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Land Suitability Evaluation for Wind Power Farms in Iraq using GIS-Based Multi-Criteria Evaluation

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Abstract: In many places, including Iraq, wind energy is a cheap, sustainable resource that is also environmentally benign. Despite its substantial wind potential, Iraq continues to experience an energy deficit due to the underutilization of renewable resources. To close this gap, this study will use a multi-criteria evaluation (MCE) technique in a Geographic Information System (GIS) context to determine the best places for wind energy development in Iraq. The assessment considers several geographic elements that affect wind farm placement, such as wind speed, land slope, distance from water bodies, and proximity to power lines and key roadways. A final suitability map that highlighted locations with differing degrees of acceptability for wind energy harvesting was created by integrating these parameters. According to the results, about 31% of the research region is highly favorable to wind farms, 30% is somewhat reasonable, and 39% is unsuitable. The southern and portions of central Iraq were the most promising regions for wind energy development. These results provide a sound scientific foundation for strategic planning and investment in sustainable energy infrastructure by energy planners and decision-makers. The study helps Iraq meet its sustainable development objectives, lessen its dependency on fossil fuels, and lessen its environmental effects.

Keywords: Remote sensing; Renewable energy; MCE

1 Introduction

Non-renewable energy sources are always running out; fossil fuels negatively affect the ecosystem, and it is becoming increasingly apparent how unstable they are [1]. In addition, smart cities are gaining popularity. By 2050, 66% of people on Earth will live in cities [2]. These days, most wealthy nations are looking for a sustainable source of income in addition to their current national resources, particularly gas and oil [3]. The energy demand will rise as a result. Population growth, climate change, technical advancements that enhance the availability of energy-consuming items, and an increase in the number of transportation alternatives (cars, aircraft, etc.) all contributed to the rise in energy demand [4].

Renewable energy must be used more frequently to create sustainable and intelligent cities in the future. After the Kyoto Protocol was ratified in 1997 [5], with increased awareness of renewable energy, emphasis is increasingly being paid to solar, wind, geothermal, hydropower, and tidal energy sources [6]. Although there are other energy sources, wind energy is growing in popularity because of advancements in technology, ease of installation, longevity, efficiency, and less area required than solar power. Numerous studies have been conducted on the installation of wind energy in various settings, such as offshore wind farms, urban areas, and wind farms [7, 8]. Nevertheless, power is also linked to several environmental problems, such as noise pollution, electromagnetic interference, ecological disruption, wildlife safety, and local climate change. In recent years, tremendous advancements have been seen in wind energy; the annual growth rate of wind energy installations in Europe over the past 15 years has been 9% [9], and this tendency is globally prevalent. Both industrialized and developing nations are seeing an increase in the use of wind energy. For example, in Denmark, 40% of household energy consumption comes from wind energy; by 2020, that percentage is predicted to reach 50% [9].

Furthermore, China's wind energy generating capacity climbed to 149 GW in 2020 from 19.3 GW in 2016 [10]. These examples show that wind energy provides a sustainable substitute for energy sources that rely on fossil fuels. Thanks to their efforts, other nations will soon be able to use this clean, renewable energy source. A key step in creating wind projects is choosing a site for a wind farm. Establishing wind energy plants will cost less if a site appropriateness analysis is done. Therefore, a study should assess the amount of wind energy accessible in different places before establishing wind energy projects. The site's location must also adhere to all ecological, topological, and structural requirements, including land use and cover and proximity to bodies of water. Therefore, selecting the locations with the fastest wind speeds is not required. Instead, to choose the best places, a trade-off must be considered between technological, economic, environmental, and social factors [11].

Highly qualified sites could be found using multi-criteria evaluation (MCE) approaches. The appropriateness of wind energy sites has been examined in several studies using GIS-based MCE techniques [12]. As a result, additional study in this area is required. Remote sensing has become an integral part of site suitability in the identification and assessment of location, and facilitating informed decision-making by authorities and policymakers [8, 13–15], particularly in local Iraqi contexts such as the Bahar Al-Najaf region [16]. Iraq does not yet have any wind farms in operation, and the installed wind energy capacity is still quite small, despite this interest. The national power grid's incapacity to efficiently absorb intermittent renewable energy, regulatory ambiguity, and a lack of investment incentives are the main obstacles. Wind energy is specifically included in the Ministry of Electricity's 2023 Renewable Energy Strategy, which aims to generate 12 GW from renewable sources by 2030.GIS-based site selection studies are crucial for this strategic direction in order to speed up project implementation and lower risks for potential investors.

Furthermore, the following serious problems have been identified in earlier studies: Baseer et al. [17] conducted a study that employed an MCE approach, about the MCE approaches utilized. Recently, investments in the solar energy industry have begun to be prioritized in Iraq's energy plan.As a result, there aren't many previous studies in this field [18]. However, a 2021 study that considered economic, environmental, and meteorological considerations used AHP and GIS to evaluate the land's potential for solar farm building in Iraq.The results showed that about 19% of the land, primarily in the south and southeast, is suitable for solar farms.

Future planning adjustments are possible using this method [19]. Al-Obaidi and Al-Dahash [20] evaluated the suitability of photovoltaic installations in Iraq using a GIS-based multi-criteria decision analysis. Their results indicated that regions with high solar radiation levels and favorable site conditions represent the most promising areas for solar power development.The findings indicated that the locations with the highest exposure to solar radiation and the lowest construction costs were the most efficient for solar panel installation [21].

Three zones may be identified in Iraq regarding wind energy: 48% of the country has low yearly wind speeds, 35% has wind speeds between 3.1 and 4.9 m/s, 8% has relatively high annual wind speeds, and the remaining portion has relatively low values.

Wind speed (WS) and wind density (WD) are the most essential aspects of wind power generation. Achieving the necessary reference material for wind turbine site analysis available to scientists, researchers, and stakeholders requires integrating many data sources, including remote sensing data, satellite images, maps, tables, and other on-site data. AHP, GIS, and remote sensing are three of the most popular and trustworthy techniques for choosing the ideal location for a wind turbine [22]. By allocating weights by criteria, the AHP is a systematic approach that evaluates several parameters and derives solutions to environmental issues locally. With AHP, decision-making mistakes may be minimized by assessing the consistency of outcomes [23].

This research aims to determine Iraq's wind potential sites using a GIS-based MCE approach. The weight criterion was also calculated using the AHP method by implementing the feature analysis raster. This study could be helpful to energy planners and decision-makers in achieving the Sustainable Development Goals. However, limited research still provides a comprehensive spatial assessment of wind energy suitability in Iraq using integrated GIS-AHP frameworks. In comparison, regional studies such as Al-braheem and Al-Awlaqi [24] in Saudi Arabia and Mahmood et al. [25] in southern Iraq applied similar methods. Still, they did not address Iraq's national-scale wind resource distribution.

A recent study published in the Engineering and Technology Journal further emphasized the effectiveness of GIS and remote sensing integration for renewable energy planning in Iraq, supporting the need for high-resolution spatial analysis in wind energy assessment [26]. The originality of this study lies in combining technical, environmental, and infrastructural parameters using MCE and AHP in a GIS environment to generate a high-resolution wind suitability map for Iraq.

2 Materials and Methods

2.1 Study Area

Iraq is the study region, which is located in the Southwestern part of Asia (As shown in Figure 1), the entire region (437072 km^2) [27], of which 432162 km^2 is land and 4910 km^2 is water [28] Iraq's latitude is between 29°00' and 37°20' North, while its longitude is between 38°45' and 48°45' East, Iraq has borders with Turkey to the North, Iran to the East, Kuwait and Saudi Arabia to the South, and Saudi Arabia, Syria, and Jordan to the West.

Iraq is a vast alluvial plain in Mesopotamia, home to the Euphrates and Tigris rivers [29]. Based on rainfall, Iraq can be classified into three climatic zones: the study region is in the Arid and Semi-Arid Zones, where yearly rainfall exceeds 400 mm [30] in April and May.

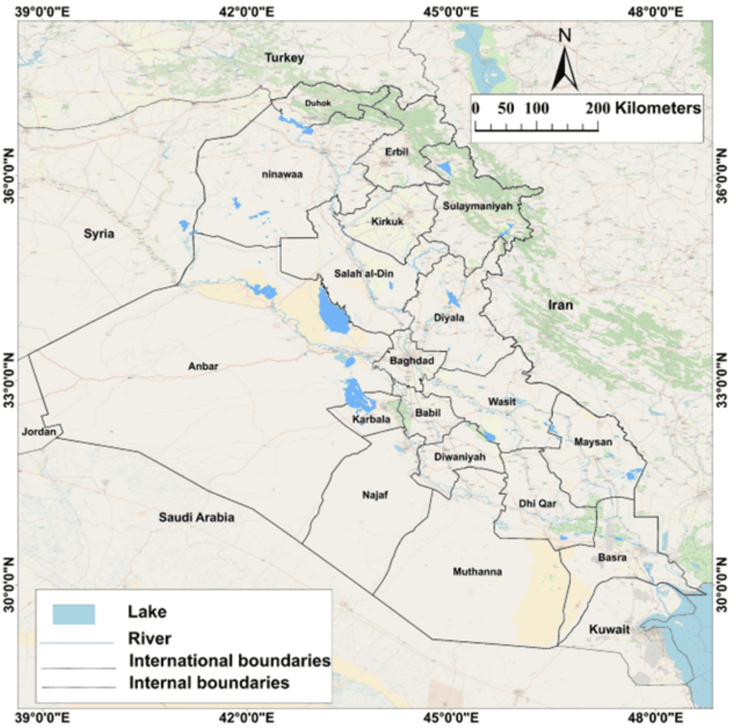

Figure 1. Location map of the study area, Iraq

The annual rainfall rate is about (100–180 mm) [31], with the majority of the precipitation falling between December and April. Iraq has a varied topography, with plateaus in the West, mountain ranges in the North, and alluvial plains in the middle and South. The country's four different seasons and geography influence its climate [32]. Iraq has a reputation for having hot, dry summers and cold, rainy winters [33].

The nation's topography varies, with desert regions in the West and South and mountains in the North. The Arabian Gulf is the Lowest point in the country, while Sheikh Dar, at 3,611 meters above sea level, is the highest mountain [3]. The country's height varies significantly.

The Zagros Mountains, located in the country's North, can generate wind energy because of the strong winds at such high elevations.

2.2 Methodology

This study employed a systematic methodology to identify potential locations for wind turbine installation using a multi-criteria GIS-based approach.

Five key spatial criteria were selected: wind speed, slope, proximity to electrical grid lines, proximity to roads, and distance from water bodies. Slope was derived from the Shuttle Radar Topography Mission (SRTM) digital elevation data, providing essential information on topographic constraints [12, 34]. Wind speed data were collected from NASA Giovanni datasets, representing average annual values from 2000 to 2024 [8, 15]. Infrastructure data, including roads and electricity lines, was sourced from the Ministry of Planning and transformed into point data for spatial analysis [35]. Water bodies were represented by proximity buffers generated through Euclidean distance analysis. All data were processed using ArcGIS 10.8.2. The raw raster and vector layers were pre-processed, reclassified, and standardized on a scale from 1 (very low suitability) to 5 (very high suitability).

The Analytical Hierarchy Process (AHP) was used to assign weights to the five criteria.

The pairwise comparison matrix was constructed using Saaty's 1–9 scale, and the consistency ratio (CR) was checked to ensure it remained below 0.1, which confirms acceptable consistency. The weights were derived through expert consultation with academic researchers and professionals from the Ministry of Electricity and Renewable Energy. Additionally, previous regional studies were consulted to support the pairwise comparisons and weighting structure. The standardized layers were then combined using the weighted overlay tool in ArcGIS, resulting in a final land suitability map for wind energy development. The methodological framework followed in this study is illustrated in Figure 2, which presents a detailed flowchart from data acquisition to final classification. The datasets and techniques were selected for reliability, spatial accuracy, and relevance to modern renewable energy site assessment. Sources such as the Ministry of Planning, NASA, and the Canadian Air Force were utilized to ensure the quality and precision of the results.

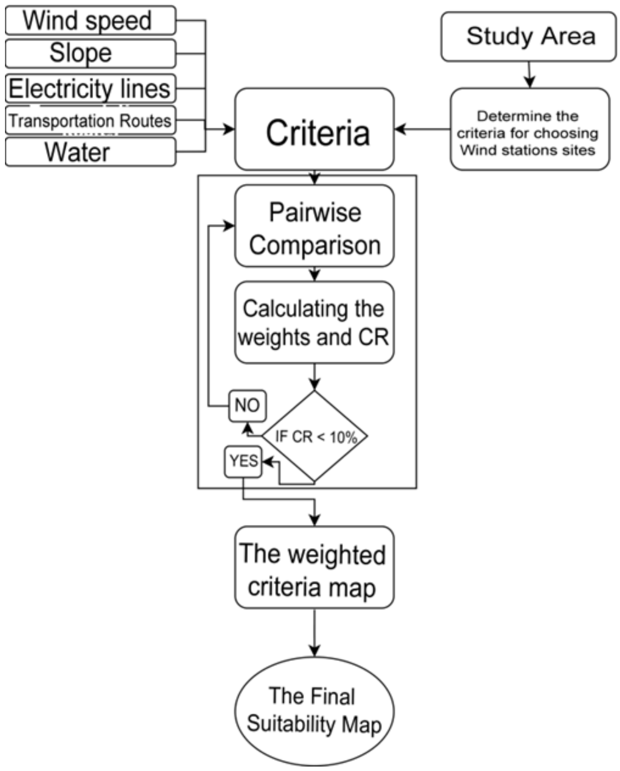

Figure 2. Methodology flowchart diagram

2.3 Selection Criteria for Suitable Wind Sites

Selecting suitable sites for wind turbines depends on criteria to ensure efficiency and sustainability. Table 1 provides vital insights into the best site for wind turbines based on five criteria.

Table 1. The study's suggested criteria

Criteria	Layer Source	Spatial Resolution	Condition	Reference
Wind Speed	Remote Sensing Data	0.5° × 0.625°	Annual average (2000–2024)	(the NASA site)
Slope	SRTM DEM	30 Meter	less than 5%	[34]
Electricity Lines	Shape file	Vector	Within 0.5 km of the main primary electricity grid	[35]
Transportation Routes	Shape file	Vector	Within 60 meters from the main roads	[35]
Water bodies	Shape file	Vector	At least 150 meters from rivers or water bodies	[35]

2.3.1 Wind speed

The current wind speed significantly impacts the wind turbines that provide energy. The wind speed data was gathered using the Kriging method after being downloaded in NetCDF format from the NASA site. Wind energy is used to generate power. Wind speeds are frequently high in the Western and Northern regions, especially those close to the borders, making them ideal sites for constructing wind farms. Average wind speeds, which usually range from 6 to 7 meters per second (m/s) or more, are suitable for producing wind energy efficiently in places like Al-Qaim in the country's west [36]. Due to these advantageous wind conditions, wind turbines can deliver significant power, supporting the nation's energy diversification objectives and helping to satisfy its rising electricity demand, as shown in Figure 3a.

2.3.2 Slope

The slope is a crucial consideration when building wind turbines [37]. Slope or high elevation areas are ideal for wind generation. Because steep slopes are thought to result in greater construction costs, sites with medium height and a slope of less than 5% are suitable for wind energy [34]. Lower-lying regions will also save money [38]. Since they get more wind, open and level locations are typically the best choices for wind energy projects [39], from the Earth Explorer site, as shown in Figure 3b.

2.3.3 Electricity lines

Economic considerations like proximity to power transmission lines are crucial when determining the best sites for renewable energy projects.

The distance to electrical transmission lines determines the transmission of wind power and the associated lower construction and maintenance costs. Therefore, the ideal locations are close to energy transmission lines, as Figure 3c shows. The appropriateness index can be chosen within a 0.5 to 20 km range.

2.3.4 Transportation routes

Another economic factor is the distance between a wind farm and a transmission line. It may be costly and time-consuming to build new electricity cables to connect to a wind farm [40]. The study concluded that the most significant locations for wind farms are those 60 meters or less from infrastructure, including primary and minor roads and railroads, as shown in Figure 3d.

2.3.5 Water bodies

The presence of adjacent bodies of water may impact the effectiveness of wind turbine installations [41]. The closeness of water features, such as rivers and lakes, to possible wind turbine construction locations in Iraq was ascertained using GIS methods, as shown in Figure 3e. This research enables the detection of isolated water bodies, as these areas may represent security problems. Wind power facilities have very little influence on the environment, particularly regarding water resources. Hence, the Euclidean distance requirement has to be used throughout the reclassification process.

2.4 Analytical Hierarchy Process (AHP)

The GIS-based AHP-MCE method views decision-making as a crucial process. Numerous factors may be taken into consideration while selecting the ideal sites for a particular activity, such as slope, wind speed [42, 43]. Some of the above-listed elements or considerations are considered to determine if a specific site is suitable for a particular application [44]. The first and most crucial step in the review process is standardization, which is transforming the criteria data into a consistent numerical measure. This study used the AHP-MCE approach to determine the best places to put wind turbines. Five target layers: wind speed, slope, power lines, transmission lines, and water bodies, were employed to achieve this. Each of these factors has to be considered when deciding whether a location is ideal for building wind turbines. A uniform 5-point scale was used to standardize the objective layers. A location's viability for wind energy harvesting should be determined after considering all pertinent considerations. The weighted overlay approach yields the final fit and facilitates the creation of the weighted hierarchy. First, the fundamental scale for evaluating the relative value of AHP criteria was used to identify each criterion's importance in the AHP analysis [45]. The actions stated below were carried out. For every component, a pairwise matrix was constructed, five of which were used in this study:

$$p = \begin{matrix} p11 & p12 & p13 \\ pn1 & pn2 & pnn \end{matrix} \tag{1}$$

where, p stands for the factors in the matrix. The second step then computes the normalized weights for the factors:

$$p = \quad wn = \frac{\mathrm{GM}n}{\sum_{i=1}^{n} \mathrm{G\,M}n} \tag{2}$$

where, w is the column cumulative weight of components and GM is the average of all column weights. The judgment coherence is ascertained by computing the CR.

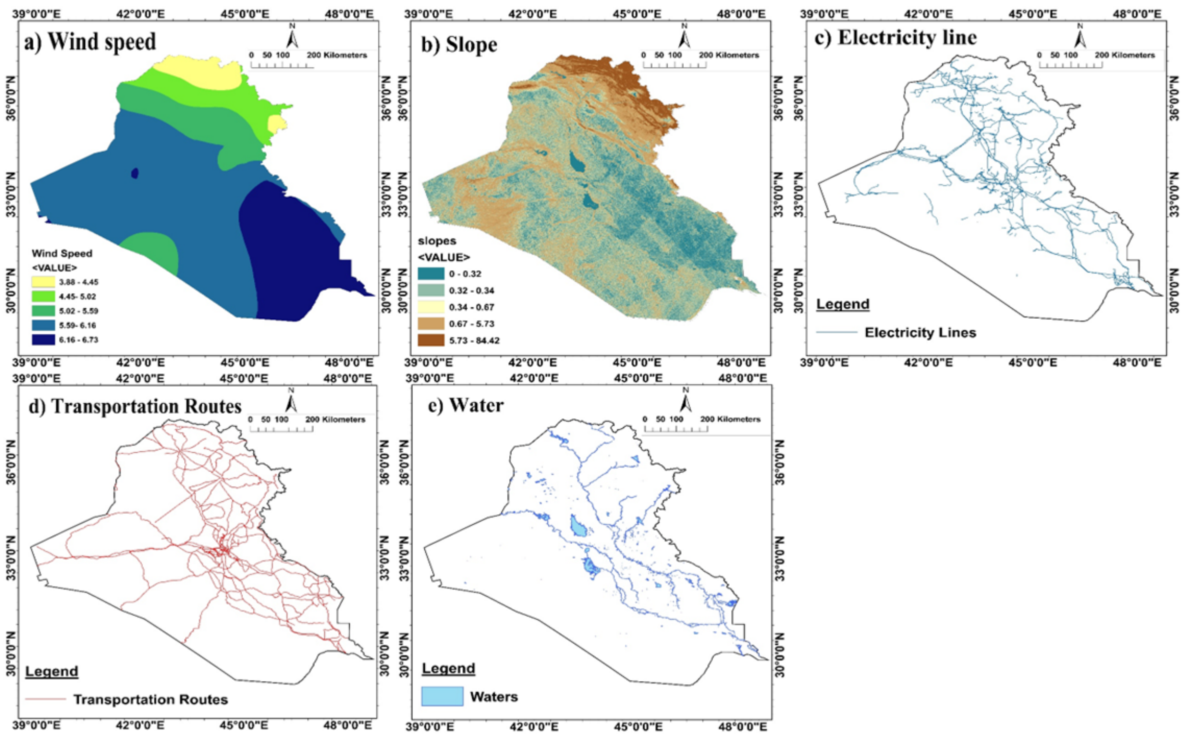

Figure 3. Suitability maps: (a) Wind speed; (b) Slope; (c) Distance to power lines; (d) Distance to roads; (e) Distance to water bodies

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

where, CI stands for the Consistency Index, and it is:

$$\mathrm{CI} = \frac{\lambda - n}{n - 1} \tag{4}$$

where, λ is the eigenvalue of the judgment matrix and may be calculated as follows:

$$\lambda = \frac{\sum_{i=1}^{n} piw}{N.w} \tag{5}$$

Table 2. Thematic layers' pairwise comparison matrix for this investigation

Criteria	Wind Speed	Slope	Electricity	Transportation	Water	Weight (%)
Wind Speed	1	2	4	7	8	44.3
Slope	1/2	1	3	6	7	29.6
Electricity	1/4	1/3	1	5	6	16.8
Transportation	1/7	1/6	1/5	1	2	5.5
Water	1/8	1/7	1/6	1/2	1	3.8

Consistency ratio (CR) = 0.8%

where, p is the factor weight and N is the total number of strata. A CR rating of less than 0.10 indicates satisfaction. The standard tables used by Saaty and Vargas [46] were utilized to construct the randomness index (RI). One must ascertain the consistency ratio (CR) to accurately assess a pairwise comparison's consistency. Revised research and recalculated results can solve this problem [45]. Weight selection considers the Pairwise Comparison Matrix, which is made feasible by the AHP technique. A comparative study of the relative value of each criterion concerning the others is provided by the matrix that the separate components generate, as Table 2 illustrates. Throughout the pairwise comparison process, each criterion is assigned a priority or weight to represent its importance within the overall decision-making framework. The components are prioritized using prior knowledge and the advice of subject-matter experts [46]. Pairwise comparisons are evaluated for consistency using a statistical metric known as the consistency ratio (CR). A low coefficient of determination (R^2) indicates robustness and consistency in the component ratings for the relative weight of the criteria.

3 Result

The first requirement for wind energy capture is that there must be enough wind, followed by the land surface's slope. As seen in Figure 4, all of the study's criteria were categorized on a consistent scale of 1 to 5 for convenience of analysis and presentation. In this study, five conventional layers were used. Wind speeds are higher in the southeast of the research region and lower in the north, as shown in Figure 4a.

These differences suggest that wind energy projects, particularly for large-scale farms, are more likely to succeed in the southeast. Smaller, localized applications might still be implemented in areas with lower wind values, although this would need more technical analysis. Except for the northern region, which has steeper slopes that may make construction, equipment transportation, and turbine stability difficult, most of the research areas have acceptable slope characteristics, according to the slope map in Figure 4b.

When choosing a site, certain topographical restrictions need to be considered. However, extensive flat lands in other study zone locations offer substantial development potential without changing the topography, which may also lower the initial construction cost.

The distance from the electrical grid is another significant concern. Since energy losses and transmission costs rise with distance, Figure 4c illustrates that regions nearer the grid are more suitable for wind energy growth. This makes prioritizing locations close to existing infrastructure more sensible and economical.

If grid expansion is planned, future projects could consider medium-suitability locations further off the grid. Another benefit of this study is its accessibility to main roadways, as seen in Figure 4d. Wind turbines and maintenance equipment can be transported more easily because the road system encircles most of the study area.

This facilitates project implementation by lowering operational expenses and logistical challenges. In terms of accessibility to water sources, Figure 4e shows that the majority of suggested locations stay a safe distance from lakes and rivers.

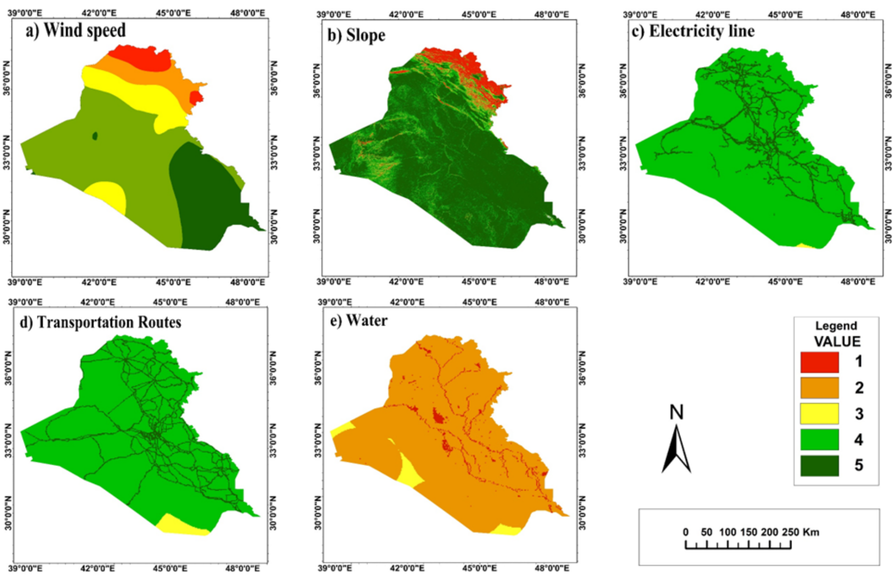

Figure 4. The raster dataset that has been categorized based on five criteria: (a) Wind speed; (b) Slope; (c) Distance to power lines; (d) Distance to roads; (e) Distance to water bodies

Figure 5 also shows the final suitability map, which shows the spatial distribution of locations categorized as high, low, or unsuitable for wind energy development. These classifications are quantitatively summarized in Table 3, which gives a clear picture of the percentage of each category. In contrast, Figure 6 shows the wind direction patterns throughout Iraq, which are essential for the best turbine alignment and performance. By assisting in ensuring that turbine orientation maximizes wind energy, this directional data aids in site planning decisions.

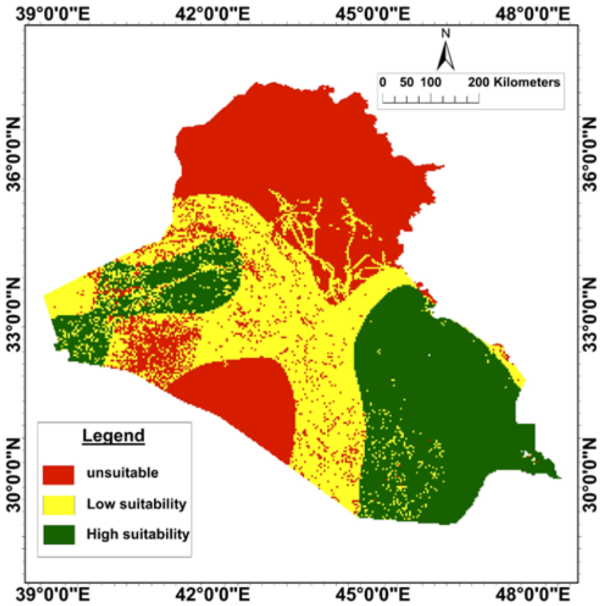

Figure 5. A figure with no subgraph.

Table 3. The area of each suitability class

Class	Area (km^2)	Area (%)
Unsuitable	168453.994	39
Low Suitability	129584.686	30
High Suitability	137341.473	31
Total Area	435380.154	100

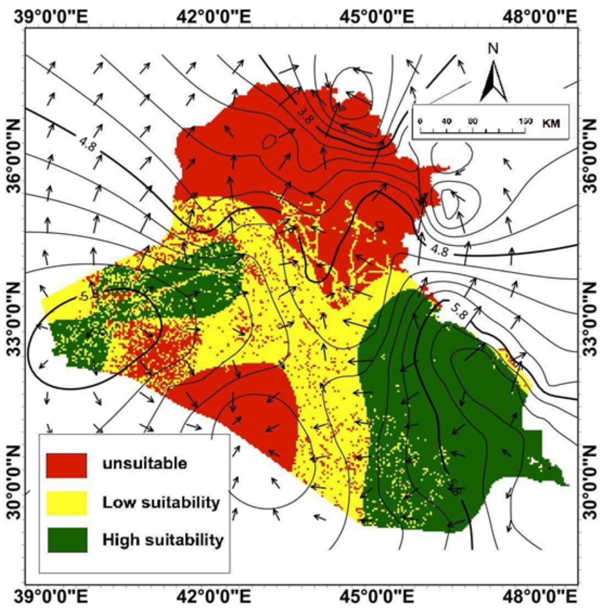

Figure 6. Wind direction

4 Discussion

The final suitability map indicates that approximately 31% of the study area is highly suitable for wind energy development, while 30% falls under low suitability and 39% is considered unsuitable (Figure 5 and Table 3). This distribution suggests considerable potential for large-scale and decentralized wind power deployment, particularly in the southeastern portion of the study area. This region exhibits favorable conditions such as strong wind speeds, flat terrain, and proximity to road networks and transmission lines, all of which reduce installation and operational costs and enhance project feasibility. The classification thresholds for suitability were based on wind speed ranges, where 4.9 m/s typically falls under low or unsuitable zones, depending on terrain and infrastructure proximity. However, the presence of extensive unsuitable zones highlights the necessity of careful spatial planning to avoid investments in areas with severe technical, environmental, or logistical limitations. These may include steep-sloped terrain, areas distant from infrastructure, or environmentally sensitive regions such as those close to water bodies, which pose challenges related to soil erosion, ecological disruption, and construction viability. From an energy policy standpoint, identifying high-suitability zones supports national goals to diversify energy sources and transition toward more sustainable and renewable options. Moreover, low- and medium-suitability zones offer opportunities for gradual development depending on technological advancements and regional demand. This layered suitability supports flexible energy planning that can accommodate utility-scale wind farms and smaller, distributed systems, depending on land-use regulations and local infrastructure capabilities. Wind direction is also a critical parameter influencing wind turbine orientation and performance. As illustrated in Figure 5, the prevailing wind direction in the study area is predominantly East–West, a pattern influenced by the Coriolis effect resulting from the Earth's rotation. This factor must be considered during the micro-siting process to ensure optimal turbine alignment. Modern yaw systems installed on upwind turbines enable the nacelle to rotate and adjust to shifting wind directions, thereby maintaining maximum efficiency. However, directional variability over different seasons necessitates robust wind resource assessment to inform design and implementation phases. Despite the strengths of the present study, certain limitations must be acknowledged. First, the wind speed data employed are derived from long-term annual averages at a coarse spatial resolution (0.5° × 0.625°), failing to capture seasonal and interannual fluctuations critical for assessing wind energy reliability. This limitation carries a substantial risk of mischaracterizing localized microclimatic variations, potentially compromising suitability assessment accuracy. Incorporating monthly or seasonal wind datasets would provide more granular insights into resource availability. Second, the analysis is based entirely on GIS and remote sensing data, with no on-site field validation. While this method is effective for regional-scale screening, we acknowledge the limitation of not conducting field validation. However, similar methodologies have proven effective in other environmental planning studies across Iraq. For example, remote sensing and GIS techniques successfully managed excess floodwaters in the Lake Hemrin region [47]. Additionally, the 60 m threshold for proximity to roads was derived from spatial planning assumptions, but future studies should validate this empirically. While efficient for large-scale screening, this approach may introduce errors when applied at the project execution level. Third, the study does not factor in conflicts with existing land uses such as agriculture, urban expansion, or environmental conservation zones, which may restrict practical development in otherwise high-suitability regions. In addition, the assertion that 31% of Iraq is "highly suitable" for wind farm development may be overoptimistic. This conclusion stems from analytical deficiencies, such as: (i) the aggregation of wind speed data over an annual period (2000–2024) obscures critical seasonal fluctuations. Such temporal averaging precludes a realistic assessment of energy output stability, a paramount consideration for viable wind energy projects; (ii) the analysis overlooks potential conflicts arising from competing land uses (e.g., agricultural expansion, urban development) within the designated "high-suitability" zones. This omission undermines the practical feasibility of the proposed sites. Furthermore, the current study did not incorporate dust storm data, despite their frequent occurrence in Iraq. This omission presents a limitation, as dust accumulation can significantly reduce turbine efficiency and increase maintenance needs. A regional wind energy assessment conducted by Al-braheem and Al-Awlaqi [24] in Saudi Arabia employed a similar GIS-AHP approach to determine optimal wind farm locations. Their study incorporated five technical, environmental, economic, and social criteria and produced a suitability map classifying the land into four categories. The most suitable zones (Class 4) were concentrated in Al Mantiqah Al Sharqiyah and Riyadh, covering land areas of approximately 14,553.57 km^2 and 65,989.50 km^2, respectively. The announced wind energy projects in these zones further validated the analytical outcomes. Their findings corroborate the methodological soundness of integrating GIS-MCDM models for wind site selection in arid and semi-arid environments. A quantitative comparison between this study and Al-braheem and Al-Awlaqi [24] reveals significant geographical differences. According to our data, over 31% of the study area in Iraq is very appropriate for wind farms, compared to 15% of the territory described in the Saudi study. Furthermore, wind speed was given the highest weight by our weighting system, indicating its crucial role in determining the feasibility of sites for wind energy projects in Iraq. In contrast, the Saudi study allocated weights more evenly across a number of factors. These variations show how important it is to modify wind site selection standards to take into account regional socioeconomic and environmental factors.

The similarity in influential factors such as flat terrain, infrastructure proximity, and stable wind resources across both studies underscores the regional applicability of such frameworks. Future research should expand upon these insights by incorporating cost–benefit analysis, stakeholder input, and policy evaluation to support strategic energy development across the Middle East. In addition, including economic layers such as cost-distance analysis is recommended to quantify infrastructure-related feasibility better and prioritize investment locations based on technical and financial suitability. The assessment of the Levelized Cost of Electricity (LCOE) for the suggested wind energy locations is a significant economic consideration that is not addressed in this study. At the provincial level, LCOE computation which includes transmission costs is crucial for assessing the financial viability of wind projects. For example, grid bottlenecks in Basra Province are said to result in additional transmission costs of about 10 cents/kWh. The most recent cost information from IRENA's 2023 cost database would improve site-level economic assessments' precision and facilitate more informed choices regarding wind energy investments. Furthermore, although this study took into account the fact that being close to infrastructure can reduce costs, data restrictions prevented it from directly quantifying building costs, transmission losses, and return on investment (ROI). To improve investment prioritization and site-level viability, further research is urged to incorporate spatialized economic measures using high-resolution geospatial and economic datasets, such as grid expansion costs, power loss estimates, and ROI models.

5 Conclusions

This study employed a GIS-based multi-criteria decision-making approach to identify and evaluate the most suitable locations for wind energy development. The analysis demonstrated that optimal siting depends primarily on wind speed, terrain slope, proximity to road networks, accessibility to electrical grid infrastructure, and distance from water bodies. The findings revealed that approximately 31% of the study area, primarily in the central-southeastern region, is highly suitable for wind energy projects. These areas represent a strategic opportunity to leverage Iraq's wind resources to reduce dependence on fossil fuels and mitigate the country's ongoing energy deficits. Furthermore, 30% of the area was classified as moderately suitable, indicating that with targeted infrastructure investments and appropriate technology, these zones could become viable in the future. However, the study also identified that 39% of the area is unsuitable for wind farm development due to limitations such as steep topography, low wind potential, or logistical constraints. This highlights the importance of comprehensive site selection and feasibility assessments before project implementation. Several limitations of the current study must be acknowledged. The analysis relied on static, long-term average wind data and did not account for seasonal variability, dust storms, or long-term climatic changes. The lack of field-based validation also introduces uncertainty in terrain interpretation and infrastructure accessibility. The study also does not consider competing land uses (e.g., agriculture, urban expansion), which may affect the practical feasibility of specific locations.

Future research should incorporate dynamic climate variables, high-resolution meteorological datasets, and field surveys to enhance the precision and reliability of spatial assessments. Moreover, integrating economic cost–benefit analysis and stakeholder engagement would ensure that the identified sites align with technical viability and local development priorities. In conclusion, Iraq holds substantial potential for wind energy expansion. Data-driven planning and strategic investment in the most promising regions can significantly contribute to national energy security, economic resilience, and environmental sustainability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C. Li, T. Zhuang, S. Zhou, Y. Xiao, and G. Hu, "Passive vibration control of a semi-submersible floating offshore wind turbine," *Appl. Sci.*, vol. 7, no. 6, p. 509, 2017. https://doi.org/10.3390/app7060509

[2] United Nations Department of Economic and Social Affairs, *World Urbanization Prospects: The 2018 evision*. UN, 2019.

[3] A. A. Ahmad, A. R. Hama, and I. A. Alawn, "Ecotourist and picnic area assessment using AHP analytical tools in sulaimani–tourism region, Iraq," *Eng. Technol. J.*, vol. 40, no. 11, pp. 1560–1572, 2022. http://doi.org/10.30684/etj.2022.135165.1263

[4] International Energy Agency, "World Energy Outlook 2024," 2024. https://www.iea.org/reports/world-energy-outlook-2024

[5] T. Gerden, "Sprejetje kjotskega protokola okvirne konvencije zn o spremembi podnebja," *Prispevki za Novejšo Zgod.*, vol. 58, no. 2, pp. 160–188, 2018.

[6] R. Blinc, A. Zidans, and I. Šlaus, "Sustainable development and global security," *Energy*, vol. 32, no. 6, pp. 883–890, 2007. https://doi.org/10.1016/j.energy.2006.09.017

[7] L. Y. Hussein, T. N. Ataiwe, and H. M. J. Al Sharaa, "Establishing a three-dimensional geodetic point network inside the university of technology, iraq-baghdad," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1374, no. 1, p. 012044, 2024. https://doi.org/10.1088/1755-1315/1374/1/012044

[8] M. H. Khudhur, I. A. Alwan, and N. A. Aziz, “Comparison of the accuracies of different spectral indices for mapping the vegetation covers in Al-Hawija district, Iraq,” *AIP Conf. Proc.*, vol. 2775, no. 1, p. 050005, 2023. https://doi.org/10.1063/5.0142004

[9] Danish Energy Agency, “The danish energy model,” 2015. https://www.ens.dk/en

[10] Y. Xu, Y. Li, L. Zheng, L. Cui, S. Li, W. Li, and Y. Cai, “Site selection of wind farms using GIS and multi-criteria decision making method in Wafangdian, China,” *Energy*, vol. 207, p. 118222, 2020. https://doi.org/10.1016/J.ENERGY.2020.118222

[11] M. Stojčić, E. K. Zavadskas, D. Pamučar, Z. Stević, and A. Mardani, “Application of MCDM methods in sustainability engineering: A literature review 2008–2018,” *Symmetry*, vol. 11, no. 3, p. 350, 2019. https://doi.org/10.3390/sym11030350

[12] N. A. Aziz, I. A. Alwan, and O. E. Agbasi, “Integrating remote sensing and GIS techniques for effective watershed management: A case study of Wadi Al-Naft Basins in Diyala Governorate, Iraq, using ALOS PALSAR digital elevation model,” *Appl. Geomat.*, vol. 16, no. 1, pp. 67–76, 2024. https://doi.org/10.1007/s12518-023-00540-9

[13] A. Rusol and Y. K. Al-Timimi, “Determination optimum sites for solar energy harvesting in iraq using multi-criteria,” *Iraqi J. Agric. Sci.*, vol. 55, pp. 25–33, 2024. https://doi.org/10.36103/ijas.v55iSpecial

[14] L. W. Said, N. A. Aziz, and L. Y. Hussein, “Spatiotemporal mapping of agricultural and meteorological drought in wasit province based on GIS and remote sensing data,” *Ecol. Eng. Environ. Technol.*, vol. 25, no. 6, pp. 115–122, 2024. https://doi.org/10.12912/27197050/186869

[15] M. H. Khudhur, N. A. Aziz, and I. A. Alwan, “Comparative study of supervised classification methods of land cover mapping using remote sensing data: A case study in Al-Hawija district/Iraq,” *AIP Conf. Proc.*, vol. 3105, no. 1, p. 050070, 2024. https://doi.org/10.1063/5.0213746

[16] M. H. Al-Helaly, I. A. Alwan, and A. N. AL-Hameedawi, “Environmental investigation of Bahar Al-Najaf region using sentinel-2 images,” *Eng. Technol. J.*, vol. 40, no. 4, pp. 732–742, 2022. http://doi.org/10.30684/etj.v40i5.2245

[17] M. A. Baseer, S. Rehman, J. P. Meyer, and M. M. Alam, “GIS-based site suitability analysis for wind farm development in Saudi Arabia,” *Energy*, vol. 141, pp. 1166–1176, 2017. https://doi.org/10.1016/j.energy.2017.10.016

[18] H. H. Al-Kayiem and S. T. Mohammad, “Potential of renewable energy resources with an emphasis on solar power in Iraq: An outlook,” *Resources*, vol. 8, no. 1, p. 42, 2019. https://doi.org/10.3390/resources8010042

[19] S. M. Khazael and M. Al-Bakri, “The optimum site selection for solar energy farms using AHP in GIS environment, a case study of Iraq,” *Iraqi J. Sci.*, pp. 4571–4587, 2021. https://doi.org/10.24996/ijs.2021.62.11(SI).36

[20] A. A. Al-Obaidi and S. H. Al-Dahash, “Assessment of photovoltaic site suitability in Iraq using GIS-based multi-criteria decision analysis,” *Int. J. Renew. Energy Res.*, vol. 10, no. 3, p. 1234–1245, 2020. https://doi.org/10.1016/j.ref.2023.100517

[21] E. J. Mahdi, “Assessment of solar energy potential for photovoltaic (PV) systems applications in Iraq,” Ph.D. thesis, College of Science, University of Baghdad, Baghdad, Iraq, 2018.

[22] T. Moodley, M. Seyam, T. Abunama, and F. Bux, “Delineation of groundwater potential zones in KwaZulu-Natal, South Africa using remote sensing, GIS and AHP,” *J. Afr. Earth Sci.*, vol. 193, p. 104571, 2022. https://doi.org/10.1016/j.jafrearsci.2022.104571

[23] T. L. Saaty, “The analytic hierarchy process (AHP),” *J. Oper. Res. Soc.*, vol. 41, no. 11, pp. 1073–1076, 1980.

[24] L. Albraheem and L. AlAwlaqi, “Geospatial analysis of wind energy plant in Saudi Arabia using a GIS-AHP technique,” *Energy Rep.*, vol. 9, pp. 5878–5898, 2023. https://doi.org/10.1016/j.egyr.2023.05.032

[25] F. H. Mahmood, A. K. Resen, and A. B. Khamees, “Wind characteristic analysis based on Weibull distribution of Al-Salman site, Iraq,” *Energy Rep.*, vol. 6, pp. 79–87, 2020. https://doi.org/10.1016/j.egyr.2019.10.021

[26] Y. K. Al-Timimi, A. M. Al-Salihi, and A. M. Al-lami, “Estimation of land surface temperature for different regions in iraq using remote sensing technique (ETM+),” *Eng. Technol. J.*, vol. 32, no. 6, pp. 1084–1091, 2014. https://doi.org/10.21839/jaar.2017.v2i5.106

[27] Z. Jabal, T. Khayyun, and I. Alwan, “Integrated approach for land surface temperature assessment in different topography of Iraq,” *Eng. Technol. J.*, vol. 40, no. 11, pp. 1465–1486, 2022. https://doi.org/10.30684/etj.2022.134581.1241

[28] Z. T. Abdulrazzaq and N. A. Aziz, “Geospatial mapping of groundwater potential zones using multi criteria evaluation based AHP approach in semi-arid region of Babil, Iraq,” *Int. J. Energy Water Res.*, vol. 9, pp. 1437–1447, 2025. https://doi.org/10.1007/s42108-025-00351-1

[29] Y. K. Al-Timimi, “Monitoring desertification in some regions of iraq using GIS techniques,” *Iraqi J. Agric.*

Sci., vol. 52, no. 3, pp. 620–625, 2021. https://doi.org/10.36103/ijas.v52i3.1351

[30] M. A. Al-Obaidi and Y. K. Al-Timimi, "Change detection in mosul dam lake, north of iraq using remote sensing and GIS techniques," *Iraqi J. Agric. Sci.*, vol. 53, no. 1, pp. 38–47, 2022. https://doi.org/10.36103/ijas.v53i1.1506

[31] S. Q. Al-Jbouri and Y. K. Al-Timimi, "Assessment of relationship between land surface temperature and normalized different vegetation index using landsat images in some regions of diyala governorate," *Iraqi J. Agric. Sci.*, vol. 52, no. 4, pp. 793–801, 2021. https://doi.org/10.36103/ijas.v52i4.1388

[32] A. Alwan, H. H. Karim, and N. A. Aziz, "Investigate the optimum agricultural crops production seasons in Salah Al-Din Governorate utilizing climate remote sensing data and agro-climatic zoning," *Iraqi J. Sci.*, vol. 60, no. 9, pp. 2087–2094, 2019. https://doi.org/10.24996/ijs.2019.60.9.24

[33] M. H. AL-Umar, M. S. Satchet, B. M. Al-Zaidi, and A. R. Abood, "Spatial study of causes and effects of the sandstorms using meteorological data and GIS: The case of Nasiriyah city, Iraq," *Period. Eng. Nat. Sci.*, vol. 7, no. 4, pp. 2012–2021, 2019. https://doi.org/10.21533/pen.v7i4.974

[34] D. Turney and V. Fthenakis, "Environmental impacts from the installation and operation of large-scale solar power plants," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3261–3270, 2011. https://doi.org/10.1016/j.rser.2011.04.023

[35] Q. Hassan, P. Viktor, T. J. Al-Musawi, B. M. Ali, S. Algburi, H. M. Alzoubi, A. K. Al-Jiboory, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "The renewable energy role in the global energy transformations," *Renew. Energy Focus*, vol. 48, p. 100545, 2024. https://doi.org/10.1016/j.ref.2024.100545

[36] K. B. Atici, A. B. Simsek, A. Ulucan, and M. U. Tosun, "A GIS-based multiple criteria decision analysis approach for wind power plant site selection," *Util. Policy*, vol. 37, pp. 86–96, 2015. https://doi.org/10.1016/j.jup.2015.06.001

[37] P. Akkas, M. Y. Erten, E. Cam, and N. Inanc, "Optimal site selection for a solar power plant in the central anatolian region of Turkey," *Int. J. Photoenergy*, vol. 2017, no. 1, p. 7452715, 2017. https://doi.org/10.1155/2017/7452715

[38] Z. K. Ding, M. L. Zhu, Z. Z. Wu, Y. B. Fu, and X. Liu, "Combining AHP-entropy approach with GIS for construction waste landfill selection—A case study of Shenzhen," *Int. J. Environ. Res. Public Health*, vol. 15, no. 10, p. 2254, 2018. https://doi.org/10.3390/ijerph15102254

[39] K. Kiatreungwattana, G. Mosey, S. Jones-Johnson, C. Dufficy, J. Bourg, A. Conroy, M. Keenan, W. Michaud, and K. Brown, "Best Practices for Siting Solar Photovoltaics on Municipal solid waste landfills. A study prepared in partnership with the environmental protection agency for the re-powering america's land initiative: Siting renewable energy on potentially contaminated land and mine sites (no. nrel/tp-7a30-52615)," 2013.

[40] D. Ignizio, "Suitability modeling and the location of utility-scale solar power plants in the southwestern United States," Master's thesis, The University of New Mexico, 2010.

[41] S. S. Aly, S. Jensen, and A. B. Pedersen, "Solar power potential of tanzania: Identifying CSP and PV hot spots through a GIS multicriteria decision making analysis," *Renew. Energy*, vol. 113, pp. 159–175, 2017. https://doi.org/10.1016/j.renene.2017.05.077

[42] M. K. Saxena, M. K. Jat, and S. Kumar, "Application of GIS and mce techniques for optimum site selection for water harvesting structures," *J. Rural Dev.*, vol. 37, no. 2, pp. 195–206, 2018. https://doi.org/10.25175/jrd/2018/v37/i2/129659

[43] K. Sayl, A. Adham, and C. J. Ritsema, "A GIS-based multicriteria analysis in modeling optimum sites for rainwater harvesting," *Hydrology*, vol. 7, no. 3, p. 51, 2020. https://doi.org/10.3390/hydrology7030051

[44] I. Mohammed, I. Alwan, and A. R. Ziboon, "Drought in Iraq: Remote sensing assessment using LSWI-Index and Landsat imagery," *Eng. Technol. J.*, vol. 42, no. 11, 2024. http://doi.org/10.30684/etj.2024.150522.1764

[45] T. L. Saaty, "Decision making with the analytic hierarchy process," *Int. J. Serv. Sci.*, vol. 1, no. 1, pp. 83–98, 2008. https://doi.org/10.1504/IJSSCI.2008.017590

[46] T. L. Saaty and L. G. Vargas, "Why is the principal eigenvector necessary?" in *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, 2012, pp. 63–70. https://doi.org/10.1007/978-1-4614-3597-6_4

[47] H. Muhamed, M. N. Hamoodi, and T. Z. Abd Alrazzak, "Managing the excess floodwaters in the lake hemrin using remote sensing and GIS techniques," *Eng. Technol. J.*, vol. 40, no. 5, pp. 779–791, 2022. http://doi.org/10.30684/etj.v40i5.1017