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Assessing the environmental impacts of a landfill site in Kenitra province using GIS-AHP and the Leopold matrix

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ABSTRACT

Waste management is a crucial issue for environmental preservation, public health, and sustainable development, especially in rapidly growing regions such as kénitra province, Morocco. This study aims to assess the potential environmental impacts associated with the establishment of a landfill site at one of the locations identified through a multi-criteria analysis (GIS-AHP).To do this, the methodology is based on the Leopold matrix, a recognized tool for environmental impact analysis that helps identify and rank interactions between planned actions and affected environmental elements. The results highlight significant environmental and social risks, including alterations to natural runoff, contamination of surface and groundwater by leachates, soil loss and erosion, as well as air pollution from dust and biogas emissions. Flora and fauna are exposed to noise disturbances, species displacement, and health risks, which are intensified by the wetland proximity. Additional concerns include pressure on infrastructure, landscape degradation, and nuisances linked to traffic and waste management, raising social concerns. Proposal alternative solutions to mitigate environmental impacts and promote sustainable, responsible project management include drainage control systems, impermeable geomembranes, collectors, and biogas capture, and recovery devices. These measures aim to significantly reduce environmental nuisances and enhance social acceptability. This assessment could provide a valuable decision-making tool for local stakeholders, offering a rigorous and systematic analysis of environmental impacts related to landfill site establishment. Moreover, it contributes to improved environmental planning, compliance with existing regulations, and support for sustainable development in a region facing intense demographic and economic pressures.

Keywords: waste, Morocco, environmental assessment, Leopold matrix, Kenitra.

INTRODUCTION

Waste management represents a critical challenge for ecological integrity and quality of life in contemporary societies. Waste treatment infrastructures, particularly landfills, can significantly disrupt the ecological balance of affected areas through landscape alteration, destruction of natural habitats, and displacement of fauna (Danthurebandara et al., 2012). More broadly, industrial activities, including mining, chemical manufacturing, agri food processing, and large scale infrastructure development generate diverse environmental impacts, such as soil and water contamination, habitat degradation, and greenhouse gas emissions (Smith et al., 2020; Zhang and Li, 2021; Kumar et al., 2023). Consequently, any transformation whether anthropogenic or natural produces both positive and negative effects on ecosystems and socio economic dynamics (Goudie, 2018).

Among waste management practices, landfilling remains a predominant method but constitutes a substantial source of pollution, notably through the emission of greenhouse gases, including methane (CH_4) and carbon dioxide (CO_2), resulting from anaerobic decomposition of organic matter. Methane exhibits a global warming potential approximately 28 times greater than that of CO_2 over a 100 year timescale (Masson-Delmotte et al., 2021). Furthermore, leachates containing heavy metals, volatile organic compounds, and pathogenic microorganisms can contaminate soils and groundwater if inadequately managed (Ez-zaouy et al., 2022). A landfill site typically generates between 0.2 and 0.5 m^3 of leachate per ton of waste per year, depending on climatic conditions and waste composition (Kjeldsen et al., 2002). The dispersion of dust, lightweight plastic debris, and emissions from transportation further exacerbate local environmental degradation. Despite these externalities, landfills continue to be widely utilized due to their capacity to process large waste volumes at comparatively low cost (Hoornweg et al., 2012).

Within this context, the selection of a suitable landfill site constitutes a strategic undertaking aimed at minimizing adverse environmental and social impacts (Guiqina et al., 2009; Sener et al., 2010; Rahmat et al., 2016). An inappropriate siting decision can lead to contamination of water resources, nuisances affecting nearby communities, and irreversible damage to ecosystems. To inform decision making, various methodological frameworks have been developed. Among the most widely applied are the analytic hierarchy process (AHP), which prioritizes criteria by relative importance (Saaty, 1990), and multi criteria decision making (MCDM) approaches, which integrate environmental, technical, and socio economic factors simultaneously (Zeleny, 1982). These methods are particularly effective when combined with geographic information systems (GIS), which enable spatial analysis and visualization of georeferenced data. The integration of GIS and AHP methodologies has demonstrated considerable efficacy in rapidly urbanizing regions (Chang et al., 2008).

The province of Kénitra, situated within the Rabat-Salé-Kénitra region in northwestern Morocco, has experienced sustained demographic and economic growth, generating approximately 267,947 tons of household waste in 2023 (Commune de Kénitra, 2023). This growth exerts increasing pressure on existing waste management infrastructure, which remains limited or inadequate. In a recent study, (Titafi et al., 2024) identified optimal landfill sites by combining GIS and AHP approaches. Complementary studies, such as those by (Moumane et al., 2025) and (Aghad et al., 2023), have further enhanced these methodologies through the integration of remote sensing data and fuzzy AHP techniques, illustrating the continuous evolution of analytical tools and the imperative of rigorous planning in contexts of accelerated urbanization. However, beyond site selection, a comprehensive environmental impact assessment remains essential to anticipate the specific effects associated with landfill development and has yet to be conducted in this region.

This study is framed within the Moroccan regulatory context, which mandates environmental impact assessments for any project likely to generate significant environmental effects. Initially established under Law No. 12-03, these assessments aim to analyze direct and indirect impacts over the short, medium, and long term and to define measures to eliminate, mitigate, or offset negative effects while enhancing positive outcomes (Benfadil, 2016). Additionally, Law No. 49-17 of 2020 extended these requirements to encompass policies, plans, and programs, introducing four regulatory instruments: strategic environmental assessment, environmental impact study, environmental notice, and environmental audit. This framework requires an integrated approach that accounts for both social and ecological dimensions from the project design phase. Furthermore, Law No. 28-00 governing waste management defines principles for collection, recovery, and disposal, assigning responsibility to local authorities to ensure sustainable waste management in alignment with sustainable development objectives.

The primary objective of this study is to evaluate the potential environmental impacts associated with establishing a landfill at one of the identified sites within the province of Kénitra by applying the Leopold Matrix methodology. This approach aims to inform decision making by systematically identifying the project's significant impacts and proposing appropriate mitigation measures, in compliance with Moroccan regulatory requirements and sustainable development principles.

Study area

The project site is situated within the administrative jurisdiction of the Rural Commune of Oulad Slama, which forms part of the Province of Kénitra in northwestern Morocco. It is located to the northeast of the city of Kénitra, adjacent to National Road No. 4 (RN4) (Figure 1). Owing to its strategic position near the cities of Kénitra and Mehdia, as well as several surrounding rural communes, the site offers favorable conditions for establishing a landfill facility that could serve the entire region. The total area of the site encompasses approximately 92 hectares.

The Kénitra region faces increasing pressure due to inadequate waste management, particularly as a result of two unauthorized dumpsites located in Oulad Berjel and Mehdia, in addition to several uncontrolled disposal areas in surrounding rural communes (Figure 2). These non compliant sites contribute significantly to environmental degradation, including severe soil contamination caused by leachate infiltration and pollution of water resources (Kjeldsen et al., 2002; Elmarkhi et al., 2014). Moreover, they release harmful gases and airborne particulates, posing additional risks to environmental and public health (El-Fadel and Massoud., 2001; Bogner et al., 2008).

Studies such as (Elmarkhi et al., 2014) have demonstrated severe impacts on local groundwater resources. These issues substantially diminish the quality of life of nearby residents (Gupta et al., 2015). Kénitra's rapid urban and industrial development, combined with the presence of a university campus hosting over 85,000 students (Agence Urbaine de Kénitra, 2024), has resulted in a densely populated area and continuously increasing waste volumes. The city alone generates nearly half of the province's household waste. Tourism activities, particularly around Mehdia and Lake Sidi Boughaba, further exacerbate this

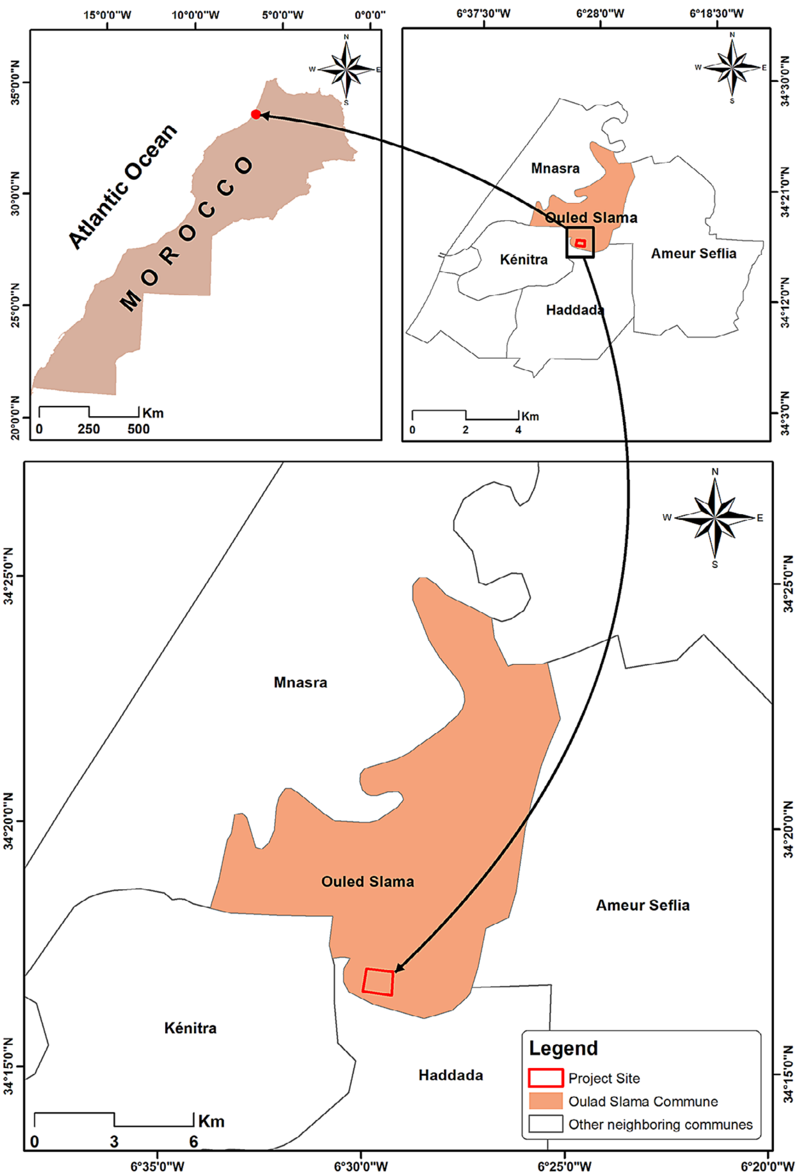

Figure 1. Geographical location of the study area

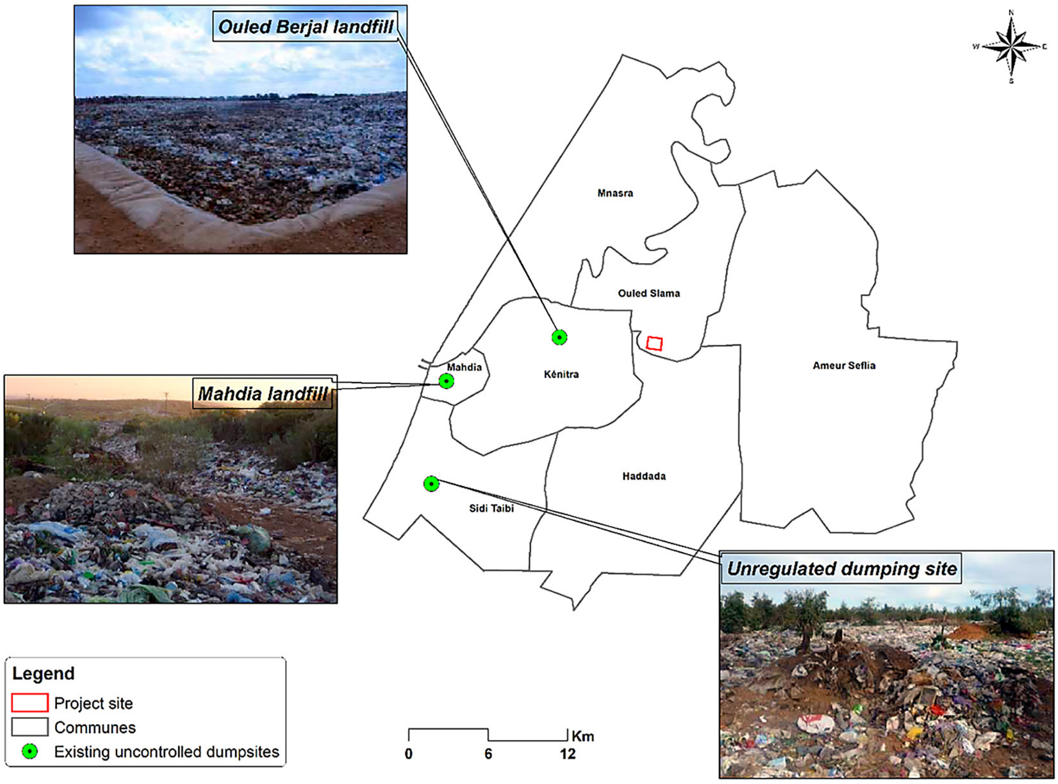

Figure 2. Distribution of illegal and uncontrolled dumpsites in the vicinity of Kénitra

pressure. This combination of demographic, economic, and touristic growth has led to a marked escalation in solid waste generation, which is projected to intensify through 2032 (Figure 3; Provincial Master Plan, 2023). In this context, establishing a compliant engineered landfill has emerged as a strategic priority to ensure efficient waste management, mitigate environmental degradation, and safeguard public health.

MATERIAL AND METHODS

The site selected for the future landfill, as previously indicated, results from a methodological approach applied at the scale of Kénitra Province (Titafi et al., 2024). This approach relies on a multi criteria evaluation of a range of criteria and sub criteria, organized into several categories: environmental, socio economic, hydrological and hydrogeological, lithological (particularly soil permeability), topographical, and factors related to accessibility and infrastructure.

The application of this method led to the identification of three potential sites suitable for the establishment of a controlled landfill. While several areas were classified as "highly suitable" based on the evaluation criteria, these three locations were retained after accounting for the dominant wind direction and validation through field surveys. The present project focuses specifically on one of these selected sites. Although the site was identified through a rigorous multi criteria analysis, it is essential to complement this selection with an environmental assessment in accordance with current regulatory requirements. This evaluation involves an in depth analysis of the site, including field investigations, to confirm its actual compatibility with environmental, technical, and social criteria.

Accordingly, it is crucial to conduct a systematic environmental impact assessment to examine both the positive and negative effects associated with landfill construction, operation, and closure phases. For this purpose, the Leopold Matrix has been adopted as a key analytical tool within the assessment process (Glasson et al., 2012). The Leopold Matrix provides a structured framework to identify and quantify interactions between project activities and environmental factors, thereby facilitating a comprehensive evaluation of potential impacts (Leopold et al., 1971). By cross referencing project actions with environmental components, the matrix supports the prioritization of

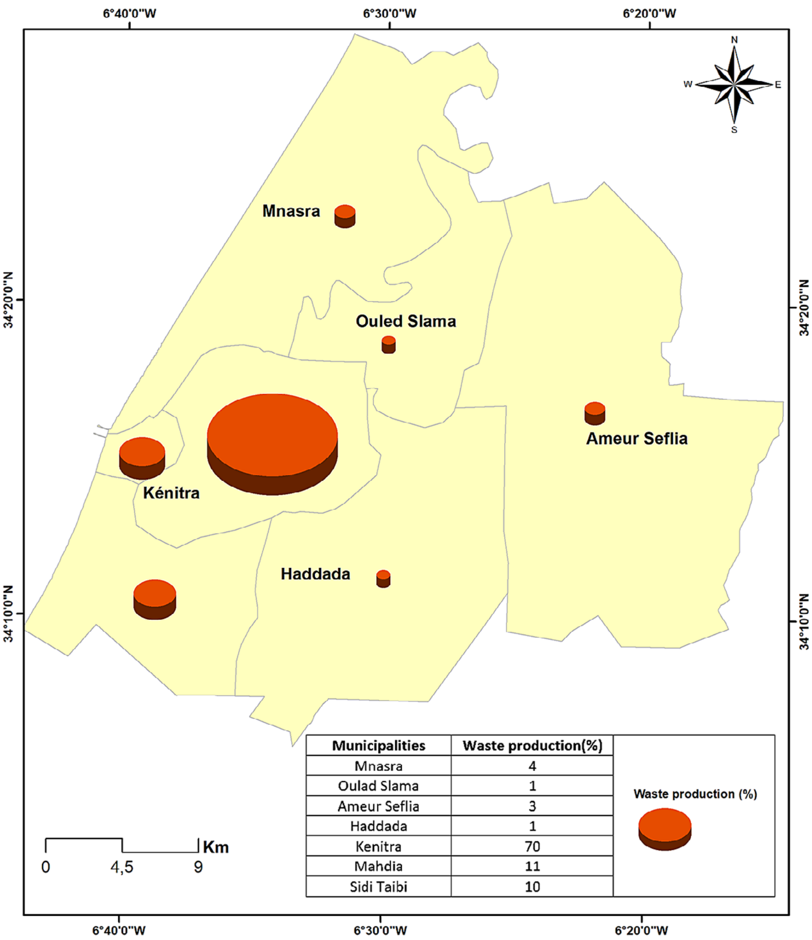

Figure 3. Projected quantities by 2032 in the concerned municipalities (Source: Commune of Kénitra)

significant impacts and the development of effective mitigation measures. This tool ensures that environmental considerations are integrated rigorously and transparently into the decision making process. The adopted methodology follows a structured and sequential approach, beginning with the preliminary identification of suitable sites for a controlled landfill and followed by the detailed evaluation of the selected site. It comprises the following main stages (Figure 4).

RESULTS AND DISCUSSION

Definition of the project's area of influence and analysis of the associated environmental impacts

The area of influence refers to the geographical zone potentially affected by the establishment of the future landfill site. Its delimitation is determined by the maximum extent of possible impacts, ensuring a thorough and comprehensive environmental assessment. The analysis of impacts on the physical environment (soil, water, air) will be conducted within this area of influence, whereas the evaluation of effects on the human and biological environment will encompass the entire municipal territory.

The environmental assessment aims to provide a holistic understanding of the project by identifying and thoroughly analyzing the environmental components that may be impacted, taking into account their interrelations. As outlined by (Glasson et al., 2012), the environmental diagnosis is based on the study of three interconnected environments: physical, biological, and socio economic.

Within the framework of this study, the inventory of potential project impacts was established through the identification of physical, biological, and socio economic environmental components. This identification is illustrated by the land use map (Figure 5), developed by integrating multiple data sources detailed in Table 1. This methodology has facilitated an accurate representation of

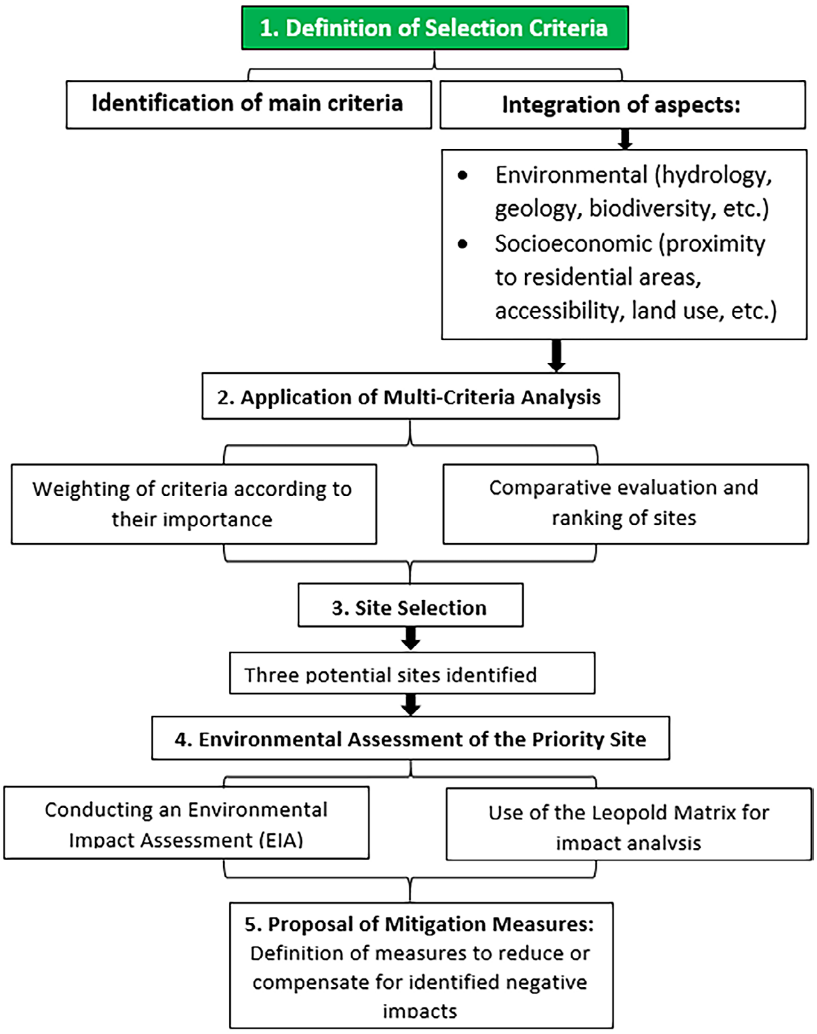

Figure 4. Flowchart methodology of the present study

Table 1. Data used

Data type	Source	Date
Field Survey	Data from site visits and direct observations	12/12/2024
Satellite Image	Google Earth Pro, WorldView-3 sensor, 30 cm spatial resolution	01/2024
Topographic Map (Scale 1:25,000) - Kénitra	Map created and published by the National Agency for Land Conservation, Cadastre, and Cartography, Directorate of Cartography, based on aerial images from 2003, supplemented by fieldwork in 2004	2004 (aerial imaging)
Topographic Map (Scale 1:25,000) - El Menzeh	Map created and published by the National Agency for Land Conservation, Cadastre, and Cartography, Directorate of Cartography, based on aerial images from 2003, supplemented by fieldwork in 2005	2005 (aerial imaging)

land use patterns and the specific physical characteristics of the study area.

The integration of geospatial data has facilitated a comprehensive analysis of the project's potential environmental impacts, considering current land use as well as the topographic and geographic characteristics of the study area. The project site is situated on agricultural land, sufficiently distant from ecologically sensitive or notable areas within the region.

The analysis of the physical environment identified the soil formations present in the commune of Oulad Slama: Tirs clay soils (characterized by a blackish color, low permeability, and susceptibility to swelling and shrinkage, predominantly located in the northern part of the commune), Dehs clay soils (light brown clay loam, fine grained, found in flood prone zones), and loose, permeable sands covering the southern part of the area and the Maâmora forest (FAO, 2015).

From a hydrological standpoint, the study area is characterized by a sparse hydrographic network with no permanent watercourses. Surface runoff is generally diffuse and occasionally feeds natural depressions and dayas, exhibiting slow flow dynamics aligned with the local slope gradients.

Regarding hydrogeology, the site is positioned at the interface between the Gharb and Maâmora aquifers. The unconfined aquifer consists of sedimentary deposits formed during a marine regression, resting on an impermeable substratum of thick blue marls. The depth of the upper layer of this impermeable formation varies from approximately 50 to over 100 meters, both at the site and within its watershed (ABHS, 2015).

Concerning the human and socio economic context, no sensitive populations are located in the immediate vicinity of the site. The center of Oulad Slama lacks a specific development plan; however, the delimitation and zoning plan provided by the municipality covers portions of Douar Laakarcha and Douar Sidi Ayache, encompassing several hectares with elevations ranging between 3 and 30 meters above the Normal Geographic Meridian (NGM) (Wilaya Région Gharb-Chrarda-Beni Hssen, 2014). Finally, no heritage sites or rare and endangered flora or fauna species have been observed on or near the site, as confirmed by field surveys (Table 2).

Given the land use characteristics surrounding the project site, a 1.5 km radius has been designated as the direct area of influence (Figure 5). This delimitation facilitates the visualization of

Table 2. Summary table of the project area characteristics

Element	Main characteristics
Soil type	Tirs (black clay, low permeability, prone to swelling) in the north; Dehs (clay loam); loose sands
Agricultural activity	Cereal crops, market gardening, sugar crops (in irrigated areas)
Hydrology	Low-density hydrographic network, no permanent watercourses, slow diffuse runoff
Hydrogeology	Boundary between the Gharb and Maâmora aquifers; unconfined aquifer over blue marls, depth 50–100 m
Altitude	Between 3 and 30 m NGM
Average wind speed	8 km/h
Wind direction	290° (northwest)
Sensitive areas	No remarkable ecosystems or observed endangered species
Nearby populations	Sparsely populated area; no development plan for Oulad Slama center; delimitation plan covers Assam and Fouarat neighborhoods

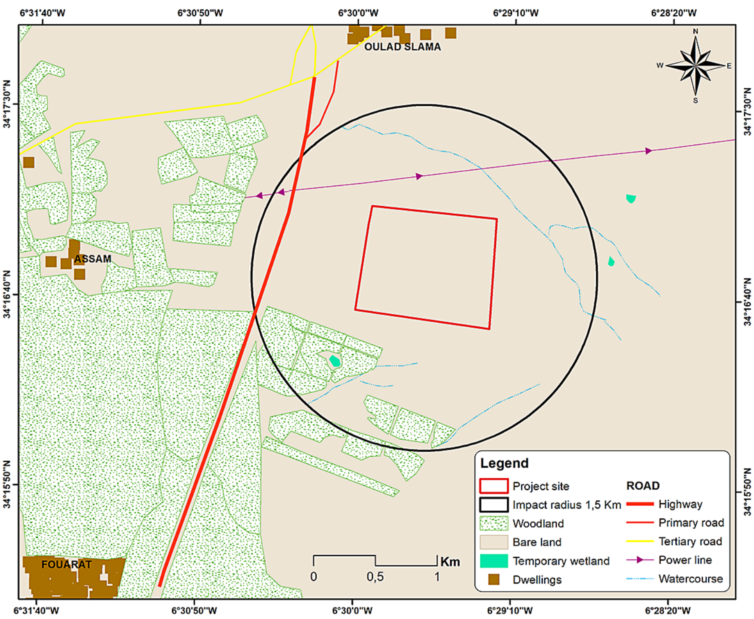

Figure 5. Land cover map of the study area

potential impact zones and the establishment of buffer areas around landfills, taking into account variations in land use and population density (Tansel et al., 2018).

According to (Kjeldsen et al.,2002), defining influence zones around landfills can be guided by the analysis of leachate dispersion and gas emissions, thereby ensuring the establishment of effective protective perimeters. In the Moroccan context, (Chofqi et al.,2004) emphasize that public landfills, particularly those located in coastal regions, pose a significant risk of groundwater contamination, which underscores the necessity of delineating specific influence zones for environmental safeguarding.

Moreover, (Christensen et al., 2001) highlight that leachate plumes may extend several hundred meters depending on soil permeability, necessitating careful demarcation of buffer zones. These findings are consistent with the recommendations of the Ministry of Land Use Planning, Water, and Environment (2002), which advocate for the definition of influence areas to evaluate potential impacts and implement appropriate mitigation measures, thus contributing to sustainable and secure landfill management.

The estimation of the atmospheric influence radius around a landfill site can be approximated using a simplified empirical formula, which is particularly useful in preliminary studies before the site's commissioning. This formula expresses the maximum influence radius (R) as a function of the average wind speed (u) and the dispersion time (t), as shown in the following equation:

$$R = u \times t \quad (1)$$

where: R is measured in meters, u is measured in meters per second, t is measured in seconds.

Although simplified, this approach is based on fundamental atmospheric dispersion principles outlined in classical works such as (Turner, 1970). It also aligns with modern dispersion models used by environmental agencies, including *AERMOD*, which is currently the reference model for industrial emissions simulation (Cimorelli et al., 2005; EPA, 2017). Considering an annual average wind speed of 8 km/h (or 2.22 m/s) and a dispersion time of one hour (3600 s) (source: Windfinder – Kénitra Meteorological Statistics), the estimated influence radius is approximately 8 km, defining the potential exposure zone to atmospheric pollutants emitted by the site.

$$R = 2.78 \times 3600 = 8\ \text{km} \quad (2)$$

The identified and potential impacts of the landfill project, both during the construction, operation, and closure phases, are presented in the following tables.

Table 3 presents a comprehensive checklist of potential environmental and socio economic impacts associated with the establishment and operation of a controlled landfill. This integrated assessment covers the project's main components throughout its life cycle, identifying key impacts on both the natural environment and human systems. It also highlights the stakeholders or affected sectors, particularly the local community (LC), and categorizes the impacts into three main target groups for clarity and coherence:

- local community (LC),
- aquatic fauna and flora (AFF), particularly in areas near wetlands,
- terrestrial fauna and flora (TFF).

Environmental impact assessment using the Leopold Matrix

The Leopold Matrix has been selected as the environmental impact assessment method owing to its flexibility and broad applicability (Leopold et al., 1971; Canter, 1996; Glasson et al., 2012). It offers a structured and adaptable framework that is widely recognized within scientific and professional communities, enabling an efficient evaluation of diverse project types.

Originally developed by geologist Luna B. Leopold and colleagues in 1971 in response to the 1969 U.S. National Environmental Policy Act, which lacked explicit guidance for federal agencies on preparing impact statements or assessing environmental effects of proposed projects (Bosko Josimovic et al., 2014), the matrix produces results that are readily comprehensible to scientists and experts alike.

The tool provides a comprehensive overview of project actions, their resultant impactful activities, and the affected environmental components, facilitating the identification of actions with the greatest impact and the environmental factors most significantly influenced (Econservation, 2017). Typically, the matrix includes up to 100 impact activities and 88 environmental conditions, resulting in approximately 8,800 possible interactions; however, in most applications, the number of interactions is constrained to between

Table 3. Potential environmental and socio economic impacts and proposed mitigation measures for the landfill project

Project component	Targets	Impacts	Phases	Proposed mitigation measures
Surface and groundwater resources	AFF, TFF	Modification of natural runoff	C/O/D	Develop a controlled drainage system (ditches, channels, retention basins) to manage runoff.
	LC, AFF, TFF	Possible contamination of surface and groundwater (leachate)	O/D	Install a waterproof geomembrane and a leachate collection and treatment system.
	LC, AFF, TFF	Risk of stagnation and uncontrolled infiltration in case of poor drainage	C/O/D	Regular maintenance of drainage structures, install pumping or gravity evacuation systems.
	LC	Water consumption for project needs	C/O	Optimize consumption (use of recycled water if possible), monitor usage volumes.
Soil	LC, TFF	Loss of fertile soil	C/D	Stockpile and reuse topsoil for rehabilitation or revegetation.
	LC, TFF	Erosion due to excavation works	C/D	Stabilize slopes, use mulching or temporary plantings.
	LC, AFF, TFF	Compaction reducing soil porosity	O/D	Limit repeated machinery movement, build dedicated pathways.
	LC, AFF, TFF	Pollution from hydrocarbons and oil leakage from machinery	C/D	Preventive maintenance of machinery, containment trays under service areas, hazardous waste management plan.
	LC, AFF, TFF	Risk of contamination from leachate	O/D	Same as water resources (waterproofing + collection system).
Air	LC, TFF	Dust emissions from excavation and vehicle movements	C	Watering of roads, speed limitation, covering of trucks.
	LC	Odors from waste decomposition	O	Daily waste covering, controlled composting, vegetative barriers.
	LC, TFF	Biogas emissions	O	Install biogas collection and flaring/recovery system.
Fauna	AFF, TFF	Noise and vibration disturbance	C/O	Limit work to specific hours, use noise-reduced equipment when possible.
	TFF	Species displacement	C/O/D	Avoid sensitive areas, create ecological corridors where feasible.
	AFF, TFF	Risk of mortality due to ingestion of waste or contamination	O	Fence the site, enforce strict control of waste disposal, raise staff awareness.
	TFF	Attraction of nuisance species (rats, birds)	O/D	Strict waste management, monitoring and trapping systems.
	AFF, TFF	Health risks	O	Controlled site access, regular pest/vector control treatments.
Flora	LC, TFF	Partial destruction of vegetation cover	C/D	Delimit work zones precisely, implement post-construction reforestation.
	LC, TFF	Soil pollution potentially affecting surrounding flora	C/O/D	Leakage prevention plan (maintenance, secure storage, regular monitoring).
Wetland	AFF, TFF	Risk of contamination from leachate	O/D	Locate landfill far from wetlands, use waterproof barriers and monitor water quality.
	AFF, TFF	Disruption of ecological balance and biodiversity	C/O	Conduct biodiversity studies, implement ecological management plan, regular monitoring.
Landfill operation	LC	Creation of direct and indirect jobs	O	Prioritize local employment, train staff on safety and environmental norms.
	LC	Potential improvement of waste management in the region	O	Implement sorting, weighing and tracking systems.
	LC	Health and social risks due to nuisances (odors, vectors, leachate)	O	Hygiene plan, fencing and signage, community awareness campaigns.
Infrastructure	LC	Pressure on access roads (truck traffic)	C/O	Prioritize use of existing roads, establish specific traffic plan.
	LC	Risk of road degradation, noise, and nuisances from machinery	C/O	Regular maintenance, limit transport to specific hours, use durable pavement.
	LC	Access infrastructure (roads, tracks)	O	Sustainable construction of access roads (drainage, stabilized surfaces).
Landscape	LC	Visual landscape change	C/O	Install vegetated screens and berms to reduce site visibility.
	LC	Decrease in land value	C/O	Aesthetic and ecological integration of site design.
	LC	Impact on recreational/residential use	C/O	Enhance and preserve nearby natural/ recreational areas.
	LC	Increased social opposition due to visual impact	C/O	Organize public consultations to gather and integrate social concerns.

Note: LC – local community; AFF – aquatic fauna and flora; TFF – terrestrial fauna and flora. C – construction; O – operation; D – decommissioning.

25 and 50. The Leopold Matrix can be utilized in both reduced and expanded formats.

Previously, the Leopold Matrix was employed to analyze the environmental impacts of the Gonabad municipal landfill and alternative waste management options (Sajjadi et al., 2017). The matrix was adjusted to better address project specific considerations, demonstrating its adaptability to various project types. The findings indicated that the landfill represented the least favorable option for the locality, highlighting its principal challenges (Figueiredo et al., 2020).

In the present study, the Leopold Matrix has been tailored to assess the environmental impacts already identified (Table 4). It has streamlined the analysis of potential effects associated with activities and processes undertaken during the construction and operational phases of the landfill.

Table 4. Environmental impact assessment of the landfill project using the Leopold matrix

Parameter		Impacts	Construction phase	Operation phase	Decommissioning phase
Physical environment	Surface and groundwater resources	Alteration of natural runoff	-	-	-
		Potential contamination of surface and groundwater (leachate)	0	--	--
		Risk of stagnation and uncontrolled infiltration in case of poor drainage	-	-	-
		Water consumption for project needs	--	-	-
	Soil	Loss of fertile soil	--	-	-
		Erosion due to earthworks	--	-	-
		Soil compaction reducing porosity	--	--	--
		Pollution from engine oils and hydrocarbons	--	-	-
		Risk of leachate contamination	0	-	-
	Air	Dust emissions from earthworks and vehicle movements	---	-	-
		Odors from waste decomposition	0	---	---
		Biogas emissions	0	---	---
		Noise and vibration disturbances	--	0	0
Biological environment	Fauna	Displacement of species	--	-	-
		Mortality risks due to ingestion or contamination	0	---	---
		Attraction of nuisance species (rats, birds)	0	--	--
	Flora	Partial destruction of vegetation cover	--	-	-
		Soil pollution affecting surrounding flora	0	--	--
	Wetlands	Risk of contamination by leachate	0	--	--
		Disruption of ecological balance and biodiversity	-	--	--
Socio-economic environment	Socio-economy	Creation of direct and indirect jobs	++	+++	---
		Potential improvement of waste management in the region	++	+++	---
		Health and social risks from nuisances (odors, vectors, leachate)	--	--	---
		Visual landscape modification (visible from residential and road areas)	--	--	---
		Decrease in surrounding land value	--	--	---
		Degradation of recreational and residential land use	--	--	---
		Increased social opposition due to visual impact	--	--	---
	Infrastructure	Pressure on access roads (truck traffic)	-	-	-
		Road degradation, noise and disturbances from machinery	--	-	-
		Access development (roads, tracks)	++	+++	+++

The impacts evaluated were selected based on observed land use within the project site and its area of influence.

The impact factors have been individually assessed for each relevant environmental component in this study and rated according to the following specific scale:

- high positive impact: +++
- moderate positive impact: ++
- low positive impact: +
- negligible impact: 0
- minor negative impact: -
- moderate negative impact: --
- high negative impact: ---

The selection of the landfill site was executed through the integration of the AHP and GIS tools, with the objective of identifying an optimal location that fulfills technical, environmental, and socio economic requirements (Errouhi et al., 2021; Chafiq et al., 2023). This methodical approach facilitated the identification of a site that complies with mandatory safety distances from sensitive areas including inhabited zones, water bodies, and infrastructure while concurrently considering proximity to residential areas to enhance the efficiency of daily waste collection routes (Tansel et al., 2018).

The environmental assessment of the site, underpinned by detailed field investigations, enabled the identification of both short and long term potential impacts. During the preliminary selection phase, stringent exclusion criteria were applied, including maintaining adequate separation from surface and groundwater sources, avoiding permeable soil strata, forested areas, and proximity to sites of biological and ecological interest (SIBE) (Titafi et al., 2024). The analytical framework was further strengthened by the utilization of the Leopold matrix (Leopold et al., 1971), which permitted a comprehensive cross analysis of project activities, impacted environmental components, and the associated effects.

In response to the identified impacts, a suite of mitigation measures has been proposed refer to Table 3. For instance, to mitigate the risk of water contamination by leachate, the installation of an impermeable geomembrane liner coupled with a leachate collection and treatment system is planned, in accordance with the recommendations of (Christensen et al., 2001). To manage stormwater runoff effectively, a systematic drainage infrastructure including ditches, gutters, and retention basins will be constructed (EPA, 2017). Soil conservation efforts will include the preservation and reutilization of topsoil to prevent the depletion of fertile layers during excavation, alongside slope stabilization and the application of temporary vegetative cover to minimize erosion.

From an ecological standpoint, disruption to fauna will be minimized through the implementation of construction scheduling aligned with appropriate temporal windows, installation of fencing to deter animal intrusion, and the deployment of monitoring protocols designed to reduce the attraction of nuisance species. Visual impacts will be attenuated by incorporating vegetated berms around the site, and public consultations are planned to address community concerns and foster stakeholder acceptance. Therefore, this integrated approach surpasses the mere identification of a compliant site; it embodies a sustainable development framework by proactively anticipating project impacts and proposing tailored, evidence based mitigation strategies for each affected environmental component (Table 3).

CONCLUSION

The province of Kénitra is confronted with mounting challenges in waste management due to the continual increase in waste production, demographic growth, and accelerated urbanization. To effectively address these challenges, this study developed a decision support tool designed to rigorously evaluate the environmental impacts related to the establishment of a landfill site within the region. Through the application of the Leopold Matrix, aligned with Moroccan regulatory frameworks, the study identified environmentally sensitive zones and principal risk factors, including the contamination of surface and groundwater, emissions of greenhouse gases, degradation of ecosystems, and social disturbances. In response to these findings, targeted mitigation and compensation measures were devised to support optimal site selection and reduce potential adverse impacts.

The outcomes of this research provide policymakers with a robust scientific foundation for territorial planning, the enhancement of solid waste management practices, and the prevention of conflicts over land use and social unrest. The incorporation of these recommendations into local policies would contribute to advancing a more sustainable approach to waste management throughout the province.

Furthermore, complementary analyses, such as hydrogeological, hydrochemical, and atmospheric modeling, could enhance the precision of risk assessments, while ongoing environmental monitoring following installation remains indispensable to appraise the efficacy of implemented measures and to adapt management strategies over time.

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