Optimizing Solar Farm Locations in El Minia Governorate Using Fuzzy AHP and GIS Remote Sensing

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Optimizing Solar Farm Locations in El Minia Governorate Using Fuzzy AHP and GIS-Remote Sensing

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Abstract: *Egypt, located within the sun belt region, holds significant potential for solar energy development. El Minia Governorate, identified as a prospective hub for renewable energy generation in Egypt, was evaluated for optimal solar farm allocation using an integrated approach combining Fuzzy Logic, the Analytic Hierarchy Process (AHP), and Geographic Information Systems (GIS) with remote sensing data. This study assessed El Minia's general suitability and designated zones for solar farm deployment. The analysis revealed that 45.6% of the region is not feasible for solar development, 32.4% is moderately to low suitability, and 22% is highly suitable, particularly in hinterlands adjacent to existing urban and rural areas. Additionally, 70.7% of the designated renewable energy areas were confirmed as suitable for solar infrastructure. These findings provide a robust foundation for policymakers to prioritize solar energy initiatives in El Minia Governorate, supporting Egypt's transition towards sustainable energy and maximizing its solar potential.*

Keywords: El Minia Governorate, Solar Farm, Suitable areas, GIS, Fuzzy-AHP.

1. INTRODUCTION

Energy provision is a critical factor in ensuring the functionality of both rural and urban built environments. As global energy demands rise, the need for sustainable and reliable energy sources has become increasingly urgent. Solar energy, a cornerstone of renewable energy systems, has emerged as a viable solution due to its cost-effectiveness, environmental benefits[1], and potential to mitigate climate change. Unlike fossil fuel-based power plants, solar energy systems significantly reduce greenhouse gas emissions, offering a cleaner alternative for energy generation[2]. Moreover, the construction of solar farms contributes to diversifying national energy markets[3], fostering energy security and sustainability. In recent years, technological advancements and economies of scale have driven an impressive 80% reduction in the cost of solar energy production[2], making it an increasingly accessible option for many nations.

Egypt, a country situated within the Sunbelt, is uniquely positioned to harness this potential. With abundant solar resources, the nation has significant opportunities to deploy photovoltaic (PV) panels across its territory[4]. However, Egypt currently faces challenges such as frequent power outages, lasting two to three hours per day. Solar energy presents a key solution to these issues, offering a reliable and sustainable energy supply to meet growing demands. To address energy shortages and reduce carbon emissions, Egypt aims to generate 22% of its total energy from solar power by 2035[5]. Therefore, the selection of appropriate locations for solar farm development is a critical step in maximizing Egypt's solar resource utilization and meeting its renewable energy targets.

This study employs an integrated approach, combining the Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) within a Geographic Information System (GIS) and Remote Sensing technologies to identify highly suitable locations for solar farm infrastructure deployment in El Minia Governorate. It also evaluates designated renewable energy zones to optimize the allocation of solar development projects.

Fuzzy-AHP, a decision-making tool that integrates fuzzy logic with the Analytic Hierarchy Process, is particularly effective in addressing uncertainties inherent in multi-criteria decision-making. By combining AHP-derived weights with fuzzy sets, it enables a more flexible and accurate evaluation of site selection factors, ensuring a robust and reliable process for identifying optimal locations and enhancing the efficiency and sustainability of solar energy development. Remote sensing data serves as an indispensable resource for assessing solar farm suitability, due to its extensive spatial coverage and high-resolution capabilities[6]. This technology provides critical parameters such as land use and land cover (LULC), solar radiation, and slope, extracted from satellite imagery and processed within the ArcGIS environment.

In this study, fuzzified values of key selection factors, including solar radiation, proximity to transmission lines, distance to roads, and distance to urban areas, are multiplied by their respective weighted values. These weighted layers are then overlaid with binary constraint layers, including areas with slopes over 8 degrees, existing land use, and lands authorized for future development.

The analysis results in a suitability map that classifies areas in El Minia Governorate into four categories: unsuitable, less suitable, moderately suitable, and highly suitable for solar farm allocation.

This integrated approach not only identifies optimal locations for solar energy infrastructure but also evaluates designated lands for renewable energy projects within the governorate, ensuring efficient and sustainable allocation of solar farms.

2. Study area:

El Minia Governorate is situated in northern Upper Egypt and is considered a central agricultural hub at the national level, with both a strong existing agricultural sector and a potential arable hinterland. With a population of 5.6 million in 2020, it accounted for 5.9% of Egypt's total population.

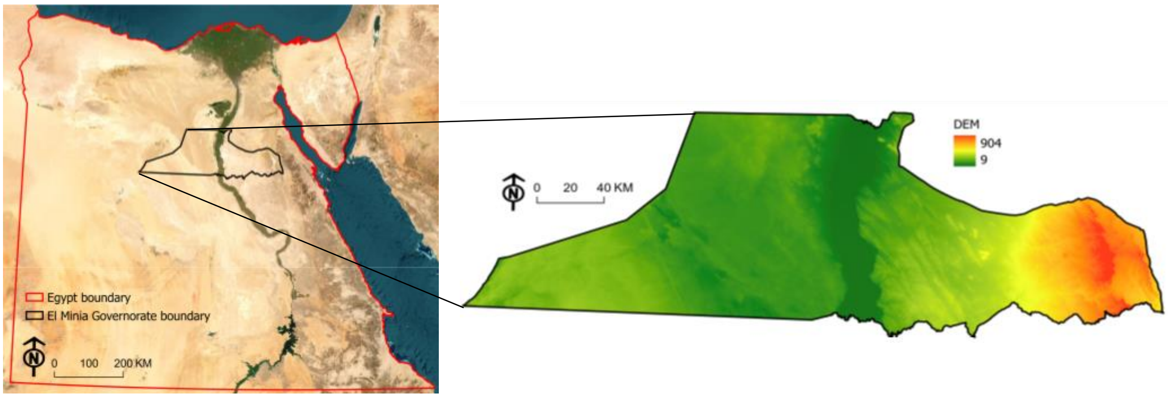


Fig. 1. study area

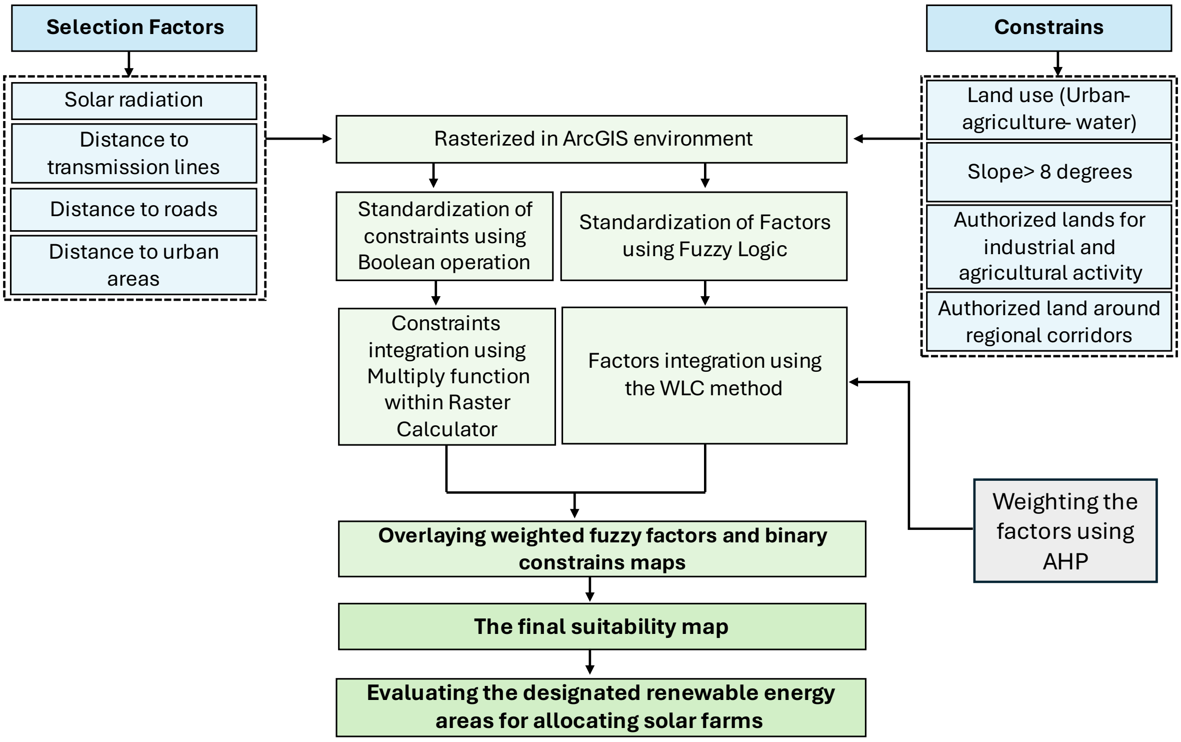


Fig.2 the modeling framework

Covering an area of 32,300 km², El Minia Governorate accounts for 7.5% of Egypt's total populated land. It was selected for the study as the government envisions it as a future hub for renewable energy, aiming to utilize its hinterland for this purpose. The location of El Minia Governorate within Egypt is shown in Figure 1.

3. Modeling Framework:

This study employs a GIS-based multi-criteria decision analysis (MCDA) approach to identify optimal locations for solar farms within El Minia Governorate, Egypt. The methodology integrates both selection factors and constraints through a combination of fuzzy logic, Boolean operations, and the Weighted Linear Combination (WLC) method within the ArcGIS Pro environment. The selection factors include solar radiation, distance to transmission lines, distance to roads, and distance to urban areas, all of which are standardized using fuzzy membership functions. Constraints, including land use (urban, agricultural, and water bodies), slopes exceeding 8 degrees, authorized land for industrial use and agricultural activities, and restricted areas around regional corridors, are processed using Boolean logic. The Analytical Hierarchy Process (AHP) is applied to assign relative weights to each selection factor. Once all inputs are rasterized, binary constraints are combined using the Multiply function, while fuzzy factors are combined using the WLC method. Finally, fuzzy and binary maps are overlaid to generate the final suitability map, effectively identifying the most suitable locations for solar energy development. Furthermore, based on these suitability results, the pre-selected renewable energy zones are analyzed for potential solar farm deployment. Figure 2 illustrates the study's methodological framework.

3.1 Selection factors

The criteria used to identify suitable locations for solar farms are fundamental to the site selection process. Additionally, acquiring reliable data for these factors is a key prerequisite in solar photovoltaic (PV) site selection studies [7]. In this study, four factors are employed to identify the most appropriate sites, as outlined below:

- **Solar Energy Potential:**

When selecting suitable sites for solar photovoltaic (PV) farms, it is essential first to assess the solar energy potential of the region [7]. Constructing solar farms in areas with low solar potential contradicts principles of efficiency and cost-effectiveness. The global solar radiation map serves as a crucial tool for site selection by identifying regions with high and low solar energy potential. However, there is no established consensus regarding the minimum acceptable solar radiation threshold for photovoltaic systems[8]. Solar irradiation mapping and analysis at specific time intervals can be conducted using the Solar Analyst tool in the ArcGIS software. This tool utilizes the region's Digital Elevation Model (DEM) to simulate and quantify solar radiation patterns, providing a robust foundation for informed decision-making in solar energy development.

- **Distance to transmission lines:**

The distance from existing transmission lines is a critical factor in determining suitable locations for solar farms. Constructing new infrastructure to connect remote solar farms to the grid significantly increases both investment and operational costs[3]. Therefore, sites in close proximity to transmission lines offer the dual advantage of reducing costs and minimizing electricity losses during transmission[7]. The spatial data for the transmission lines were sourced from [9]. Proximity maps were then generated using the Euclidean Distance tool in ArcGIS software to evaluate and identify optimal locations for solar farm development based on their distance to existing grid infrastructure.

- **Distance to Roads:**

Proximity to major roads is a key factor in reducing both expenses and the negative environmental impacts associated with constructing new access infrastructure [10]. Allocating solar farms near highways offers several advantages, including lower transportation costs and improved logistical efficiency[2]. The spatial data for the road networks were obtained from the General Organization of Physical Planning (GOPP), Egypt.

- **Distance to urban areas:**

Solar power farms should be strategically located to strike a balance between environmental considerations and energy demand. While it is advisable to site solar plants away from urban areas to reduce environmental impacts, proximity to urban and rural regions remains essential for

Meeting local energy needs and minimizing transmission costs[7]. Close proximity to populated areas minimizes the expenses associated with transferring generated electricity to end users, thereby enhancing economic efficiency[3]. Spatial data of urban areas were digitized within the ArcGIS environment.

Although soil and temperature conditions are generally considered critical factors in solar farm development, they were excluded from this study due to the relative homogeneity of these variables across the region.

3.2 Fuzzy Standardization

Fuzzy standardization is a process that converts all layer values into a uniform scale and unit, ensuring comparability across diverse factors [3].

In this study, fuzzy logic standardizes the selection factors by applying membership functions that transform input values into a normalized scale from 0 to 1. For each input layer, every pixel is assigned a fuzzy value based on the appropriate membership function. These resulting fuzzy maps provide cell values that represent the degree of suitability for each factor, enabling an integrated assessment of site suitability [3].

Two types of membership functions were applied to normalize the factors: linear and sigmoidal. A linear membership function was used for both solar radiation and distance to transmission lines, but with opposite scaling directions to reflect their different influences on suitability. Specifically, a linear increasing function was applied to solar radiation because higher values correspond to greater suitability for solar energy production. Conversely, a linear decreasing function was assigned to distance to transmission lines, so locations closer to transmission lines receive higher suitability scores, while those farther away are considered less suitable due to increased infrastructure costs and power losses.

The sigmoidal membership function was applied to the factors Distance to Urban Areas and Distance to Roads to better represent their influence on site suitability. This function is characterized by four key parameters [11], as follows: Point "a": The distance at which the membership value begins to rise above 0. In this study, distances of 500 meters from urban areas and 100 meters from roads were designated as restricted zones. Point "b": The distance at which the membership value reaches 1, indicating maximum suitability. Point "c": The distance at which the membership value starts to decrease from 1. Point "d": The distance at which the membership value drops to 0, indicating complete unsuitability.

The fuzzy module in TerrSet software was employed to generate the standardized fuzzy maps (see Fig. 3). Table 1 provides a detailed summary of the membership functions and fuzzification parameters applied to the factor layers.

Table.1 Membership functions and fuzzification parameters of the selection factors

Factors	Fuzzy type	Unit	a	b	c	d
Solar Radiation	Linear	$Kw/m^2/year$	446	1734		
Distance to transmission lines	Linear	Km	0	206.7		
Distance to urban areas	Sigmoidal	Km	0.5	0.501	10	100.8
Distance to roads		Km	0.1	0.101	10	236.3

3.3 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was employed to derive the weights of the selection factors using the pairwise comparison method. This approach assigns numerical values ranging from 1 to 9 to indicate the relative importance of one factor over another (see to Table 2). In this study, the pairwise comparison values were adopted from previous research [2, 3, 7, 12] and subsequently input into the Weight module in TerrSet software to compute the factors weights and evaluate the

Consistency Ratio (CR). To ensure the reliability of the results, the CR value must be ≤ 0.1, indicating an acceptable level of consistency [13].

Table 2. A pairwise comparison approach used to derive the factors weights for solar farm allocation

Factors	Solar radiation	Distance to transmission lines	Distance to roads	Distance to urban areas
Solar radiation	1	3	5	5
Distance to transmission lines	1/3	1	2	2
Distance to roads	1/5	1/2	1	2
Distance to urban areas	1/5	1/2	1/2	1

3.4 Constraints of Selecting the Suitable Sites

The constrained areas refer to locations where solar energy projects cannot be developed due to environmental, technical, or legal restrictions. In this study, the restricted zones include the following:

- **Land Use and Land Cover**

Land Use Land Cover (LULC) is a critical factor in determining suitable locations for solar farm development [5]. Deploying solar farms in open areas, such as deserts, barren land, and idle agricultural land, offers environmental benefits and represents a more sustainable approach [12]. Consequently, agricultural land, water bodies, and urban areas were excluded from the suitability analysis by applying a masking technique. The LULC map used in this study was generated from Esri Sentinel- 2 imagery with 10-m spatial resolution.

- **Sloped lands with more than eight degrees.**

Elevated terrain and steep slopes are generally unsuitable for large-scale photovoltaic (PV) farm development [2]. High slope gradients significantly increase installation costs, as deploying PV panels on sloped surfaces often requires extensive grading and excavation [4]. To minimize such costs, areas with slopes greater than eight degrees were classified as restricted. The slope map was derived from a Digital Elevation Model (DEM) using the Slope tool in the ArcGIS environment.

- **Authorized Lands for Future Development**

Future development areas refer to zones designated for specific land uses under Egypt's national plans, including future agriculture expansion, industrial zones, and development areas around regional roads. These areas were excluded from the solar farm suitability analysis to ensure alignment with planned land uses. The spatial data for these zones were obtained from the General Organization for Physical Planning (GOPP), Egypt.

The constrained maps were generated using the Boolean logic method, resulting in a binary classification. As illustrated in Figure 4, each pixel was assigned a value of 1, indicating permitted areas for solar farm development, or 0, representing restricted zones where installation is not permitted.

3.5 Overlaying Raster Layers:

The raster layers were generated and compiled into a 30-meter spatial resolution raster format. These layers, including both selection factors and the overall restriction map, were integrated using the Weighted Linear Combination (WLC) approach to produce the solar farm suitability map.

In this approach, each cell value in the fuzzy-standardized raster is first multiplied by the assigned weight of the corresponding factor and then further multiplied by its binary value from the restriction map. The following equation mathematically represents this relationship [11]:

$$\mathrm{SSI} = \sum_{k=1}^{n} w_k R_k\, C$$

Where SSI refers to the site suitability index, k denotes each individual selection factor, n is the total number of factors, w_k is the relative weight of each factor, R_k represents the fuzzified factor value for every cell ranging from 0 to 1, and C refers to the cell score of the overall restriction map (0 for restricted areas, 1 for permissible areas).

This process ensures that the final suitability map accurately reflects the weighted influence of each factor while effectively incorporating the exclusion of restricted areas. The raster calculator tool in ArcGIS pro 3.3 was utilized to generate the overlaid solar farm suitability map.

4. Results:

The results of this study are presented in two parts: first, the identification of suitable areas within El Minia Governorate for solar farm allocation; and second, the assessment of designated renewable energy zones to determine optimal solar farm sites.

4.1 Suitability of solar farms allocation in El Minia Governorate:

Based on the AHP analysis, the assigned weights for the evaluated factors were as follows: solar radiation (0.56), distance to transmission lines (0.20), distance to roads (0.13), and distance to urban areas (0.092). The consistency ratio (CR) was calculated as 0.0243, indicating a high level of consistency and reliability in the pairwise comparisons. The overall restriction map was generated using the Multiply function in the Raster Calculator within ArcGIS. This approach ensures that a cell is assigned a value of 1 only if it has a value of 1 in all individual restriction layers. If any restriction layer assigns a value of 0, the cell is classified as 0 in the final map. In the resulting restriction map, cells with a value of 0 are considered unsuitable, while those with a value of 1 are initially regarded as suitable for solar farm development (see Figure. 5). According to Equation 1, the Site Suitability Index (SSI) is calculated by summing the fuzzified factor values for each cell, each weighted by their corresponding AHP-derived weight, and then multiplying the result by the overall restriction map. This process generates the initial fuzzified suitability map (see Figure. 6). This suitability map was then classified into four categories: (1) unsuitable areas with 0 value, (2) less suitable areas with fuzzified values ranging from 0.6 to 0.7, (3) moderately suitable areas with values between 0.7 and 0.8, and (4) highly suitable areas with values exceeding 0.8 (see Figure 7).

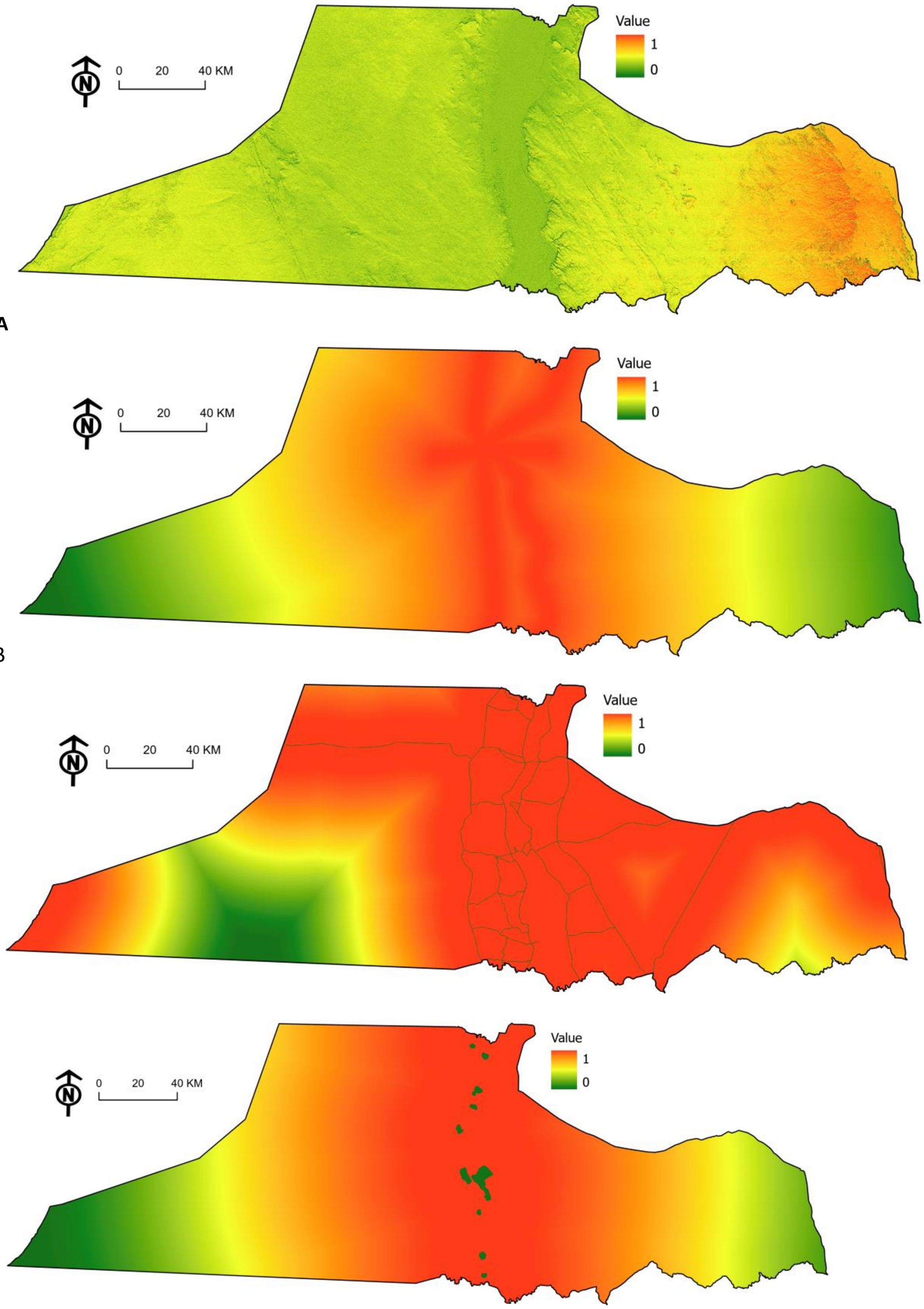
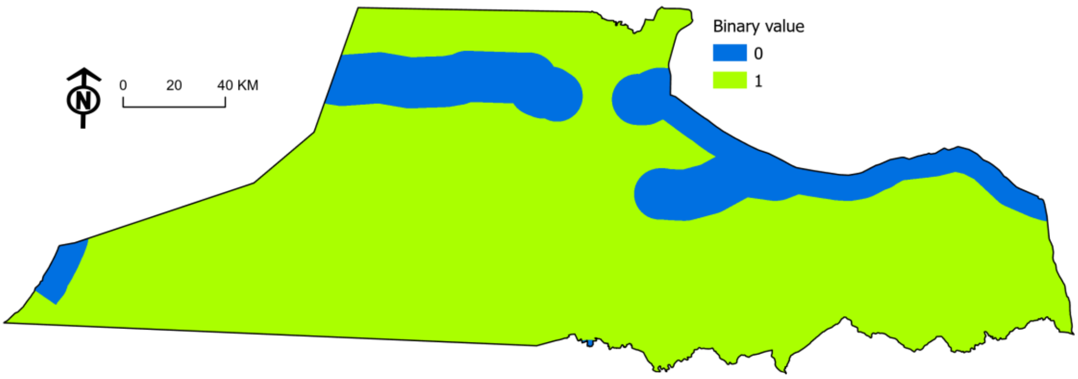
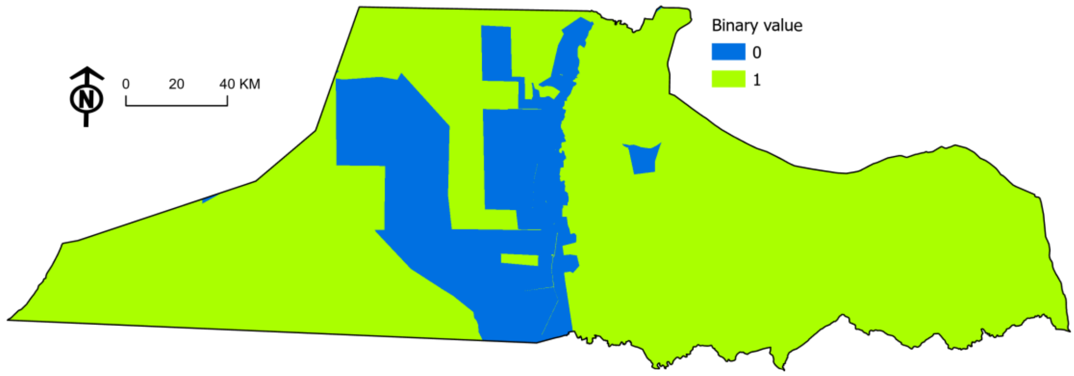


Fig.3 standardized factors layers: A. Solar radiation, B. Distance to transmission lines, C. Distance to roads, and D. Distance to urban areas



A



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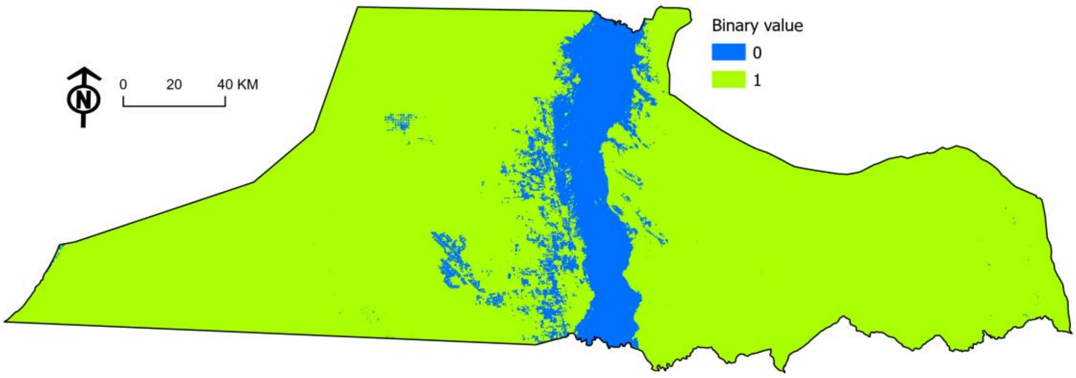

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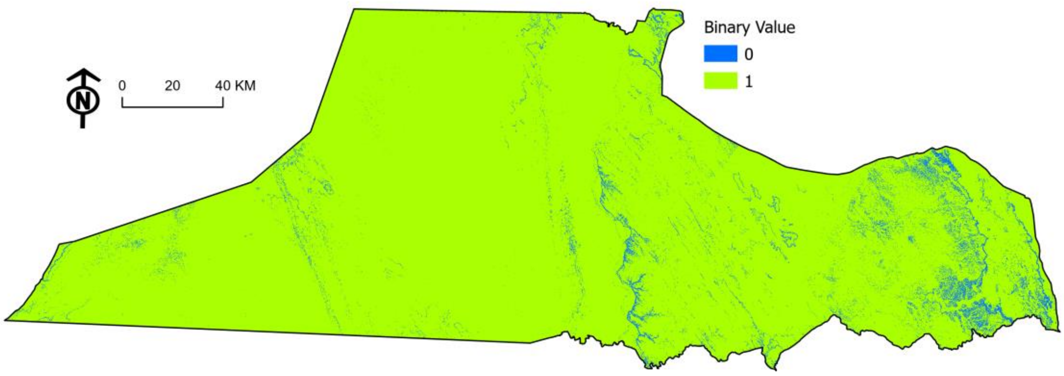

D

Fig.4: Restricted areas: A. Authorized lands for future development around the regional roads, B. Authorized lands for future agriculture and industrial development and, C. Existing land use (Agriculture, urban, and water), and D. Areas with slope greater >8 degrees.

Based on Figure 7, the unsuitable areas account for approximately 45.6% of the total land area, covering around 15,560 km². These areas include restricted land uses and zones designated for future development. Spatially, they are primarily concentrated in existing built-up areas, lands surrounding major transportation corridors, and the national agricultural development project located west of El Minia Governorate.

The highly suitable areas account for 22% of the total land area, covering approximately 7,511.4 km², and are Primarily located in the immediate hinterland and its extensions of the existing urban areas. These areas are advantageous due to their proximity to urban centers, roads, and transmission lines, in addition to receiving a reasonable amount of solar radiation. This makes them ideal locations for solar projects, minimizing both new infrastructure costs and labor commuting expenses.

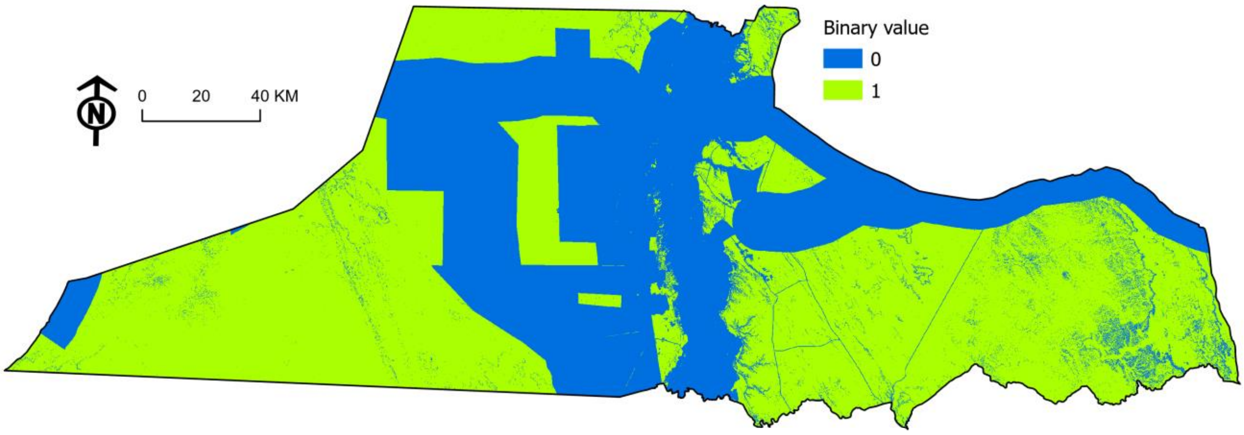

Fig.5 Final restriction map for allocating solar farms

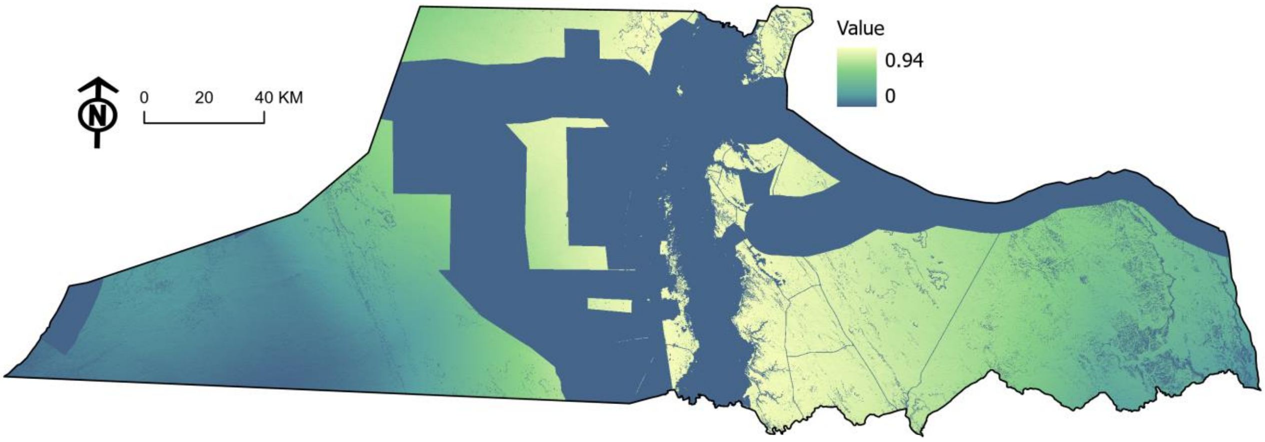

Fig.6 Initial site suitability map for allocating solar farms

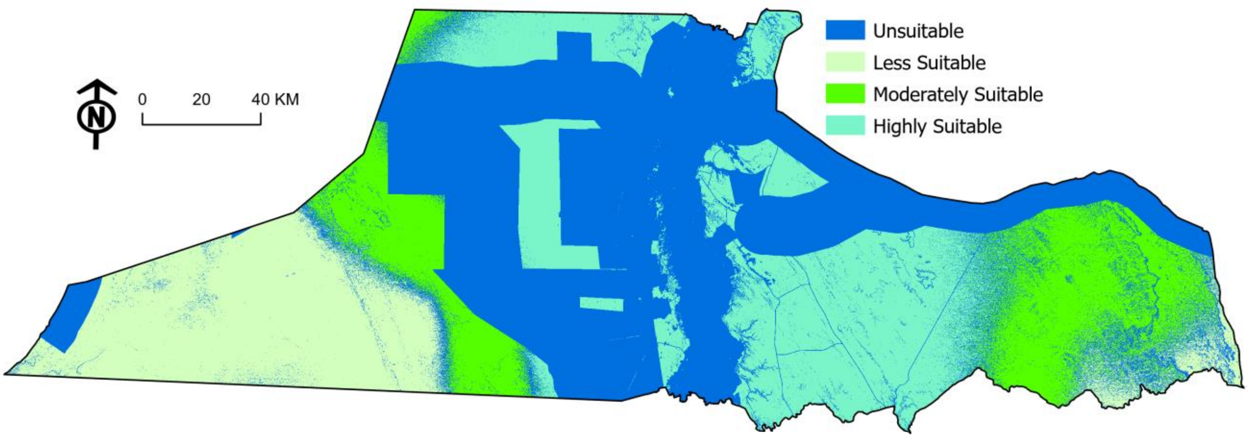

Fig.7 Final suitability map for allocating solar farms

4.2 Suitability of solar farms within the designated renewable energy areas in El Minia Governorate:

The Egyptian government has designated El Minia Governorate as a strategic hub for renewable energy production at the national level, allocating 2,917.1 km² for this purpose (see Figure. 8). Based on a comprehensive suitability analysis of the entire region, 29.2% of the designated renewable energy areas are considered unsuitable for solar farm development, primarily due to their location within authorized lands adjacent to major transportation corridors. Additionally, only 0.1% of these areas are classified as moderately suitable. In contrast, 70.7% of the designated areas exhibit high suitability for solar farm deployment (see Figure 9). These findings indicate that the majority of the designated renewable energy zones in El Minia are highly conducive for large-scale solar farm development, optimizing the potential for renewable energy generation in the region.

These highly suitable areas exhibit favorable spatial characteristics that make them ideal for prioritizing large-scale solar farm allocation. This suitability is attributed to several key factors, including proximity to existing urban areas and major roads, close distance to transmission lines, and minimal land slope. These factors collectively enhance cost efficiency in infrastructure development and minimize potential land-use conflicts, ensuring long-term viability for solar energy projects.

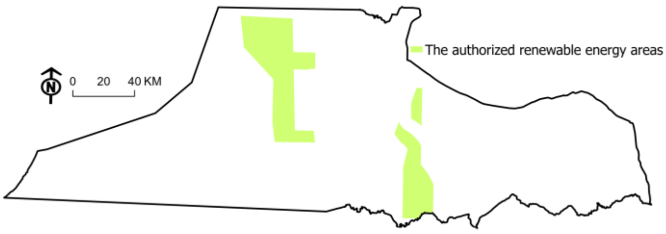

Fig.8 The designated areas for renewable energy development within El Minia Governorate

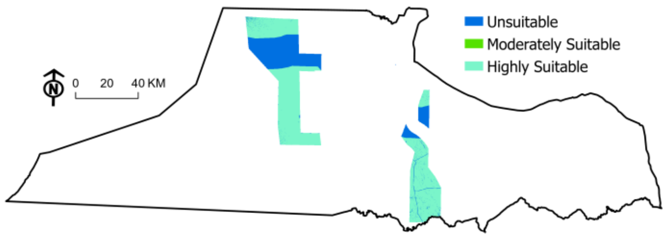

Fig.9 The suitability of designated renewable energy areas for allocating solar farms

5. Conclusion:

This study employed an integrated approach that combines Fuzzy Logic, the Analytic Hierarchy Process (AHP), and Geographic Information Systems (GIS) with remote sensing data to identify highly suitable locations for solar farm deployment in El Minia Governorate, Egypt. In addition, it assessed the designated renewable energy zones within the region to evaluate their potential for solar energy development. The analysis focused on four key determinant factors: solar radiation, proximity to transmission lines, distance to roads, and distance to urban areas. These factors were evaluated alongside restricted areas, including existing land use, steep slopes, and areas authorized for future development. The weighted selection factors and restricted layers were integrated and overlaid within the ArcGIS environment to generate a comprehensive site suitability map for solar farm allocation. The results revealed that 45.6% of the region is unsuitable for solar development, 32.4% is classified as moderately or less suitable, and 22% is considered highly suitable, particularly in the hinterlands of existing urban and rural areas. Furthermore, the study indicates that 70.7% of the designated renewable energy areas are suitable for solar farm infrastructure development. The methodology and findings presented in this study can serve as a model for conducting similar assessments in other regions, provided that the necessary raster and vector data are available.

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