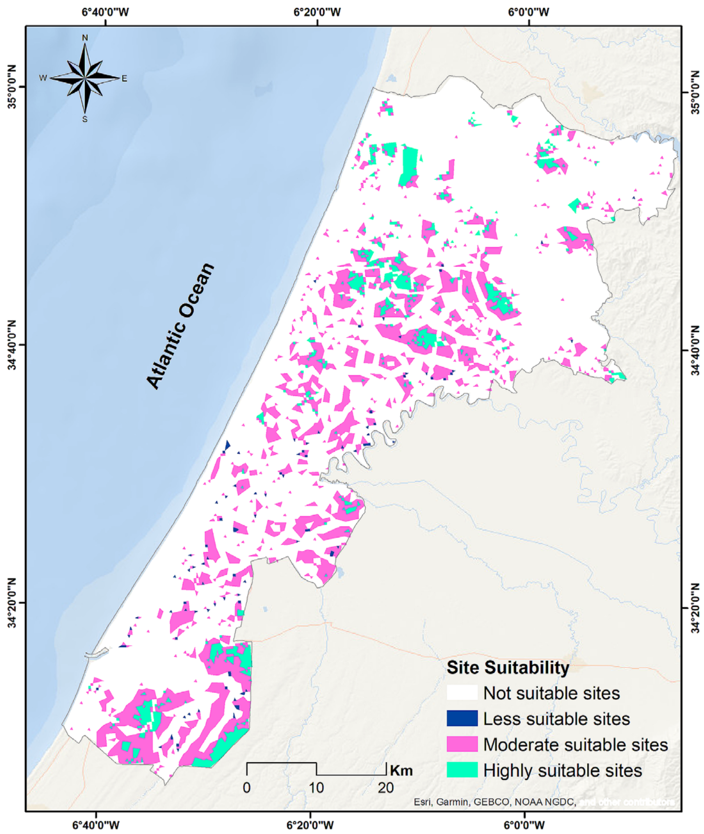

Figure 5. Relevance map of a landfill site based on AHP analysis

After excluding sites with an area less than 20 hectares due to their inability, the final relevance map was developed. The locations sought for landfill installation require a considerably adequate area for long-term waste storage. The final map obtained is then classified into four categories: not suitable, less suitable, moderately suitable, and highly suitable, allowing differentiated evaluation of sites based on their suitability for waste management (Table 6).

To identify suitable landfill sites, existing landfills within the Kenitra province were incorporated into this analysis. Given the environmental and social threats posed by these landfills, and the fact that they are situated in unregulated areas susceptible to such risks, classifying four of them as unsuitable demonstrates the reliability of the obtained results and adopted method. This finding reinforces the effectiveness of the approach employed in identifying more appropriate sites, which in turn reduces the environmental and social risks associated with waste disposal (Figure 6).

The proposed scenario suggests establishing three landfill sites adjacent to current sites in the province. A single landfill appears insufficient to meet the needs of the entire province, especially considering the diversity of highly suitable sites identified on the results map. Therefore, strategically placing three landfill sites offers a more effective solution for optimal waste management in the province. These sites should be located near Kénitra and Mahdia to take advantage of their geographic proximity, as well as close to Souk El Arbaa and Moulay Bouselham proximity, near Souk El Arbaa, and near Moulay Bouselham (Figure 7).

When selecting these sites, it is essential to consider wind direction, as it can significantly impact issues such as odor dispersion, fine particle emissions, and contaminants. This highlights the importance of wind patterns in influencing local environment and public health.

Table 6. Class and total risk score

Suitability class	Percentage of area
Not suitable	78%
Less suitable	1%
Moderately suitable	17%
Highly suitable	4%

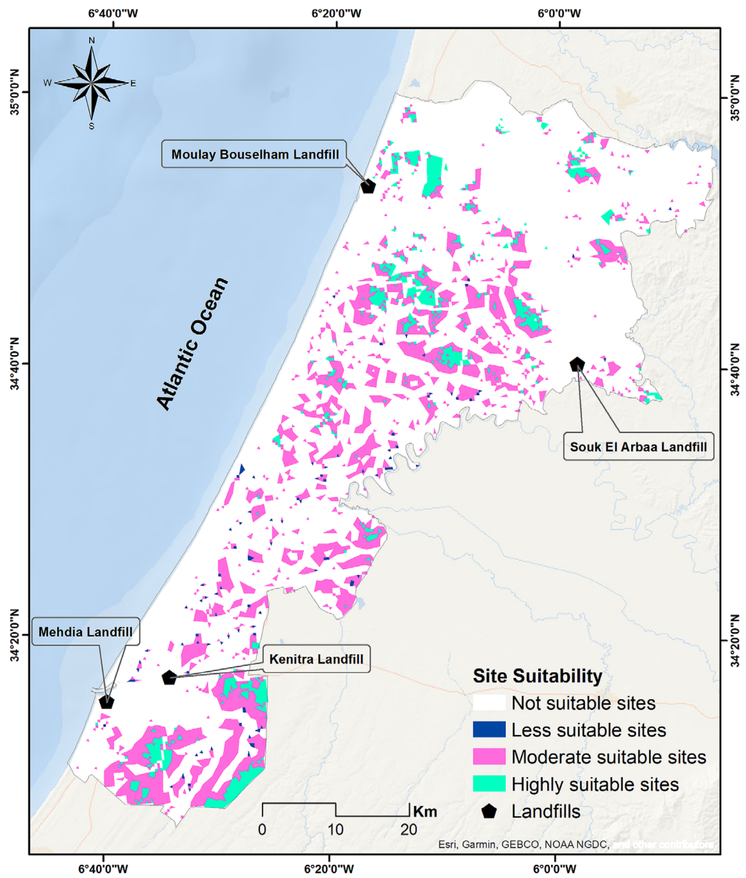

Figure 6. Map indicating the relevance of a landfill site, with the locations of existing landfills

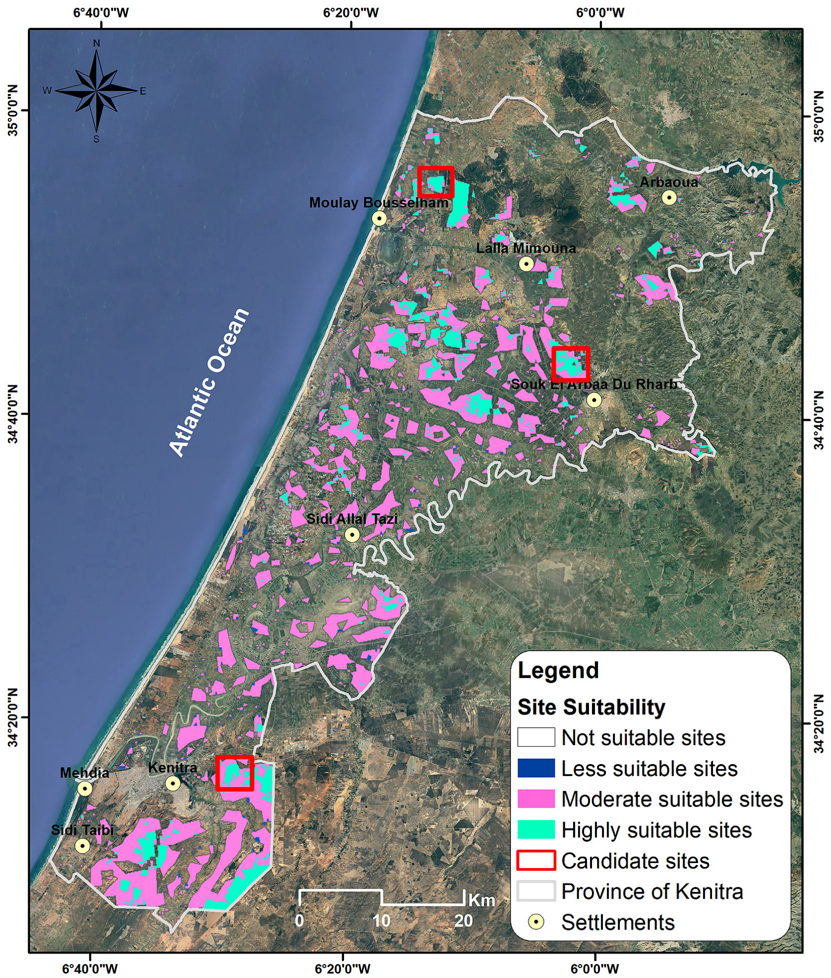

Figure 7. Relevance map of landfilling

CONCLUSIONS

The selection of a waste landfill site emerges as a complex process, demanding thorough analysis of multiple environmental, social, and economic parameters. The criteria examined, primarily focused on environmental considerations, and underwent rigorous evaluation using GIS tools, proving to be economical and practical instruments for producing high-quality maps. This approach streamlined efforts by identifying favorable sites in advance, even before conducting field surveys.

The integration of GIS with AHP has emerged as an effective strategy for landfill siting, facilitating spatial data visualization, criterion prioritization, and weighting of their respective importance. This methodology played a crucial role in identifying optimal sites by considering various social, environmental, and economic aspects, thereby contributing to the reduction of environmental and health impacts associated with solid waste landfills.

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