Using MCDA approach in the GIS for Locating the Best Solar Energy Sites: A Case Study in the Great Nile Bend Region, Northern State, Sudan

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***Abstract*--This study presents a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) to identify suitable locations for solar energy development in the Great Nile Bend region, Northern State, Sudan. Given the region's high solar potential and the need for sustainable energy planning, a spatial suitability framework was developed by integrating key environmental, topographic, and land use criteria. Relevant spatial datasets were processed and standardized, and criterion weights were assigned according to their relative importance. A weighted overlay analysis was used to produce a solar energy suitability map classifying the study area into five suitability classes. The final suitability results were converted into vector format to support detailed spatial analysis, and the highest suitability zones were extracted as optimal areas for potential solar energy deployment. The results show clear spatial variation in solar energy potential and are consistent with previous GIS-based studies in arid and semi-arid regions, confirming the reliability of the methodology. Overall, the study highlights the Great Nile Bend region as a promising solar energy hotspot in Sudan and demonstrates the applicability of the proposed GIS-based framework as a decision support tool for sustainable regional energy planning.**

***Index Terms*--Great Nile Bend region, Multi-Criteria Decision Analysis, Renewable Energy Planning, Solar energy hotspot, Weighted Overlay Analysis.**

***المستخلص*-- تقدم هذه الدراسة تحليلا مكانيا قائما على نظم المعلومات الجغرافية وتحليل إتخاذ القرار متعدد المعايير لتحديد المواقع الملائمة لتطوير الطاقة الشمسية في منطقة إنعطاف النيل الكبرى بالولاية الشمالية في السودان. ونظرا لما تتمتع به المنطقة من إمكانات عالية للطاقة الشمسية والحاجة المتزايدة إلى التخطيط المستدام للطاقة، فقد تم تطوير إطار مكاني للملاءمة من خلال دمج مجموعة من المعايير البيئية والطبوغرافية ومعايير إستخدامات الأراضي ضمن بيئة نظم المعلومات الجغرافية. وتمت معالجة البيانات المكانية ذات الصلة وتوحيدها، كما تم إسناد أوزان نسبية للمعايير وفقا لأهميتها في إختيار مواقع الطاقة الشمسية. وتم تطبيق أسلوب التراكب الوزني لإنتاج خريطة شاملة لملاءمة الطاقة الشمسية، حيث جرى تصنيف منطقة الدراسة إلى خمس فئات تتراوح بين أقل ملاءمة وأعلى ملاءمة. بعد ذلك، أعيد تصنيف الخريطة النهائية وتحويلها إلى صيغة متجه لإجراء تحليل مكاني أكثر تفصيلا. أظهرت النتائج تباينا مكانيا واضحا في إمكانات الطاقة الشمسية داخل منطقة الدراسة حيث ترتبط هذه المناطق بشكل رئيسي بإرتفاع الإشعاع الشمسي، وإنخفاض الإنحدار الطبوغرافي، وقلة القيود المرتبطة بإستخدامات الأراضي. ولدعم التفسير المكاني، تم إستخراج المناطق الأعلي ملاءمة في طبقة مستقلة تمثل المناطق المثلى لتطوير الطاقة الشمسية. تتوافق أنماط التوزيع المكاني ونتائج الملاءمة في هذه الدراسة مع نتائج دراسات سابقة أجريت في مناطق جافة وشبه جافة، مما يؤكد موثوقية المنهجية المعتمدة. هذه الدراسة تسهم بصورة كبيرة في سد فجوة بحثية من خلال تقديم تقييم مكاني شامل لملاءمة الطاقة الشمسية في منطقة إنعطاف النيل الكبرى؛ كما تظهر الدراسة أن هذه المنطقة تمثل نقطة ساخنة محتملة للطاقة الشمسية في السودان، وتوفر إطارا داعما لإتخاذ القرار في التخطيط الإقليمي للطاقة المتجددة.**

I. Introduction

Sudan's energy crisis has reached a point where sustainable solutions are not only desirable but also essential. The country faces persistent electricity shortages due to frequent power outages, increasing economic pressures, and war that erupted in April 2023. These challenges significantly impact households, industrial productivity, and agricultural operations, creating urgent socio-economic and environmental concerns. In this context, solar photovoltaic (PV) systems offer a practical and immediate solution. By connecting these systems directly to the national grid, Sudan can stabilize energy access, reduce operational costs, and enhance the quality of life for both urban and rural communities. The economic relief and social improvements generated by reliable solar electricity highlight the critical importance of this research.

Sudan is uniquely positioned to harness solar energy. The country benefits from exceptionally high solar irradiance throughout the year, coupled with expansive open lands, especially along the Nile segment in the Northern State. These natural endowments allow for the installation of large-scale PV systems with minimal topographical constraints and optimal energy yield [1], [2]. Leveraging these resources addresses both the energy deficit and the environmental imperative of reducing carbon emissions, promoting clean and sustainable energy generation across the country.

The integration of solar PV systems with agricultural operations presents additional opportunities for socio-economic development. Agriculture remains a primary economic sector in Sudan, and combining energy generation

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with irrigation, agro-processing, and rural electrification can enhance productivity, optimize land use, and create sustainable livelihoods [3]. This dual-use strategy maximizes the value of available land while supporting both food security and energy sustainability, a combination particularly relevant in regions where agriculture is a major source of income and investment.

Geographic Information System (GIS) play a pivotal role in planning and site selection for solar energy projects. GIS enables the spatial analysis and integration of environmental, topographic, infrastructural, and land-use data, providing a robust platform for evidence-based decision-making. When coupled with multi-criteria decision analysis or the Analytic Hierarchy Process (AHP), GIS allows systematic evaluation and prioritization of potential solar PV sites, taking into account factors such as solar radiation, slope, land cover, proximity to roads and transmission lines, water bodies, and built-up areas [1], [4]. This approach ensures that selected locations are technically feasible, socially acceptable, and environmentally sustainable, enabling policymakers to make informed and effective decisions.

Several recent studies demonstrate the application and effectiveness of GIS-based Multi-Criteria Decision Analysis (MCDA) for solar energy site selection. These studies highlight the integration of environmental, infrastructural, and socio-economic factors to optimize site selection, reduce implementation costs, and enhance the feasibility of solar PV projects.

Ahmed [3] in 2024 applied a GIS–MCDA framework in Khartoum State, Sudan, incorporating proximity to roads, water bodies, urban areas, and protected zones, thereby highlighting the role of GIS in ensuring socially and environmentally compatible site selection. In the same year, Islam et al [4] conducted a comprehensive GIS–AHP study in Bangladesh, integrating solar radiation, slope, land cover, and proximity to infrastructure to identify optimal PV sites, while emphasizing the importance of balancing technical feasibility with accessibility to existing infrastructure. Noorollahi et al [5] in 2022 confirmed the robustness of GIS-based approaches for national-scale solar energy planning by integrating environmental, technical, and land-use constraints. Prieto et al [6] in 2021 evaluated regional solar farm suitability using a multi-criteria GIS framework that combined land-use, topographic, and environmental factors to produce weighted overlay maps identifying optimal locations for solar farms. Foundational contributions were provided by Al Garni and Awasthi [7] in 2017, who employed GIS–AHP to identify suitable solar PV sites in Saudi Arabia, and Sánchez-Lozano et al [8] in 2016, who demonstrated the effectiveness of GIS–MCDA methods for large-scale solar power planning in Mediterranean regions.

While these studies provide valuable methodologies, this study is distinct in several key aspects. It focuses on a study area characterized by high solar irradiance and extensive open lands. Unlike prior research, this study explicitly incorporates a direct connection to the national grid, emphasizing the economic benefits of energy delivery to communities and industries. Additionally, it considers the potential integration with agriculture, enabling dual-use of land for both energy generation and farming activities, thereby enhancing socio-economic impact. Finally, a tailored GIS-MCDA framework is applied, specifically designed for regions with vast open lands and high solar irradiance, balancing technical feasibility, environmental sustainability, and social considerations.

This combination of factors, technical, environmental, economic, and social, represents the unique contribution of this study, offering a practical and comprehensive guide for sustainable solar energy planning in Sudan.

The main objectives of this study are to:

1. Assess the solar energy potential of the Great Nile Bend region using key environmental, topographic, and land-use factors.
2. Classify the study area into suitability levels and identify optimal zones for large-scale PV development.
3. Demonstrate the applicability of the GIS-MCDA framework as a transferable tool for other regions of Sudan.

II. Materials And Methods

This study adopts a rigorous and systematic methodological framework to identify optimal sites for solar photovoltaic development using an integrated GIS-MCDA approach. The methodology is founded on extensive data collection, careful data validation, and detailed spatial processing to ensure the reliability and robustness of the suitability assessment. Multiple spatial datasets (Table I) representing solar radiation, topographic, land-use, and infrastructural characteristics were acquired from diverse authoritative sources and harmonized within a unified geospatial environment.

TABLE I
Spatial datasets and sources

Dataset	Source	Spatial Resolution	Format
DEM	SRTM / NASA-USGS	30 m	GeoTIFF
Solar Radiation	EUMETSAT CM SAF	≈0.05° (≈5.5 km)	GeoTIFF
Land Cover	Esri Global Land Cover	10 m	Raster
Roads, Waterways, and Buildings	OpenStreetMap / BBBike	±5–30 m	Shapefile
Electricity Transmission Lines	Global Transmission Network	±5–10 m	Shapefile
Protected Areas	WDPA / UNEP-WCMC	±100 m	Geodatabase (.gdb)

Significant effort was devoted to preprocessing and standardizing all datasets, including projection unification, spatial resolution matching, and clipping to the study area boundaries. Each dataset was critically examined for relevance, accuracy, and applicability to solar energy planning in arid environments. Advanced spatial analysis tools within ArcGIS 10.8 were employed to perform raster derivation, buffer generation, reclassification, and weighted overlay operations. These procedures required iterative testing and refinement to ensure that each criterion accurately reflects real-world constraints and opportunities for solar energy deployment.

The methodological workflow emphasizes transparency, reproducibility, and scientific rigor by explicitly defining criteria selection, data processing steps, and weighting schemes based on established literature and best practices. Through the integration of high-resolution spatial data and systematic decision-making techniques, the adopted approach enables a comprehensive evaluation of solar site suitability that balances technical feasibility, environmental protection, and infrastructural accessibility. This methodology provides a solid analytical foundation for generating reliable suitability maps and supports informed decision-making for sustainable solar energy planning across comparable regional contexts.

A. Study Area

The study area for this research (Fig. 1) is defined within the geographic coordinates 18.0°N–19.3°N latitude and 30.4°E–32.0°E longitude, lying entirely within the Northern State, Republic of Sudan. Geographically, the study area corresponds to the Great Nile Bend region, a distinctive fluvial–geomorphological segment where the Nile River exhibits a pronounced curvature as it flows through Northern Sudan. This section of the Nile extends between Dongola and the vicinity of Abu Hamad, forming a wide bend that strongly influences regional settlement patterns, land use, and accessibility. This region characterized by an arid hot desert climate with minimal cloud cover, extremely low precipitation, and high annual sunshine duration. Such climate conditions result in some of the highest solar radiation values globally, making this area an ideal candidate for solar energy exploitation [9]-[12]. Empirical analyses indicate that the entire northern region, including segments within the specified coordinates, receives abundant solar energy throughout the year, with annual average daily global solar radiation reaching levels that are among the highest in the world, often exceeding 6.0 kWh/m²/day under clear-sky conditions [10], [12].

The climatic regime of the Sudan Northern State is dominated by clear skies and high insolation, essential characteristics for photovoltaic and concentrated solar power (CSP) systems. The hot desert climate within this segment ensures consistently high Global Horizontal Irradiance (GHI) and long sunshine hours annually, supporting the feasibility of large-scale utility PV installations as well as off-grid solutions for rural electrification and agricultural uses [10], [12]. Moreover, the flat terrain and sparse vegetation within the study area simplify site preparation for solar plants and minimize shading impacts on solar arrays [11].

The decision to focus this research on the study area is grounded in both solar resource potential and strategic developmental needs. Multiple solar radiation studies across Northern Sudan highlight that this part of the country exhibits solar potential among the highest in the world, with continuous high levels of global solar radiation and extended sunshine duration conditions, which are core determinants in solar energy system design and optimization [10], [12]. These high irradiance levels significantly increase the energy yield of photovoltaic systems and decrease the levelized cost of energy (LCOE) compared to regions with lower solar resource availability [11], [14].

In addition to physical solar resource attributes, the Northern State's energy access challenges and low penetration of grid electricity further justify its selection. Prior research and national energy assessments emphasize the strategic importance of deploying renewable energy, especially solar, to enhance energy security, diversify energy sources, and promote sustainable development in remote and underserved areas [10], [11], [14].

Additionally, Sudan's limited national grid coverage and heavy reliance on non-renewable generation further reinforce the strategic significance of expanding solar energy deployment within the study area. National energy assessments have highlighted that grid penetration outside major urban centers is low, and the country still depends heavily on hydropower and fossil fuel generators to meet demand, with renewable energy sources beyond hydropower contributing only a marginal portion of electricity supply [10], [11], [14]. Responding to this energy access gap, policymakers and researchers emphasize that harnessing solar potential, which is among the highest globally due to favorable climatic conditions, is critical to reducing dependency on traditional generators, lowering fuel costs, and improving energy equity.

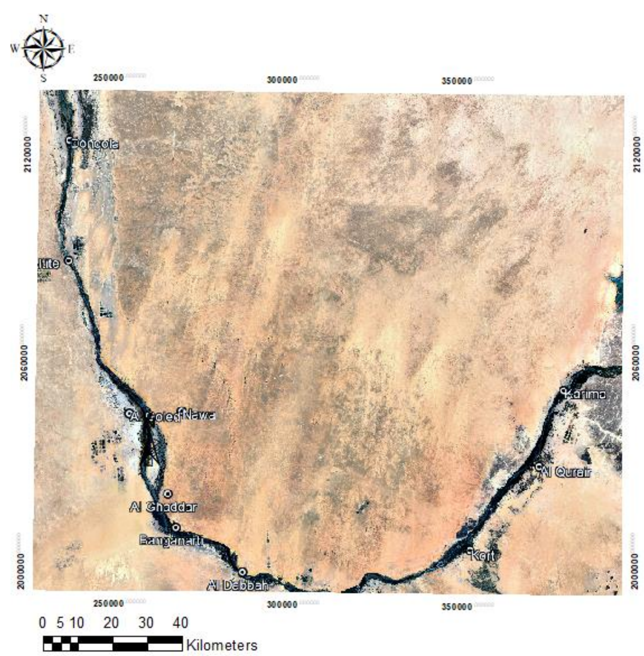

Fig. 1. Study Area [13]

B. Criteria Selection and Justification

In this study, the selection of spatial criteria for the GIS-based solar site suitability analysis follows established frameworks and precedents in the literature that systematically integrate environmental, topographic, and infrastructural factors. Geographic information systems, combined with multi-criteria decision analysis or the analytic hierarchy process, have been widely applied in recent research to identify optimal locations for solar photovoltaic installations based on multiple criteria that represent physical, climatic, accessibility, and land-use considerations.

Numerous studies emphasize the importance of solar radiation and topographic conditions such as slope and aspect due to their direct influence on photovoltaic performance and land suitability for installation infrastructure [1], [4]. Solar radiation is the primary determinant of potential energy yield, while slope and aspect affect construction feasibility, system stability, and shading effects. These factors have been consistently incorporated in GIS-AHP and MCDA-based models across diverse geographic and climatic contexts.

Land use/land cover (LULC) constitutes a fundamental criterion in solar site selection, serving both as a constraint and a suitability indicator. LULC analysis enables the exclusion of environmentally or socially incompatible areas such as urban settlements, water bodies, and protected zones, while highlighting open and undeveloped lands that are suitable for PV installations. Previous studies consistently apply land cover classifications to delineate exclusion zones and identify feasible land parcels within GIS-based suitability models [6].

Proximity to transportation networks (e.g., major roads) and existing electrical infrastructure (e.g., transmission lines) is commonly considered in solar site suitability assessments to minimize construction, maintenance, and grid connection costs. Several case studies integrate accessibility-related criteria within weighted overlay analyses, recognizing that reduced distance to infrastructure enhances technical feasibility and economic viability [6].

Additional constraint criteria, including proximity to waterways and built environments (e.g., buildings and urban areas), are incorporated to mitigate environmental risks and avoid potential conflicts with human activities. These constraints ensure the protection of sensitive ecosystems, reduce flood-related hazards, and address safety and land-use compatibility considerations. The use of buffer-based exclusion zones around watercourses and built-up areas is well documented in GIS-MCDA applications for renewable energy planning [1], [3].

Although population density is frequently applied in solar site suitability studies as a socio-economic indicator, it was excluded from the model in this study due to its strong spatial correlation with the built-environment layer and its limited discriminatory power in sparsely populated regions. The buildings layer was considered sufficient to represent settlement-related constraints while maintaining model parsimony and reducing redundancy among criteria.

Protected areas are commonly included as a criterion in GIS-based solar site suitability analyses to ensure environmental conservation and avoid ecologically sensitive zones. In this study, a protected areas layer was incorporated following standard procedures; however, spatial data analysis revealed that the study area does not contain any designated protected zones. Despite the absence of such areas, including this criterion ensures methodological consistency and aligns with best practices in renewable energy site selection [6].

Overall, the selected criteria, including slope, aspect, solar radiation, land cover, proximity to infrastructure (roads and transmission lines), water bodies, built environments, and protected areas, are consistent with established academic practices for GIS-based solar site selection. The adopted framework aligns with proven methodologies in renewable energy suitability modeling and ensures a robust, context-sensitive evaluation of optimal locations for solar PV development [1], [3], [4], [6].

C. Data and Software

The spatial database for this study was constructed using a set of geospatial layers relevant to identifying optimal sites for solar energy projects in the study area of Sudan's Northern State.

Polygon Shapefile: Initially, a polygon shapefile representing the study area was created using ArcGIS 10.8, which served as a mask to clip all other layers and ensure spatial consistency with the target area.

Digital Elevation Model (DEM): A 30 m DEM was used to extract slope, aspect, and other topographic characteristics. The data are available in GeoTIFF format from the Shuttle Radar Topography Mission (SRTM) provided by NASA/USGS [15].

Solar Radiation: Annual average solar radiation on a horizontal surface (Global Horizontal Irradiance, GHI) was obtained to assess solar energy potential and support site selection. The dataset is provided in GeoTIFF format and has a spatial resolution of approximately 0.05° (≈5.5 km per pixel). The data are derived from EUMETSAT CM SAF satellite observations and are suitable for processing in ArcGIS 10.8 [16].

Land Cover: Esri Global Land Cover data with a 10 m spatial resolution were used to classify land surface types, including water, trees, flooded vegetation, crops, built areas, bare ground, and rangeland. These data were applied to identify suitable and restricted areas for solar energy development [17].

Roads, Waterways, and Buildings: Spatial data for roads, waterways, and buildings were obtained from OpenStreetMap (OSM) through the BBBike service. These datasets were used to evaluate the proximity of potential solar sites to existing infrastructure and to assign relative weights within the multi-criteria suitability analysis. The spatial accuracy of these layers is approximately ±5–10 m in urban areas and ±10–30 m in rural regions, depending on mapping density and data availability [18]-[20].

Electricity Transmission Lines: Data were sourced from the Global Transmission Network (EnergyData.info / World Bank) in shapefile format to evaluate proximity to the electrical grid. Its spatial accuracy is similar to that of OSM data (≈ ±5–10 m in mapped areas) [21].

Protected Areas: Data on protected areas were obtained from the World Database on Protected Areas (WDPA) maintained by the United Nations Environment Programme – World Conservation Monitoring Centre (UNEP-WCMC) in file geodatabase (.gdb) format, with an approximate spatial accuracy of ±100 m [22].

The spatial analysis and multi-criteria evaluation in this study were conducted using ArcGIS 10.8 [23], a leading geographic information system platform widely adopted in environmental and renewable energy research. ArcGIS provides robust tools for geospatial data management, spatial analysis, and visualization, enabling the integration of multiple data layers including solar radiation, topography, land use, infrastructure, and environmental constraints. Its spatial analyst and raster calculator modules facilitate reclassification, buffering, and suitability mapping, which are essential for GIS-based solar site selection. The software's capability to handle high-resolution datasets and perform weighted overlay analysis ensures accurate, reproducible, and context-sensitive evaluation of potential solar energy sites. ArcGIS 10.8 was selected for this study due to its reliability, extensive functionality, and compatibility with multiple data formats, which collectively support rigorous site suitability modeling for renewable energy planning.

III. Results And Discussions

All spatial data processing and analysis for this study (Fig. 2) were conducted using ArcGIS 10.8. To ensure consistency across all datasets and enable accurate multi-criteria analysis, a systematic preprocessing workflow was established.

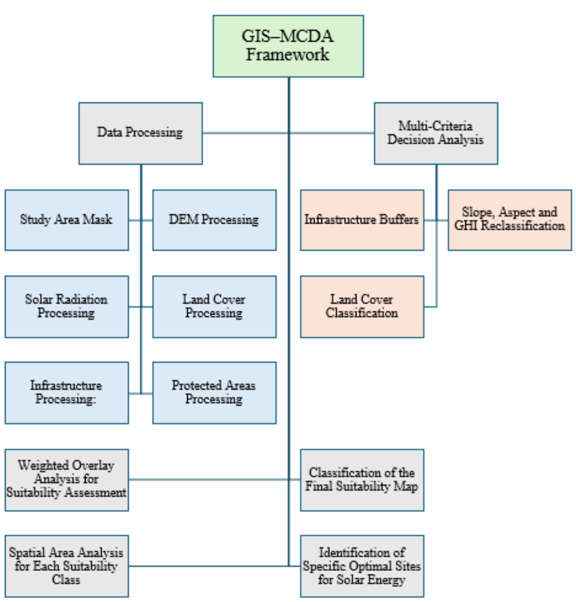

Fig. 2. GIS–MCDA Framework for Solar Energy Site Suitability Analysis

A. Data Processing

Initially, a polygon shapefile representing the study area was manually digitized to delineate its spatial extent. The study area shapefile was assigned the WGS 1984 UTM Zone 36N coordinate reference system, which is appropriate for the geographic location of the study area. This shapefile was subsequently used as a spatial mask to clip all raster and vector datasets, ensuring consistent spatial extent and projection across all layers prior to further analysis.

The digital elevation model covering the study area (Fig. 3) was initially provided in multiple adjacent tiles, which were merged into a single continuous raster to ensure complete spatial coverage. The resulting raster was clipped to the boundary of the study area. The DEM was then converted to a consistent raster format for compatibility with subsequent analyses. To enable accurate distance and area-based calculations, the raster was reprojected to the WGS 1984 UTM Zone 36N coordinate reference system, consistent with the spatial framework adopted for all datasets in this study. Data voids within the DEM were corrected to remove surface discontinuities. Slope (Fig. 4) and aspect (Fig. 5) were obtained from the processed DEM and used in the solar energy site suitability analysis.

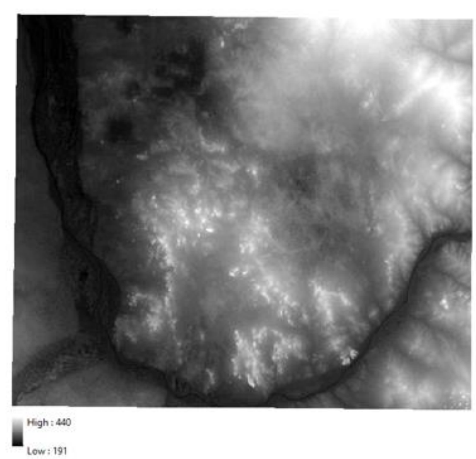

Fig. 3. Digital Elevation Model of the Study Area

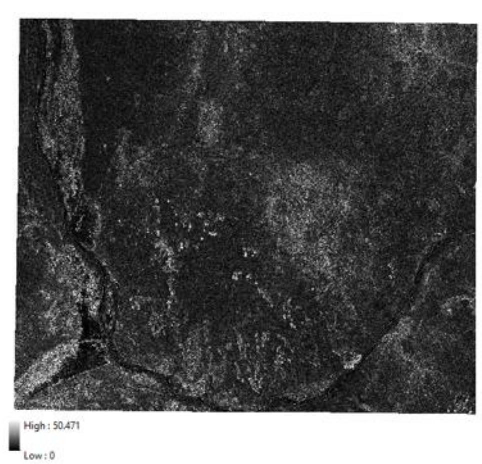

Fig. 4. Slope Map of the Study Area

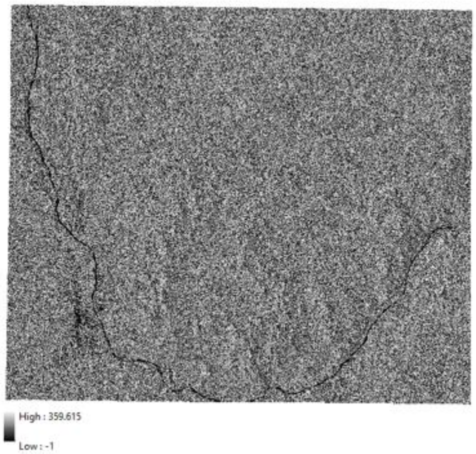

Fig. 5. Aspect Map of the Study Area

Annual average global horizontal irradiance data (Fig. 6) were clipped to the boundary of the study area to ensure spatial consistency. The raster data were then reprojected to the WGS 1984 UTM Zone 36N coordinate reference system, with bilinear interpolation applied to maintain the continuity of solar radiation values. To harmonize spatial resolution with the previously processed DEM, the raster was resampled to a 30 m pixel size, ensuring compatibility for subsequent spatial analyses and integration in the solar energy site suitability assessment.

Fig. 6. Solar Radiation Distribution in the Study Area

Land cover data for the study area (Fig. 7) were provided in two raster layers, which were merged into a single continuous raster to ensure complete spatial coverage. The resulting raster was clipped to the boundary of the study area to maintain spatial consistency with other datasets. To harmonize with the DEM, the raster was reprojected to the WGS 1984 UTM Zone 36N coordinate reference system and resampled to a 30 m pixel size.

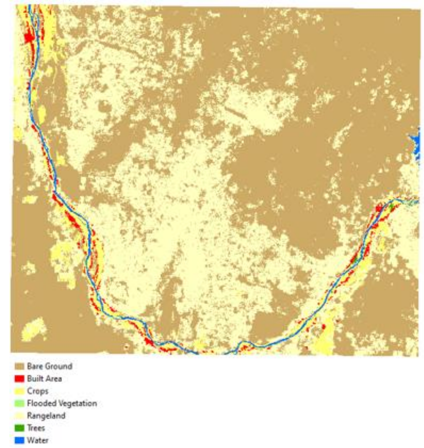

Fig. 7. Land Cover Map of the Study Area

Shapefiles for roads, waterways, and buildings (Fig. 8) were obtained and clipped to the boundary of the study area to ensure spatial consistency. All layers were reprojected to the WGS 1984 UTM Zone 36N coordinate reference system to maintain compatibility with other datasets. These layers were used to evaluate the accessibility and suitability of potential solar sites, considering proximity to existing infrastructure and potential exclusion zones in the multi-criteria site suitability analysis.

The electricity transmission lines shapefile (Fig. 8) was obtained and clipped to the boundary of the study area to ensure spatial consistency. The layer was reprojected to the WGS 1984 UTM Zone 36N coordinate reference system to maintain compatibility with other datasets. The processed transmission lines were used to assess the proximity of potential solar sites to the electrical grid, which is a critical factor in the multi-criteria site suitability analysis.

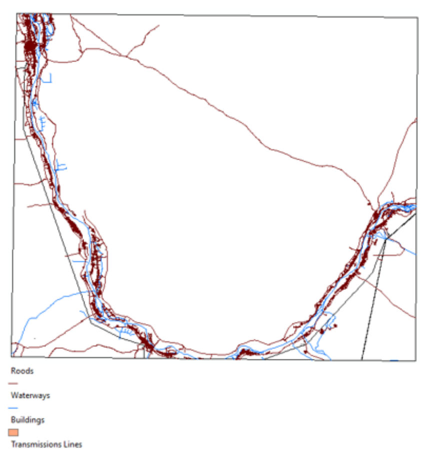

Fig. 8. Spatial Data Layers Used in the Analysis

The protected areas dataset covering Sudan was initially obtained, and the layers were clipped to the boundary of the study area to ensure spatial consistency. After processing, no protected areas were identified within the study area boundary. Consequently, this layer did not impose any exclusion zones for the solar energy site suitability analysis.

B. Multi-Criteria Decision Analysis

Multi-criteria decision analysis is a widely adopted methodology in GIS-based renewable energy planning, designed to integrate multiple spatial and environmental factors for the identification of optimal locations for solar power plants. In this study, MCDA was implemented following a structured multi-step approach, ensuring a systematic and quantitative evaluation of site suitability.

(1) Creation of Infrastructure Buffer Zones for Suitability Analysis:

To exclude areas that are technically or environmentally unsuitable for large-scale solar development, buffer zones were systematically generated for each infrastructure and constraint layer (Table II). Buffering serves to spatially represent proximity effects and to ensure safe distances from critical infrastructure, thereby aligning with established GIS-based solar site selection methodologies [24]-[26].

TABLE II
Setback rules and buffer distances for solar site selection

Constraint Layer	Rule / Regulation	Buffer Distance
Roads	Ensure safe construction & operation, maintain access	150 m
Waterways	Protect environment and mitigate flooding risk	100 m
Buildings	Avoid shading and land use conflict	200 m
Electricity Transmission Lines	Ensure safety and maintenance access	500 m

A 150 m exclusion buffer was applied around the roads within the study area to ensure safe distances for the construction and operation of solar power plants. This buffer distance was selected to minimize potential conflicts with transportation infrastructure while maintaining adequate accessibility for construction and maintenance activities, consistent with established GIS-based solar site selection practices [24], [25].

A 100 m buffer was generated around the waterways to reduce potential environmental disturbance and mitigate flooding risks. Maintaining a setback from hydrological features is consistent with environmental land-use standards commonly applied in solar site suitability assessments [26].

A 200 m buffer was applied around the buildings to avoid shading effects and land-use conflicts with residential or commercial zones, thereby ensuring compliance with spatial planning considerations and optimizing solar energy capture [26].

A 500 m buffer was established around the electricity transmission lines to address safety requirements and construction constraints. This distance reflects commonly adopted thresholds in GIS-based suitability analyses aimed at balancing grid accessibility with operational and safety considerations [25].

All buffer layers for roads, waterways, buildings, and transmission lines were converted to raster format at a 30 m cell size, consistent with the DEM used as a spatial reference to ensure uniformity across all study layers. A study area mask was applied to each raster to restrict the analysis to the area of interest. The rasters were then reclassified into a binary constraint scheme, assigning a value of 0 to buffer zones (unsuitable) and 1 to all other areas (suitable). Finally, the reclassified layers were integrated to produce a unified infrastructure constraint raster (Fig. 9), representing all restricted and permissible areas while maintaining consistent cell size and spatial alignment for subsequent multi-criteria analysis.

Fig. 9. Infrastructure Constraint Areas

(2) Reclassification of Slope, Aspect and Solar Radiation:

Following the exclusion of constrained areas, continuous suitability criteria, including slope, aspect, and solar radiation, were reclassified into standardized suitability classes to enable integration within the multi-criteria decision analysis framework.

A raster-based infrastructure constraints layer was employed to exclude unsuitable areas from the continuous suitability criteria. The infrastructure constraints raster was applied to the slope, aspect, and solar radiation layers to mask restricted zones. Cells corresponding to constrained areas were assigned NoData values, while permissible areas retained their original values. This preprocessing step ensured that the reclassification of slope, aspect, and solar radiation was conducted exclusively within spatially feasible locations for solar energy development.

The slope, aspect, and solar radiation layers processed above were reclassified into a standardized suitability scale from 1 (least suitable) to 5 (most suitable) following the exclusion of constrained areas (Fig. 10 to 12). Slope and solar radiation were scored based on lower slope and higher radiation values, respectively, while aspect was reclassified to favor south-facing directions, with constrained areas retained as NoData.

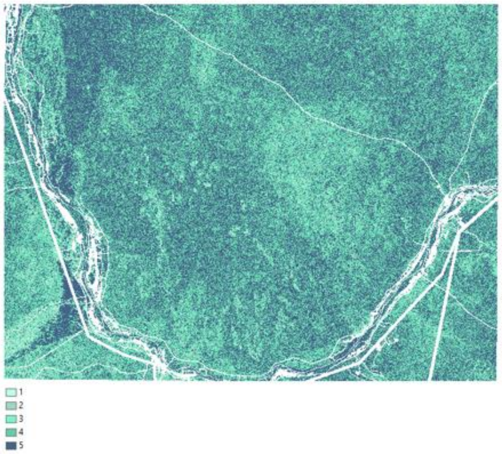

Fig. 10. Reclassified Slope Map

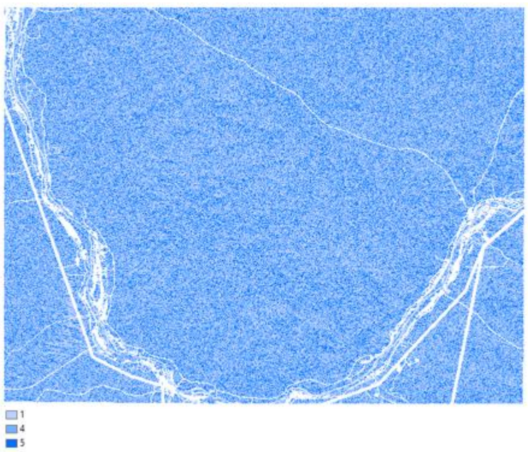

Fig. 11. Reclassified Aspect Map

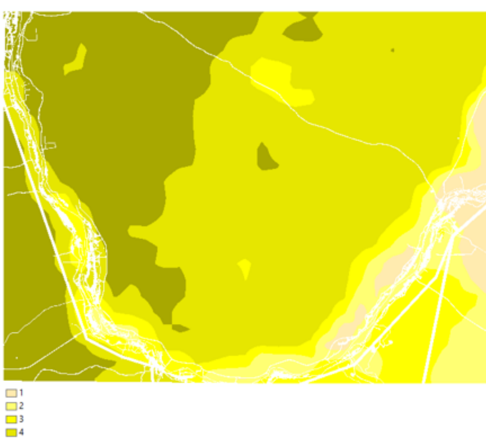

Fig. 12. Reclassified Solar Radiation Map

(3) Land Cover Classification:

The land cover layer was classified into suitability classes based on surface type, with scores ranging from 1 (least suitable) to 5 (most suitable). Bare ground received the highest score (5) due to its high installation feasibility and minimal shading, followed by rangeland (4) and crops (3). Trees and flooded vegetation were assigned intermediate values (2), while built-up areas and water bodies received the lowest score (1). This scoring system aligns with previous GIS-based solar site selection studies.

Within ArcGIS 10.8, the land cover raster was constrained using the infrastructure constraints layer, assigning NoData values to all restricted areas. The raster's cell size was matched to the DEM, and a study area mask was applied to limit the analysis to the defined spatial extent. The resulting permissible areas were then reclassified (Fig. 13) into the standardized suitability scale as described above, enabling integration with other spatial layers and supporting a comprehensive assessment of potential solar energy locations within the study area.

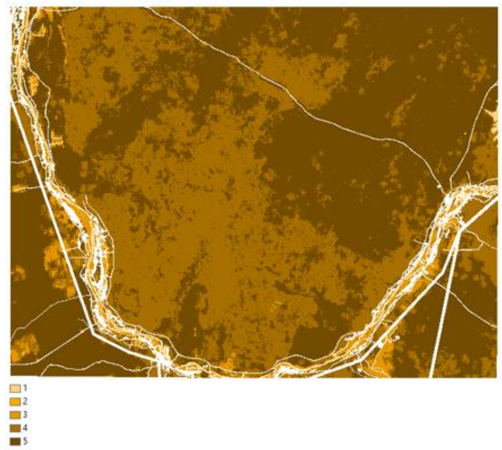

Fig. 13. Reclassified Land Cover Map

C. Weighted Overlay Analysis for Suitability Assessment

Following the preparation and reclassification of all individual criteria layers, a weighted overlay analysis was conducted to integrate the standardized rasters and generate a composite solar energy suitability map for the study area. The analysis was implemented within a GIS-based multi-criteria decision analysis framework within ArcGIS 10.8.

The relative importance of each criterion was represented through assigned weights based on their influence on photovoltaic energy production, installation feasibility, environmental suitability, and economic considerations. The weights were normalized to a total of 100%, consistent with standard practice in GIS-based weighted overlay analyses.

Infrastructure constraints were applied prior to the weighted overlay analysis to exclude restricted areas, ensuring that all subsequent layers only considered permissible locations. Solar radiation (40%) was assigned the highest weight, as it directly controls photovoltaic energy yield and represents the primary determinant of solar farm performance. Slope (30%) received a high weight due to its strong influence on construction feasibility, installation costs, and system stability. Land cover (25%) was weighted to reflect land availability, shading effects, and potential land-use conflicts, favoring bare and sparsely vegetated surfaces.

Aspect (5%) was assigned a lower weight because of its limited influence on solar energy potential in low-latitude arid environments [1], [4].

The weighted overlay analysis was performed within ArcGIS 10.8. The slope, aspect, solar radiation, and land cover suitability rasters were added as input layers, and their corresponding weights were assigned according to the previously defined weighting scheme. The cell size and snap raster were set to match the digital elevation model, and the processing extent was defined as the intersection of all input raster extents. The weighted overlay operation combined the input rasters using a linear weighted summation approach, producing a composite suitability index raster that represents the relative suitability of each location for solar energy development.

D. Classification of the Final Suitability Map

For visualization and interpretation purposes, the resulting composite suitability raster was reclassified within ArcGIS into five suitability classes, ranging from 1 (least suitable) to 5 (most suitable). This classification facilitated clear identification and visualization of areas with varying suitability levels, allowing spatial assessment of solar energy potential across the study area. Areas classified as highly suitable (classes 4 and 5) were considered optimal locations for potential solar energy development.

E. Spatial Area Analysis for Each Suitability Class

To quantitatively assess the extent of each suitability class within the study area, the final reclassified raster representing solar energy potential (classes 1–5) was first converted to vector polygons within ArcGIS. To simplify the analysis and produce clearer maps, all polygons belonging to the same class were merged into single polygons based on the gridcode attribute (Fig. 14). Each resulting polygon was attributed with its gridcode value, and its area was calculated in square kilometers.

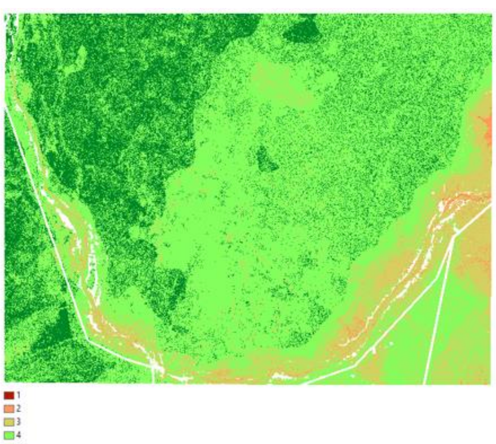

Fig. 14. Final Solar Energy Suitability Map

Subsequently, the total area for each class was summarized, and a percentage field was computed to represent the relative coverage of each suitability category (Table III). This vector-based, dissolved polygon approach facilitates a precise and visually clear representation of spatial suitability, enabling effective identification of optimal regions for solar energy development and supporting spatial comparisons across different classes.

TABLE III
Solar energy suitability Classification

Gridcode	Class	Area (km^2)	Percentage (%)
1	Lowest Suitability	0.449	0.002
2	Low Suitability	112.507	0.579
3	Moderate Suitability	2289.7487	11.781
4	High Suitability	12,334.831	63.462
5	Highest Suitability	4,698.967	24.176

F. Identification of Specific Optimal Sites for Solar Energy

To identify specific locations with the highest potential for solar energy development, areas classified as High (Class 4) and Highest (Class 5) suitability were selected from the final dissolved suitability polygons. These optimal areas were extracted within ArcGIS and exported as a separate feature layer (Optimal Sites) to facilitate focused spatial interpretation (Fig. 15).

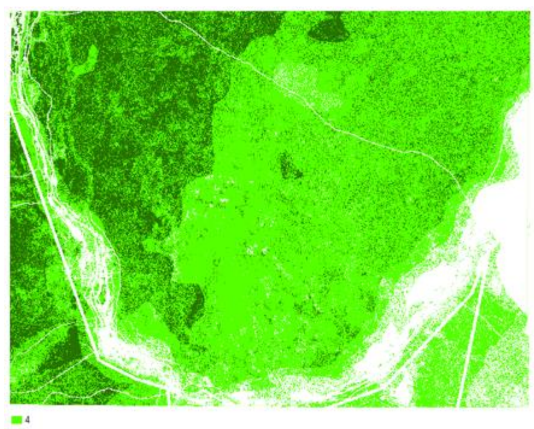

Fig. 15. Optimal Sites for Solar Energy Development

Quantitative spatial analysis demonstrates that the High and Highest suitability classes occupy a substantial proportion of the total study area (Table 3), highlighting the significant potential of the Great Nile Bend region for solar energy exploitation. In contrast, areas categorized as low and lowest suitability are relatively limited in extent and are generally associated with restrictive environmental or land-use conditions.

The spatial distribution of the High and Highest suitability zones shows strong alignment with the key environmental and infrastructural criteria incorporated in the multi-criteria analysis. These areas are predominantly characterized by high solar irradiation levels, gentle topographic conditions, and suitable separation from restricted land-use categories. The spatial continuity and considerable extent of these zones suggest their suitability for large-scale solar energy development rather than isolated or small-scale installations.

The findings of this study are consistent with previous GIS-based solar energy suitability assessments conducted in arid and semi-arid regions. Similar studies have reported that highly suitable areas for solar energy development are primarily associated with high solar irradiation, and low slope. The spatial patterns observed in this study align well with existing literature, reinforcing the reliability and applicability of GIS-based multi-criteria decision analysis as an effective approach for regional-scale solar energy planning.

Despite these methodological similarities, this study makes a distinct contribution by focusing on the Great Nile Bend region in Northern Sudan, an area that has received limited attention in previous solar energy suitability research. By providing the first comprehensive spatial delineation of optimal solar energy zones in this region, the study highlights its potential role as a solar energy hotspot within Sudan. In the context of the country's growing need for sustainable and diversified energy sources, the results offer timely and valuable insights that can support national renewable energy strategies and long-term planning initiatives.

The analysis highlights that the highest suitability zones are not only determined by solar irradiation and slope but also by other spatial factors such as land use restrictions and environmental constraints. These spatial factors significantly influence the feasibility of large-scale solar energy development. Furthermore, the study emphasizes the interplay between multiple criteria, demonstrating how certain areas may appear suitable in terms of solar potential but are limited by environmental or land use restrictions. By providing a detailed narrative alongside the quantitative results, the study ensures that the rationale behind site selection is fully transparent and substantiated.

Other studies have applied alternative methods for solar energy site selection, such as Analytic hierarchy process [5], Fuzzy Logic [7], and hybrid multi-criteria decision analysis approaches [8]. These methods consider similar environmental, topographic, and land use criteria but differ from this study in how the criteria are weighted or combined.

IV. Conclusions

This research concludes that:

1. A GIS-based multi-criteria analysis can effectively assess solar energy suitability in the Great Nile Bend region, Northern State, Sudan.
2. The study classified the region into five suitability classes, with High and Highest classes (4 and 5) covering a substantial portion of the study area.
3. The optimal solar zones closely correspond to areas with high solar irradiation, favorable terrain, and minimal land-use constraints.
4. The results provide a practical spatial framework for future planning and decision-making, serving as a baseline for more detailed feasibility studies that incorporate economic, technical, and infrastructural considerations.
5. The research contributes to the limited body of solar energy planning studies in Sudan and highlights the Great Nile Bend region as a promising area for renewable energy investment.
6. The GIS-based framework used is transferable and adaptable, allowing extension to other regions of Sudan to support national sustainable energy strategies.

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