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GIS and remote sensing coupled with analytical hierarchy process (AHP) for the selection of appropriate sites for landfills: a case study in the province of Ouarzazate, Morocco

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Abstract

The province of Ouarzazate has a population of 10,744 and is divided into 17 communes (15 rural communes and 2 urban communes), the majority of which have a population of less than 2000 people. Currently, more than 42% of the total population does not have access to a controlled landfill that meets all the socio-environmental criteria defined by Law 28-00 and its implementing regulations. The most typical landfills are located in small villages that resemble illegal dumps or dark areas close to the inhabitants. Moreover, in 2009, a controlled landfill was established near the city of Ouarzazate. Over time, urban extensions tend to move towards the site of the landfill following the development plans of the city, which influences the environmental life and health of the new population. Indeed, this landfill is considered to be located in the wrong place according to the results of our study; it does not meet all the main socio-environmental criteria. For these reasons, this study was conducted to identify appropriate landfill sites and waste transfer centers using geographic information systems (GIS) and remote sensing coupled with multi-criteria evaluation techniques such as AHP. Eleven criteria were selected, including distance to protected areas, wind direction, subsurface geology, lineament density, distance to surface water (river systems and dams), soil quality, distance to roads, elevation, and slope. The rasters of all the criteria were prepared, processed, and overlaid in the GIS environment by assigning each parameter its weight according to its importance. In the field, five sites have been provisionally selected, but only sites D and B have been given higher priority because of their geographical location, large surface area, geological imperviousness, zero risks, better soil quality, distance from any protection zone, any water point or hydrographic network, and their accessibility by provincial roads. These sites are located very close to the province's waste hubs, which helps reduce the cost of transporting waste to the new landfill.

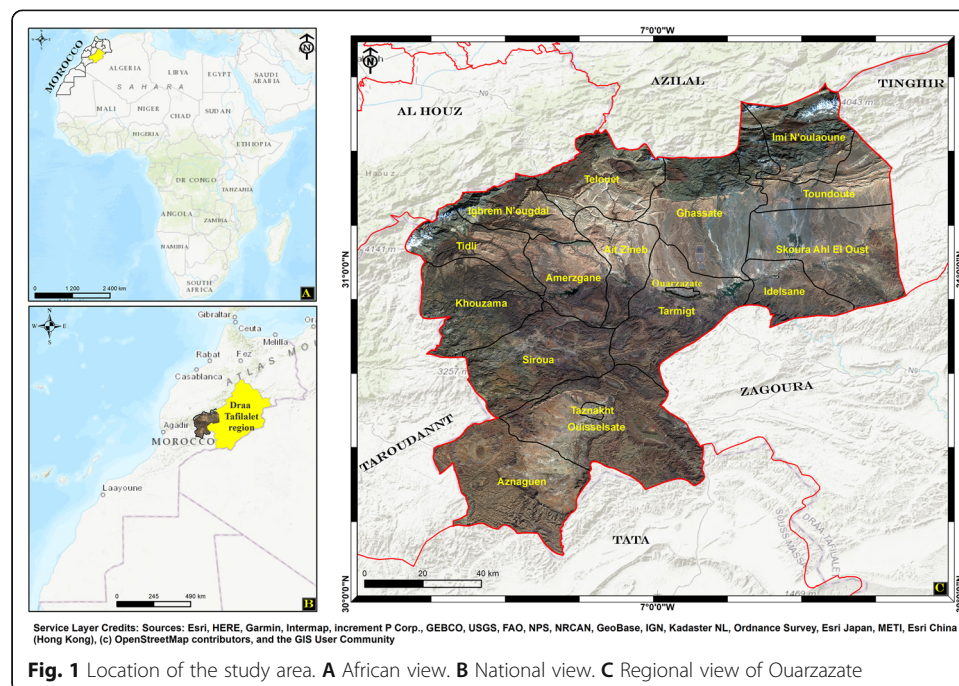
Keywords: GIS, Remote sensing, AHP, Landfill selection, Waste transfer center, Ouarzazate province, Morocco



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Introduction

Solid waste management is a matter of great international concern from an environmental, morphological, and socio-economic viewpoint [18, 23, 56]. Effective management of municipal solid waste (MSW) is a major challenge for local authorities and planners due to the rapid industrialization, population increase and land scarcity [42]. This expansion of urban growth endangers sustainable urbanization and has resulted in many challenges. Efficient waste management systems that can provide reliable services are needed to confront the increasing amounts of solid waste, as many current systems fail to satisfy the needs [70]. Waste management in the study area is performed in a very crude and conventional form, except in the city of Ouarzazate, and does not take into account the improvement of the standard of living and work of the workers and rag pickers and does not take into consideration the approach to environmental protection in which Morocco has been engaged. The urban population lives essentially in the areas of the cities and urban centers of Tarmigte, Amerzgane, Kourkoda, Tachakouchte, Timjijte, Anzal, Tabourahte, Ait Ben Haddou, Timdline, Telouet, Ighrem Nougdal, Agouim, Tidili, Skoura, Toundoute, Iminoulaoune, and Ghessate et Idelsane. This population currently totals 309,000 inhabitants and will reach 393,000 by 2032 whether the region's socio-economic development projects are implemented. The amount of waste produced by this urban population and to be landfilled is estimated at 20,600 T/year in 2014, which justifies implementing of a new controlled landfill in the study area, respecting all socio-environmental standards. The study area (Fig. 1) belongs to the province of Ouarzazate, which is bordered to the north by the province of El Haouz, to the east by the province of Azilal, to the south by the province of Tinghir, to the south-west by the province of Zagora and to the west



by the province of Tata Taroudant. Administratively, the province of Ouarzazate is currently composed of 2 circles (Ouarzazate and Amerzgane), two urban communes (Ouarzazate Taznakhte) and 15 rural communes (Tarmigte, Tarmigte, Idel-sane, Toundoute, Ghessate, Iminoulaouene, Iznaguen, Khouzama, Siroua, Ouisselssat, and Telouet). The surface area of the province of Ouarzazate increased after 11 June 2009 (date of creation of the province of Tinghir) to reach 12,169 km², i.e., 1.7% of the total area of Morocco.

The present study consists in a critical analysis of the current situation concerning waste management on different aspects, and in proposing solutions and recommendations for the improvement of the situation in the province of Ouarzazate, among them the selection of a landfill site based on the Geographic Information System (GIS) and the multi-criteria evaluation technique. Site selection using GIS can be an effective technique, considering all restrictions at once [14]. The parameters for selecting a landfill site include environmental, economic, and social criteria, some of which may conflict, making landfill selection a complex and challenging process [21]. In recent years, a variety of multi-criteria decision analysis (MCDA) methods have been employed for the landfill site selection, (LSS) research [22], encompassing the analytic hierarchy process (AHP) [9, 71], preference ranking organization method (PROMETHEE) [34], Fuzzy TOPSIS [17], fuzzy analytic hierarchy process (FAHP) [35], analysis network process (ANP) [11], and technique for order preference by similarity to ideal solution (TOPSIS) [9].

In this work, we rely on the best known multi-criteria analysis method AHP coupled with GIS, although the MCDA method integrated with GIS is the most commonly used model for LSS [22]. However, the AHP uses materiality to compare qualitative and quantitative criteria, which can minimize inconsistency of judgment [9, 71]. This approach has also been favored by various researchers for landfill selection, namely [23] who assessed the suitability of potential municipal solid waste landfill sites in northeastern Greece by applying GIS combined with AHP and trade-off programming methods. Furthermore, [72] determined the location of a solid waste disposal site for Konya, Turkey, while [14] assessed landfill sites in Morocco using GIS-based Boolean and AHP models. The GIS/AHP has therefore proved to be a powerful tool for assessing potential landfill sites. Similarly, [43] studied the location of a municipal solid waste landfill in Qom, Iran, using both GIS and AHP. (A. J [20].) selected a landfill site for Babylon, Iraq, using GIS and AHP, and [69] used an AHP approach in a GIS environment for the selection of a sanitary landfill site and the optimization of its use in São Paulo, Brazil [50]. also applied GIS-based multi-criteria evaluation technique for landfill site selection in Srinagar city, India [13]. also applied three methods Fuzzy Logic and AHP and WLC coupled with GIS for Landfill Site Selection in Razan City, Iran.

Data and methodology

Data

In this study, 11 input map layers, including topography (elevation and slope), human settlements (urban centers and villages), roads (main roads and village roads), sensitive

ecosystems, soil quality, land cover, surface water, lineaments density, geology, and demography were collected and prepared in a GIS environment. All layers have been converted into individual matrix maps of the same unit [65]. In this study, we rely on data such as data from the administrative division of the province of Ouarzazate was downloaded from (<https://www.diva-gis.org/gdata>), also socio-economic data such as land use data, bare land, buildings, forests was downloaded from OpenStreetMap. Other geospatial data are used of hydrological type received from the agency of hydraulic basin of Ouarzazate containing the qualitative results of groundwater withdrawals with coordinates. However, concerning the geological data were downloaded from NAZA website (<https://certmapper.cr.usgs.gov/data/apps/world-maps/>). Topographic data used as the DEM SRTM of 30 m resolution were downloaded from the NASA site (<https://earthexplorer.usgs.gov/>). Finally, satellite data namely Sentinel 2A images were downloaded from the NASA site (<https://earthexplorer.usgs.gov/>), helped us to extract the lineaments automatically and to map the soil degradation in the province. Other calibrated climate data (wind direction and annual precipitation) were downloaded from the websites (<https://www.ncdc.noaa.gov/cdo-web/datatools> and <https://globalwindatlas.info/>).

Methodology

Figure 2 presents schematically the methodology followed in this work, and the details of which will be presented later step by step.

Before selecting the most important criteria and subcriteria for site choice, a preliminary study was carried out on the search for the best factors controlling landfill sites. Various authors have already worked on the selection of landfill sites by integrating different criteria and (Table 1) presents them in detail and with references.

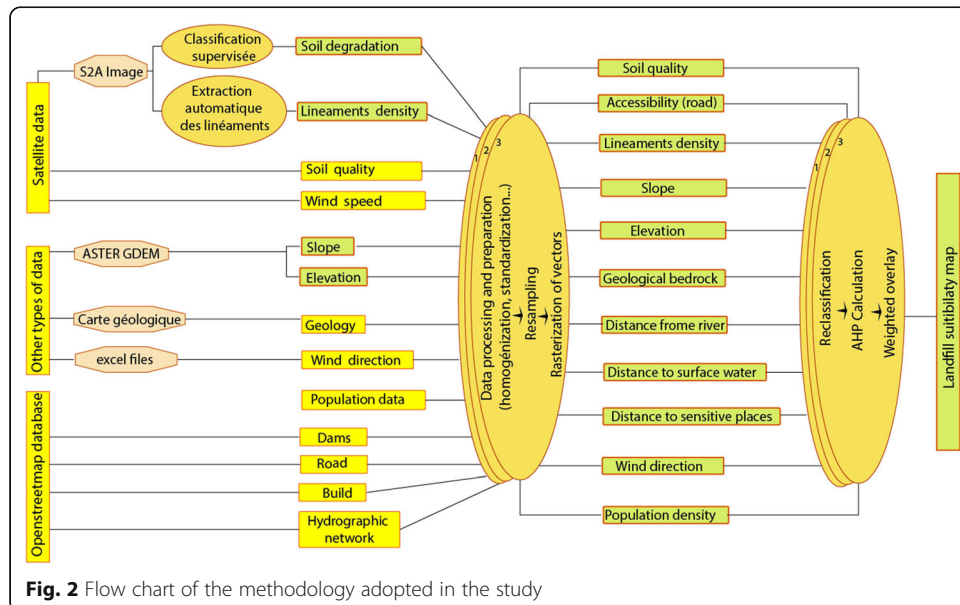


Fig. 2 Flow chart of the methodology adopted in the study

Table 1 Subcriteria selected according to standard site selection methods

Subcriteria selected	References
Land-use and land-cover types, groundwater depth, lineament, soil permeability, river, water pipe-lines, slope, main and secondary roads, and constraints thematic maps of boreholes, built-up areas, and green area.	[12]
Distance to groundwater, distance to surface water, sensitive ecosystems, land cover, distance to urban and rural areas, land uses, distance to roads, slope, soil type, and distance to waste generation places	[58]
Flora and fauna, air quality, land use, waste disposal, effects of odors, employment health, public awareness, road traffic, investment cost, cost of operating the landfill waste, transport cost, cost of landfill rehabilitation	[26]
Land elevation, slope, soil, geology, land use land cover, distance to surface water, distance to tube wells, distance to roads, distance to industrial belts, distance to sensitive places, and land cost	[68]
Depth of groundwater, distance from surface- and groundwater, access routes, residential areas, industries, power transmission lines, flood-proneness, faults, slope, and distance from gardens and agricultural lands were taken into account	[74]
Aquifer type, groundwater depth, distance from surface waters, land use, aspect, distance from protected areas, curvature, slope, elevation, transport network, and waste production area	(E [64].)
Elevation, bedrock, soil, land use, distance from residential areas, distance from airport, distance from protected area, distance from road, distance from fault, distance from spring, distance from well, distance from river, distance from aqueduct, wind direction, slope, and aspect	[63]
Natural park, forest environment, agricultural surface, city, village, sacred area, roads, hydrographic network, sources and wells, lakes, slope, and flaw.	[25]
Distance to residential areas, aspect (wind), geology (lithology), distance to faults, distance to surface water, groundwater table, land use, distance to roads, elevation, and slope are considered in the siting assessment.	[14]
Water body, road, slope, elevation, rail lines, forest, vacant and agricultural lands, soil, geology, and urban areas	[53]
Urban area, rivers, roads, soil types, elevation, wind, slope, and archaeological, historical and religious sites	(L. [41])
Slope, elevation, soil texture, aquifers, groundwater table, surface water, geological fault area, floodplain, road network, waste production, residential areas, historical places, and land use	[39]
Distance from residential area, distance from built-up area, distance from road network, distance from railway line, distance from water bodies, distance from airport, distance from agricultural area, slope, and elevation	[50]

Geospatial data collection

The criteria used in this study were selected considering the literature [10, 11, 17, 67, 71, 73] with some adjustments to the Moroccan context. They were classified into two main groups: (1) the economic group included the criteria of distance to roads, slope, and elevation; (2) the geo-environmental group includes land use, distance to residential areas, geology, water resources, and aspect (wind).

Elevation and slope data The geomorphology of the province of Ouarzazate is very diverse; it presents a mosaic of structures and geomorphological forms. In general, we find at this level structures with flat morphology and massive mountainous structures whose dip is greater than 30%. Among the most recognized structures, the depression of Ouarzazate or Ouarzazate basin structure is located in the central part of the provincial territory of Ouarzazate; the flat tabular characterizes the southern part of the Pre-African furrow, which is a major South-Atlantic accident. The topographic slopes at the

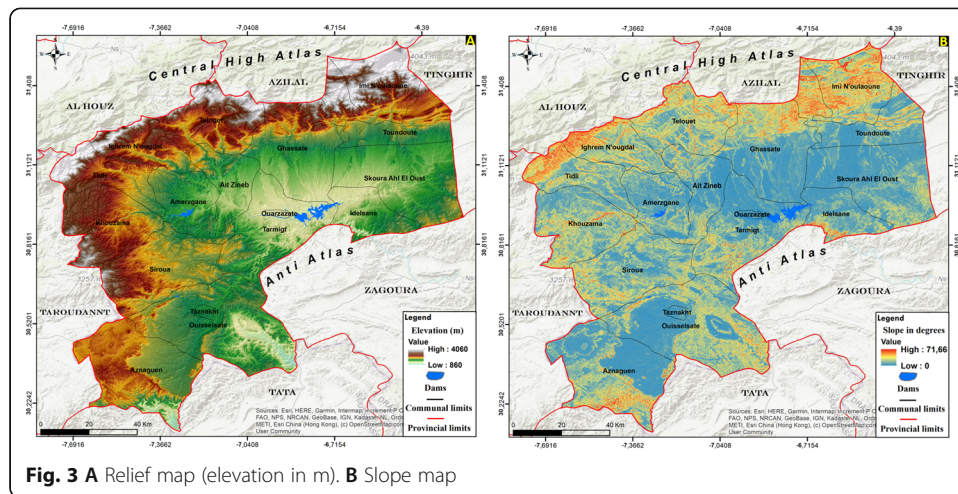


Fig. 3 A Relief map (elevation in m). B Slope map

level of the basin does not exceed 5% (Fig. 3). Eastern Anti-Atlas, a geomorphological structure, occupies the southeast of the province of Ouarzazate, and it is represented by the ancient massif of Saghro. On the northern slopes of this massif, the slopes vary between 5 and 30%, but in the central part of the massif, the slope exceeds 30%. The central Anti-Atlas is delimiting the province of the West and Southwest, and we find in this structure two main morphological substructures and provincial scale, which are the volcanic massif of Siroua, whose highest point is 3304 m.

Geological and lineaments data The foreland-type Ouarzazate Basin is located on the southern border of the Central High Atlas as part of the intracontinental Atlas Basin [51]. The facies that form this basin extend from the Meso-Cenozoic to the Plio-Quaternary series (Fig. 4A). These formations, which fill the basin, are offset in unconformity to the south, on the Paleozoic and Precambrian lands of the Anti-Atlas. The lithostratigraphy of the sedimentary series that form the Ouarzazate Basin shows that they are composed of marine and continental sediments that reflect well-defined

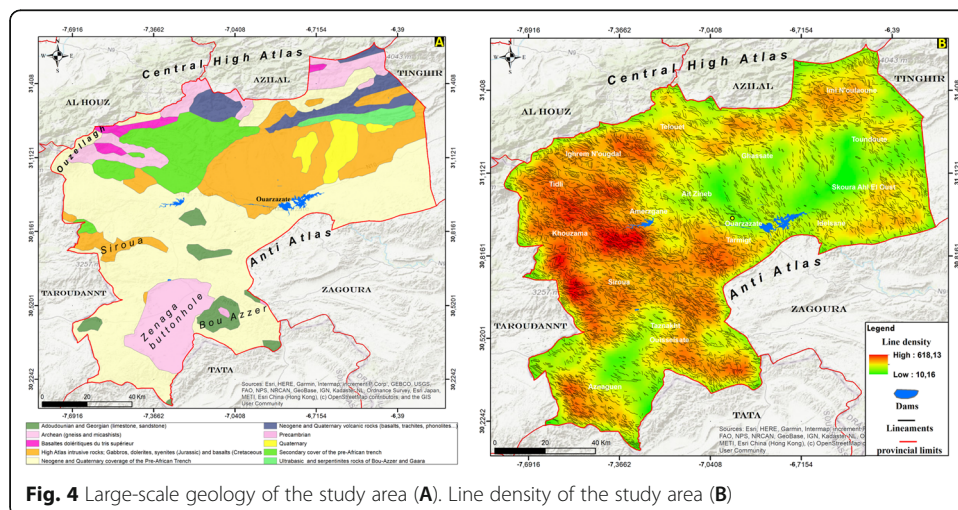


Fig. 4 Large-scale geology of the study area (A). Line density of the study area (B)

paleogeographic and structural domains. The lower part of the series corresponds to basin fill formations developed during the rifting phase [47, 51], while the upper part represents either the upper part represents either the coverage of the Central High Atlas or the filling of the Ouarzazate basin. From a tectonic point of view, the studies show the presence of thrust lines of E–W to ENE–WSW direction, with variable dip and south vergence. They are accompanied by EW to ENE–WSW folds. The folds and thrusts were highlighted by the pioneering work of [30, 37, 59]. The automatic extraction of lineaments was performed by the LINE MODULE algorithm of the PCI Geomatica 2016 software. Various user-defined parameters require automatic lineament extraction [2, 4, 33]. Automatic lineament extraction was applied for the seven stacked bands of the Sentinel 2A image, for each of the four shaded relief images of the DEM image mosaic (N0°, N45°, N90°, and N135°), and on the four images derived from the 7X7 matrix directional filtering of the CP1 neo component. Overlaying the extracted lineaments on ArcGIS-specific high-resolution terrain imagery (Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, AeroGRID, IGN, and the GIS User Community) has been well endorsed in the lineaments extraction validation [2, 28]. The results reveal that the lineaments extracted directly from the Sentinel image very much reflect the reality of the terrain (Fig. 4B).

Soil quality and pedology Generally speaking, the soils are alluvial, not significantly evolved and with an alkaline tendency, moderately to strongly degraded in the Ouarzazate basin [28]. In some places, they have quite high salt contents. In the valleys, pedogenesis is not very active because of the arid climate. The soil types identified in the area can be grouped into 3 main categories: 1—soils with undifferentiated profiles: raw mineral soils (Litho sols rego soils, alluvial-colluvial soils), 2—soils with a poorly differentiated profile: soils that are not very advanced, 3—soils with a differentiated profile: isohumic soils, soils with iron sesquioxides, and browned soils. Soils in the last two categories may be affected by the accumulation of soluble salts. Indeed, the unavailability of soil maps covering the study area, geospatial data of soil quality of 30 m resolution (Fig. 5A) from the algorithms of remote sensing techniques was downloaded from the

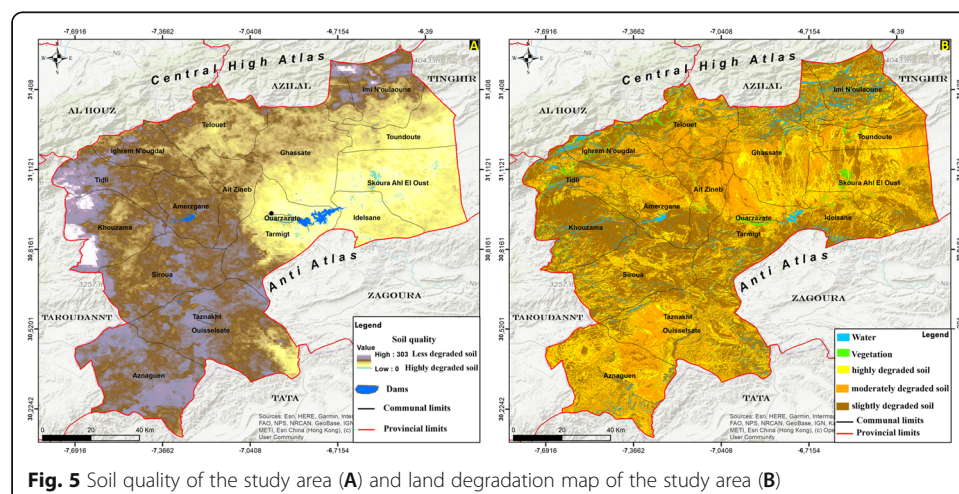
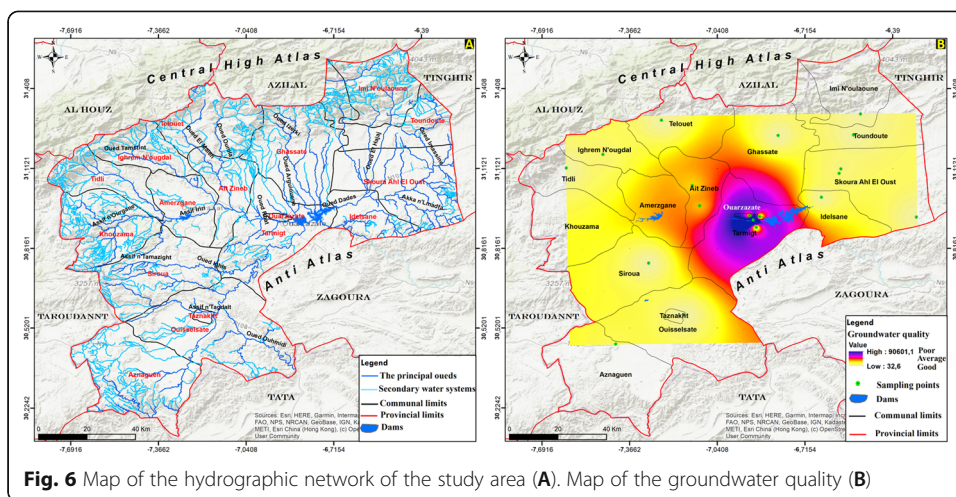


Fig. 5 Soil quality of the study area (A) and land degradation map of the study area (B)



site. Also, a map of the state of soil degradation (Fig. 5B) was made based on processing a satellite image type Sentinel 2A by supervised classification using the SPC plugin of QGIS software. Spectral signatures were chosen based on soil sampling during field missions made in August 2020 and published more recently [28].

Surface water The support land of the future provincial landfill of Ouarzazate is part of the hydraulic unit of the Draa basin, which forms a basin between the High Atlas to the north and the Anti-Atlas to the south. With about 15,170 km², it is one of the most important basins in Morocco. Surface flows (Fig. 6A) from the northern edge of the Anti-Atlas between Jbel Saghro and the Ouarzazate basin are collected by Oued N'Ait Douchchène, essentially an uncontrolled wadi and a tributary of Ouarzazate wadi, which also has tributaries on the left bank from the High Atlas. The contributions of Oued N'Ait Douchchène would be between 60 and 70. 106 m³/year. In addition, the Oued Dadès collects the inflows of the affluents of the northern flank of the Saghro (1445 m²), i.e. about 20 to 25,106 m³/year. The upper reaches of the Oued Drâa receive 80 to 95,106 m³/year of runoff from the northern flank of the Anti-Atlas, and much of this runoff is collected at dams built along the Upper Drâa watershed (<http://www.abhsm.ma/>). In the High Atlas, groundwater provides most of the perennial flow of the wadis, which are abundant. These water resources are better regulated in the East (Oued Dadès and Mgoun), where limestone soils dominate in the West (Oued Ouarzazate) where metamorphic and granitic soils are less permeable. Regarding the quality of groundwater, we note that in areas of high population density, the quality of water is very poor, and when away from these urban centers, the quality of water becomes good (Fig. 6B). The water department of Ouarzazate provides groundwater sampling data.

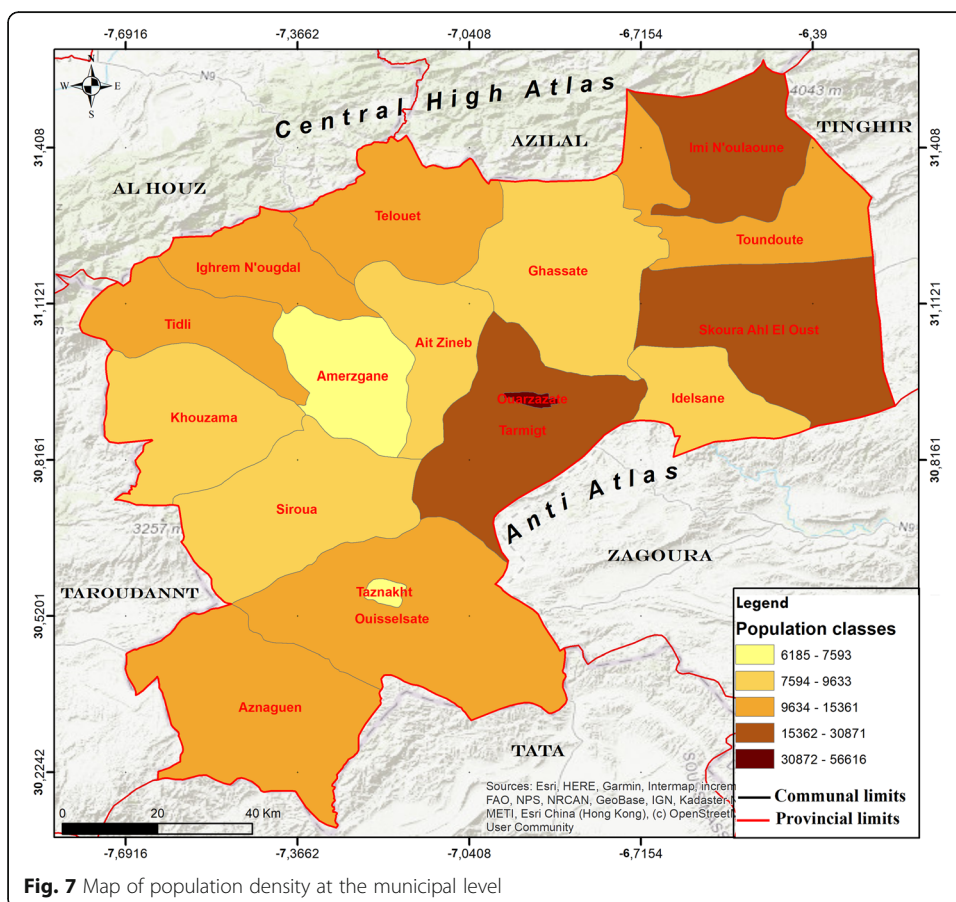
Social and economic framework demographics The following table summarizes the various socio-demographic data of the most waste-producing urban communes in the province of Ouarzazate (Table 2). This population of urban centers is taken into consideration in the proposals of our study. The demographic distributions or population density (last census) of the communes of the province in Ouarzazate are presented in map form (Fig. 7).

Table 2 Quantities of waste generated in the province's urban centers and cities

Municipality	Urban center	2021		2032	
		Population	Wastes (T/AN)	Population	Wastes (T/AN)
Ouarzazate	Ouarzazate	56,616	21,792	98,570	26,565
Taznkhate	Taznkhate	30,872	2381	10,768	2902
Tarmigte	Tarmigte	6185	14,164	70,631	19,035

The barycenters of production of household and similar waste (2012–2027) at the provincial level are concentrated in the municipality of Tarmigte near the city of Ouarzazate because they are the two most productive municipalities in terms of household and similar waste.

Land use, road network, and wind direction The province of Ouarzazate has a network of 1620 km. This network is divided into 27% of national roads, 18% of regional roads, and 55% of provincial roads. Of the 1620 km of the network, 770 km are paved or 46% (Fig. 8A). Concerning the wind, the prevailing winds blow from the west and north-west (Fig. 8B) with moderate speeds of 2 to 4 m/s to very strong in case of disturbances (trade winds) related to the Atlantic Influence. However, the Siroua massif (Tikirt Basin) is a strong barrier to this oceanic influence. The winds circulating at high speeds generally blow from the NNW. The number of days of thunderstorms is 2 days/year on average, with a maximum registered in August (Ouarzazate Station-Period: 2000–2012).



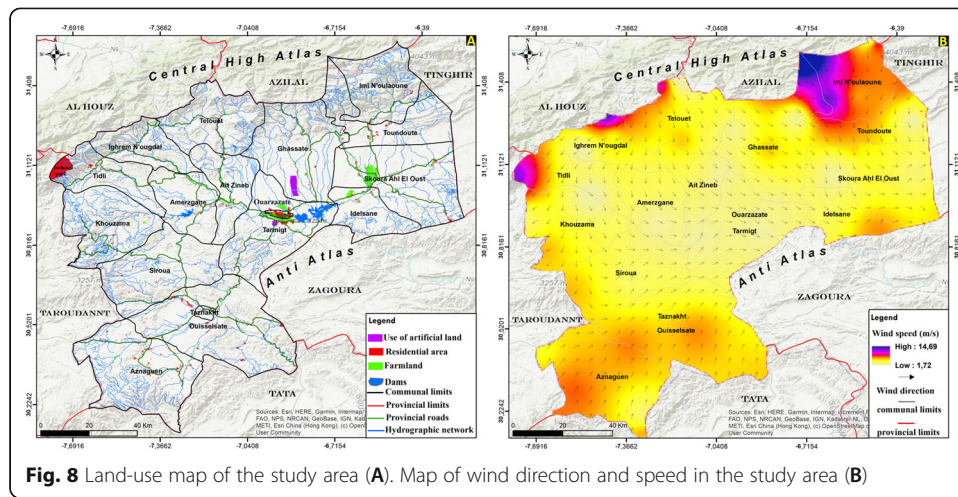


Fig. 8 Land-use map of the study area (A). Map of wind direction and speed in the study area (B)

Standardization

Each criteria map has a measurement range and a scale. The multi-criteria analysis and evaluation must match the measurement scale. The criteria standardization process can be used to match the measurement scales and convert them to comparable units. The analytical hierarchy process method can be used to normalize the data. For example, it organizes all map layer values into classes as desired by the decision maker (Table 3).

Table 3 Suitability scores of the selected criteria

Criteria	Subcriteria	Highly suitable	Moderately suitable	Less suitable	Much less suitable
Socio-economic	Distance from protected area (C1)	> 6000 m	4000–6000 m	2000–4000 m	< 2000 m
	Population density (C2)	15361–56,616	15,361–56,616	6185–15,361	< 6185
	Distance from road (C3)	0–200 m	200–800 m	800–1000 m	> 1000 m
Physiography	Elevation (C4)	0–1600 m	1600–2000 m	2000–2600 m	> 2600 m
	Slope (C5)	0–5%	5–10%	10–20%	> 20%
Geology	Lineaments density (C6)	10–210	220–410	410–480	> 480
	Soil quality (C7)	> 187	187–187	163–187	< 16
	Litology (C8)	Precambrian and Archean formations	Infracabrian and Georgian language training	Acadian, Triassic, Jurassic and Cretaceous formations	Quaternary, continental Miocene and Eocene formations
Surface water	Distance from river (C9)	> 2000 m	1000–2000 m	500–1000 m	< 500 m
	Distance from dams (C10)	> 6000 m	4000–6000 m	2000–4000 m	< 2000 m
Climate	Wind direction (C11)	NE–SW	N–S	NW–SE	W–E

AHP

The analytical hierarchy process method is a multi-criteria analytical approach to decision support. It is fundamentally based on complex calculations using matrix algebra. It was developed by Thomas Saaty in 1970 and allows to decompose a complex problem into a hierarchical system, in which binary combinations are established at each level of the hierarchy [8]. The combination of geographic information systems and analytical hierarchy process is a powerful tool for developing future policies that are relevant to urban growth [5], and greatly facilitates the decision-making process [66], it is one of the most comprehensive systems designed for making multi-criteria decisions, as it offers the ability to develop problems hierarchically [74]. This combination is flexible and powerful for the qualitative and quantitative study of multi-criteria issues [48].

In this study we have developed the decision-making process necessary for using the analytical hierarchy process method, this process is presented in steps, of which beforehand the problem or the purpose of the analysis must be well identified. The steps are as follows [62]: develop the hierarchical structure of the project (Fig. 9); carry out the pairwise (binary) comparisons of criteria with respect to the objective; establish the matrix of comparison judgments; calculate the priority vectors; give the random index value (IA); calculate the average of the priority value (γ_{max}); calculate the coherence index (CI); calculate the coherence ratio (CR); calculate the final aggregation of projects; and express the final decision.

Elaboration of the hierarchical structure of the project This approach consists of carefully expressing the hierarchy structure that will reflect the problem to be solved. This hierarchical structure clarifies the issue and makes it possible to identify the contribution of each element to the final decision. The objective of the problem is located at the highest level of the hierarchy. The criteria and subcriteria, being the elements that influence the objective, are found in the intermediate levels of the hierarchy. The alternatives are the lowest level of the hierarchy. In this study, four hierarchical levels were constructed. Level 0 is the objective, level 1 compares the criteria against the objective, level 2 compares the subcriteria against the criteria, and level 3 compares the

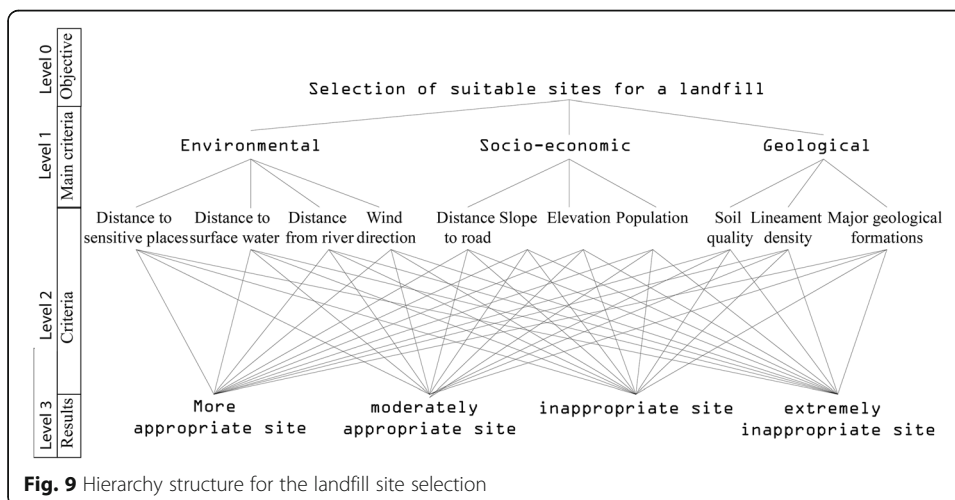


Fig. 9 Hierarchy structure for the landfill site selection

alternatives against the subcriteria. Each analysis aims to target the best criterion and the best alternative in relation to the higher hierarchical level.

Binary comparisons Analytical hierarchy process is used to derive ratio scales from pairwise comparisons. Using a nine-point scale that includes 9, 8, 7..., 1/7, 1/8, 1/9, the comparison was performed, where 9 represents extreme preference, 7 represents very strong preference, 5 represents strong preference, and so on down to 1 which means no preference.

Comparison judgment matrix The criteria comparison table was transformed into a matrix known as the judgment’s matrix in Table 4.

We designate an important value of “a” elements of the evaluation in relation to the comparisons of two criteria C1 and C2; we put the value “a” in the cell “i” column and “j” line of a criterion considered important, and after we have to put the value ratio of “1/a” in the cell considered less important of the comparison.

a = the value which is in the intersection of the cell i column and j line, and noted (aij). C1, C2 to Cn = the criterion of comparison posed in line “i” and column “j” corresponding to the value comparison of evaluation Ci and Cj.

(1) Judgment matrix

$$A = [a_{ij}] = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{pmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{pmatrix} \end{matrix}$$

Table 4 Pairwise comparison matrix for subcriteria

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1.00	1.00	4.00	4.00	2.00	2.00	2.00	0.50	0.50	3.00	5.00
C2	1.00	1.00	4.00	4.00	2.00	2.00	2.00	0.50	0.50	3.00	5.00
C3	0.25	0.25	1.00	1.00	0.33	0.33	0.33	0.20	0.20	0.50	2.00
C4	0.25	0.25	1.00	1.00	0.33	0.33	0.33	0.20	0.20	0.50	2.00
C5	0.50	0.50	3.00	3.00	1.00	1.00	1.00	0.33	0.33	2.00	4.00
C6	0.50	0.50	3.00	3.00	1.00	1.00	1.00	0.33	0.33	2.00	4.00
C7	0.50	0.50	3.00	3.00	1.00	1.00	1.00	0.33	0.33	2.00	4.00
C8	2.00	2.00	5.00	5.00	3.00	3.00	3.00	1.00	1.00	4.00	6.00
C9	2.00	2.00	5.00	5.00	3.00	3.00	3.00	1.00	1.00	4.00	6.00
C10	0.33	0.33	2.00	2.00	0.50	0.50	0.50	0.25	0.25	1.00	3.00
C11	0.20	0.20	0.50	0.50	0.25	0.25	0.25	0.17	0.17	0.33	1.00
Total	8.53	8.53	31.50	31.50	14.42	14.42	14.42	4.82	4.82	22.33	42.00

Number of comparisons = 55, principal eigen value = 11,1996, eigenvector solution: 4 iterations, delta = 3, E-8

after calculating the relative importance of each element of the hierarchy, the determination of the priorities of the elements of each matrix is carried out by solving the eigenvector problem to then calculate of the λ_{max} eigenvalue. We will multiply the matrix A by the elements of priority vector (x) , x is the eigenvalue of priority vector (n) , we calculate the average of the found values. The result is called λ_{max} value.

We pose a_{ij} = the judgment matrix of the value of the element (i) of i th row and the element (j) j th column.

The normalized value a_{ij} is equal to:

(2) Normalized value

$$a_{ij} = \frac{W_i}{W_j} \text{ et } a_{ij} = 1, a_{ij} = \frac{W_j}{W_i} = \frac{1}{a_{ij}}$$

W_i = the contribution to the selection of the best choice and to each of the criteria

W_j = the contribution of the specific criteria to the main objective

Saaty (1990 [61]) suggested that the largest max eigenvalue is

(3) Eigenvalue of γ_{max}

$$\gamma_{max} = a_{ij} * \frac{W_j}{W_i}$$

The results obtained can be used to determine the average of the max value

$n = 11$, “ n ” number of criteria.

$$\gamma_{max} = 132,17/11 = 11,20, \gamma_{max} = 11,20$$

Determining the random index (RI) value Saaty developed a scale where the random indexes IA (Table 5) were established by making random judgments for a high number of replications. This random indexes number represents the average of the indices calculated at each replication for different square matrix size (N) . The reading of the IA value is indicated by a random index table 21: n = number of criteria [24]

We have $n = 11$, the corresponding value is equal to 1.51, IA = 1.51

Computation of the coherence ratio (CR) The coherence ratio (CR) is the ratio of the coherence index calculated on the matrix corresponding to the judgments of the decision-maker and the random index IA of a matrix of the same dimension.

If $CR \leq 0.1$ or $CR \leq 10\%$, the matrix is considered sufficiently coherent, in the case where this value exceeds 10%, the judgments may require some revisions.

(4) Ration of consistency

Table 5 Random consistency index (RI), [24]

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

$$RC = \frac{IC}{IA}$$

We have $IC = 0.02$ and $IA = 1.51$ then $RC = IC/IA = 0.02/1.51 = 0,01$ or 1%.

$RC = 1.3\% < = 10\%$, so conclusion:

OR = 1.3%, the degree of comparison consistency is acceptable.

Finally, we summarize in a Table 6 called criteria judgment table: full priority, the results of calculations such as: judgment matrix, priority, eigenvalue (λ_{max}), consistency index (CI), and consistency ratio (CR).

Analytical hierarchy process has been widely applied in previous research dealing with solid waste management applications (A [19, 27, 32, 42, 52].)

The thematic maps of all criteria were realized using ArcGIS 10.5 software and then converted into raster format using weight values obtained from Boolean and analytical hierarchy process methods. The final suitability map was derived using a raster calculator and overlay analysis tools in ArcGIS 10.5 software for the spatial analyst.

Reclassification and homogenization of the data

All vector layers were converted to raster layers in the same projection system (WGS-1984) and reclassified to an equal pixel size with a scale value of 1–4 (Fig. 10) in a GIS (ArcGIS 10.5).

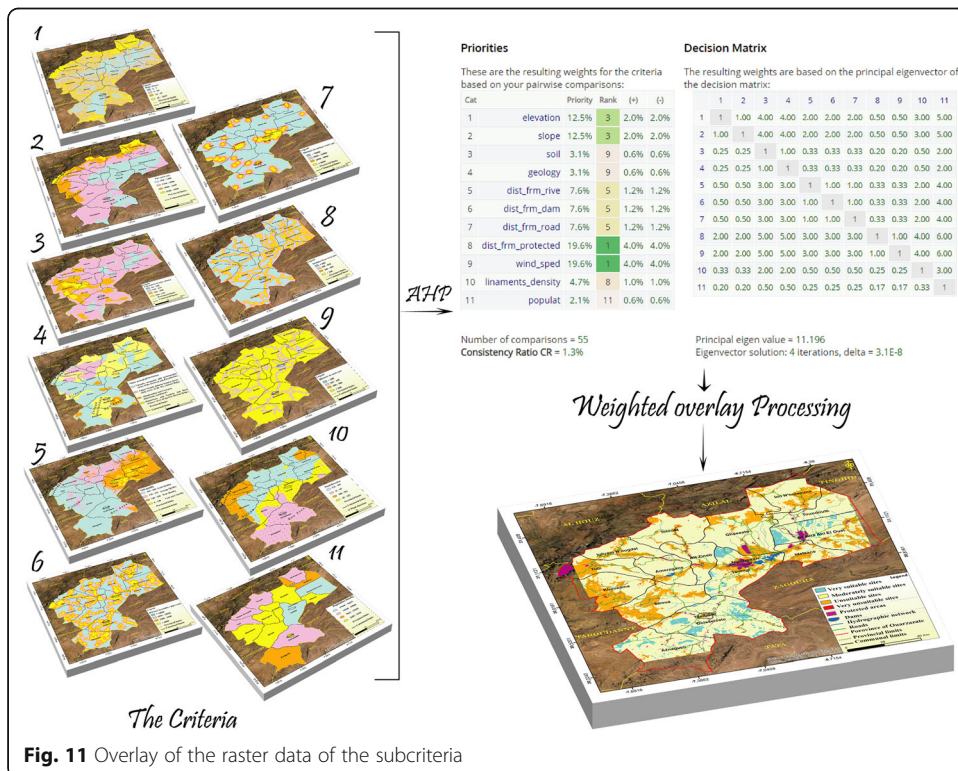
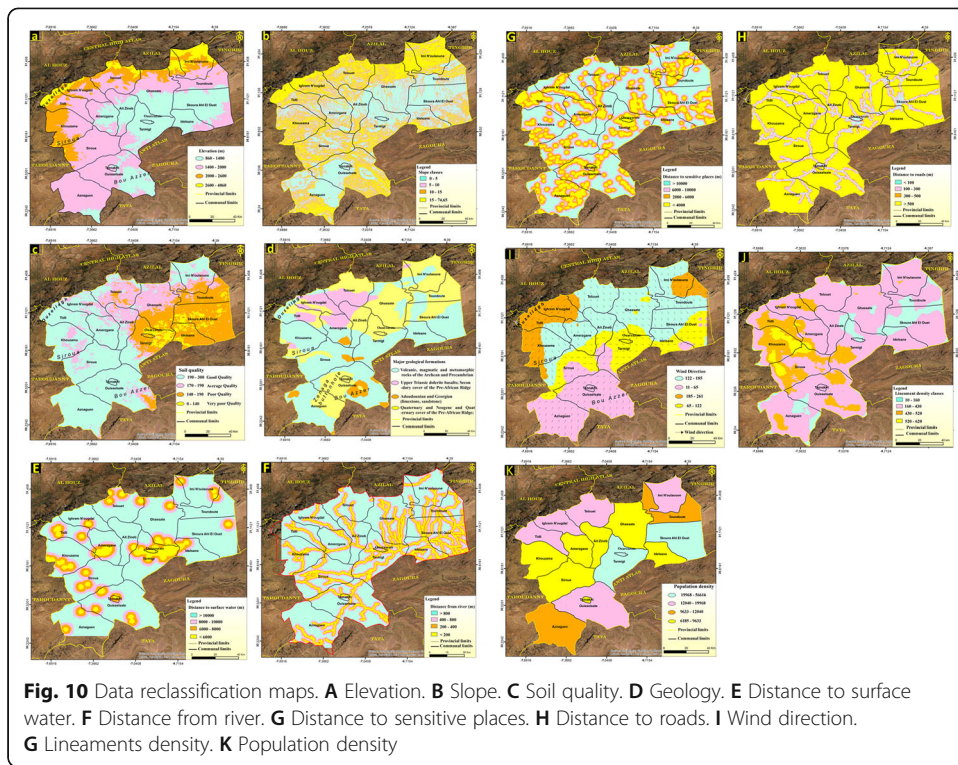
Weighted overlay

The weighted overlay tool (Fig. 11) involves one of the most widely used approaches to solving multi-criteria problems, including site selection and suitability models. In GIS, this function allows users to combine different spatial layers to obtain a final result. ArcGIS uses the following process for this analysis. Each raster layer is assigned a weight in the suitability analysis. The raster layer values are re-ranked on a common suitability scale. This technique has been successfully applied in various studies and analyses, including landfill site selection land use suitability ([6, 7, 36]; L. [41, 49, 53]), analysis soil erosion, and landslides ([16, 31, 46, 54]),

Table 6 Suitability ranking of factors and AHP pairwise comparison

Criteria	Priority	Rank	(+)	(-)
Elevation	12%	3	2%	2%
Slope	12%	3	2%	2%
Soil quality	3%	9	0.60%	0.60%
Geology	3%	9	0.60%	0.60%
Distance from river	8%	5	1.20%	1.20%
Distance from dams	8%	5	1.20%	1.20%
Distance from road	8%	5	1.20%	1.20%
Distance from protected area	20%	1	4%	4%
Wind direction	20%	1	4%	4%
Lineaments density	5%	8	1%	1%
Population density	2%	11	0.60%	0.60%

Consistency measure = 11.20, consistency ratio CR = 0.03 = 1.3%, coherence index CI = 0.02



groundwater exploration [38, 40, 55, 57]. In this study, weighted overlay analysis (WOA) was used to identify optimal and suitable sites for a landfill based on the AHP-calculated weights assigned to each factor considered in the study. All selected criteria in raster format were re-ranked into equal-sized cells and combined into a single suitability layer. WOA is defined as follows: $WOA = \sum_{i=1}^n W_i \times R_i$ where W_i is the weight of a particular decision criterion, R_i is the matrix layer of the same criterion, n is the number of decision criteria.

Results and discussion

The identification of a landfill site is based on a multi-sectoral analysis involving geomericians, engineers, geologists, chemists, biologists, naturalists, economists, sociologists, political scientists, etc. There is no universal method for studying the siting of landfills. Each country, or even each region, must adopt methods that consider their specific environmental and socio-economic characteristics. Nevertheless, the issue addressed remains the same: to avoid or minimize the impacts of the landfill on the environment at the lowest cost. The current orientation in this field is to consider the landfill as a socio-environmental work with geological and hydrogeological, environmental, social, and economic predominance. It must respond to the quality standards required by the regulations in vigor. Therefore, it appears to be necessary to organize the preliminary studies of landfill implementation in sequential steps, each of which must answer precise questions to allow the deciders to make a rational choice. On the other hand, geographic information systems (GIS) and remote sensing coupled with AHP constitute an ideal, less expensive, efficient, and innovative approach for this type of preliminary studies because of their ability to manage large volumes of spatial data from various sources [45]. The choice of the site of the future controlled landfill of the province is an operation that requires a multi-criteria analysis through the analysis of several parameters aiming at the minimization of the environmental nuisances likely to be generated by such a work. The choice of the best site that will house the controlled landfill will optimize the investment costs and the operating costs of the landfill. It will contribute considerably to the protection of the environment in the logic of sustainable development. The principle that governs the determination of the marks attributed to each higher objective is based on recognizing the environment that is the object of the search for a household waste disposal site on the one hand, and on the evaluation of the potential of this environment on the other hand. Care should be taken to ensure that the weights assigned to each higher-level objective accurately reflect the reality of the environment, as these scores will influence the final screening result for the site. The score assigned to each of the higher-level objectives must be greater than zero. The total sum of the points assigned must equal 100. Concerning the province of Ouarzazate and the environment, we have identified 11 criteria: (1) elevation; (2) slope; (3) soil quality; (4) geology; (5) distance from wadis and rivers; (6) distance to water surfaces (dams); (7) distance to roads; (8) distance to sensitive areas; (9) wind direction; (10) density of lineaments; and (11) population density. The weights assigned to each factor are respectively 12%, 12%, 3%, 3%, 8%, 8%, 20%, 20%, 5%, and 2%. The water component in the Ouarzazate region is of paramount importance, hence the need to

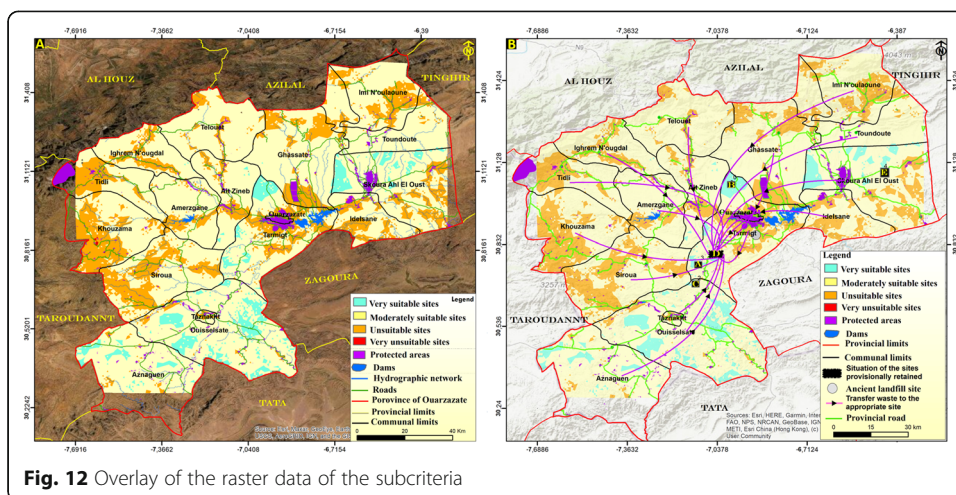


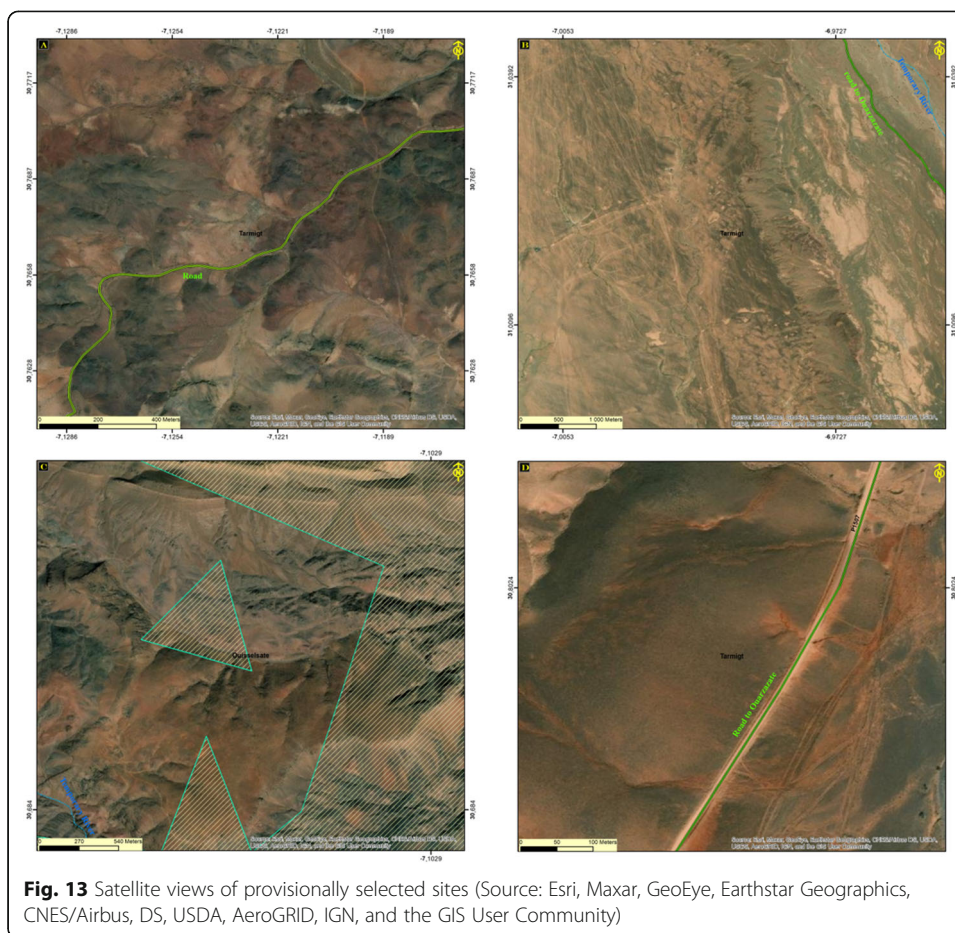
Fig. 12 Overlay of the raster data of the subcriteria

protect it, which is why it was assigned second place after the morphological factors. Ouarzazate is one of the region’s best known for its great tourist and film potential on a national and global scale. The component of sensitive areas was given an important score in third position. The higher objectives can be translated into lower objectives based on environmental conditions. The score assigned to the lower objectives identified using the same reasoning as for the higher objectives. After determining the degree of realization of the determining factors (Table 6), the application of the multi-criteria analysis and, based on the considerations and calculations developed above, the prioritization of the various sites selected, we can show the following map (Fig. 12).

After having proceeded to the extraction of the lands in conformity with the implantation of the provincial controlled landfill by superimposing all the thematic maps of the different exclusion criteria with the definition of the safety perimeters for each component, we find vacant zones where the site of the future controlled landfill of the province can be accommodated. It is what we call “free surfaces = pixels colored in cyan on the map.” The pre-selected empty surfaces have very variable surface areas and only the surfaces with a surface area greater than the needs of the future landfill are kept and classified according to their importance. The aim is to identify the most suitable sites for a landfill in open areas, preferably (but not necessarily) in areas of low environmental and economic value. The selection of sites will be based primarily on general topography of the site; potential landfill volume; proximity to waste generation areas; storage capacity and therefore life span; location in relation to prevailing winds; location in relation to runoff; road and trail access; water and electricity supply; social acceptance; availability of materials (equipment of the bottom of the casier (clay and draining materials); and of the cover (rehabilitation).

Analysis and classification of provisionally selected sites

Of the hundreds of such open space sites, only five sites (Fig. 13) have sufficient area to meet the project horizon of 20 years or more. Furthermore, to easily store the 1.5



million m³ over 20 years, areas of at least 20 ha are required. The following table shows the characteristics of the provisionally selected landfill sites (Table 7).

Transfer sites

The transfer of waste cannot be studied independently of the location of the dumpsites and the treatment units. To identify the impacts of different scenarios, we propose the use of an indicator of the transport function, which is the Tonne/km of distance between the collection center of the communes and the waste dumping sites. Some sites will be allocated to transfer stations (Fig. 12B) that will be used to reduce the number of vehicles going to the proposed landfill (site D). For example, relatively large distances between the waste production center and the collection areas (Taznakhte being 50 km from the landfill of site D), the transfer will be economically and technically interesting to carry out at site C, or at one of the lands conforming to the waste storage of the municipality (pixels in cyan on the map of sites).

Conclusion

The proposed study allows the controlled management of household waste of the entire population of the province of Ouarzazate. This work is also in line with a logic of sustainable development since it aims to reduce the environmental pollution of the

Table 7 The characteristics of the provisionally selected landfill sites

	Site A	Site B	Site C	Site D	Site E
Municipality	Tarmigt	Tarmigt	Ouisselane	Tarmigt	Skoura ahl El Ouest
Superficie	25.6 ha	1600 ha	91 ha	19 ha	200 ha
Latitude	– 7,10272883	– 6,985129	– 7,113929	– 7,049464	– 6,43962142
Longitude	30,7653565	31,056557	30,692557	30,801132	31,09681265
DFB	30 km	20 km	40 km	25 km	60 km
Topography	Irregular terrain, slope < 10°	Flat terrain, slope < 5°	Flat terrain, slope < 5°	Flat terrain, slope < 5°	Flat terrain, slope < 5°
Geology	Precambrian-Paleozoic basement	Sedimentary cover	Precambrian-Paleozoic basement	Precambrian-Paleozoic basement	Sedimentary cover
Soil quality (bedrock)	Impermeable soil, they are magmatic rocks	Permeable soil, marl, sandstone, sometimes clay	Impermeable soil, these are magmatic rocks	Impermeable soil, these are magmatic rocks	Medium permeability soil, these are marl, sandstone and sometimes clay
Accessibility	Access via the national road N9	Access via the unclassified roads	Access via the national road N9	Access via the national road R307	Access via the national road N10
Distance to water surfaces	Presence of some wadi tributaries	No wadi or water surface near the land	No wadi or water surface near the land	No wadi or water surface near the land	No wadi or water surface near the land
Wind direction	West–East	North–South	SW–NE	West–East	West–East

After comparing the “provisionally selected” sites (Table 7), it is concluded that the most suitable sites for the future provincial landfill of Ouarzazate are sites D and B. Sites A, E, and C are excluded.

agglomerations, especially that of Ouarzazate and Tarmigte, which is the barycenter of the province. This work also proposes proven solutions for the transfer of all the waste produced on the territories of the communes towards a socio-environmental landfill where all the required standards are respected. This approach is innovative for Morocco and will require a consequent accompaniment of the various actors. In this regard, due to the large size of the study area, geographic information systems (GIS), and spatial remote sensing techniques coupled with multi-criteria analysis (MCA) are proving to be very useful in the site selection process due to their ability to handle a multi-source dataset and use it in a well-organized and systematic manner. While multi-criteria evaluation can be used productively to address municipal solid waste management issues due to its low cost and quick implementation. These techniques have been increasingly used for the landfill siting process in other similar studies. For waste management at the provincial level, a restriction map is obtained from the criteria used to evaluate the constrained areas. It, therefore, cannot be used for the siting process. However, five sites (A, B, C, D, and E) are provisionally selected for the siting of the landfill; among these five sites, site D was selected for the siting of the new landfill since all the criteria seem to be very important are found in this site. The chosen site is located in an open area in the south of the territory of the urban commune of Tarmigt at the limit of the commune of Ouissane with a maximum area of 19 ha, on the provincial road N23, far from the city of Ouarzazate of 25 km, far also from areas of social and cultural interest, areas to be protected or areas declared of natural protection. The site is located in an urban commune with a very high population density and is nearer the barycenter of waste production (Ouarzazate). The land’s topography is generally flat with a slope of less than 5%, and the altitude around 2000 m. The site is

located in a terrain formed by an impermeable crystalline bedrock of Precambrian-Paleozoic age and is also situated in an area with low to medium lineament density and no geological faults (non-fractured area). The wind direction on the site is West-East. The selected site is far from any water body (dams), affluents or wadis whose safety radius is very high. Other sites are selected with the same characteristics, namely site B, but the results of analysis confirm the site D by preference, but it is necessary to have with the other actors on this decision.

Abbreviations

AHP: Analytical hierarchy process; GIS: Geographic information systems; DEM: Digital elevation model; MSW: Municipal solid waste; NASA: National Aeronautics and Space Administration; MCDA: Multi-criteria decision analysis; LSS: Landfill site selection; PROMETHEE: Preference ranking organization method; WOA: Weighted overlay analysis; WGS: World Geodetic System; CR: Consistency ratio; CI: Coherence index; IA: Random index; SPC: Semi-automatic classification; N: North; W: West; LSS: Landfill site selection

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Authors' contributions

FA: investigation, methodology, writing—original draft. BY: investigation, methodology, writing—original draft. IM: investigation, methodology, writing—original draft. AA and AAB: Validation, writing—review and editing, supervision. The authors read and approved the final manuscript.

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Competing interests

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