

Landfill site selection with GIS-based multi-criteria evaluation technique. A case study in Béni Mellal-Khouribga Region, Morocco

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Abstract Given the potential negative environmental impacts linked with wild landfills in Béni Mellal-Khouribga Region, there is a significant need to accelerate the development of controlled intermunicipal landfills. Any landfill project requires identification of the most suitable sites to prevent environmental adversity. So, this study was conducted to identify candidate landfill sites using geographic information system (GIS) and multi-criteria evaluation techniques. Ten suitability criteria including 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. The thematic maps of all criteria were prepared in GIS environment using Boolean and analytic hierarchy process (AHP) standardization. After hiding unsuitable areas of landfill sites identified by the Boolean method, each criterion was evaluated with the aid of AHP and the final landfill site suitability map was generated using the overlay analysis in GIS. The results showed that 54% of the study area is not suitable, 12% is lowly suitable, 24% is moderately suitable, and indeed 10% is highly suitable for landfilling. The identified suitable areas will require careful field studies before the final decision for landfill site selection. Nonetheless, this study can help planners and local and regional authorities to better manage the solid waste in the region.

Keywords Landfill site selection · GIS · MCE · Boolean and AHP models · Suitability map

Introduction

The concept of sustainable development and environment can become a source of danger through natural processes, economic activities (energy, industry, etc.), and human activities. This is the case of poor waste management, primarily the landfills which are a source of air pollution by release of noxious odors and gases, chemical and biological water pollution, degradation of life quality in urban areas, soil contamination by dangerous products (pesticides, heavy metals), pollution of coastal and marine environment (Abu-Qdais and Abu-Qudais 2000; Kontos et al. 2003), etc. Environmental management is improved, after collection and storage, through the treatment and recycling.

The socioeconomic development and urban dynamic that Morocco has experienced have forced the country to confront the waste management while initiating a series of strategic actions to reform the waste management sector (PNDM 2008; SWEEP-Net 2014). The problem of solid waste (about 6 million tons per year in Morocco) does not arise from their collection, but especially for the selection and management of landfill sites. Recognizing environmental risks related to poor waste management, several Moroccan administrative regions envisaged the realization of intermunicipal landfills. This work forms part of this prospect and tries to suggest favorable sites for installing the controlled landfill in Béni Mellal-Khouribga Region.

Site selection for landfills is a critical and complex phase because it depends on different factors and regulations. It requires further study taking into account various economic and environmental factors (Yesilnacar and Cetin

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2008), in order to offer the best site with low socioeconomic and environmental costs (Lober 1995; Siddiqui et al. 1996). Many assessments of urban landfill sites have been done in the main parts of the world, and they have used various criteria, such as economic, social, and environmental, for site selection. Environmental factors are very important, knowing that the landfill can affect the biophysical environment and the ecological system of surrounding areas (Alanbari et al. 2014). These various and multiple (economic, social, and environmental) criteria make landfill sitting suitability assessment complicated because it is difficult to combine criteria and to assign them the weights of influence. Therefore, GIS-based multi-criteria evaluation (MCE) technique is the ideal tool for such analysis due to its ability to manage large volumes of spatial data from various sources (Kontos et al. 2003; Malczewski 2004). This technique has become a preferred method to find solutions to different problems related to land with multiple alternatives (Jankowski 1995). Owing to their ability to manage a large volume of spatial data from a variety of sources (Kontos et al. 2003), GIS-based multi-criteria suitability evaluation represents one of the effective evaluation techniques that allow developing models for predicting the site suitability for waste landfills. It has been increasingly used for this purpose in the last decade (e.g., Delgado et al. 2008; Sumathi et al. 2008; Wang et al. 2009; Geneletti 2010; Nas et al. 2010; Moeinaddini et al. 2010; Şener et al. 2010; Donevska et al. 2012a, b; Gorsevski et al. 2012; Eskandari et al. 2012, 2016; Beskese et al. 2015; Bahrani et al. 2016; Rahmat et al. 2017; Torabi-Kaveh et al. 2016).

In this process of MCA, one of the challenges is to identify the relative score or weight of selected criteria that influence land suitability unequally. While several methods could be used in determining weights of these criteria, it has usually been approached using Boolean logic and analytical hierarchy process (AHP) based on evaluation criteria. A Boolean logic is taken to assign to the selection criteria, the scores of either '1' or '0' (binary digit values) that represent either 'suitable' or 'no suitable' to the selection criteria and that in order to identify the constrained areas for landfill site selection. AHP, the most popular method used in the literature, is widely used to determine the weight of criteria based on pairwise comparisons of parameters according to their relative importance (Şener et al. 2011; Aydi et al. 2013; Kumar and Hassan 2013; Beskese et al. 2015; Bahrani et al. 2016; Eskandari et al. 2016; Rahmat et al. 2017; Torabi-Kaveh et al. 2016). The combination of AHP and GIS techniques helps in decision support systems by the creation of final suitability map.

Municipal solid wastes from different municipalities of Béni Mellal-Khouribga Region are disposed in wild and

uncontrolled landfills, which could cause various environmental problems. However, with the Morocco Municipal Solid Waste (MSW) Management Program—2008–2022, launched by the Moroccan government, all municipalities must have access to controlled landfills by 2022. With this purpose, the present work was done in order to define suitable locations of landfill sites for Béni Mellal-Khouribga Region. Spatial analysis was made with quantifiable data on a number of criteria, using Boolean and AHP methods in a GIS environment.

Materials and methods

Study zone

The study zone is part of the administrative region of Béni Mellal-Khénifra which extends from $32^{\circ}10'34''$ to $33^{\circ}24'36.41''$ N and from $5^{\circ}15'50''$ to $7^{\circ}06'50''$ W. This administrative region contains five provinces which are Béni Mellal, Azilal, Fkih Ben Salah, Khénifra, and Khouribga (Fig. 1), in which Béni Mellal town is the chief center. It covers an area of 33208 km² and recorded a population of 2,520,776, representing 7.4% of Moroccan's total population. Major sources of income to the population are agriculture, livestock, and minor forest activities. The climate of the region is semiarid to arid with a dry season from April to October and a rainy season from November to March. The average annual rainfall is 350 mm, with an

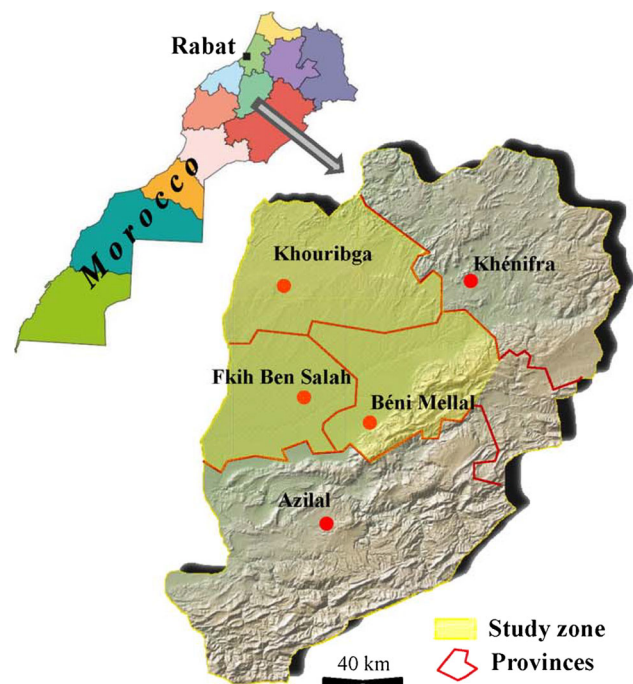


Fig. 1 Local map of the study area

annual evaporation of about 1800 mm. The annual temperature ranges from 3.5 °C in winter to 38 °C in summer, with a mean of 17 °C. From a water resources point of view, the region is one of the major water reservoirs in the kingdom, including huge reserves of groundwater and surface water.

The region is experiencing a fast increase in the quantity of MSW generation as a result of rapid growth and urbanization and of change in consumption pattern. In addition, in all municipalities, especially rural, there is no suitable method for the waste storage. Solid waste is often accumulated in wild dumps located on the banks of periodic rivers and thalweg or even close to agglomerations. These places are generally considered as temporary landfill areas. For this, the conception of a controlled landfill, provincial or interprovincial in the region is necessary to protect fertile soils, water resources, and human health and to reduce the negative environmental impacts of waste disposal.

Materials and methods

The studied zone covers three provinces which are Béni Mellal, Fkih Ben Salah, and Khouribga (Fig. 1). The waste in the study zone is dumped often without applying any environmental standards, which increase the environmental problem. Whence, the objective of our study is to contribute to solving part of the problem by the proposal of sites capable of harboring solid waste landfills while respecting environmental standards and minimizing the economic cost. The landfill site selection process followed in this study is illustrated by the flowchart in Fig. 2. It is done in two stages after the selection phase of criteria. The first stage of analysis, using Boolean approach, allowed for the identification of unfavorable areas for landfilling prior to undertaking further investigations of the favorable areas. Constraint criteria used to designate the unfavorable areas have been expressed as a Boolean map in which a scale value of 0 was assigned to the excluded areas and a scale value of 1 was assigned to those potentially suitable for landfilling (Eastman et al. 1993). The second stage involved the application of the AHP-based pairwise comparisons to result from the first stage, in order to calculate the weight for each factor and sub-factor. Following this, the landfill suitability map was generated by overlaying raster maps of all elements, using the weighted overlay raster analysis.

Criteria selection and data processing

MCE process was employed to select suitable sites to install the controlled landfills. The first fundamental step of this multi-criteria analysis is the creation of the list of

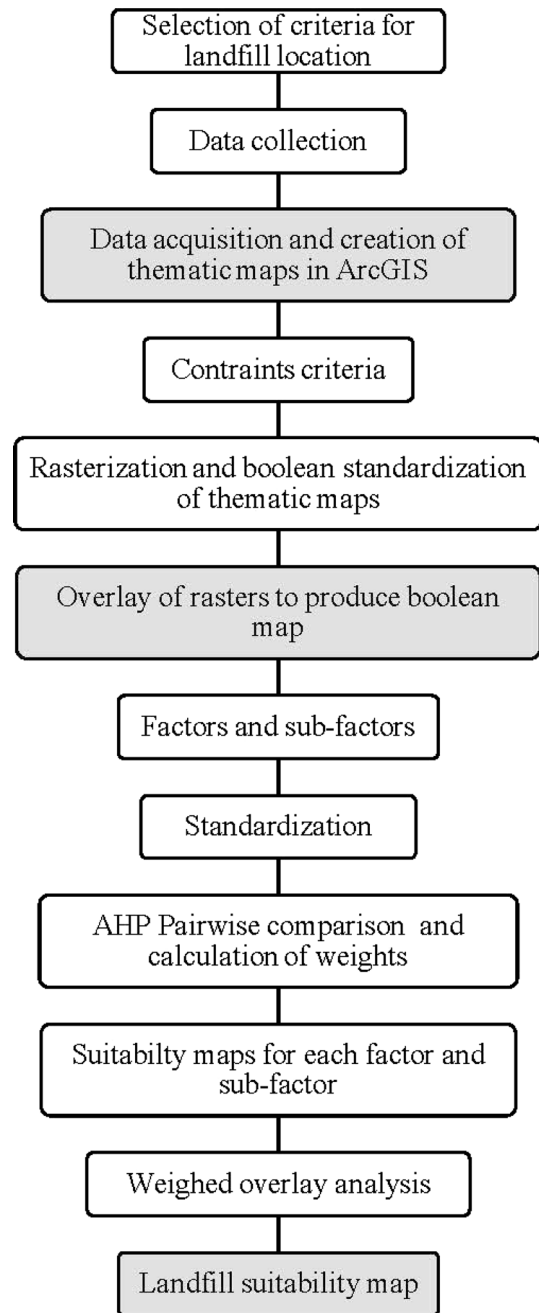


Fig. 2 Flowchart of the methodology used in the study

criteria to assess the ability of a site to satisfy our objectives. Particularly, there are no predefined and systematic construction methods of specific criteria, and also the Moroccan law on waste management and their disposal presents no requirement for the optimal choice of the potential landfill site. The criteria used in this study were selected under consideration of the literature (e.g., Chen et al. 2010; Şener et al. 2010, 2011, Aydi et al. 2013, Beskese et al. 2015, Shahabi et al. 2014; Yazdani et al. 2013; Bahrani et al. 2016; Torabi-Kaveh et al. 2016) with

some adjustments to the Moroccan context. They were classified into two main groups: (1) economic group included distance from roads, slope, and elevation criteria, and (2) geo-environmental group included land use, distance to residential areas, geology, water resources, and aspect (wind) criteria (Table 1). Each criterion is decomposed into sub-criteria (Table 1).

Chosen in order to reduce negative social and environmental impacts, these considered criteria were classified as constraint and factor. Geologic (distance to fault), water resource, slope, land use (forest and agriculture), distance to residential areas, and roads criteria were used as constraints (exclusion criteria) to exclude the areas where landfills cannot be installed due to the potential risk on environment and human health or due to the excessive cost. The safety buffers tested at three provinces (Guelmim, Larache, and Chefchaouen) in Morocco (Ezzouaq and Chouaouta 2002) (Table 2) were applied in the present investigation. This analysis provides us a map with excluded and acceptable areas. The acceptable areas were subjected to a classification by the MCE and AHP methods at the second stage of the analysis which is based on all selected criteria.

The data used in this study to prepare the selected criteria were collected from various sources. Administrative boundary map with province limits of the study area was downloaded from the High Commission for Planning, Morocco (2016). The geologic map was digitized from geological paper maps edited by the Division of Geology of Moroccan Ministry of Energy and Mining and covering the study area, such are the 1:200,000 scale geological maps of Afourer, Béni Mellal, Imilchil, Kasba Tadla, and Oued Zem, the 1:200,000 scale geological map of Plateau des Phosphates, and the 1:500,000 scale geological map of Rabat. The road map was created from 1:250,000 scale road network maps (Ministry of Equipment and Transport 2016). The geo-referencing followed by the digitization of all previous base maps has been used to prepare their corresponding vector data layers. The digital elevation model (DEM) with a 30–30 m resolution of the study area, downloaded from ASTER GDEM, was used to obtain elevation and slope information. The land use map was determined using the moderate-resolution satellite images, namely Landsat-8 ETM+ (15–30 m) of May 2016 downloaded from the USGS Global Visualization server (GloVis). The processing and analysis of satellite images were made using ENVI 5.1 software. It was classified using supervised classification technique and field information and Google Earth image. Groundwater level data were collected from 109 wells over the study area. Groundwater level map was prepared using inverse distance weighting (IDW) interpolation technique in ArcGIS.

The thematic maps of all criteria were realized using ArcGIS 10.22 software and then converted into raster format using weight values obtained from Boolean and AHP methods. The final suitability map was derived using raster calculator and overlay analysis tools in ArcGIS 10.22 software for the spatial analyst.

Boolean and AHP methods

Boolean logic In this study, the Boolean logic was used in the early stage of the analysis to delineate the areas considered suitable for waste disposal for each of the constraints maps. This method is mostly used in the early screening stages (Kamran 2008) or when parameter maps are divided into suitable (yes) and unsuitable (no) areas (Malczewski 1999). It transforms related information from each input raster map into binary form true or false or 0 and 1. These classes 0 and 1 were assigned to areas excluded from consideration (restricted areas) and others (desired) areas, respectively (Malczewski 1999). The output map is a binary map because it had two polygons. At the end, in order to prepare final suitability map for landfilling, all created binary maps for the constraints have been combined using the Boolean logic model. In this model, all binary maps were considered of equal importance of delineating areas suitable for waste disposal, and consequently, an equal weighting was assigned to all binary thematic maps.

AHP method: calculating criterion weights

In the second stage, after extraction of the constrained areas obtained from the early screening stage, the land suitability was done on the identified potential landfill areas (alternatives) in the study region. Landfill susceptibility mapping requires the application of multi-criteria approach and spatial analysis method for the decision-making process. MCE in GIS environment is one of the modeling approaches that are widely used to convert spatial and non-spatial data into information used to assist in making critical decisions (e.g., Chen et al. 2010; Nas et al. 2010; Gorsevski et al. 2012; Donevska et al. 2012a, b; Motlagh and Sayadi 2015; Khan and Samadder 2015). GIS-based MCE evaluation involves a set of quantifiable spatial factors influencing the landfill suitability and the techniques for expressing preferences regarding the relative importance of each factor. To determine the weights of the factors which have unequal levels of importance, the AHP method, one of the most widely known and used approaches to handling multiple and heterogeneous factors, has been applied. The weight of each criterion was calculated by ranking its importance and suitability.

Table 1 Main criteria, criteria, sub-criteria, and their relative weights calculated with AHP method

Main criteria	Weight	CR	Criteria	Weight	CR	Sub-criteria	Weight	CR	Σ Weight			
Economic	0.25	0	Distance to roads (m)	0.633	0.033	<250	0.503	0.054	0.080			
						250–500	0.26		0.041			
						500–750	0.134		0.021			
						750–1000	0.068		0.011			
						>1000	0.035		0.006			
			Elevation (m)	0.26					<500	0.503	0.054	0.080
									500–1000	0.26		0.041
									1000–1500	0.134		0.021
									1500–2000	0.068		0.011
									>2000	0.035		0.006
			Slope (°)	0.106					<5	0.503	0.054	0.080
									05–10	0.26		0.041
									10–15	0.134		0.021
									15–20	0.068		0.011
									>20	0.035		0.006
Environmental	0.75		Aspect	0.021	0.006	SW	0.047	0.0422	0.001			
						NE	0.047		0.001			
						NW	0.07		0.001			
						SE	0.091		0.001			
						N	0.108		0.002			
						W	0.141		0.002			
						E	0.195		0.003			
						S	0.298		0.005			
			Distance to residential areas (m)	0.221					<1000	0.035	0.054	0.006
									1000–2000	0.068		0.011
									2000–3000	0.134		0.022
									3000–4000	0.26		0.043
									>4000	0.503		0.083
			Geology (lithology)	0.04					Highly impermeable	0.557	0.043	0.017
									Impermeable	0.29		0.009
									Semipermeable	0.11		0.003
									Permeable	0.043		0.001
			Distance to faults (m)	0.061					<250	0.035	0.054	0.002
									250–500	0.068		0.003
									500–750	0.134		0.006
									750–1000	0.26		0.012
									>1000	0.503		0.023
			Distance to surface water (m)	0.207					<500	0.035	0.054	0.005
									500–1000	0.068		0.011
									1000–1500	0.134		0.021
1500–2000	0.26	0.040										
>2000	0.503	0.078										
Groundwater table (m)	0.194					<10	0.035	0.054	0.005			
						10–20	0.068		0.010			
						20–30	0.134		0.019			
						30–40	0.26		0.038			
						>40	0.503		0.073			
Land use	0.255					Bare soil	1	0.002	0.191			

Table 2 Safety buffer of Boolean constraints

Criteria	Security buffer
Distance to residential areas (isolated dwellings and agglomerations)	500 m
Distance to residential areas (towns and urban centers)	2 km
Distance to roads	300 m
Slope	5°
Geology (distance to fault)	500 m
Distance to surface water (river/streams/lakes/wells)	500 m
Land use (distance to agricultural and forest lands)	300 m

As described by Saaty (1977, 1994), the AHP process derives the weights of the parameters, by following three different steps (Elaalem et al. 2011). The first step was to construct the decision-making problem into a hierarchical structure including objectives, criteria, sub-criteria, and alternatives. The hierarchical model used in this study is listed in Fig. 2. The objective was the landfill suitability map, and the factors consisted of 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; each of which had some sub-factors, and some of the sub-factors were divided into several alternatives.

The second step was to assign the relative importance of criteria at each level of the hierarchical structure, based on Saaty and Vargas' preference scale (2001), and to derive the pairwise comparison matrix. The pairwise comparison matrix of various criteria included in the same level is constructed based on experts' views, by assigning nine points scoring from 1 to 9, in which 1 represents equal preference and 9 represents extreme preference (Table 3).

The pairwise comparison matrix created consists of $n(n-1)/2$ comparisons for n number of elements on the level (Malczewski 1999; Ozturk and Batuk 2011). Once the pairwise matrix is made, the weights are determined by normalizing the pairwise comparison matrix. The normalized pairwise comparison matrix is taken by dividing each matrix element by the total of its column. Then, the weights are obtained by measuring the mean of elements in

Table 3 Saaty and Vargas preference scales

Intensity of importance	Description
1	Equal importance
2	Equal to average importance
3	Average importance
4	Average to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong or super strong importance
9	Super strong importance

each row of the normalized matrix. The calculated weights are within the range of 0–1, and their sum is equal to 1 (Malczewski 1999; Ozturk and Batuk 2011). In this study, an AHP Excel template was used to compute the weight of all factors relatively to their suitability, and the results are listed in Table 1. In order to check that these weights are suitable, consistency index (CI) is calculated as:

$$CI = \frac{\lambda_{\max} - 1}{n - 1}$$

where CI is the consistency index (1), λ_{\max} is the maximum eigenvalue of the matrix, and n is the order of the matrix. The ratio, CI/RI, derived from CI compared to the random matrix (RI), is termed the consistency ratio, CR. Saaty (1991) suggests the value of CR should be equal to or less than 0.1 for the matrix to be consistent. For this study, the results of this stage are shown in Table 1. The CR computed at each level of hierarchy is less than 0.750, indicating thereby that the matrix was proper to use (Table 1).

The third step consisted of producing the final landfill susceptibility map using the results from the two stages described above. The final map was determined by computing the landfill suitability index (LSI), in the following manner:

$$LSI = \sum_{i=1}^n w_i * x_i \text{ (after Cengiz and Akbulak 2009)}$$

where n is the total number of LS criteria, w_i is the weight index of factor, and x_i is the weight index of sub-criteria.

Higher LSI values indicate areas more suitable for landfills. The final landfill suitability map was generated using ArcGIS 10.2.2 by combining ten criteria maps and overlaying weights of individual criteria.

Results and discussion

Description of criteria

The identification of suitable sites for solid waste disposal should be based on a number of criteria distributed between an economic, social–cultural, environmental group. The criteria used to evaluate the areas suitable for landfilling in

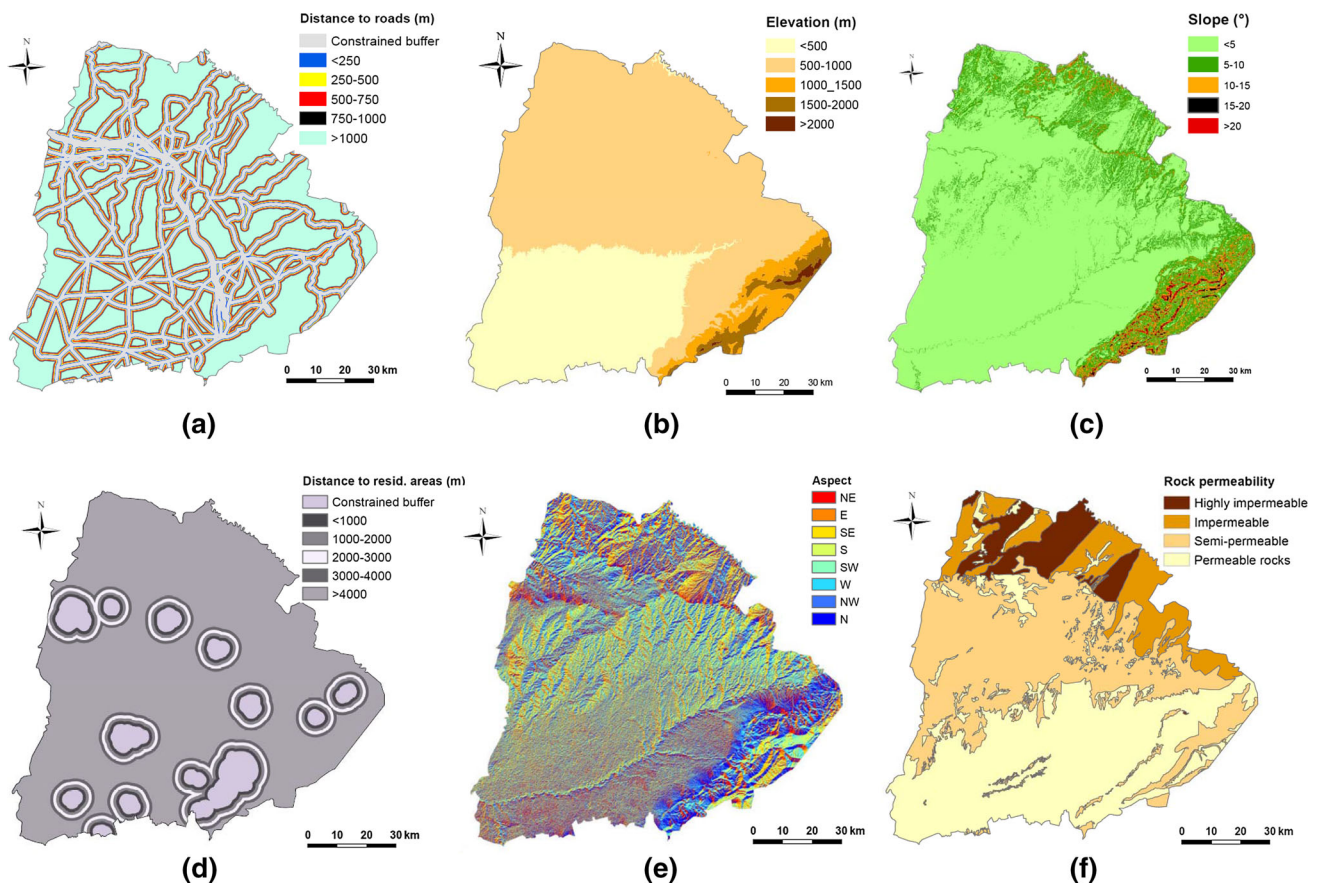


Fig. 3 a Map of distance to roads; b elevation map; c slope map; d map of distance to residential areas; e aspect map; f permeability map

the study region are in number of ten and were the 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. The main reason for using these criteria is their frequent and adequate utilization for assessment of areas suitability for landfilling. The influence of these criteria varied according to the studied zone specificities. The criteria used are explained in detail in the following sections. The buffers for each criterion were developed according to the classification reported in Ezzouaq and Chouaouta (2002).

Distance to roads

A solid waste discharge must be placed either in the immediate vicinity of the traffic roads to minimize negative environmental effects (odor and visual pollution) or not too far from existing roads to avoid the high cost of construction of road servicing the landfill and to further reduce the cost of transportation. Therefore, in this study, the road network map including highway, main roads, and secondary roads, was generated and buffered, after extracting the constraint areas of 300 m, into five zones of 250 m (Fig. 3a). The lowest suitability score has been given to the

buffer distance far away from roads. The buffer map was converted to raster map with a 30 × 30 m resolution, and each buffer zone was weighted by AHP (Table 1).

Elevation

Areas with high altitude or high slope are not suitable landfill sites. The elevation is an important factor that has an effect on other selection factor, namely slope and aspect. Also, higher elevation makes access difficult and leads to higher transportation costs. In study region, the difference between the highest elevation point (Atlas Mountain of Béni Mellal, 2260 m) and the lowest elevation point (Tadla basin, 320 m AMSL) is about 1940 m. This elevation difference was divided into five classes that are <500, 500–1000, 1000–1500, 1500–2000, and >2000 m, knowing that the class with low elevation is considered the most suitable and the >2000 m class is the least suitable. The elevation map was prepared from the digital elevation model (DEM) of the study area (Fig. 3b). Much of the region is characterized by an altitude between 320 and 1000 m. The southeastern part of the region is characterized by high altitudes ranging from 1000 to 2260 m. Weight for the each elevation class was calculated using AHP (Table 1).

Slope

The selection of landfill sites is closely related to the topography (slope) of the area which affected many landscape processes such as soil water content, erosion potential, runoff, and surface and subsurface flow velocity. The areas with slopes less than 6° are considered as the most appropriate, but those with slopes higher than 17° are not appropriate (Donevska et al. 2012a, b). Digital elevation map was used to create the spatial slope map of the study area (Fig. 3c). The slope was evaluated as five classes: <5 , 5–10, 10–15, 15–20, and $>20^\circ$. The areas having lower slope were taken as the high suitable and have been given the highest score. The thematic map showed that most of the study zone was mostly flat in terrain and was mostly suitable for landfill sites.

All buffer areas were weighted by AHP (Table 1).

Distance to residential areas

The landfill areas should be situated at a significant distance away from urban and rural settlement areas, in order to avoid public concerns because of problems such as water, air and visual pollution, insects and vermin, fire, and noise. For this purpose, a safety buffer zone of 2000 m around these residential areas was applied in this study (Table 2), and then the thematic layer was prepared with five buffers, <1000 , 1000–2000, 2000–3000, 3000–4000, and >4000 m, according to distance from residential areas (Fig. 3d). The most suitable areas are buffer very far from residential areas, while the closer buffer was assigned with the lowest suitability. The buffer zones were rasterized into a map with a 30×30 m resolution, and each buffer zone was weighted by AHP (Table 1).

Aspect (wind)

Landfills are usually responsible for emissions of unpleasant odors and dust carried by the wind, especially when the prevailing wind direction blows toward residential areas. Therefore, the predominant wind direction was taken into consideration because it should be considered to hinder residential areas from dust and odor. It is also an established fact that the direction and velocity of winds vary with altitude, slope, aspect, and terrain roughness (Kontos et al. 2005). To evaluate the wind direction of the study area, an aspect map was prepared using a digital elevation model with a 30×30 m resolution (Fig. 3e). The predominant wind direction in the study area is northeast (NE) and southwest and was therefore assigned the lowest value of suitability, while the higher value of suitability was assigned to the direction with the least

frequent wind. And all other directions were weighted by AHP, depending on their wind frequency (Table 1).

Lithology (permeability)

The landfill is to be constructed over an impermeable substrate, thick enough, and having no crack to prevent groundwater pollution (Ezzouaq and Chouaouta 2002). The study area is characterized by the presence of several lithological formations that have been grouped into four lithological units based on their permeability, including highly impermeable rocks (clays, quartz, basalts, granite), impermeable (schist, quartzite), semipermeable rocks (sandstone bedrock), and permeable rocks (calcareous, sands, silt, etc.), with the dominance of permeable and semipermeable classes (Fig. 3f). The lands having low permeability represent the more appropriate location for landfill sites, and it gave them a high rating compared with those having high permeability, and subsequently, each permeability class was weighted by AHP (Table 1).

Distance to faults

The substratum without fault is one of the best criteria for landfill selection. The faults can promote infiltration of leachates from the landfill, which could be a potential source of surface water and groundwater contaminations. For this, the landfills should be implanted placed as far away as possible from fractured areas. In this study, the minimal distance from the fault line is 500 m (restricted area). The fault layer was generated from geology maps, and the buffer zones at intervals of 250 m were drawn around the restricted areas (Fig. 4a). The closer buffer to the fault has been taken as inappropriate areas for landfill placement. All buffers were weighted by AHP (Table 1).

Distance to surface water

The proximity of a landfill project to a surface water source is considered as a disadvantage because the landfill activities have the potential to alter the quantity of surface water in the near localities (Gorsevski et al. 2012), through movement of leachate and erosion of waste. Therefore, the landfill sites should not be constructed near any surface water (Şener et al. 2010). Hence, in this study area, a 500-m buffer zone was drawn around the surface water systems. The thematic layer prepared from the DEM was buffered into five buffers (<500 , 500–1000, 1000–1500, 1500–2000, >2000 m) around all excluded areas (safety buffer) (Fig. 4b). Buffer lying close to the surface water systems is considered inappropriate for landfill siting. The relative weights of all buffers are achieved by AHP pairwise.

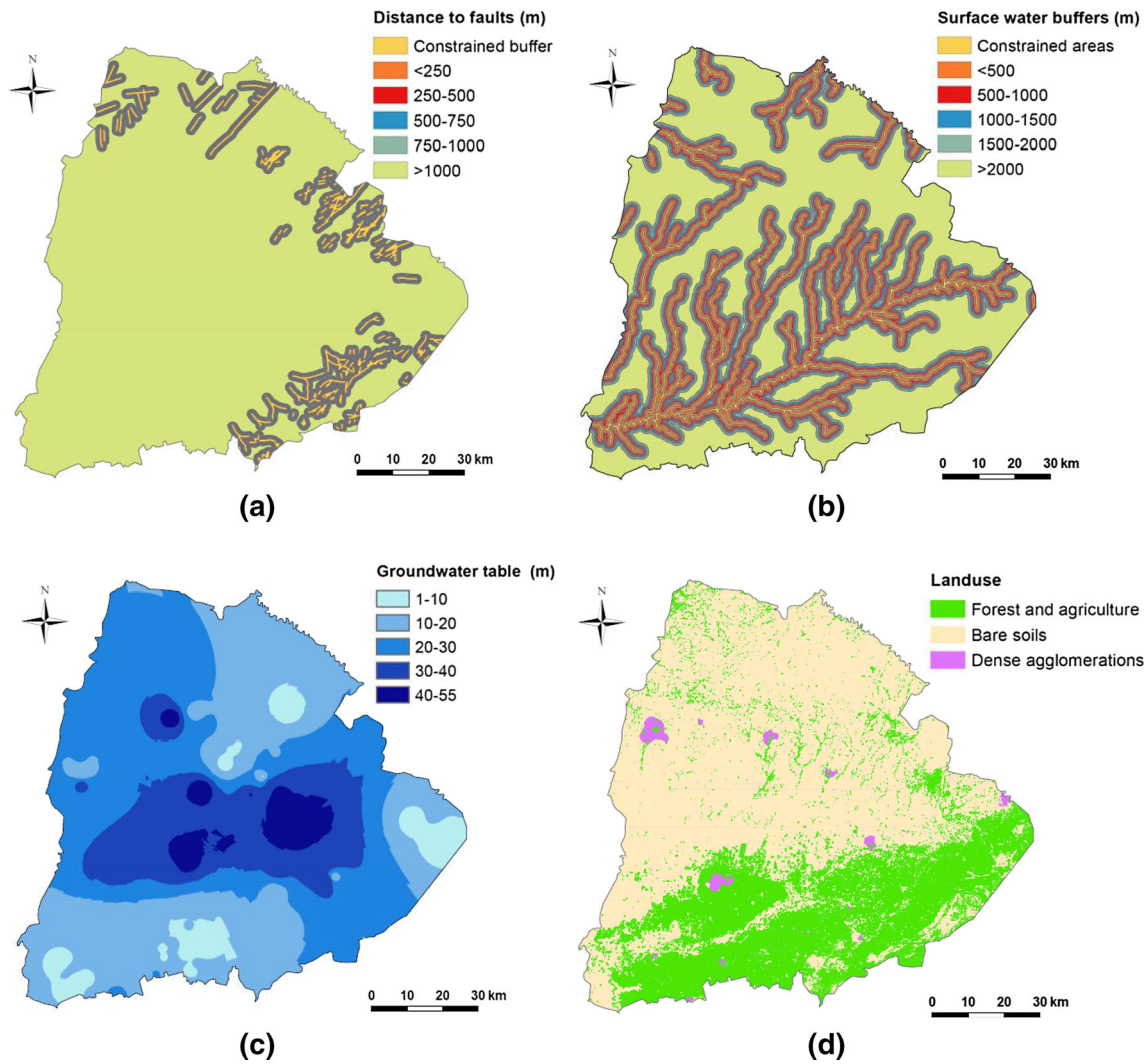


Fig. 4 **a** Map of distance to faults; **b** map of distance to surface water; **c** map of groundwater table; **d** land use map

Groundwater table

The depth of groundwater table is a significant parameter in determining the contamination risk of groundwater in order to limit potential contamination. In order to prevent groundwater contamination through leachate infiltration, the selected landfill site must not be implemented on important aquifers that have high vulnerability such as shallow aquifers. According to Bolton (1995), aquifer depths less than 15.24 m should be considered less suitable. From the field data on water levels in wells in the study area, collected in March and April 2016, the piezometric surface layer was developed in ArcGIS from inverse distance-weighted interpolation. It was buffered into five depth intervals (<10, 10–20, 20–30, 30–40, and >40) that were scored in such a way that the deepest water table interval is the most suitable and vice versa (Fig. 4c). All depth buffers were weighted by AHP method (Table 1).

Land use

The landfill site must not be located close to or inside the forest or agricultural areas to avoid degradation and contamination of the soil which is a slowly renewable source. In this study, the spatial land use map was prepared after the classification of Landsat-8 optical satellite images by the supervised classification method and then converted in raster map of 30 × 30 m resolution. The highest score was given to the most appropriate areas for landfills including bare soils; however, forest and agriculture areas and the housing have a zero weight and are considered as constrained (excluded) areas (Fig. 4d).

Suitability map

In this study, land suitability for installation of the inter-municipal landfill was assessed by using Boolean, AHP,

and GIS approaches. Ten economic and environmental criteria were selected and used as constraints and/or factors. Finding suitable landfill sites was performed in two steps. In the first step, the Boolean analysis was used to distinct between “suitable” and “unsuitable” areas, based on constraint criteria. Through overlapping Boolean maps of each exclusion criteria, the final constraint map was generated with the excluded areas and the most candidate areas for landfill sites (Fig. 5). From this map, we noticed that 54% (533,200 ha) of the study area is considered unsuitable and 46% (454,200 ha) could be taken into consideration. High elevation and steeper slopes of the mountain areas represented the most important constraints criteria that reduced the suitability of landfill sites. Also, these mountain areas showed a dense forest cover with high biodiversity. This further restricted the use of these areas for landfill installation. While 10% of the study area presents small variation in slope and lack of forest cover, 40% of it consists of agricultural lands. These lands occupying the Tadla basin located between the Béni Mellal Atlas and the phosphates’ plateau are characterized by high fertility that allows them to be used largely for intensive farming and consequently limits their use for landfilling. The phosphates’ plateau has land undeveloped and very little fertile which restricts, in addition to the lack of water, their use in modern farming purposes. Consequently, these areas which represent 20% of the total surface could be considered as suitable areas for landfills.

In the second step, after eliminating sites considered by the Boolean approach to be unsuitable for landfilling, the analysis would only concern the remaining suitable zones in order to identify potential landfill sites. It has been

conducted taking into account a combination of various factors, sub-factors, and alternatives. The weight of each criterion was determined by AHP, and then the land suitability index (LSI) for landfill location was calculated by the mathematical formulae described as follows:

$$\begin{aligned} \text{LSI} = & [(A) * ((A_{1c_{wi}} * A_{1sc_{wi}}) + (A_{2c_{wi}} * A_{2sc_{wi}}) \\ & + (A_{3c_{wi}} * A_{3sc_{wi}})) + (B) * ((B_{1c_{wi}} * B_{1sc_{wi}}) \\ & + (B_{2c_{wi}} * B_{2sc_{wi}}) + (B_{3c_{wi}} * B_{3sc_{wi}}) \\ & + ((B_{4c_{wi}} * B_{4sc_{wi}}) + (B_{5c_{wi}} * B_{5sc_{wi}}) \\ & + (B_{6c_{wi}} * B_{6sc_{wi}}) + (B_{7c_{wi}} * B_{7sc_{wi}}))] \end{aligned}$$

where LSI: Landfill suitability index; A : weight index of economic main criterion; $A_{1c_{wi}}$: weight index of distance to roads criterion; $A_{1sc_{wi}}$: weight index of distance to roads sub-criterion; $A_{2c_{wi}}$: weight index of elevation criterion; $A_{2sc_{wi}}$: weight index of elevation sub-criterion; $A_{3c_{wi}}$: weight index of slope criterion; $A_{3sc_{wi}}$: weight index of slope sub-criterion; B : weight index of environmental main criteria; $B_{1c_{wi}}$: weight index of aspect criterion; $B_{1sc_{wi}}$: weight index of aspect sub-criterion; $B_{2c_{wi}}$: weight index of distance to residential areas criterion; $B_{2sc_{wi}}$: weight index of distance to residential areas sub-criterion; $B_{3c_{wi}}$: weight index of geology (lithology) criterion; $B_{3sc_{wi}}$: weight index of geology (lithology) sub-criterion; $B_{4c_{wi}}$: weight index of distance to faults criterion; $B_{4sc_{wi}}$: weight index of distance to faults sub-criterion; $B_{5c_{wi}}$: weight index of distance to surface water criterion; $B_{5sc_{wi}}$: weight index of distance to surface water sub-criterion; $B_{6c_{wi}}$: weight index of groundwater table criterion; $B_{6sc_{wi}}$: weight index of groundwater table criterion; $B_{7c_{wi}}$: weight index of land use criterion; $B_{7sc_{wi}}$: weight index of land use sub-criterion.

From the AHP approach applied to comparing the weights of criteria at each main criterion and the weights of sub-criteria at each criterion, the weights and CR obtained are listed in Table 1. The CR values of all comparisons were less than 0.75, suggesting that the weights obtained are consistent. The results of the pairwise comparison used to obtain priorities between the economic criteria showed that the distance to roads is the most important criterion with a relative weight of 63.3%, followed by the elevation criterion, and then the slope criterion having the weights of 26 and 10.6%, respectively. For the environmental criteria, the weights of criteria with highest priority are 25.5% of land use, 22.1% of distance to residential areas, 20.7% of distance to surface water, and 19.4% of the groundwater table. The lowest weights of 2.1, 0.4, and 6.1% were calculated with regard to environmental concerns, for the aspect (wind), geology (lithology), and distance to faults criteria, respectively. The same priority whether for environmental or for economic criteria was highlighted by other studies using

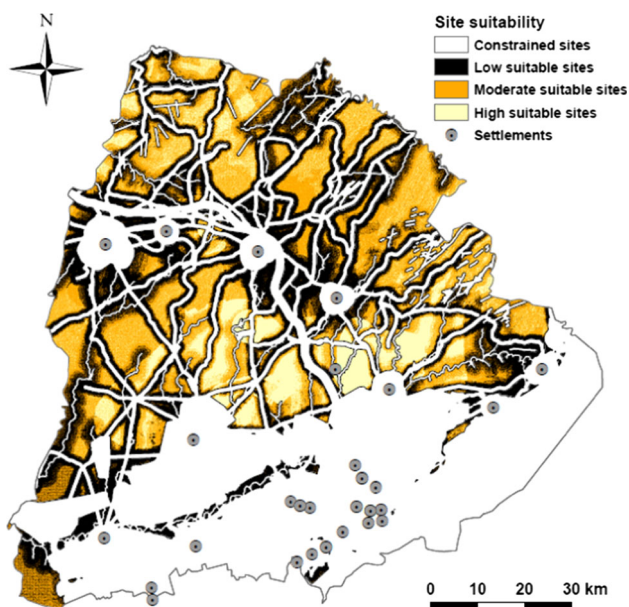


Fig. 5 Final landfill suitability map

similar method (AHP) for the landfill site selection (i.e., Moeinaddini et al. (2010); Şener et al. (2010)).

A thematic layer of each criterion was generated by using the ArcMap application in ArcGIS 10.22 software, and then the final suitability map for landfill sites was produced by overlapping all thematic layers using the weighted overlay technique in GIS (Fig. 5). The land suitability for landfill sites was classified by suitability index calculated using AHP weighting. The LSI values ranged between 0 and 0.382, knowing that the highest values of LSI indicate the most suitable areas for landfills. It is categorized using equal interval classification method in ArcMap into three suitability classes, i.e., highly suitable (LSI = 0.304–0.382), moderately suitable (LSI = 0.227–0.304), and lowly suitable (LSI = 0–0.227). Regarding the final suitability map, different appropriate areas were distinguished for landfilling (Fig. 3). As a result, about 54% of the study area is not suitable, about 12% had a very low suitability, and about 24% had a moderate suitability for landfill siting. Indeed 10% whole areas are highly suitable for landfill placement. This showed that despite the vast extent of the study area, the lands suitable for landfill remain sufficiently limited.

The results of the combination of GIS and MCE methods seem very consistent with our knowledge and field observations of the region. More than half of the surface of the study area, especially the southern part, is not suitable since there are agricultural (irrigated perimeter of Tadla plain) and forest lands. In the northern half of the region, soils are not better for agriculture, but are not well suited to intensive agricultural uses. However, they are handicapped by the remoteness, extraction of phosphate deposits, and the presence of several urban centers. The candidate sites are located in the center of the study region, almost halfway between the cities highly populated in the study area, which could play an important role in landfill site selection by minimizing the MSW transportation cost. With regard to socio-environmental concerns, the suitable sites are located typified by a small population widely dispersed. Also, the selected sites coincided mainly with collective land belonging to ethnic communities, facilitating their administrative expropriation in the public interest. However, a detailed feasibility study should be carried out on the most suitable sites before any landfill construction, in order to prevent conflicts between land users and to minimize all pollution risks. Other favorable sites located in the north of Khouribga Town are considered economically unsuitable for landfill sites due to their location far from the other agglomerations of the region and their small spatial extent.

To sum up, landfill site selection in the study area is a result of a combination of economic and environmental criteria by following a step-by-step methodology and while coupling GIS and MCE methods. It is important to notice

that the methodology was effective and provided correct results for the selection of landfill sites that are consistent with field observations. Furthermore, it is recommended that these sites be considered for further evaluation based on other local criteria and field studies prior to making final decisions on the best site, because some of these criteria need to be investigated in landfill sites, as reported in the landfill environmental impact assessment regulation. For example, the consultation of local residents and the detailed geological, hydrogeological, and geotechnical investigations will be performed to obtain good precision to the landfill site selection.

Some other studies emphasized that the judgment (weights) used in the analysis similar to this study was based on the experts' opinions and information on MSW management laws (i.e., Qdais and Alshraideh 2016; Babalola 2015) would produce different results. Moreover, methods designed based on MCE are developing to select landfill sites. Nevertheless, the AHP approach used in combination with GIS in this study could be seen interesting and can be adapted to a number of variables and scenarios. The clearest proof of this is that the obtained results are consistent with the reality on the ground. Our results, therefore, support the findings from the previous scientific literature, like those of Chabuk et al. (2017), Ghobadi et al. (2017), Rahmat et al. (2017) and Eskandari et al. (2012). Consequently and obviously, the applied approach in this study can be used as a guiding framework in a decision-making process of choosing the best option for MSW landfill site selection and provides a benchmark for future studies in other Moroccan or regional areas.

Conclusion

Landfill site selection requires evaluation and combination of various criteria controlling the land suitability for landfill siting. The present study was conducted to identify appropriate landfill sites in Béni Mellal-Khouribga Region based on ten environmental and economic criteria, i.e., 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. A comparison of such criteria was possible only with applying of MCE and GIS methods that are capable of handling different types of data.

The Boolean approach is used to categorize the study zone into suitable or unsuitable areas for landfilling. AHP method was applied to calculate the weight values of selection criteria based on their relative importance. The consistency of the AHP results is evaluated by the measurement of CR that is less than 0.75. From the overall weights calculated, the criteria of distance to residential

areas, distance to surface water, groundwater table, land use, and distance to roads are quite important criteria.

GIS was used to map each criterion and then to produce by overlay analyses of the final suitability map. The land suitability indicates that 54% of the study area is not suitable, 12% has low suitability, 24% has moderate suitability, and 10% has high suitability for landfill placement. The highly suitable sites are located in the center of the study region and, consequently, are marked as economically favorable with a view to minimizing the MSW transportation cost. Additionally, these sites also coincided with the collective owned land, facilitating their administrative expropriation. Even if we assume that this study gives accurate results for landfill site selection, further evaluation and some supplementary field studies including other local criteria, consultation of local residents and detailed geological, hydrogeological, and geotechnical investigations are recommended before making final decisions on the most suitable landfill sites.

The present study has demonstrated how the Boolean logic and AHP approach in MCE can be used to address the MSW management issues in the region due to its low cost and rapid execution. The methodology applied here gives more accurate results on the selection of suitable sites for landfill construction at Béni Mellal-Khouribga Region that are very consistent with the reality in the field. It can be used as a strategic decision supporting tool for decision makers, planners, and, especially, communes already struggling with limited budgets, but with the condition of having substantial goals and information about the main criteria used to assess the suitable landfill and their priority and ranking.

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