

Waste Management Future Planning in Iraq's Middle Euphrates Region through GIS-Based Multi-Criteria Decision Making for Optimal Landfill Siting

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ABSTRACT

The Middle Euphrates region comprises four provinces: Najaf, Babylon, Karbala, and Qadisiya. These Iraq's central region provinces severely suffer from poor solid waste collection and disposal systems. There is no landfill site that meets the environmental standards, and this has led to several open dumping practices all around the region which negatively impacted public and environmental health. The lack of national strategies and properly designed landfill sites necessitated urgent action to implement a sustainable waste disposal method. This study tackles this problem by finding some safe locations for sanitary landfill employing a combination of MCDM and GIS techniques. Selecting a landfill site involves many criteria and restrictions, making it a challenging process. So, a range of factors, including sixteen criteria, were determined and weighted using AHP and SRS methods. A suitability index map for potential landfill sites was created by integrating these criteria. The final suitability maps (AHP and SRS) indicated that the majority of the region falls within moderate-to-high suitability classes, and eight candidate landfill sites (two per province) were selected within the 'high' and 'most suitable' zones for possible land filling. The study contributes to future waste management planning in Iraq's Middle Euphrates Region by integrating GIS-based suitability analysis with projected waste generation and landfill capacity requirements up to 2040.

1. Introduction

Rapid population growth, urbanization, and economic development have led to constant increases in municipal solid waste generation, posing significant challenges for sustainable waste management in developing countries. Inadequate infrastructure, limited financial resources, and reliance on uncontrolled dumping or poorly managed landfills have raised environmental and public health risks, including soil and groundwater contamination, air pollution, and ecosystem degradation. Besides population growth, the increasing level of welfare and living standards are becoming the main cause of rising solid waste production in the world. The expansion of economic and manufacturing activities in urban areas has also increased waste generation, making the management of growing volumes of solid waste a critical challenge in modern urban environments. Waste management involves a range of techniques and processes for the collection, transportation, treatment, and final disposal of waste materials, with the objective of minimizing adverse environmental, economic, and public health impacts [1]. In low and middle-income countries, landfilling is the most practical waste management option due to its relatively low costs, ability to handle unsorted waste, and lower technical requirements compared to other methods [2]. Therefore, landfilling, whether through multiple local sites or a single centralized facility, remains the most common disposal method in developing countries. When properly engineered, landfills represent a significant environmental improvement over open dumping. Therefore, sanitary ground-based landfilling is generally preferred over

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open space waste dumping everywhere [3].

Solid waste management also involves waste gathering generated by industrial, commercial, residential, and public sectors. It represents a technical and systematic approach aimed at conserving natural resources by minimizing resource consumption and promoting waste reduction, reuse, and recycling. This framework ensures that all waste materials, whether solid, liquid, gaseous, or radioactive, are properly handled, treated, and disposed using appropriate methods to minimize their adverse impacts on the natural environment [4]. The importance of these systems has grown in parallel with industrial and societal development of our communities. At the beginning of the industrial revolution, better understanding of disease caused vaccination, sanitation systems, and public health contributing to lower mortality rates, particularly among children, and increasing average life expectancy. While at the same time, the rise of consumerist culture has contributed to an increase in the production of various types of wastes and their related diseases [5]. Hence, municipal systems must adapt effective approaches to preserve public health, hygiene, aesthetics, economic stability, and the environmental quality while the cities are developing [6]. Consequently, proper waste disposal through accurate and careful siting of the disposal facility has become crucial.

When selecting a site, numerous factors must be considered, such as population growth, governmental laws, social and environmental regulations, public health and safety issues, together with funding limitations from state and municipal sources [2]. Moreover, increasing the environmental awareness, limited land availability for waste disposal, and rising social and political opposition to regional landfill sitings are emerging challenges in this field [7, 8]. In landfills, the biological breakdown of buried organic material generates methane gas and leachate [1]. Waste disposal also leads to the release of toxic and other greenhouse gases, and it will contribute to global warming and environmental degradation to large scales [9]. All these limitations make landfills a transitional pathway toward more advanced integrated waste management systems in the intermediate term. Over the longer term, however, municipal waste disposal methods are expected to evolve towards more advanced and sustainable options, including waste incineration, large-scale composting, anaerobic digestion, and integrated recycling systems. The share of each may differ across regions, and decisions are made based on the amount of waste generated, waste composition, technological needs, and the urban planning capacity. Landfilling is easier to implement than other methods, and in general, it is inevitable in many cases. Therefore, even in countries with diverse waste management approaches, landfills continue to be essential for disposing of unusable or residual waste [10]. They also play a significant role in energy recovery from organic waste like an active bioreactor, which remains an ongoing concern [11]. So alongside the novel methods, i.e., waste reduction, recycling, reuse, composting, and energy recovery, landfilling is still and most probably in the future will be considered as an alternative for municipal waste disposal [12]. This approach involves the controlled burial of waste in the ground with multiple engineering measures to limit leachate and gas emissions [13]. Although landfill design and operational requirements are well documented in standards, guidelines, and technical handbooks [2], landfill siting remains a location-specific decision that must account for regional characteristics, country-specific regulations, and local constraints, necessitating modern methods and advanced tools [6, 7]. Recent studies have increasingly applied integrated remote sensing (RS), geographic information systems (GIS), and multi-criteria decision making (MCDM) techniques for municipal landfill site selection. Methodological transparency, robustness checking, and the production of planning-oriented outputs to support decision-making in data-scarce contexts are what are specifically emphasized in these studies [7, 14–17]. Amirsoleymani et al. [7] evaluated spatial restrictions for urban sanitary landfill siting in Mazandaran Province, Iran, using an integrated GIS and Analytic Hierarchy Process (AHP) approach. Environmental, geological, hydrological, and socio-economic criteria were weighted using expert judgment and spatially analyzed to identify suitable areas in accordance with Iran's national regulations. Elkhachy et al. [14] employed RS data combined with GIS-based MCDM to identify suitable landfill sites in Najran City, Saudi Arabia, demonstrating the effectiveness of spatial analysis in addressing environmental and socio-economic constraints. Similarly, Saha and Roy [15] applied an RS–GIS-based MCDM framework to identify suitable waste disposal sites in Cooch Behar Municipality, India, aimed to help sustainable site selection under rapid urban growth. Sharma et al. [16] proposed an integrated GIS–MCDM framework incorporating zoning, ranking, and sensitivity analysis, highlighting the importance of robustness and decision reliability in landfill siting processes. In more complex regions, Chaturvedi et al. [17] combined RS–GIS tools with AHP and VIKOR methods to address landfill site selection challenges in hilly regions, demonstrating improved decision accuracy under topographic constraints. Collectively, these studies confirm that integrated GIS–MCDM approaches provide systematic and reliable tools for environmentally sound and socially acceptable landfill site selection.

It is worth noting that although sanitary landfills are accepted worldwide as a proper waste disposal method, they are not a common practice in Iraq, where open dumping is still widely used. Limited financial resources and lack of regulatory enforcement and strategic national waste management plans, besides geological and hydrological difficulties, such as shallow groundwater levels in many areas, seem to be the reason of prevalent open dumping traditions there. However, there are ongoing efforts in some Iraqi governorates to identify and develop suitable sanitary landfill sites based on the future scenarios and tourist activities variable [1, 8, 18]. This study aims to determine the optimal landfill sites in the Middle Euphrates region by applying key criteria aligned with ecological and technological regulations. Despite the extensive application of GIS–MCDM techniques in landfill siting studies, regional-scale analyses comparing multiple weighting approaches within a region remain limited, particularly in data-scarce contexts like Iraq. This study contributes to fill this gap in Iraq by jointly applying AHP and SRS methods within a GIS environment to support regional landfill planning across four provinces, while linking suitability outcomes with long-term waste generation and capacity projections up to 2040.

2. Study area

The study area of this paper is located within Iraq, a country in Western Asia bordered by several nations in the Middle East

region. Iraq covers an area of approximately 438,000 km² and exhibits diverse climatic, topographic, and hydrological conditions. The country experiences predominantly hot summers and mild to cool winters, with precipitation varying significantly across regions. In recent decades, the country has experienced rapid population growth and urban expansion, causing increasing pressure on infrastructure systems, particularly municipal solid waste management. The study region comprises four provinces: Najaf, Babylon, Karbala, and Qadisiya of the country of Iraq. Together, these provinces form the majority of the Middle Euphrates area, spanning about 47,426 km² and accounting for 10.82% of Iraq's total area (Fig. 1).

Al-Najaf Province is located in southern Iraq within the Mid-Euphrates Region. It is in a desert area, with an elevation of 70 meters above sea level [18]. The province borders Saudi Arabia externally. It spans roughly 28545 km² and has a population of 1,778,739 in 2024 [19]. It accounts for 6.6% of Iraq's total land area and is located at coordinates latitudes 31° 59' 16" N and longitudes 44° 19' 40" E. For administrative purposes, Al-Najaf is divided into three districts i.e., Al-Najaf, Al-Kufa, and Al-Manathera [20]. Babylon Province is one of the most renowned ancient cities worldwide. Founded 4,100 years ago, Babylon served as the political centre of a vast and influential empire [21]. It spans an area of 5337 km² in central Iraq, approximately 100 km south of Baghdad, situated at coordinates longitudes 44° 25' 28" E and latitude 32° 28' 00" N. Based on census data from 2024, approximately 2,702,600 residents live within this province, distributed across its cities [22]. The primary district in the Babylon Province includes Al-Hillah, Al-Musayib, Al-Mahawil, Al-Qasim, and Al-Hashimiyah [23]. These primary cities are connected to sixteen smaller towns. Karbala Province covers 4,986 km² and has a population of approximately 1,418,950 people [22]. It is centrally located in Iraq between 44° 01' 48" E longitude and 32° 37' 12" N latitude. The area includes three districts: Karbala, Ain Al-Tamur, and Al-Hindiya. Muslims consider Karbala a sacred city because it contains some holy shrines for Shia Muslims. Each year, millions of pilgrims participate in various events in Karbala City. During the major gathering, Al-Arba'een, over 20 million pilgrims travel to Iraq for 15 to 20 days [23]. Al-Qadisiyah Province, also known as Al-Diwaniyah, is a major city located in south-central Iraq. It lies at latitudes 31°59'00", and longitudes 44° 55' 00" E [24]. The province covers an area of 8558 km² and is divided into four primary districts, which include fifteen administrative regions, Al-Diwaniyah, Al-Shamiya, Afak, and Al-Hamza, and eleven sub-districts [25]. According to data from the Iraqi Ministry of Planning [22], the population is 1,430,714. These four provinces have implemented identical waste management strategies and are facing similar issues and challenges. A shared problem among all of them is the mismanagement in the collection, transportation, and disposal of municipal solid waste into standard sanitary landfills.

This study tries to estimate municipal waste generated in the Middle Euphrates Provinces by following a series of steps and calculations derived from recent local studies. The data collected enables the projection of waste generation up to 2040 (period of 2024-2040), considering a 2.5% annual population growth. The daily waste per person for the four provinces was estimated using data over the past five years, assuming a yearly increase of 1% in waste generation rates [19, 26]. The waste generated by visitors in Al-Najaf Ashraf and Holy Karbala was estimated too [23]. For calculating the area required for each landfill, the study assumed that 60% of the total waste comprises biodegradable materials, primarily organic components. This figure is grounded in prior research examining urban waste composition across the four provinces in the study region [27]. Accurately estimating the total volume of solid waste that requires disposal is a critical step in selecting appropriate landfill sites. To find optimal landfill site in each region spatial analyses were carried out within the GIS environment, utilizing consistent spatial referencing and raster processing settings to maintain methodological coherence.

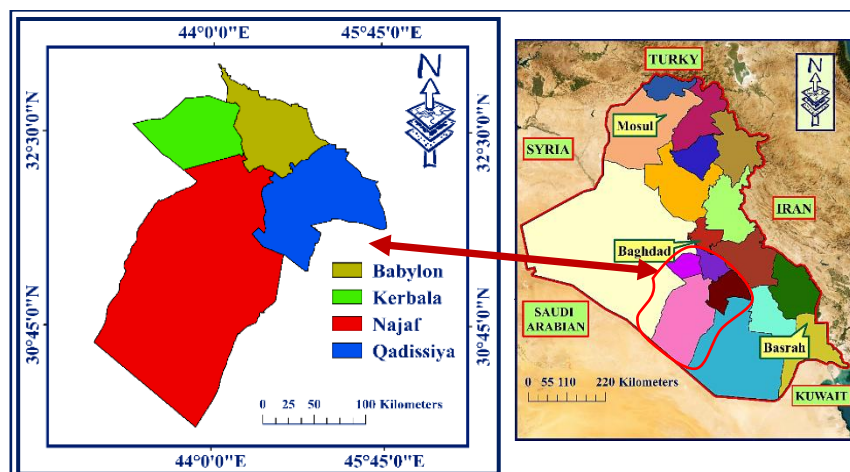


Fig. 1. The study area (Middle Euphrates region) consists of four provinces.

3. Material and methods

3.1. Conceptual model and hierarchies

Fig. 2 presents a summary of the proposed model designed for identifying landfill sites across the four Middle Euphrates Provinces in Iraq. It shows a structured framework that integrates environmental, technical, social, and economic factors to identify and compare suitable locations for a landfill. Environmental Criteria like the location of rivers, slope, land use, soil types, ground water level, etc are the core components of this conceptual model while technical and social-economical criteria like distance from residential areas (cities and villages), cultural sites, airport, refineries, power lines and accessibility to the site are other

complementary criteria. For the criteria, there are some absolute exclusion or buffer zone requirements to protect lands. Some countries have strict and clear national and regional environmental laws for the exclusions while Iraq lacks such detailed national regulations specifically for landfill siting and relying instead on broader environmental laws and plans that emphasize general protections. This step by step model first eliminates areas that violate legal and environmental constraints obtained through the literature and previous studies and do the suitability analysis for the remaining areas using weighted criteria and finally rank and classify the areas. The candidate sites compare for the accessibility and ownership ability and preferred site with minimum area needed for the waste produced along the period of operation will be selected. The processing steps of GIS, including buffering, distance mapping, reclassification, and weighted overlay, are described below in detail to ensure reproducibility.

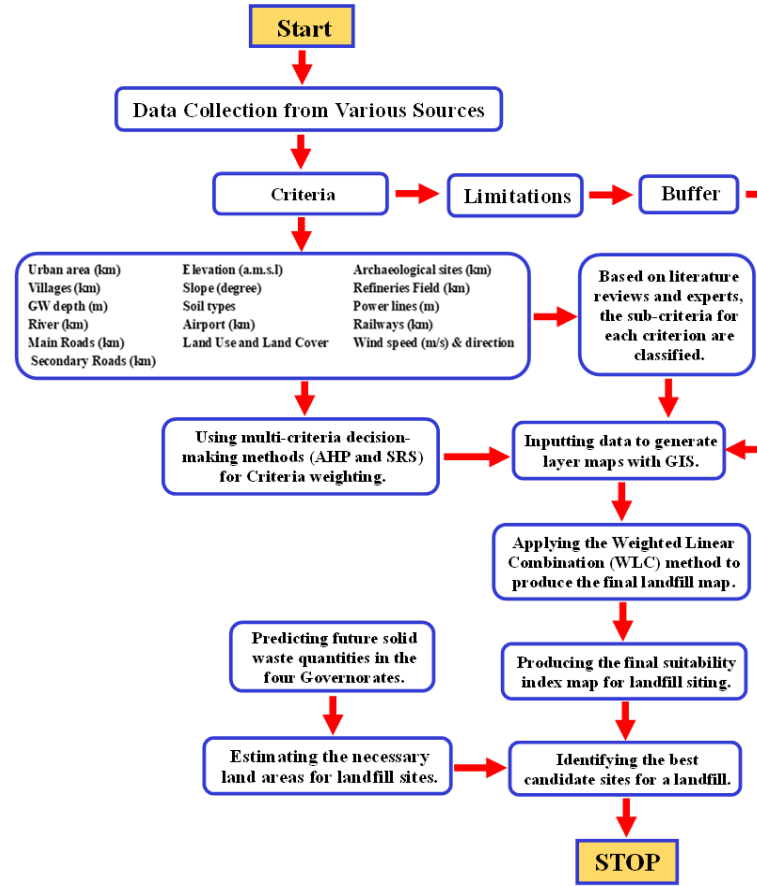


Fig. 2. Landfill site selection model and hierarchy of decision-making.

Environmental and artificial factors for landfill siting in the study area illustrated in Fig. 3. Although there are many potential criteria, using all of them is neither practical nor scientifically possible. Some out of many will be selected based on the scale and purpose of the study, legal and regulatory requirements, direct influences on environmental and public health risk, conditions of study region and expert local knowledge and judgment. Therefore, between numerous criteria proposed for landfill siting in the literature, only a limited number were selected in this study. The selected criteria represent the most influential, non-redundant factors, technical feasibility, and regulatory compliance at the regional planning scale.

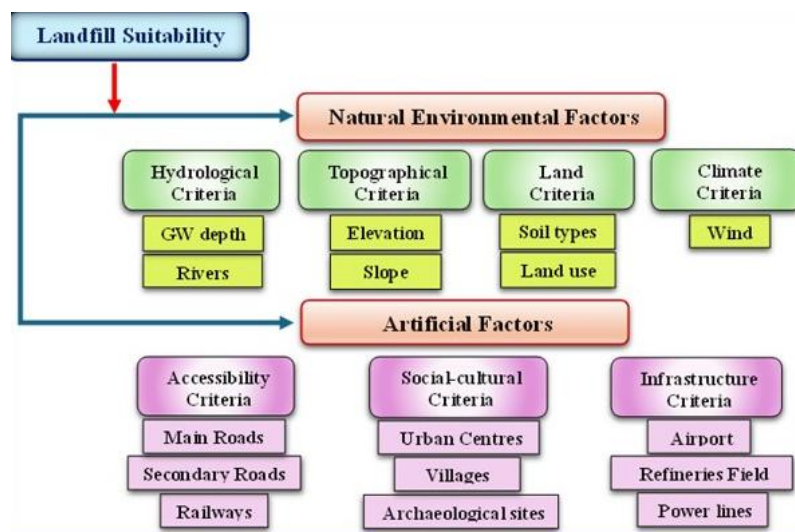


Fig. 3. Environmental and artificial factors for landfill siting in the study area.

3.2. GIS map layers

Various methods were employed in this study to generate the necessary map layers within GIS software. The first approach focused on creating individual shape files for various features, including urban areas, rivers, primary and secondary roads, villages, elevation, slope, power lines, refinery fields, and railways. The second technique utilized published information maps comprising geometric polygons representing locations, along with data stored in shape files, such as the soil types, sourced from Iraq's exploratory soil map, created at a scale of 1:1000000 [28] and the archaeological map of Iraq at the scale of 1:1500000, based on the World Digital Library, which is used to pinpoint archaeological and religious sites across the study provinces. The third approach uses kriging, an advanced spatial interpolation method, within ArcGIS's spatial analysis tools. It helps fill gaps between known data points, offering a more detailed view of spatial relationships. This method was used to generate a groundwater depth map from data collected from 222 wells across four provinces, based on information from the Iraqi Ministry of Water Resources [22]. The generated maps are used to convert vector maps into raster format, enabling easier provision and visualization of the raster data. All spatial datasets were processed within the ArcGIS environment (ArcGIS version 10.8) using the Spatial Analyst extension. A unified coordinate reference system (CRS) was applied to all layers (WGS 84 / UTM Zone 38N), and all raster datasets were resampled to a consistent spatial resolution of 30×30 m to ensure spatial compatibility prior to buffering, reclassification, and weighted overlay analysis. GIS operations including Euclidean Distance, Buffer, Reclassify, Raster Calculator (Map Algebra), and Weighted Overlay were applied systematically to generate standardized suitability layers.

3.3. Criteria selection

In the study, sixteen distinct criteria were created as layers encompassing the study region. Various GIS processes, including buffering, clipping, extracting, overlaying, proximity analysis, converting, reclassifying, and map algebra, were performed to generate the final layers, with each criterion being categorized within GIS. Based on earlier research and expert opinions, each class has been assigned an appropriateness rating, as presented in Table 1. For each criterion, the geographical feature or key location was encircled by a buffer zone. To develop the criteria map layers within the GIS framework, the entire study area was divided into several zones. Subsequently, the buffer maps were converted into raster maps using the following process.

A digital GIS database was created, and the exclusion zones were set up to enforce mapping restrictions. It helps to establish appropriate buffer zones or specific restrictions around the key areas to meet all criteria on the maps. MCDM models are used to identify the most suitable option by assigning weights to each criterion according to its relative importance in achieving the research objectives. Sub-criteria weightings are established based on literature, expert judgment, and environmental laws and regulations. To develop an effective index map and indicate the priorities for landfill site selection, all weighted criteria derived from AHP and SRS methodologies within GIS were overlaid.

Table 1. Suitability score for each selected criterion and its sub-criteria.

No.	Criteria	Buffer zone	Rating values	Notes
1	Urban area (km)	0 – 5 km	0	Buffer zone of 5 km [29-31]
		5 – 10 km	10	
		10 – 15 km	7	
		> 15 km	4	
2	Villages (km)	0 - 1 km	0	Buffer zone of 1 km [31, 32]
		> 1 km	10	
3	Groundwater Depth (m)	0 – 3 m	4	>30 m [33]; > 15 m [34]; 10 m [35]
		3 – 10 m	6	
		10 – 30 m	7	
		30 – 50 m	8	
		50 – 75 m	9	
4	Rivers (km)	0 - 1 km	0	Buffer zone of 1 km [32, 36, 37]
		> 1 km	10	
5	Main Roads (km)	0 - 0.5 km	0	Buffer zone of 1 km [38, 39]
		0.5 – 1 km	7	
		1 – 2 km	10	
		2 – 3 km	5	
6	Secondary Roads (m)	> 3 km	3	Buffer zone of 100 m [40, 41]
		0 - 100 m	0	
		100 – 500 m	5	
		500 – 1000 m	7	
		> 1000 m	10	

7	Elevation (a.m.s.l)	7 – 91 m	9	An essential aspect in waste disposal is the sea level of the area. Locations that are much higher above sea level and incur high transportation costs are usually deemed unsuitable. Conversely, areas close to sea level are more vulnerable to water contamination and flooding risks [33, 40]
		91 – 182 m	10	
		182 – 273 m	7	
		273 – 364 m	5	
		364 – 455 m	4	
8	Slope (degree)	0° - 5°	10	The best slope of landfilling is 0–5° [30, 41, 42]
		>5°	6	
9	Soil Types	SH (34)	3	Brown soil, medium and shallow phase over gypsum Brown soil, deep phase Gypsiferous Gravel Soils River Levee Soils River Basin Soils, Silted Phase Basin Depression Soils Periodically Flooded Soils Haur Soils Silted Haur and Marsh Soils Active Dune Land Mixed Gypsiferous and Desert Land Sand Dune Land Stony desert land Saline lake bottom land River Basin Soils in the Poorly Drained Phase
		SW (35)	4	
		S1	1	
		S4	5	
		S5	7	
		S6	9	
		S7	10	
		S8	9	
		S9	6	
		S11	4	
		S17	2	
		S18	3	
S20	6			
S21	3			
S5'	8			
10	Airport (km)	0 - 5	0	Buffer zone of 5 km [32];3 km [40, 43]
		5 - 10	5	
		> 10	10	
11	Land-Use (LU)	Water bodies	0	Land-use (LU) items were adopted according to [39, 44, 45]
		Build up areas	0	
		Agriculture & Fertile	0	
		Unused lands	10	
12	Archaeological sites (km)	0 - 1 km	0	Buffer zone of 1 km [32, 36, 42]
		1 – 3 km	5	
		> 3 km	10	
13	Refinery fields (km)	0 – 5 km	0	Buffer zone of 5 km [32, 41, 44]
		> 5 km	10	
14	Powerlines (m)	0 – 30 m	0	Buffer zone of 30 m [37, 41]
		> 30 m	10	
15	Railways (km)	0 - 0.5 km	0	Buffer zone of 500 m [9, 41, 46]
		> 0.5 km	10	
16	Wind speed (m/s) & direction	2.19 - 2.42	5	In Al-Najaf City In Babylon City In Al-Qadisiya City In Karbala City Sites should be located away from residential areas, taking into account the prevailing wind direction [36]
		1.93 - 2.19	6	
		1.64 - 1.93	7	
		≤ 1.64 m/s	8	

The maps of sixteen GIS layers are as follows. "Urban Area" in which buffer zone was divided into four categories, as illustrated in Fig. 4a, ranging from 0 - 5 km, 5 - 10 km, 10 - 15 km, and over 15 km. These categories were scored as 0, 10, 7, and 4, respectively. The buffer zones in the "Villages" layer, extending from each village to the landfill site, have been categorized into two classes: 0-1 km and over 1 km. These categories were assigned scores of zero and ten (Fig. 4b). For "Groundwater Depth", potential sites were assigned rating grades of 4, 6, 7, 8, 9, and 10 based on depths of 0 - 3 m, 3 - 10 m, 10 - 30 m, 30 - 50 m, 50 - 75 m, and more than 75 m, respectively (Fig. 4c). The "River" grading criteria assigns a zero score to the buffer zone within 0-1000 m from the river boundary, and a score of 10 for zones beyond 1000 m, indicating surface water protection from contamination (Fig. 4d). The buffer zones of the "Main Road" layer, which extend from roads to landfill sites, are categorized into five distinct ranges, as shown in Fig. 4e. The ranges are 0 - 500 m, 500 - 1000 m, 1000 - 2000 m, 2000 - 3000 m, and over 3000 m, with respective scores of 0, 7, 10, 5, and 3. The buffer zones of the "Secondary Road" layer, which extend from roads to landfill sites, are divided into four categories, as shown in Fig. 4f. The zones are categorized as 0 - 100 m, 100 - 500 m, 500 - 1000 m, and over 1000 m, with scores of 0, 5, 7,

and 10 assigned accordingly. The Elevation map (Fig. 4g) contains mean sea level (a.m.s.l.) related calculations. The elevation values were 9, 10, 7, 5, and 4, classified into five categories (a.m.s.l.) of 7-91, 91-182, 182-237, 237-364, and 364-455, respectively. Elevations from 91 to 182 (a.m.s.l.) were considered the most suitable elevation for landfill siting, whereas those between 7 and 91 (a.m.s.l.) were considered only appropriate. To prepare the "Slope" layer map, areas with slopes of 0–5 degrees were assigned a score of 10, while those with slopes of 5–15 degrees received a score of 6 (Fig. 4h). The soil in the Middle Euphrates is composed of alluvial deposits, which are detrital materials. These deposits extend over the entire region to a depth of more than 50 meters, with no bedrock exposed [47]. Furthermore, the soil shows no evidence of cracks or faults. Therefore, the Middle Euphrates area is not classified as a seismic hazard zone [48]. According to Buringh [28], the 'Soil Types' layer in the study area includes fifteen different types (Fig. 4i). These include Brown soil with medium and shallow phases over gypsum; Brown soil with deep phases; Gypsiferous Gravel Soils; River Levee Soils; River Basin Soils with Silted Phases; Basin Depression Soils; Periodically Flooded Soils; Haur Soils; Silted Haur and Marsh Soils; Active Dune Land; Mixed Gypsiferous and Desert Land; Sand Dune Land; Stony Desert Land; Saline Lake Bottom Land; and River Basin Soils with Poorly Drained Phase. Each has been assigned scores of 3, 4, 1, 5, 7, 9, 10, 9, 6, 4, 2, 3, 6, 3, and 8 based on their features. The buffer zone for the "Airport" layer was divided into three categories (Fig. 4j). The first category, covering buffer zones of fewer than 5 km around the airport, is prohibited and assigned a value of zero. The second category includes buffer zones of 5-10 km, which received a value of 5. The peak rate of 10 was given to buffer > 10 km.

The "Land Use Classification" (LUC) map of the study area was divided into four categories, shown in Fig. 4k: agriculture and fertile land, water bodies, unused lands, and built-up areas. Each category was assigned a score of 0, except for Unused Land, which received a score of 10. The buffer zone for the "Archaeological Sites" layer was categorized into three classes, as depicted in Fig. 4l. Areas within 1 km of archaeological sites were excluded and given a zero value. Buffer zones between 1 and 3 km received a value of 5, and those exceeding 3 km were assigned the maximum value of 10. The buffer zone of the "Refinery fields" map layer was categorized into two classes, as shown in Fig. 4m. The first category covers buffer zones of 0 - 5 km around oil and gas sites with a zero score, indicating it is banned. The second category, which includes buffer zones > 5 km, received a score of 10. The buffer zones of the "Powerlines" layer, which include areas from powerlines to landfill sites, were categorized into two classes (0 - 30 m and over 30 m) as shown in Fig. 4n. These classes were assigned scores of 0 and 10. The buffer zones in the "Railways" layer, which include areas from railways to landfill sites, are divided into two classes (Fig. 4o). These classes are 0-0.5 km and over 0.5 km, assigned scores of 0 and 10. For the "Wind Speed" layer map, wind speeds were categorized into four classes: 2.19-2.42 m/s, 1.93-2.19 m/s, 1.64-1.93 m/s, and below 1.64 m/s. These classes were assigned grades of 5, 6, 7, and 8, respectively (Fig. 4p).

3.4. MCDM weighting

MCDM methods improve decision quality by clarifying, streamlining, and making the decision-making process more rational. Think of multi-criteria decision making (MCDM) as a core component of modern decision science and operational research. It deals with many decision criteria and options, providing a range of choices that consider different factors [16, 44]. Once the criteria maps are completed in the GIS, the process of selecting suitable waste burial sites in the study area begins. Two different methods were employed to assign weights to the criteria, using various styles within the MCDM techniques to assess each criterion's importance. These approaches are among the most frequently used in MCDM. The use of MCDM methods consists of the pairwise comparison method (AHP) and the Ranking method (SRS). The following methods were employed to identify the key weights of the criteria.

- Analytical Hierarchy Process (AHP)

This method is considered to facilitate faster decision-making, to analyse data, and assign appropriate weights to the selected criteria. A key step involves constructing a pairwise comparison matrix to evaluate the relative importance of the selected criteria with respect to the overall decision goal. This method was used across all provinces in the Middle Euphrates region to select appropriate landfills, showing its strong theoretical basis. It employs a nine-point scale, frequently utilized in analytic hierarchy processes, which indicates the relative importance of two factors at each point (see Table 2). This allows decision-makers to evaluate the contribution of each factor for achieving the goal through pairwise comparisons, thereby streamlining the decision procedure [49].

Table 2. The relative importance in pairwise comparisons [50].

Importance Intensity	Definition
1	Equal importance
2	Equal to moderately important
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

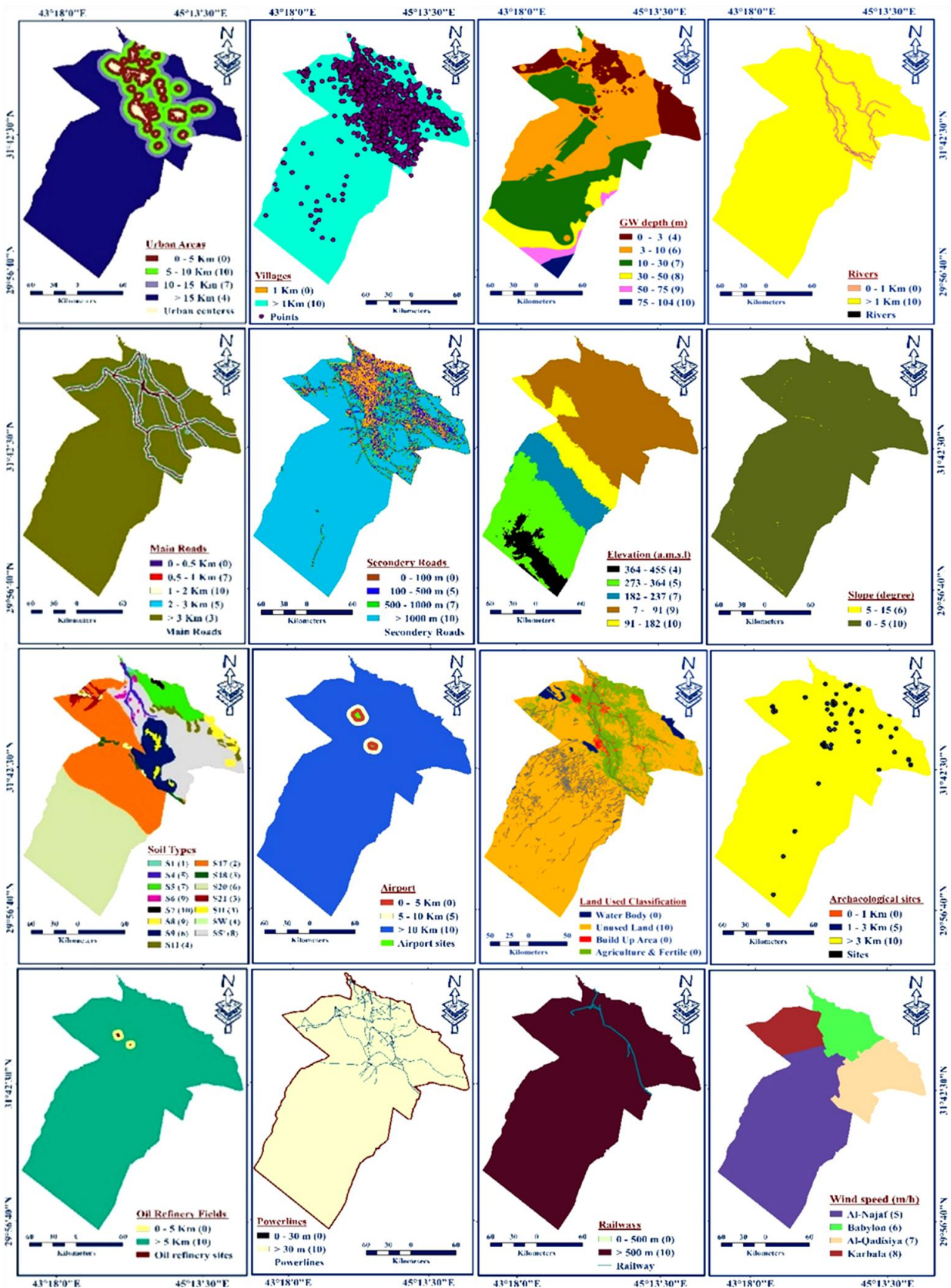


Fig. 4. Classified maps of the study area for (a) urban area, (b) villages, (c) GW depth, (d) rivers, (e) main road, (f) secondary road, (g) elevation, (h) slope, (i) soil types, (j) airport, (k) land use land cover (LULC), (l) archaeological sites, (m) Refinery fields, (n) powerlines, (o) railways, (p) wind speed.

In this study, the pairwise comparison matrix was constructed to compare the relative importance of the selected criteria, resulting in an $n \times n$ matrix, where n represents the total number of criteria ($n = 16$). Uyan [32] indicated that the elements of the pairwise comparison matrix are denoted by a_{ij} , where $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$. The comparison values are placed in the upper triangular part of the matrix, while the reciprocal values are used to fill the corresponding entries below the diagonal, as expressed in Eq. 1:

$$a_{ji} = \frac{1}{a_{ij}} \tag{1}$$

where a_{ij} is the element of the matrix representing the relative importance of the criterion i over criterion j .

The significance of the criteria from the standard comparison matrix can be illustrated in a matrix for decision-making on any problem using the method outlined below. This process involves multiplying each row of the original pairwise comparison matrix by the value of each criterion in the corresponding column for that row, applying the same multiplication across all rows. It is expressed using Eq. 2:

$$Eg_i = \sqrt[n]{a_{11} \times a_{12} \times a_{13} \times \dots \times a_{1n}} \tag{2}$$

where n is the number of criteria and Eg_i represents the geometric mean of the pairwise comparison values for the criterion i . To obtain the priority vector (Pr_i), the geometric mean values are normalized by dividing each component by the sum of all geometric mean values, as shown in Eq. 3:

$$Pr_i = \frac{Eg_i}{\sum_{k=1}^n Eg_k} \tag{3}$$

The maximum eigenvalue (λ_{max}) was estimated based on the weighted sum of the pairwise comparison matrix and the derived priority vector, following the standard AHP procedure described in the literature.

$$\lambda_{max} = \sum_{j=1}^n WC_j * \sum_{i=1}^m a_{ij} \tag{4}$$

where, WC_j means the weighting value for each criterion, corresponding to the priority vector of the matrix. Here, i and j range from 1 to m and n , respectively. Additionally, a_{ij} indicates the sum of the criteria for each column of the matrix. The λ_{max} value in this study is 16.66. Lastly, Eq. 5 is employed to calculate the consistency index (CI):

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{5}$$

This study shows that the CI is 0.0446, which indicates the variability of the estimated mistake around the actual value. As per Sólnes [51], n indicates the size of the matrix for the comparison components, while CI denotes the mean deviation. Alonso and Lamata [52] provided the average random index (RI) for matrices of various sizes in Table 3. Since this study involves 16 criteria, the RI value for $n = 16$ is 1.5978.

In this study, the consistency ratio (CR), which was 0.0279, is determined by dividing the consistency index (CI) by the random index (RI), as illustrated in Eq. 6.

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

According to Coyle [53], a CR of zero indicates perfect consistency in any matrix, while Setiawan et al. [54] state that a CR above 0.1 suggests the need to reconsider or reverse the pairwise comparisons. In this study, sixteen criteria were used to create the pairwise comparison matrices. The calculated CR was 0.0279, which is well below 0.1, indicating a reasonable level of consistency in the current pairwise comparisons. Additionally, the RI value for $n = 16$ was estimated at 1.5978 for all matrices.

Table 3. RI for different values of n [52].

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59	1.59

Table 4 shows the priority vector and weight values for each criterion involved in the decision-making process. The study assessed the significance of each criterion compared to others, based on input from experienced field experts. Each criterion received a weight reflecting its importance. These weights were then used to build the AHP matrix, which allowed for calculating the precise weight of each criterion.

Table 4. The matrix of random pairwise comparisons used to estimate landfill site criterion weights.

Criteria	UR	Villages	GW	River	M-Road	S-Road	Top.	Slope	Soil	Airport	Land Use	Arch.	Refinery	Power	Railways	Wind
UR	1	2	2	3	4	4	5	5	5	6	6	7	7	8	8	9
Villages	0.50	1	1	2	3	3	4	4	4	5	5	6	6	7	7	8
GW	0.50	1.0	1	2	3	3	4	4	4	5	5	6	6	7	7	8
River	0.33	0.50	0.50	1	2	2	3	3	3	4	4	5	5	6	6	7
M-Road	0.25	0.33	0.33	0.5	1	1	2	2	2	3	3	4	4	5	5	6

S-Road	0.25	0.33	0.33	0.5	1	1	2	2	2	3	3	4	4	5	5	6
Top.	0.20	0.25	0.25	0.33	0.5	0.5	1	1	1	2	2	3	3	4	4	5
Slope	0.20	0.25	0.25	0.33	0.5	0.5	1	1	1	2	2	3	3	4	4	5
Soil	0.20	0.25	0.25	0.333	0.5	0.5	1	1	1	2	2	3	3	4	4	5
Airport	0.17	0.20	0.20	0.25	0.333	0.33	0.5	0.5	0.5	1	1	2	2	3	3	4
Land use	0.167	0.200	0.20	0.25	0.333	0.333	0.5	0.50	0.5	1	1	2	2	3	3	4
Arch.	0.143	0.167	0.167	0.20	0.25	0.25	0.33	0.33	0.33	0.5	0.5	1	1	2	2	3
Refineryfield	0.143	0.167	0.167	0.20	0.25	0.25	0.33	0.333	0.33	0.5	0.5	1	1	2	2	3
Power	0.125	0.143	0.143	0.17	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.5	0.5	1	1	2
Railways	0.125	0.143	0.143	0.17	0.20	0.200	0.25	0.25	0.25	0.333	0.33	0.5	0.5	1	1	2
Wind	0.111	0.125	0.125	0.14	0.167	0.167	0.20	0.2	0.2	0.25	0.25	0.33	0.33	0.5	0.5	1

To determine the weights of criteria using the AHP, a structured questionnaire was employed. The questionnaire was distributed to 31 experts with professional backgrounds in environmental engineering, urban planning, and municipal solid waste management, as shown in Table 5. The respondents were selected based on their academic qualifications and practical experience in waste management and environmental planning. Individual pairwise comparison matrices were collected and aggregated using the geometric mean method to derive the final comparison matrix. The reliability of the collected judgments was evaluated for each using the consistency index (CI) and consistency ratio (CR), which confirmed an acceptable level of consistency.

Table 5. Expert profile and questionnaire summary used for AHP weighting.

Item	Description
Number of questionnaires distributed	31
Expert background	Environmental engineering, urban planning, GIS, and solid waste management
Professional experience	More than 5 years
Affiliation	Universities, municipalities, environmental and planning agencies
Questionnaire type	Structured AHP pairwise comparison questionnaire
Judgment aggregation method	Geometric mean
Reliability assessment	Consistency Index (CI) and Consistency Ratio (CR < 0.1)

The criteria weighting process was designed to ensure transparency and reproducibility by combining expert judgment with established guidance from the literature and relevant environmental planning considerations. Literature and regulatory guidelines were also used to define exclusion constraints and inform the relative importance of criteria, while the final weighting values primarily reflect the collective expert assessment of regional environmental and planning priorities. The assignment of weights to the criteria was based on the primary goal of minimizing environmental and public health risks while ensuring practical feasibility at the regional planning level. Criteria that are directly related to environmental protection and human exposure, such as distance from urban centers, groundwater depth, and proximity to surface water bodies, were given higher weights because they play a crucial role in preventing contamination and health impacts. In contrast, criteria associated with technical accessibility and infrastructure, including roads, power lines, and railways, received lower weights since these factors can be addressed through engineering solutions during the design and operation of landfills. The final weights represent a balanced integration of expert judgment, established landfill siting guidelines found in the literature, and regional planning considerations specific to the Middle Euphrates area.

- Straight Rank Sum (SRS) Technique

This technique is among several ranking methods utilized in multi-criteria decision-making analyses. Based on literature and expert judgment, it offers a straightforward approach for assigning weights to criteria by ranking them from most to least important using the expression $n - r_i + 1$. To standardize these weights, each criterion weight is divided by the total sum of all ranking values, which is obtained by summing $(n - r_g + 1)$ as shown in Eq. 7 [30, 44]:

$$W_i = \frac{n - r_i + 1}{\sum (n - r_g + 1)} \tag{7}$$

In Eq. 7, W_i is the normalized weight of the i th criterion, n is the total number of criteria ($n = 16$), and r_i is its assigned rank ($r_i = 1$ for the most important and $r_i = n$ for the least important). The summation term normalizes the weights so that $\sum W_i = 1$, and the resulting SRS weights are reported in Table 6.

Table 6. The weights assigned to criteria in the SRS method and their normalized values.

No.	Criterion	Criteria weights ($n - r_i + 1$)	Normalized weights (W_i)
1	Urban centres	16	0.1176
2	Villages	15	0.1103
3	Groundwater depth	14	0.1029

4	Rivers	13	0.0956
5	Main Roads	12	0.0882
6	Secondary Roads	11	0.0809
7	Elevation	10	0.0736
8	Slope	9	0.0662
9	Soil types	8	0.0588
10	Airport	7	0.0515
11	Land use	6	0.044
12	Archaeological sites	5	0.0368
13	Refinery fields	4	0.0294
14	Power lines	3	0.0221
15	Railways	2	0.0147
16	Wind	1	0.0074

The Weighted Linear Combination (WLC) method then calculated the appropriateness index for potential locations using the following formula:

$$Y_i = \sum_{j=1}^n W_j \times C_{ij} \quad (8)$$

where n represents the total number of criteria, Y_i is the suitability index, W_j indicates the criterion's relative importance weight, and C_{ij} is the grading value for criterion i [55].

Using the GIS “Map Algebra” tool, the WLC method was applied to generate the suitability index map. The standardized raster layers of each criterion were multiplied by their corresponding weights and subsequently summed to produce the final suitability index.

4. Results and discussion

The suitability index is developed using criterion weights derived from the Analytical Hierarchy Process (AHP) or the Straight Rank Sum (SRS) method, and by integrating both approaches within the GIS environment. These methods were used to quantify the relative importance of siting criteria, where AHP was based on expert judgment through pairwise comparisons, while SRS applied a direct rank-based weighting scheme. The weighted linear combination of the criteria was then used to produce a spatially continuous acceptability index, which was subsequently classified to identify suitable landfill sites. Table 7 presents the criterion weights obtained using both AHP and SRS methods. Some criteria were assigned higher weights under the AHP approach compared to the SRS method. The differences observed between the suitability results derived from the AHP and SRS methodologies reflect their distinct theoretical foundations and implications for regional planning. The AHP method relies on expert judgment and pairwise comparisons, which tend to emphasize environmentally sensitive criteria such as proximity to urban areas, groundwater depth, and surface water protection. Consequently, the AHP-based suitability map presents a more conservative spatial pattern, with a smaller proportion of areas classified as “most suitable”. In contrast, the SRS method adopts a linear rank-based weighting scheme that distributes importance more evenly across the selected criteria, resulting in a broader spatial extent of areas classified as high and most suitable. The comparison between these two approaches highlights the complementary strengths of each method and supports the use of both AHP and SRS in parallel. This combined application enhances the robustness of the decision-making process and provides a more balanced framework for regional landfill planning.

A numerical comparison of the derived weights further explains the observed differences between the AHP- and SRS-based suitability maps. For instance, environmentally sensitive criteria such as distance from urban centers and groundwater depth received noticeably higher weights under the AHP method (0.1929 and 0.143, respectively) compared to the SRS method (0.1176 and 0.1029), reflecting the stronger influence of expert judgment in emphasizing environmental protection. Conversely, criteria related to accessibility and physical characteristics, such as elevation and slope, exhibited relatively higher weights under the SRS approach due to its rank-based structure, which distributes importance more evenly across criteria. These numerical differences directly contributed to the more conservative spatial extent of high and most suitable areas in the AHP results, and the broader distribution observed in the SRS-based suitability map, as reflected in Table 8.

Table 7. Weight of criteria according to multi-criteria decision-making techniques (SRS and AHP).

No.	Criteria	AHP	SRS	No.	Criteria	AHP	SRS
1	Urban centres	0.1929	0.1176	9	Soil types	0.0463	0.0588
2	Villages	0.143	0.1103	10	Airport	0.0303	0.0515
3	GW depth	0.143	0.1029	11	Land use	0.0303	0.044
4	Rivers	0.102	0.0956	12	Archaeological sites	0.0203	0.0368
5	Main Roads	0.0704	0.0882	13	Refinery fields	0.0203	0.0294

6	Secondary Roads	0.0704	0.0809	14	Power lines	0.014	0.0221
7	Elevation	0.0463	0.0736	15	Railways	0.014	0.0147
8	Slope	0.0463	0.0662	16	Wind	0.0102	0.0074

The final suitability GIS map is obtained through a weighted overlay process, where each spatial criterion is standardized, weighted, and mathematically combined. This approach enables the integration of heterogeneous spatial datasets while preserving the relative importance of each criterion as determined by the decision-making framework. To facilitate interpretation and decision-making, the continuous suitability index was divided into seven categories. The classification was performed using the natural breaks (Jenks) method to ensure a data-driven separation of suitability classes. Each suitability class encompassed specific spatial extents, quantified as a percentage of the total study region. The classes include unsuitable areas, very low suitability, low suitability, marginally suitable, moderately suitable, high suitability, and most suitable. Fig. 5a and 5b display the suitability maps produced by the AHP and SRS methods, accompanied by Table 8. The lower suitability classes are primarily associated with areas constrained by environmental sensitivity and unfavorable physical conditions, such as proximity to surface water bodies or urban or rural zones. In contrast, areas classified as high and most suitable are generally associated with locations exhibiting favorable combinations of environmental protection, technical feasibility, and accessibility, indicating their higher potential for landfill development under the applied criteria.

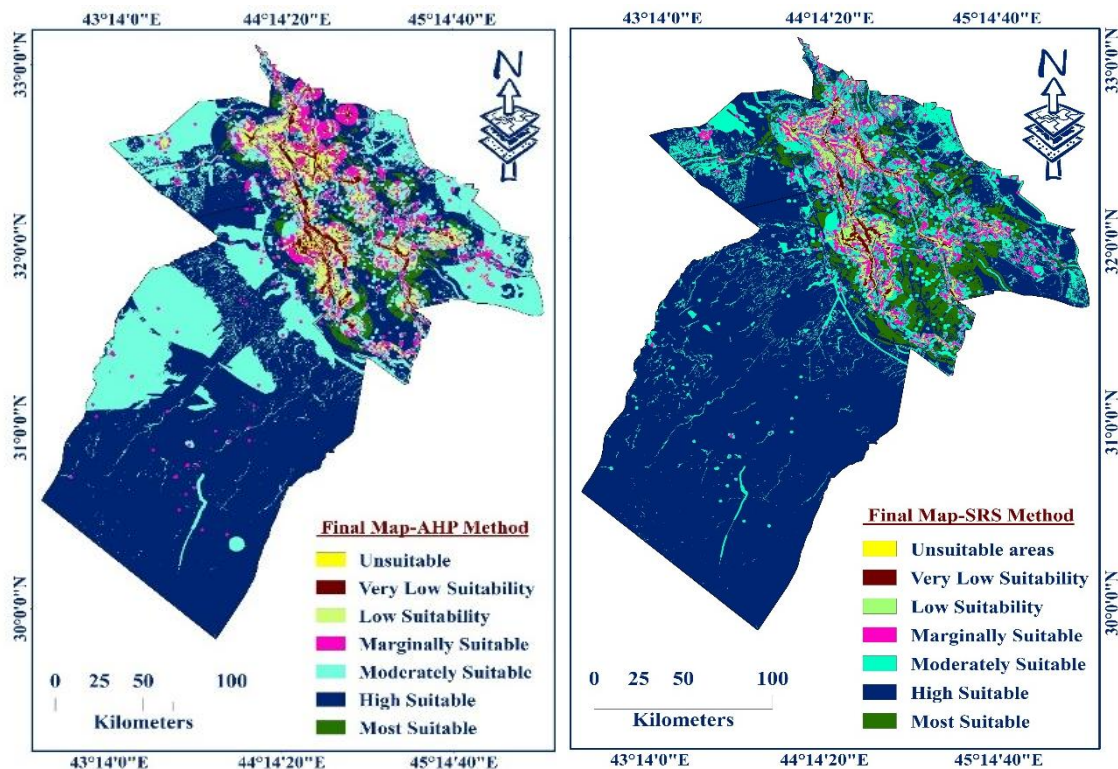


Fig. 5. Suitability final maps for landfill in the Middle Euphrates Region using (a) AHP, (b) SRS.

To enhance the reliability of the generated suitability maps, the distribution of unsuitable and low-suitability areas was qualitatively compared with established environmental and planning constraints, such as rivers, urban settlements, agricultural lands, and shallow groundwater zones. Additionally, the identified high- and most suitable areas were reviewed by domain experts to ensure their practical feasibility within the context of regional planning.

Table 8. The areas and their proportion of landfill maps classes in GIS, using AHP and SRS methods.

No.	Class	AHP method		SRS method	
		Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
1	Unsuitable areas	80.91	0.18	10.33	0.02
2	Very Low Suitability	808.15	1.70	347.03	0.79
3	Low Suitability	2130.08	4.50	1527.14	3.22
4	Marginally Suitable	2771.93	5.84	2490.23	5.25
5	Moderately Suitable	13550.89	28.57	7122.65	15.02
6	High Suitable	26750.09	56.40	32902.98	69.38
7	Most Suitable	1334.58	2.81	2999.27	6.32

The area of each suitability class was calculated directly within the GIS environment based on raster cell counting. Following the weighted overlay process, the final suitability maps were reclassified into seven classes, and the number of raster cells belonging

to each class was extracted. The area corresponding to each class was then computed by multiplying the number of cells by the area of a single raster cell. For example, if a suitability class contains N raster cells and each cell represents an area of A km², the total area of that class is calculated as $\text{Area} = N \times A$. The same procedure was consistently applied to both AHP- and SRS-based suitability maps, and the resulting areas and proportions are summarized in Table 8. The suitability index was also classified into seven categories to provide sufficient differentiation between unsuitable, marginal, and highly suitable areas while maintaining interpretability for regional planning purposes. This classification scheme is consistent with commonly adopted practices in GIS–MCDM landfill siting studies, allowing decision-makers to clearly distinguish between restricted zones and priority areas for potential development. The class thresholds were derived from the natural breaks in the continuous suitability index values generated by the weighted overlay process, ensuring a data-driven rather than arbitrary classification. The same classification framework was applied to both AHP- and SRS-based suitability maps to enable consistent comparison, and the spatial extent and proportion of each class are reported in Table 8. Model validation was conducted by two main methods: (i) ensuring that the 'most suitable' outputs do not overlap with exclusion zones, such as urban buffers, surface water buffers, and protected or archaeological areas, and (ii) having experts review the proposed candidate sites to confirm their practical feasibility at the regional planning scale.

In the Middle Euphrates region, the projected population for 2040 includes 4,012,025 residents in Babylon, 2,640,548 in Al-Najaf, 2,106,439 in Karbala, and 2,123,903 in Al-Qadisyiah. The anticipated solid waste production in these provinces by that year is calculated about 464,788 tons in Babylon, 290,061 tons in Al-Najaf, 243,583 tons in Karbala, and 224,570 tons in Al-Qadisyiah. Additionally, the total solid waste from 2024 to 2040 is projected to be 6,075,446 tons in Babylon, 3,854,826 tons in Al-Najaf, 3,292,411 tons in Karbala, and 2,935,457 tons in Al-Qadisyiah, based on calculations by Chabuk [19]. The solid waste density at disposal sites in the Middle Euphrates region is assumed to be 700 kg/m³, consistent with recent studies [19, 56, 57]. The total waste volume was therefore estimated as 8,679,209 m³ for Babylon, 5,506,894 m³ for Al-Najaf, 4,703,444 m³ for Karbala, and 4,193,510 m³ for Al-Qadisyiah, respectively. The volumes are obtained by dividing the cumulative solid waste quantity by the waste density.

According to Chabuk [19], the groundwater depth from the surface in the Middle Euphrates region is shallow. As a result, an average groundwater depth of 2 meters has been adopted for the candidate sites identified in the study. Based on this condition, the necessary area to hold the total produced waste from 2024 to 2040 in the study provinces is calculated as 4.34 km² for Babylon, 2.75 km² for Al-Najaf, 2.35 km² for Karbala, and 2.1 km² for Al-Qadisyiah. It should be noted that the assumed waste density and groundwater depth values represent average regional conditions. Therefore, detailed site-specific geotechnical and hydrogeological investigations are required prior to final landfill design and implementation. Based on these considerations, eight candidate landfill sites were proposed for the region, with two sites selected within each province to ensure balanced regional coverage. The selection was based on a combination of high and most suitable classes derived from both AHP and SRS methods, minimum area requirements calculated from projected waste volumes, accessibility considerations, and overall planning feasibility. The proposed sites span areas of 6.1 and 7.4 km² in Babylon, 7.2 and 6.0 km² in Qadisyiah, 7.3 and 6.8 km² in Al-Najaf, and 5.6 and 5.0 km² in Karbala, as illustrated in Fig. 6.

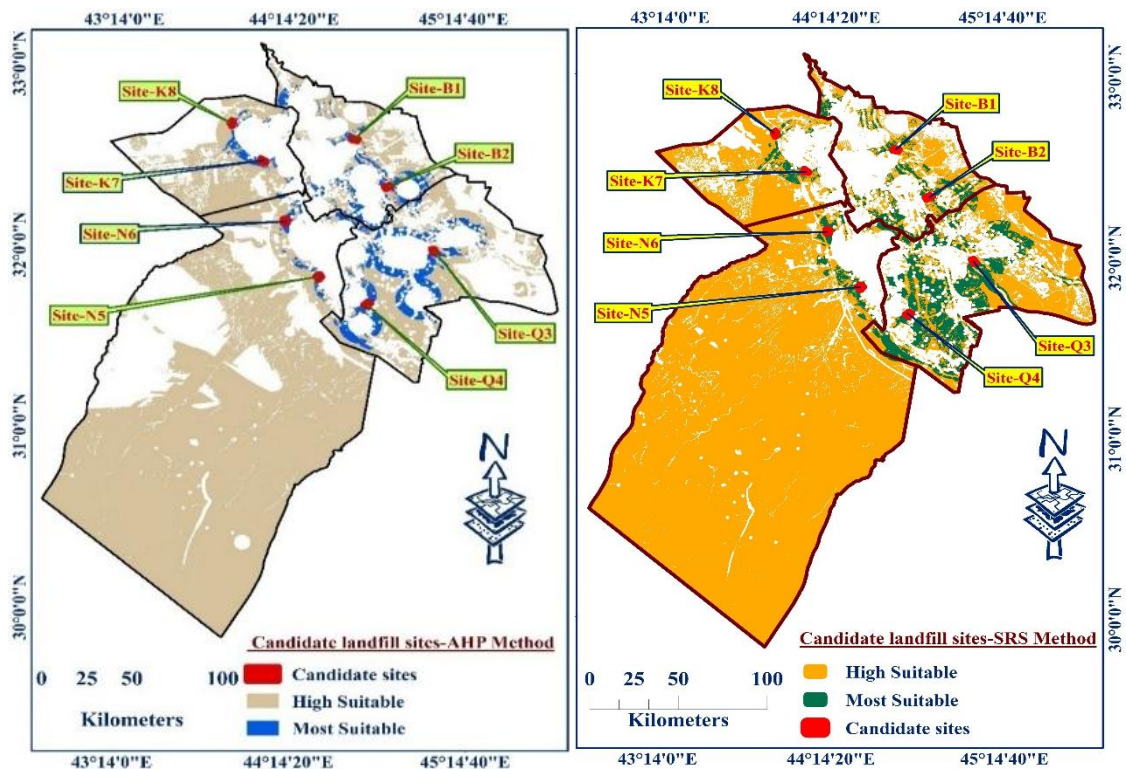


Fig. 6. Candidate landfill sites within the high and most suitable classes using MCDM methods.

Table 9 presents the spatial extent of the identified candidate landfill sites alongside the land area available there to accommodate the total volume of waste generated in the Middle Euphrates provinces over the period of 2024–2040. It should be noted that the calculated landfill area is based on waste volume and assumed landfill geometry, and therefore represents a minimum theoretical

requirement. In practice, the total land area needed for landfill is substantially larger due to the inclusion of other infrastructure and operational facilities. These usually include internal and access roads, parking areas, security zones, administrative buildings, leachate management systems, vehicle washing facilities, and areas reserved for future expansion and environmental protection measures. Consequently, candidate sites with areas only marginally exceeding the calculated disposal requirement may not be sufficient to support long-term landfill operation. However, the sites offering significantly larger areas provide greater operational flexibility, allow for phased development, and improve compliance with environmental and safety regulations. This consideration is particularly important for regional landfill planning, where facilities are expected to serve multiple cities in a large region and accommodate fluctuations in waste generation rates over time. Finally, detailed site-specific investigations, including geotechnical surveys and infrastructure planning, are required to confirm whether the identified candidate sites can realistically meet the waste management needs of the region and the candidate sites have favorable land ownership conditions.

Table 9. Suggested locations and required areas for landfill sites in the study area for the period of 2024 to 2040.

Province	Area km ²	Site symbol	Required area km ²
Babylon	6.1	Site B1	4.34
	7.4	Site B2	
Al-Qadisyiah	6.0	Site Q3	2.10
	7.2	Site Q4	
Al-Najaf	7.3	Site N5	2.75
	6.8	Site N6	
Karbala	5.6	Site K7	2.35
	5.0	Site K8	

Several studies have investigated before landfill siting in different regions of Iraq using GIS-based multi-criteria decision-making (MCDM) approaches. Similar to previous studies the present study employs GIS-based spatial analysis and MCDM techniques to evaluate landfill suitability by considering key environmental and planning constraints relevant under Iraqi conditions. However, this study differs from previous studies by emphasizing on future-oriented planning instead of current conditions and investigating four provinces of Middle Euphrates Region besides integration of regulatory and regional constraints. Former studies focused on a single governorate, usually <3000 km², often only one administrative unit. For instance, Chabuk et al. [58] evaluated fifteen criteria layers and located ten sites for different district of Babylon Governorate. They looked for small and local landfills for individual districts, while this study adopts a strategic regional landfill siting approach, identifying two large-capacity landfill sites designed to meet the long-term waste management needs up to 2040. Ishaq et al. [59] and Salman and Hamdan [60] each explored landfill siting within limited local areas i.e. Tal Afar and Al-Zubair districts, respectively. Ishaq et al. [59] only consider six key factors while Salman and Hamdan [60] evaluated nine criteria and suggested one suitable site within the study area considering long-term capacity. Al-Alanbari and Ensaif [61] considered 19 criteria layers including socioeconomic, accessibility, infrastructure, morphology, and hydrology criteria along the Karbala governorate and found ten suitable candidate landfill sites in the local scale.

Iraq lacks unified national regulations specifically governing landfill siting, while the accessibility of reliable spatial and environmental data is limited. As a result, researchers have independently selected decision criteria based on data availability and perceived importance, with the number of criteria varying widely, typically ranging from 6 to 19. Moreover, most existing studies are confined to individual cities or single governorates and are primarily based on current conditions, without incorporating future waste generation or long-term planning considerations. In this context, the present study addresses a critical gap by overcoming data scarcity through data integration and by extending the analysis to a larger regional scale, encompassing four governorates within Iraq's Middle Euphrates Region. By adopting a regional and future-oriented GIS-based MCDM framework, this study represents one of the first efforts to support long-term landfill siting and waste management planning beyond localized case studies in Iraq.

5. Conclusion

Waste disposal facilities in Iraq's Middle Euphrates region aren't meeting environmental and engineering standards. Switching from open dumping to sanitary landfill is considered a crucial first step toward sustainable waste management in Iraq. This transition helps to reduce environmental pollution by controlling leachate and gas emissions, improving public health, and enabling better waste management practices in the region with minimal funding and maximum efficiency. This study aimed to demonstrate the effectiveness of integrating Geographic Information Systems (GIS) with multi-criteria decision making (MCDM) techniques for addressing the complex challenge of municipal solid waste landfill site selection on a larger scale in Iraq's Middle Euphrates region. Efforts are made to plan for future waste management scenarios that accommodate population growth, tourism-related waste production, and evolving waste generation patterns. Also, work is carried out to follow suitable selection procedures while reducing environmental concerns and considering local social problems. To develop a decision-making process, sixteen layers of criteria were added to GIS. The layers, in order of significance, included urban area, villages, groundwater depth, rivers, main highways, secondary roads, elevation, slope, soil types, airports, land use, archaeological sites, power lines, railroads, and wind. For determining the criteria weightings, MCDM utilized the AHP and SRS methods. The weighted linear combination (WLC) process was then applied to create final maps of suitable landfill sites in the Middle Euphrates region by multiplying each criterion weight by its corresponding sub-criterion weights. The results highlight that a substantial proportion of the study area is restricted due to environmental sensitivity and regulatory limitations, underscoring the necessity of science-based planning approaches in waste

management. Eight landfilling sites were identified in the study provinces, with two sites allocated to each province. Based on the final maps generated by the AHP and SRS methods, these sites were chosen within areas classified as highly suitable and most suitable. The area of the selected sites is sufficient to handle all the waste produced from 2024 to 2040 in the Middle Euphrates provinces, when compared to the required area for each province. The main novelty of this study lies in the integrated application of GIS with two distinct weighting approaches (AHP and SRS) at a national planning scale, enabling a transparent comparison between expert-based and rank-based decision-making frameworks. Overall, this research demonstrates that GIS–MCDM frameworks are well suited for supporting sustainable waste management strategies in Iraq. By linking spatial suitability analysis with future waste generation projections and site capacity assessment, the study provides planning-oriented outputs that go beyond conventional landfill siting maps and offer practical decision support for solid waste management in Iraq. Future studies should focus on integrating higher-resolution spatial data, sensitivity and uncertainty analyses, and dynamic urban growth scenarios into a nation wide strategic planning. Expanding this approach to other regions of Iraq would contribute to the development of a unified, science-based national strategy for sanitary landfill planning and environmental protection.

Statements & Declarations

Author contributions

Ammar Rasheed Al-Hamami: Conceptualization, Formal analysis, Writing - Original Draft.

Ozeair Abessi: Supervision, Methodology, Data curation , Writing - Review & Editing.

Ali Chabuk: Supervision, Investigation, Validation, Visualization, Writing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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