Analytic hierarchy process geographic information system based model for sustainable construction and demolition waste landfill site selection

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ABSTRACT

Properly managing waste generated by buildings and public works is a significant challenge in Tunisia, particularly in the city of Bizerte. The inadequate disposal of such waste can cause substantial harm to human life, property, and the environment. This paper proposes an multi-criteria decision making (MCDM) that utilizes the analytic hierarchy process (AHP) decision support tool to identify suitable landfill sites for construction and demolition waste (CDW) in Bizerte. The AHP method is widely used in MCDM applications. The approach involves classifying different scenarios based on various exclusion and appreciation criteria to determine the optimal locations for future landfills. Furthermore, the paper develops a conceptual approach for identifying better sites for the disposal of CDW, resulting in a comprehensive database capable of storing, accessing, and extracting information at both conceptual and operational levels. The proposed model considers spatial, technical, and environmental criteria in the selection of a suitable landfill site. The proposed methodology offers an effective and practical solution for properly managing CDW waste in Bizerte, Tunisia, and can be applied to other regions facing similar challenges.

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1. INTRODUCTION

The interest in environmental preservation has witnessed a significant surge, leading governments and industries to incorporate environmental protection as an integral part of their ongoing initiatives [1]. This heightened awareness stems from the realization of the profound impact that construction and public works waste have on the environment, particularly water resources [2]. Industrial growth, increased production, and urban population density have significantly increased solid waste volume, resulting in the uncontrolled flooding of public landfills [3]. These constitute a real and permanent threat to the quality of life. Tunisia has seen growth in the past few decades which has led to more urban development putting more strain on nature and causing the excessive use of natural resources. To address this Tunisia has been gradually putting in place environmental protection measures that have now become a foundation, for promoting growth. Managing waste properly is a part of sustainable development as it helps protect the environment and public health. Zhang *et al.* [4] looked into how construction and demolition waste management aligns with sustainable development goals (SDGs) focusing on (clean water and sanitation), pesponsible consumption and production (SDG12), and sustainable cities and communities (SDG11). In Tunisia, solid waste management follows framework law no. 96 41 from 1996. This law categorizes waste based on their characteristics. Sets rules for collecting, transporting, treating and disposing of waste. This study specifically looks at construction and demolition waste (CDW) which falls into three categories; waste, non hazardous waste and hazardous waste. Inert waste makes up the majority (90%) of CDW. Remains chemically stable over time without changes in its properties. This makes it generally safe, for the environment as it does not pose threats. In contrast dangerous waste includes metals, valuable or uncommon metals, (like platinum and palladium) and semi valuable metals (such, as titanium, cobalt, molybdenum and vanadium). Unlike dangerous waste hazardous waste shows harmful characteristics that can negatively impact both human health and the environment. The effective management of CDW plays a pivotal role in Tunisia's development strategy, with an increasing recognition of the necessity for enhanced CDW management practices. In any case, for these initiatives to work and for goals to be met, carefully thought-out alternatives must be considered in the context of Tunisia as a whole and individually for each province in the country. In this context, the objective of this study is to identify an appropriate solution for establishing construction waste landfill sites in the Bizerte region of Tunisia. The study proposes a multicriteria analysis based on the analytic hierarchy process (AHP) to identify sites that meet the criteria for CDW disposal. AHP is a particular paradigm that has been widely used in MCDM [5].

The remainder of the article is organized as follows: section 2 provides an overview of the current state of the art. Section 3 begins by examining the study area, covering its geographical, geological, and hydrological aspects. This section also outlines the methodology employed for landfill site selection, utilizing AHP and geographic information system (GIS) tools. In section 4, the results are presented and discussed. The article concludes in section 5 by summarizing the findings and offering future perspectives.

2. LITERATURE REVIEW

CDW pertains to the solid waste generated from activities within the building and construction sectors. The generation of this waste stream is a direct consequence of various construction-related activities, such as construction, renovation, and demolition operations. These activities encompass a wide range of tasks, including civil works, site clearance, road construction, land excavation, grading, and demolition activities. Environmental disasters such as floods, earthquakes, and hurricanes also produce significant CDW [6]. Typical materials utilized in DW encompass a range of substances such as rock, masonry, asphalt, metals, sand, plastics, asbestos, plasterboard, and cardboard. CDW accounts for over 30% of global solid waste generation [7]. Effective CDW management minimizes its impact on ecosystems, human health, and natural resources [8]. Sustainable practices and innovation in waste reduction, recycling, and disposal are needed. Proper CDW management is an interdisciplinary topic encompassing engineering, management, technology, and policy perspectives, contributing to the circular economy. Massive quantities of CDW are generated worldwide. For instance, China produced approximately 2,300 million tons in 2019, making it the largest CDW producer globally. According to the global waste management outlook report in 2015 [9] about 85% of global solid waste is disposed of in landfills, with low reuse and recycling rates. In Beijing, China, 70-80% is dumped in landfills [10]. The AHP is a decision-making methodology introduced by Saaty in 1977 [11]. It facilitates evaluating and prioritizing alternatives by considering a predefined set of criteria. The provided framework presents a methodical approach to navigating intricate decision-making processes through the examination of the hierarchical structure inherent in the problem at hand. The AHP is a methodology that utilizes pairwise comparisons to ascertain the relative significance of various elements. In the decision-making process, individuals assess the relative significance of various projects or alternatives by engaging in pairwise comparisons and assigning numerical values to encapsulate their judgments. Subsequently, the priority ratios between the alternatives are derived based on the pairwise comparisons.

The AHP has the potential to be effectively combined with a range of other methodologies, including linear programming, quality function deployment, and fuzzy logic. The flexibility inherent in this system enables users to integrate various methodologies and leverage their synergistic effects, thereby enhancing the effectiveness and efficiency of decision-making processes [12]. The AHP has found extensive utilization across diverse domains in practical scenarios. In the field of healthcare research, the AHP has been utilized to assess and prioritize treatment options, evaluate patient needs, and analyze the allocation of resources. The AHP is a valuable tool in the field of project management, as it aids in the selection and prioritization of projects within a portfolio. Transparent and objective criteria guide this process. The application of AHP has also been observed in the evaluation of domain-specific modeling languages to develop intricate intelligent systems. Within the realm of waste management, the AHP can be employed as a means to discern and choose appropriate landfill locations for the management of CDW. The procedure examines multiple factors and criteria, including the proximity to the waste source, environmental consequences, financial implications, and ease of access. The AHP allows decision-makers to methodically assess these factors and make well-informed decisions concerning the selection of landfill sites to implement effective and sustainable practices in the management of CDW. In study [13], the fuzzy analytic hierarchy process (FAHP) approach was used to assess different CDW management alternatives (landfilling, recycling, reusing, and reduction) in Tehran, Iran. The proposed alternatives were investigated concerning different criteria, and divided into four different groups (environmental, social, technical, and economic). The FAHP approach helps in determining the most suitable CDW by providing a comprehensive and systematic way to evaluate different alternatives based on multiple criteria analyses. The study of Ghafourian *et al.* [14] aims to empirically investigate sustainable CDW management in Malaysia. It combines both qualitative and quantitative data to provide an accurate and holistic assessment of waste management practices. López *et al. et al.* [15] integrate AHP, GIS, and remote sensing (RS) to provide a management tool to assist decision-makers in effectively selecting landfill sites while promoting territorial sustainability. It identifies fourteen sub-criteria and categorizes them into physical, environmental, and socioeconomic factors. The results show highly, moderately, marginally, and unsuitable areas for landfill sites. The study by Shah [16] uses AHP and GIS to identify and prioritize suitable landfill sites in India. It aids town planning departments in identifying waste processing and collection centers for cities that highly contribute to solid waste. Grave *et al.* [17] use AHP and sensitivity analysis (SA) to improve classification reliability in Geographical information systems-multicriteria decision analysis (GIS-MCDA). The study helps stakeholders identify the classification scheme that best conveys the coastal zone's differential exposure to hurricanes.

Our study is focused on addressing the challenges of solid waste management in the governorate of Bizerte. It aims to find sustainable solutions for these waste management issues that take into consideration the specific spatial and environmental features of this area. The first step towards achieving this goal is the establishment of landfill sites that comply with the standards set by the Tunisian government. To conduct our analysis, we employ the AHP in combination with GIS. Additionally, we offer the user the opportunity to define the GIS model and spatial constraints using a specific spatiotemporal conceptual model named modeling of application data with spatio-temporal features (MADS) [18], [19]. MADS is considered one of the best geographical spatiotemporal models [20], [21]. It is directly transformed into a relational database management system that easily finds all the features that should be analyzed and assessed for AHP. We provide users with a simple tool to identify their constraints and shield them from the complexities of the information system while dealing with intricate computerized transformations. Our approach enables the making of informed decisions and the efficient management of solid waste in the region.

3. METHOD

This research involved gathering data from multiple fields such as geomorphology, geology, hydrology, and hydrogeology to develop a spatial reference information system for Bizerte using ArcGIS software. A multicriteria evaluation using the AHP was conducted for the waste disposal site selection, involving criteria divided into factors (suitability) and constraints (exclusion). Six constraint layers and five-factor layers were identified, with scenario selection based on varying the weight of certain factors. The methodology, validated by local experts, emphasizes adaptability to each new case study's geographical nuances, suggesting that the generalizable approach requires customization based on specific local conditions [22].

3.1. The study area

The province of Bizerte-Tunisia, located in the extreme northeast of the country, benefits from a privileged location with a wide opening on the Mediterranean Sea: 250 kilometers of coastline as shown in Figure 1. The provinces of Ariana and Manuba border Bizerte to the south, Beja to the west, and the Mediterranean Sea to the north. The area comprises diverse geographical features such as mountainous relief, hills, alluvial plains, gypsum deposits in the Medjerda Valley, Sebkhas, lagoons, and valleys of major rivers.

Alluvial valley soils and colluvium, frequently accompanied by sandy and loamy outcrops, flank gently sloping terrains without significant cliffs, are characteristics of the lands crossed. When the ground is well-drained, the current pedogenesis is brown. But when the ground is confined, it has vertical or hydrodynamic dynamics that are affected by the geochemical context and can sometimes have noticeable saline effects. The land use in the region includes concentrated urbanization along the coast, regions with polycultures, agricultural areas employing plowed systems, and rural agro-pastoral zones. The hydrographic network features streams that flow east-northeast, connecting lakes and marshy areas. The area benefits from a well-developed road network, and it experiences a Mediterranean climate with mild winters, hot summers, and varying rainfall. Hydrogeologically, the region is characterized by phreatic aquifers with different salinity levels as well as deep aquifers that support various uses and provide water to the area. Table 1 represents the characteristics of the Bizerte ‘data we collected and used in this study.

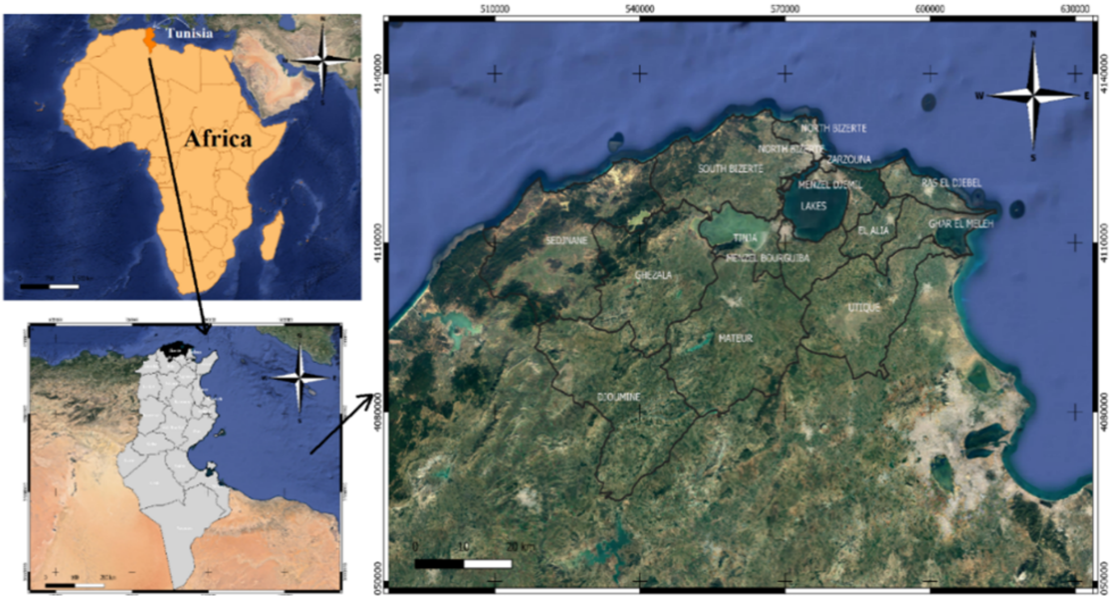

Figure 1. Location of the study area

Table 1. Data used in this study

Data type	Description	Resolution/scale	Source
Digital elevation model (DEM)	ASTER GDEM	30 m	Earth explorer
Slope	Extracted from the DEM	30 m	Earth explorer
Hydraulic Networks	Digital	1/50,0000	Digitization
Pedology	Digital	1/50,0000	Digitization
Road networks	Digital	1/50,0000	Digitization
Groundwater	Digital	1/50,0000	Digitization
Deep groundwater	Digital	1/50,0000	Digitization
Land use	Digital	1/50,0000	Digitization

3.2. The criteria conditioning landfill sites

The prospective search for suitable sites for landfill activity is carried out based on the evaluation of exclusion criteria and appreciation criteria defined in the context of this study. The criteria of exclusion (constraints) aim to limit the search for suitable sites, in domains of an exclusive nature that do not tolerate any competition. The following exclusion constraints have been chosen:

– Watercourse: poorly designed landfills threaten surface water sources. Water pollution can result from CDW containing landfill chemicals and byproducts. Uncontrolled landfill leachate contaminates ecological resources and endangers people who drink and touch this water. At least 300 m is the safety radius for all hydrographic elements [23].

- Groundwater: a hydrogeological study must locate shallow and deep groundwater aquifers to choose a landfill site. This study aims to minimize and predict the impact of CDW on surface water and groundwater, as many factors can pollute groundwater and make it unsuitable for special activities and consumption. A buffer zone of 2 km [24] is required around deep aquifers and 800 m around shallow ones.
- Hill dams and lakes: we marked zonal hydrography (lakes), punctual hydraulic structures (hill dams), and isolated hydraulic structures (hill lakes) on the hydrographic network map for the study area. We set a 300 m safety radius for all hydrographic elements [23].
- Residential areas: the proximity of a landfill site to a residential area gives rise to a range of environmental concerns, including those related to human health, land values, and urban development. It can also lead to various harmful environmental pollution due to odors and noise from landfills. A buffer zone of 1 km around residential areas is required.
- Road networks: road network proximity is a major factor in city distance and main road access. If the landfill site is far from the road, it will increase transportation costs and pollution; if it is close, it will look bad [23]. For this reason, a buffer zone of less than 500 m from roads has been chosen.
- Pedology: how much groundwater recharge can penetrate the soil affects how well pollutants can move vertically through the unsaturated zone. Sandy soils are highly porous and permeable, making them unsuitable for landfills and affecting local water quality. Motlagh and Sayadi [25] suggested that loamy clay is the best soil texture, followed by loamy sand.
- Land occupancy: The land use layers may inform development decisions and regional development guidelines. We chose protected areas, forests, farmlands, and agricultural lands. A buffer zone of 300 meters is permitted around these areas [26].
- Historical and archaeological site: all areas that exhibit cultural aspects (archaeology and natural heritage) must be excluded. A buffer zone of 500 meters has been selected.
- The coastal features: coastal areas are attractive spaces subject to high population pressure. They are diverse territories with very different environments (beaches, cliffs, and dunes) that host multiple uses (commercial, industrial activities, and fishing). Consequently, several strategies have been implemented to protect coastal interests in Tunisia.

The general rule of the appreciation criterion in AHP is to evaluate and compare the relative importance of different criteria concerning a common goal. Table 2 shows the appreciation constraints that have been chosen, and the description of each constraint is listed below:

- Topography: the slope is considered an important criterion for selecting landfill sites. Any increase in slope leads to infiltration of contaminated leachate into adjacent residential areas, especially in areas with high altitudes. In this study, the slope should be between 0 and 10% [27].
- Hydrogeological factors: they include proximity to watercourses. The proximity criterion to watercourses has been standardized by considering the distance values through a monotonic increasing function.
- Social factors: proximity to residential areas reflects the primary social factor in decision-making to select the best sites.
- Economic factors: they include proximity to the road network.
- Environmental factors: the soil has a significant effect on the quantity of groundwater recharge that can penetrate the soil and thus on the ability of pollutants to move vertically in the unsaturated zone.

Tables 2 and 3 provide a concise summary of the decision factors for our analysis, including their respective sub-factors and corresponding criteria and buffer zones.

Table 2. Hierarchical structure for selecting the best landfill site location

Decision factor	Sub factors	Exclusion criteria	Appreciation criteria
Topography	Slope		x
	Watercourse	x	x
Hydrogeology	Groundwater	x	
	Hill dams and lakes	x	
Social	Residential areas	x	x
Economy	Road network	x	x
	Pedology	x	x
Environment	Land occupancy	x	
	Historical and Archaeological sites	x	
	Coastline	x	

Table 3. The data set for the buffer zone analysis

Decision sub factor	Buffer zones
Watercourse	300 m
Groundwater: deep aquifer	2000 m
Groundwater: shallow aquifer	800 m
Hill dams and lakes	300 m
Residential areas	1000 m
Road network	500 m
Pedology	'Clay loam soil' or 'Sandy loam soil'
Land occupancy	300
Historical and Archaeological sites	500
Coastline	250

3.3. The criteria conditioning landfill sites

In decision-making methods such as multicriteria analysis, the user may consider that all criteria do not have the same importance. Thus, most multicriteria methods translate this importance into weights, to make them comparable and to integrate them into the suitability calculation model. The method is based on comparing the different factors, pairwise. Starting from the construction of a square matrix, as shown in Table 4, the relative importance of one factor to another is evaluated using an adequate scale proposed by Saaty [28]. Pairwise comparisons of all factors were taken as input data for the matrix. Once the comparison matrix is filled, the eigenvalue of each one and its corresponding eigenvector are calculated. The eigenvector indicates the priority order or weight of the studied factors. This result is important for probability evaluation since it will be used to indicate the relative importance of each factor.

The factors having been standardized, were subsequently weighted by the pairwise comparison method. The pairwise comparison of factors is intended to help the decision-maker, whether public or private, refine his decision-making process by examining the coherence and logic of his preferences. The pairwise comparison generates a matrix from which the relative importance of each factor is deduced. This importance is expressed according to Saaty [28] by weights on a scale of values from 1 to 8 and it is shown in Table 4 as the intensity of importance. These values make it possible to develop matrices of pairwise, reciprocal, and positive comparisons. Using statistical tests, the comparison matrix leads to a weighting matrix. The latter defines priority values called eigenvectors or weighting coefficients, whose sum is equal to 1. For example, in scenario 2, as per Table 5, to estimate the weighting coefficient of the social factor, the procedure requires the calculation of the eigenvector of the pairwise comparison matrix of the criteria according to (1):

$$v_p = \sqrt[n]{\prod a_{ij}} \quad (1)$$

where n is the number of factors and a_{ij} is the value of the element (i) in the ith row and the element (j) in the jth column. The values of these eigenvectors (v_p) are determined by calculating their geometric mean by (2):

$$v_p = \sqrt[5]{\frac{1}{2} \times \frac{1}{2} \times 1 \times 1 \times 1} \approx 0.76 \quad (2)$$

Thus, the weighting coefficient for each factor is derived by standardizing the eigenvector by dividing each eigenvector by its sum.

$$\text{Weighting coefficient} = \frac{v_p}{\sum v_p} \quad (3)$$

For the social criterion listed in Table 5 as one of the decision criteria, the weighting coefficient is:

$$\text{Weighting coefficient} = \frac{0.76}{1.32 + 2.05 + 0.76 + 0.76 + 0.64} \approx 0.14 \quad (4)$$

This calculation was performed for the other factors (topography; hydrogeology; economy; environment).

Table 4. Binary comparison scale [28]

Intensity of importance	Expression of a criterion in relation to another
1	Equal importance
3	Low importance of one over the other
5	Essential importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate

Table 5. Calculation of weighting coefficients for decision factors

Decision criteria	Topography	Hydrogeology	Social	Economic	Environment	Eigenvector	Weighting coefficient
Scenario 1 (same weighting for all factors)							
Topography	1	1	1	1	1	1	0.2
Hydrogeology	1	1	1	1	1	1	0.2
social	1	1	1	1	1	1	0.2
Economic	1	1	1	1	1	1	0.2
Environment	1	1	1	1	1	1	0.2
Scenario 2 (hydrogeology > topography > environment; social; economy)							
Topography	1	1/3	2	2	3	1.32	0.24
Hydrogeology	3	1	2	2	3	2.05	0.37
social	1/2	1/2	1	1	1	0.76	0.14
Economic	1/2	1/2	1	1	1	0.76	0.14
Environment	1/3	1/3	1	1	1	0.64	0.12
Scenario 3 (topography > hydrogeology > environment; social; economic)							
Topography	1	3	2	2	3	2.05	0.37
Hydrogeology	1/3	1.0	2	2	3	1.32	0.24
social	1/2	1/2	1	1	1	0.76	0.14
Economic	1/2	1/2	1	1	1	0.76	0.14
Environment	1/3	1/3	1	1	1	0.64	0.12
Scenario 4 (social > topography > environment; economic > hydrogeology)							
Topography	1	3	1/3	2	2	1.32	0.24
Hydrogeology	1/3	1	1/3	1	1	0.64	0.12
social	3	3	1	2	2	2.05	0.37
Economic	1/2	1	1/2	1	1	0.76	0.14
Environment	1/2	1	1/2	1	1	0.76	0.14
Scenario 5 (economy > topography > environment; social > hydrogeology)							
Topography	1	3	2	1/3	2	1.32	0.24
Hydrogeology	1/3	1	1	1/3	1	0.64	0.12
social	1/2	1	1	1/2	1	0.76	0.14
Economic	3	3	2	1	2	2.05	0.37
Environment	1/2	1	1	1/2	1	0.76	0.14

The verification of Saaty's pairwise comparison matrix [11] relies on two metrics: the consistency index (CI) and the consistency ratio (CR). CI is founded upon the principle of judgment transitivity. For instance, if the preference is given to A over B and to B over C, transitivity dictates that A should be preferred to C. Hence, CI gauges the reliability of comparisons made through consistent judgments. A higher CI indicates greater consistency in the expressed judgments within the comparison matrix, and conversely. The formula for CI is described as (5):

$$CI = \frac{\lambda_{\max} - k}{k - 1} \tag{5}$$

where:
- k, being the number of compared factors.
- λ_{max}, a value calculated based on Saaty's matrix [28], eigenvectors, and k.

The CR is defined by Saaty in 1980 [28] as the ratio of the CI calculated from the matrix corresponding to the judgments of the actors (matrix resulting from pairwise comparison) and the random index (RI) of a matrix of the same dimension. The RI shown in Table 6 is derived from a sample of 500 randomly generated positive reciprocal matrices of size 11 by 11. This method ensures a robust and consistent assessment of the judgments made by the actors involved in the decision-making process. Table 7 shows the calculated consistency ratio (CR). The following formula gives the equation of CR:

$$CR = \frac{CI}{RI} \tag{6}$$

The research, citing [28], highlights that a CR above 10% indicates incoherence in comparisons. To ensure the coherence of pairwise comparisons at the matrix level, CR was calculated and found to be well below 0.1, confirming consistency. The study used a mathematical approach to determine the best scenario for landfill site selection from five options by calculating the average of the weighting coefficients for each criterion. This method, flexible to changes or additions in criteria, is detailed alongside results in Table 8. The prioritization emphasizes locating the landfill on low-slope terrain with specific soil textures. For multicriteria evaluation, three aggregation methods were explored: complete aggregation, which eliminates incomparability; partial aggregation, which accepts it; and local aggregation, an iterative approach seeking optimal solutions. The study employed a complete aggregation method, reducing multiple criteria to a single one for decision-making, and utilized ArcGIS's weighted sum functionality with the weighted linear combination (WLC) algorithm for factor aggregation. This produced a suitability map for burying CDW in Bizerte, presented in the research, to identify optimal landfill sites.

Table 6. Value of RI [28]

Number of criteria (n)	2	3	4	5	6	7	8	9	10	11
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 7. Calculation of the CR

λ_{max}	CI	CR
5.23	0.06	0.05

Table 8. Calculation of weighting coefficients for decision factors in the average scenario

Average scenario	Weighting coefficient
Topography	0.26
Hydrogeology	0.21
Social	0.20
Economic	0.20
Environment	0.14

3.4. Conceptual approach

To enhance the clarity, extensibility, and reusability of our work, we based our approach on the MADS framework, a conceptual model specifically designed for modeling spatiotemporal data [18]. According to the state of the art, MADS is one of the best models in this category [20], [29], [30]. We have elaborated on using the MADS model to develop a conceptual framework that accurately represents the entities and topological relationships involved in the site selection process for construction and demolition waste. These relationships are clearly and effectively depicted in the MADS conceptual model. Furthermore, we have implemented these relationships generically in PL/Python and PL/Pgsql, presenting a model that can be easily extended and reused for any geographic AHP study. The MADS model simplifies the conception of the spatiotemporal case study, ensuring clarity and comprehensibility. Additionally, the development of new generic functions facilitates the integration of any conceptual model reflecting a geographic AHP study into PostgreSQL/PostGIS [29], [30]. This enhancement increases the flexibility and applicability of our approach, making it a valuable tool for geographic AHP case studies.

3.4.1. Choice of design methodology

Beyond the various models for conceptual spatiotemporal data modeling, we note that the MADS model, which has been highly regarded in numerous studies, also proves to be more advantageous than other models in meeting our requirements. In terms of clarity, MADS stands out as the best option compared to other models. It supports orthogonality between different concepts of the model, allowing spatial, temporal, and spatiotemporal dimensions to be freely assigned to different classes and associations. Furthermore, MADS facilitates the graphical attribution of spatial and temporal constraints on associations within the model. Based on our requirements, we are confident that the MADS model fully meets our needs [20], [29], [30].

3.4.2. Conceptual data model

In this section, we present the various entities, attributes, and methods of our conceptual schema created using the MADS formalism. As depicted in Figure 2, our model comprises a primary entity named StudyAreaAHP, along with six additional entities: pedology, slope, urban areas, groundwater table, road, and hydraulic network. These entities are designed to align with the constraints of our case study, emphasizing the necessity to analyze their characteristics to select the optimal location for public building demolition waste. The entities are described as follows:

- Pedology: provides detailed information on the organization and description of different soil types encountered in the area.
- Slope: contains all the values of the topographic slope within the Bizerte area.
- Groundwater table: includes data on both shallow and deep groundwater tables.
- Road: represents the various road segments in the road database.
- Hydraulic network: depicts the different watercourses present in the Bizerte area.
- Urban area: describes the characteristics of the closest urban area relative to the StudyAreaAHP.

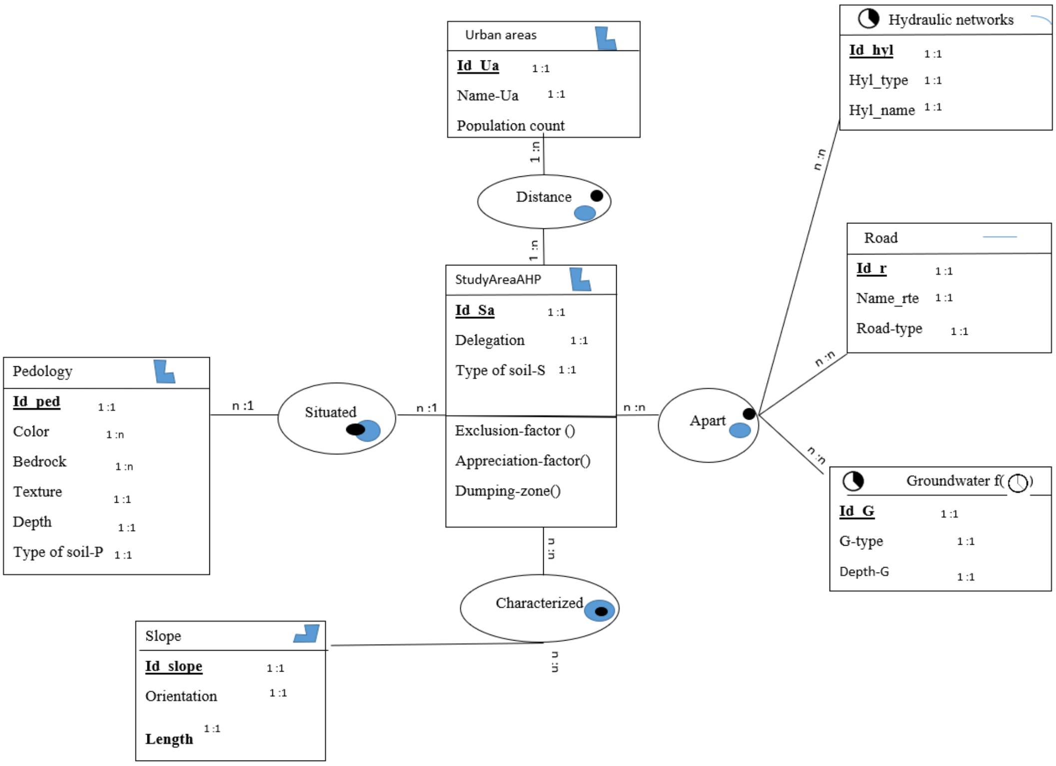

Figure 2. Conceptual schema of the landfill site database

Each of these six entities is connected to the StudyAreaAHP through topological relationships, which are graphically represented using MADS. The characteristics of these topological relationships are visually depicted, allowing for an intuitive understanding of their interactions. Furthermore, each pictogram used to characterize the topological relations is automatically transformed and utilized in the physical model, facilitating the AHP analysis. For instance, the topological relationship “distance” between the entities urban area and StudyAreaAHP automatically calculates the distances between all semantically possible instances of urban areas and the corresponding instances of StudyAreaAHP.

4. RESULTS AND DISCUSSION

The results of this study focus on two key aspects critical to effective landfill site selection. First, a suitability map was developed to represent average environmental, social, and economic conditions, providing a balanced view of potential areas. Second, specific areas were identified as highly suitable for landfill location, based on aggregated factors such as land use compatibility, accessibility, and minimal impact on densely populated or ecologically sensitive zones.

4.1. Development of the suitability map for the average scenario

The map presented in Figure 3 is based on the analysis of two types of criteria, exclusion and appreciation. As shown in Figure 4 once the appreciation factors were established and weighted, they were aggregated using the WLC algorithm in ArcGIS. The dark green areas in Figure 5 represent the most suitable locations for the placement of landfill sites, whereas the least suitable locations are depicted in shades of red.

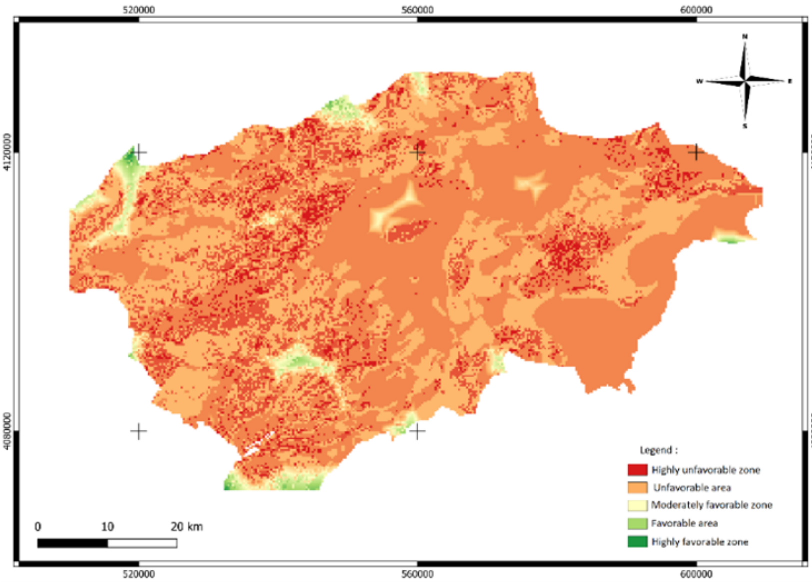

Figure 3. Output suitability map of landfill sites

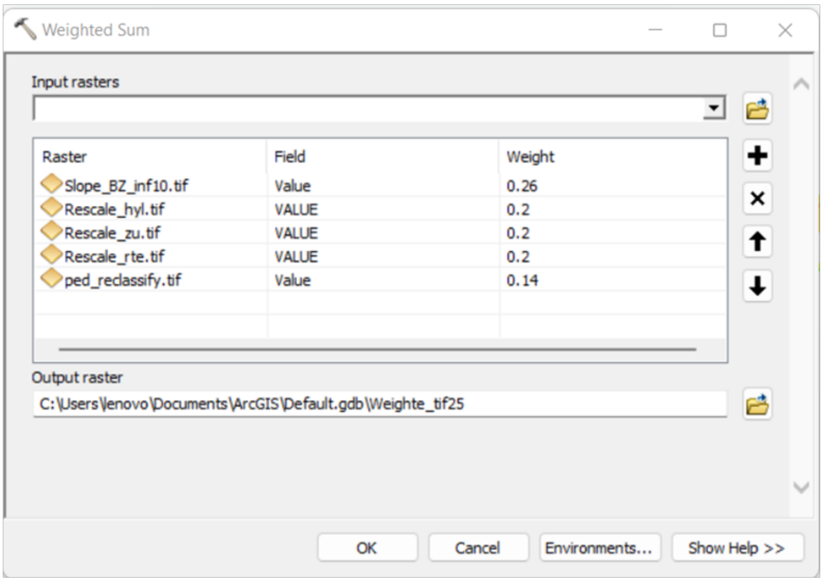

Figure 4. The graphical interface of the “weighted sum” tool on ArcGIS

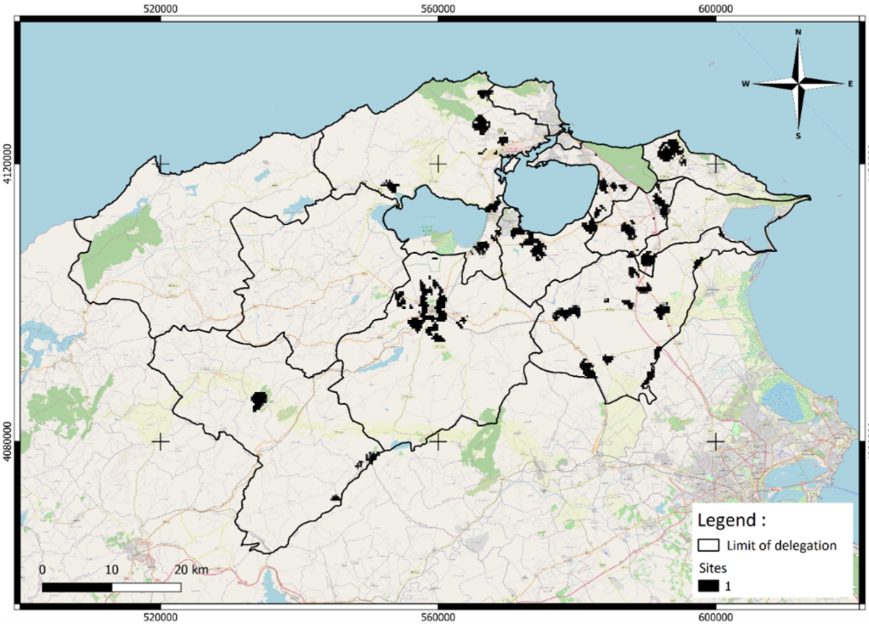

Figure 5. Location of suitable sites for the establishment of a landfill site for CDW

4.2. Elaboration of the final map

The final step of our approach is to combine the transformed outputs (the suitability maps of the average scenario) of land use types, slope, distance to leisure facilities, roads, and distance to urban areas. Figure 5 illustrates the most favorable sites for the installation of CDW landfill sites are in the western part of the Bizerte governorate, especially in the delegations of Joumine, Ghezela, Mateur, and the western part of the delegation of Bizerte Sud. The concentration of landfill sites in these delegations can be explained by the low density of land use and the low rural population. This distribution can also be explained by a combination of constraints concentrated in the delegations of the eastern part of the Bizerte governorate, such as Bizerte Nord, Zarzouna, Menzel Jemil, Ras Jebel, El Alia, Menzel Bourguiba, Utiques, and Tinja, especially the clear effect of land use, the concentration of urban areas, the great diversity of agricultural operations, forest areas (such as Rimel forest), the existence of a highway with its safety radius, and the existence of the majority of water resources in these regions.

Regarding the implementation of our approach, a significant advantage lies in the utilization of the MADS conceptual model. This model provides a simple and clear tool for creating a conceptual schema that illustrates all the relations we need to consider in our AHP analysis. The topological connections between the main entities representing the cadaster subject of the study and other spatial objects, such as urban zones and road maps, are established. Additionally, the buffer's value is incorporated as a feature in the topological relation. Once the conceptual schema is completed, we proceed with its comprehensive implementation into a database using a relational database management server. To ensure efficient functionality, we developed the $factor\_exclusion()$, $appreciation\_factor()$, and $landfill\_zone()$ methods in PL/Pgsql, while the $landfill_zone()$ method was specifically developed in PL/Python. The following methods enriched this model: i) $factor\_exclusion()$ method: involves extracting buffer zones and multiplying them together; ii) $appreciation_factor()$ method: involves applying the weighting formula (7); iii) $landfill\_zone()$ method: this is a general method for detecting optimized areas for the deposition of waste from buildings and public works. This function calls upon both $factor\_exclusion()$ and $appreciation\_factor()$ method.

$$\begin{aligned}&(Topography \times 0.26) + (Hydrogeology \times 0.21) + (Social \times 0.2)\\&+(Economic \times 0.2) + (Environment \times 0.14)\end{aligned} \tag{7}$$

To visualize and analyze the results effectively, we employed ArcGIS, which enabled us to display the outcomes and generate the necessary result maps. This integrated implementation ensures a streamlined and reliable analysis of our approach, facilitating informed decision-making in solid waste management. The study assessed disposal options, for construction waste materials without showing bias towards any specific option. Of favoring one scenario the results from each scenario were averaged to determine the suitable locations. This method was chosen to minimize biases and assess each site considering factors like accessibility, capacity, costs, environmental and social impacts and geological conditions. By using AHP method and other analytical tools each site was evaluated systematically. The results were combined to create an overall assessment. This approach ensures that decisions are made objectively while taking into account benefits and minimizing community impacts. However, this initial evaluation is the beginning; further discussions with stakeholders and a detailed analysis of each sites impacts are necessary to refine the recommendation. In conclusion, this method offers a rounded evaluation of waste disposal sites that lays a strong groundwork for sustainable waste management decisions, in the area under study.

5. CONCLUSION

The study focused on identifying suitable areas for solid waste landfill sites while considering constraints using a multicriteria analysis approach, specifically the AHP. It distinguished between exclusion and appreciation criteria to map favorable landfill locations, creating five scenarios by varying factor weights and determining the optimal scenario through an average weighting equation. The research introduced a general conceptual model, MADS, implemented in a PostgreSQL database for enhanced design and application clarity. In landfill site selection, the application of AHP has been extensively discussed in literature. However, existing methodologies tend to be tailored to areas or a limited number of criteria. What sets our research apart is developing a generic model that combines AHP with the specific spatiotemporal conceptual model MADS offering enhanced flexibility and adaptability, across diverse applications. Our approach is the first to propose a complete end-to-end solution that includes conceptual modeling, data integration, and visualization through GIS. Furthermore, our model pinpoints landfill locations in Bizerte and establishes a methodological framework that can be extrapolated to address similar challenges in other regions. By incorporating environmental factors into the evaluation process we ensure that chosen sites are aligned with sustainability objectives. By furnishing decision makers with a tool that considers both exclusion and appreciation criteria comprehensively our model proves advantageous, for urban planners seeking to implement sustainable waste management strategies or any similar application leveraging GIS and AHP methodologies effectively. The plans consider adding factors and using real-time data analysis and artificial intelligence (AI) to predict the best landfill sites, with precision improving decision-making for eco-friendly waste management. Depending on AI and GIS AI could also make use of past data records and, on-site assessments to provide additional perspectives to the suggested method. These improvements might enhance the precision of selecting landfill sites. Contribute to creating more effective waste management systems worldwide.

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