

Article

# A GIS-Based Entropy–AHP Hybrid Framework for Site Suitability Assessment of Radio Astronomy Observatories in Southern Jordan

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## Abstract

This study aims to build a spatial model for selecting the optimal site for a radio astronomy observatory in southern Jordan. Geographic Information Systems (GISs) and Multi-Criteria Decision Analysis (MCDA)-based methodology were used in this study to develop a spatial model for choosing the best location for a radio astronomy observatory in southern Jordan. The criteria were weighted using a hybrid framework that combined the Analytic Hierarchy Process (AHP) and the entropy method to account for the actual spatial diversity of the data, in addition to expert judgment. The study assesses site suitability by considering several environmental and logistical factors that mitigate radio frequency interference (RFI), including elevation, cloud cover, artificial light pollution, and accessibility. A final map highlighting the optimal areas for radio astronomy observatories in southern Jordan has been created. The study methodology started with MCDA, and was followed by several stages, including visual evaluation, overlay analysis, establishment of 500 m buffer zones, extraction of the “Very High Suitability” class, and conversion to a transparent vector layer that is free from urban overlap and electromagnetic interference. The results show that the majority of large observatories (10 km<sup>2</sup>; equivalent to ≥10,000,000 m<sup>2</sup>) are located in Aqaba and Ma'an, which offer natural isolation and wide expanses ideal for global projects. Medium observatories (0.5–10 km<sup>2</sup>; equivalent to 500,000–10,000,000 m<sup>2</sup>) were generally identified at a reasonable cost in Ma'an and Aqaba, with the possibility of radio surveillance and infrastructure expansion. Many small observatories (0.01–0.5 km<sup>2</sup>; equivalent to 10,000–500,000 m<sup>2</sup>) were constructed near academic institutions, providing viable, easily accessible places for university research with little regulatory restraints. This research contributes to national astronomy infrastructure planning and serves as a model for other countries experiencing dry or semi-arid climates. It also offers decision-makers a useful spatial database.

**Keywords:** site selection; multi-criteria decision analysis (MCDA); geographical information system (GIS); radio astronomical observatory; analytic hierarchy process (AHP); entropy weights

Academic Editors: Wolfgang Kainz and Jamal Jokar Arsanjani

Received: 15 April 2026

Revised: 29 May 2026

Accepted: 22 June 2026

Published: 6 July 2026

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## 1. Introduction

Site suitability assessments are critical for determining the best location for astronomical observatories with the highest efficiency [1]. Site selection involves multi-criteria-based evaluation and decision-making [2,3]. The ideal radio astronomy observatory site selection requires balancing numerous criteria, with a focus on lowering terrestrial interference and increasing observation efficiency [4].

MCDA is a prevailing technique, and when it is incorporated with GIS, it offers an effective tool for site selection, as well as the ability to manage vast and dense information of different types from different sources [5,6]. There has been considerable interest among researchers in the development of remote sensing (RS)- and GIS-based approaches for site selection, including the application of MCDA and AHP [7,8]. Ever since Saaty proposed the AHP tool in 1980 [9,10], it has been one of the most commonly used decision analysis methodologies. It is defined as a decision process in which the weights of different criteria are determined based on pairwise comparisons [10–12]. The reliability of the process was enhanced by the selection of weights by experienced decision-makers who investigated the criterion comparative weights [13].

GIS mapping, integrated with AHP, entropy, and MCDA, has increasingly been employed as a tool for determining the optimal site in various studies across different fields [6,14]. Recently, the integration of GIS with MCDA methodologies has resulted in a promising tool for solving complex, multipart spatial planning problems. Among the MCDA methodologies, AHP is widely used for determining criterion weights based on expert opinions, while entropy is highly effective in determining criterion weights based on the inherent variability of spatial data. The integration of AHP and entropy, also called the AHP–Entropy model, has therefore contributed to increasing recognition of its potential in improving the reliability and objectivity of spatial decisions. The AHP–Entropy model is highly effective in avoiding bias by integrating expert opinions and data evidence, making it highly effective in various applications, e.g., land suitability analysis, renewable energy planning, flood and flash flood susceptibility mapping, ecological vulnerability analysis, and emergency facility planning, among others [10,15–17]. The integration of AHP–Entropy in a GIS environment is highly effective in synthesizing multiple criteria, generating highly accurate suitability maps, and supporting sustainability in spatial decisions [15–18].

The two primary steps of the procedure are, in theory, site selection and site testing. To focus on the areas where site-testing observations, including the standard criteria, would be carried out, it is essential to choose the best locations [13]. Standard criteria used to assess the suitability of a location for a radio astronomy observatory include elevation (altitude), cloud cover (Sky Transparency), radio frequency interference (RFI), and artificial light pollution.

Accessibility (Infrastructure and Logistics) is important because even if a site is ideal physically, without roads, power, data connectivity, and maintainability, it will not work [3,19–21].

This study incorporates elevation, cloud cover, radio frequency interference, artificial light pollution, and accessibility to assist evidence-based site selection. With MCDA and sophisticated GIS tools, this study fills a significant gap in the area of astronomical infrastructure. It provides a replicable model for future arid observatory planning. This study proposes a GIS-MCDA hybrid approach that utilizes the AHP in conjunction with the entropy technique to determine the optimal locations for a radio astronomy observatory in Jordan. The quality of the planning choice will be improved by using GIS as a spatial decision support tool for output analysis and visualization in the form of raster suitability maps.

## 2. Literature Review

GIS with MCDA has been widely integrated for optimal site selection across various sectors. GIS for analyzing large, heterogeneous datasets, and MCDA for evaluating multiple, often conflicting criteria. Remote sensing (RS) data has been integrated into GIS-MCDA frameworks to enhance the accuracy and scalability of spatial analysis and site selection studies. RS allows the rapid acquisition of spatially continuous data, such as elevation, land cover/land use, and climatic variables, which are critical in the site suitability assessment. Several studies have increasingly integrated RS in GIS-supported approaches supporting the spatial decision-making process.

Aksaker et al. [3] developed a GIS-based MCDA framework for selecting a global astronomical observatory site. With the incorporation of RS and satellite imagery, the study generates a Suitability Index for Astronomical Sites (SIAS). Environmental and atmospheric variables, including cloud cover, elevation, and artificial light pollution, were involved in site suitability identification on a global scale and mapped the spatial suitability, but did not incorporate hybrid weighting approaches or robustness evaluation through sensitivity analysis. Similarly, Rajalakshmi et al. [8] applied RS and GIS to site selection for urban infrastructure, highlighting the geospatial technologies employment to handle composite, multi-dimensional datasets. These studies are examples that support the worth of RS-GIS integration for up-to-date, data-driven site selection.

Yılmaz [13] proposed a GIS MCDA approach to identify potential locations for an astronomical observatory in urban areas. Such sites within urban contexts are determined using a fuzzy AHP and the Best–Worst Method (BWM). The site suitability analysis was implemented as a fuzzy-based MCDA to manage uncertainty during site selection. However, fuzzy membership functions and weighting assignments may still involve subjective assumptions, especially when expert-defined linguistic scales are used. The study concentrated on suitability in urban areas and did not investigate implementation-oriented spatial considerations or radio astronomy-related environmental constraints.

In the field of MCDA techniques, AHP is a widely recognized criteria-weighting technique that relies on structured pairwise comparisons that stakeholders can use to prioritize criteria [9].

In this study, site suitability assessment for a radio astronomical observatory was implemented within a GIS framework. Environmental, atmospheric, and human-related factors are thoroughly discussed in an MCDA approach. For weighting such criteria, both AHP and entropy were used in a hybrid weighting method to balance subjective scientific knowledge and objective data variability. AHP and entropy methods were combined to reduce potential subjectivity while increasing robustness and incorporated both expert judgment and objective variability in data, leading to balanced and reliable suitability assessments. This hybrid method has proven especially useful in complicated decision-making scenarios, including diverse environmental, technical, and social aspects.

The proposed framework analyzes sensitivity, infrastructure constraints, and spatial classification of the highest-suitability prospect sites, which help in enhancing the robustness and practical applicability of the suitability analysis. The current study not only generates suitability maps but also provides a comprehensive spatial decision-support framework for future radio astronomy observatory planning in southern Jordan.

GIS-MCDA and AHP approaches are extensively employed in environmental and urban planning, but their usage in radio astronomy site selection is limited, particularly in the Middle East. The selection of radio observatories requires taking into account many factors, such as elevation, cloud cover, radio frequency interference (RFI), artificial light pollution, and accessibility, all of which have a direct impact on observational quality and operational feasibility. Several global studies integrate these criteria and produce suitability

ity maps via MCDA and GIS, guiding the observatory site selection [3,19,21,22]. Nevertheless, there are currently no specialized radio astronomy observatories in Jordan, and few studies have used geospatial multi-criteria approaches in this field.

Although GIS-MCDA and AHP are widely used in environmental management and infrastructure planning, their application to the siting of radio astronomy observatories in Jordan remains unexplored. This gap can be addressed by integrating GIS with AHP and entropy, thereby minimizing subjective bias while allowing the inclusion of several environmental, technological, and logistical aspects. Additionally, RS data improves the spatial analysis accuracy and supports evidence-based planning. To address this gap, this work proposes a GIS-MCDA hybrid methodology that combines entropy and AHP techniques to select the best sites for a radio astronomy observatory in southern Jordan.

Prior research has relied on a small set of criteria and focused on non-Middle Eastern locations. Furthermore, the majority of these studies produced only spatial suitability maps, without further analyzing the findings from an applied and implementation perspective. This study, however, goes beyond the stage of traditional suitability maps by performing a spatial analysis that includes identifying only the best first-order sites, excluding influential and intersecting infrastructure, classifying sites by size, and recommending the appropriate observatories for each category. Then the results are more practically applicable. Despite radio astronomy being one of the main pillars of contemporary astronomical research, Jordan lacks a radio astronomy observatory, making this study crucial. It enables the examination of cosmic phenomena, including the birth of galaxies, pulsars, molecular clouds, and the cosmic microwave background radiation, that are not visible with optical telescopes [23,24]. The research emphasizes that southern Jordan is well-positioned to host a radio astronomy observatory due to its low population density, minimal radio interference, dry climate, and suitable altitudes. In addition, given the extreme shortage of radio astronomy observatories in the Middle East, this study helps close a major regional gap. It offers a thorough scientific and methodological framework for planning and establishing future observatories in the region. Failure to take advantage of these natural advantages may represent a scientific and strategic loss at the national level.

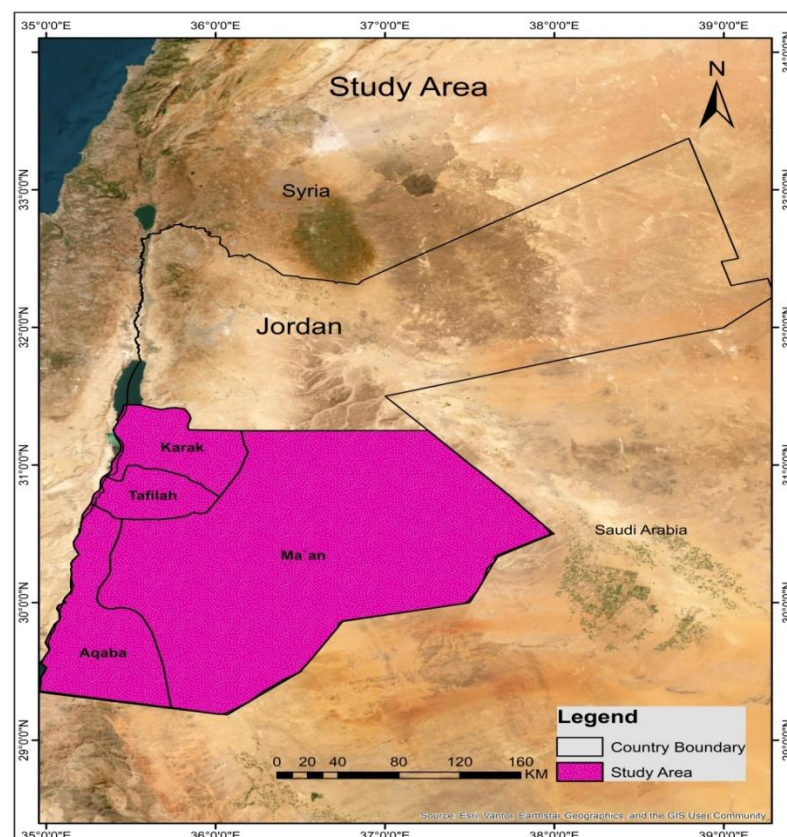
### 3. Study Area

The study area is located in southern Jordan, covering the governorates of Karak, Tafilah, Ma'an, and Aqaba, and extends approximately between latitudes 29–31° N and longitudes 35–37° E (refer to Figure 1).

Because of its appropriate geographical, climatic, and human characteristics that enhance the quality of radio astronomy observations and limit sources of electromagnetic interference, southern Jordan was selected as a study area for the establishment of a radio astronomy observatory. The study area is situated within a topographically diverse region that includes mountain ranges and extensive desert valleys, with elevations ranging from 300 m to more than 1500 m above sea level. Similar to what is used at international astronomical observatories like the Green Bank Observatory, these topographical features help improve observation conditions by limiting the spread of undesired radio waves from nearby areas. The surrounding mountains and deep valleys achieve this [25]. In addition, southern Jordan has a dry desert climate with little cloud cover for most of the year, resulting in clear, stable skies necessary for successful optical and radio astronomical observations (Britannica, Climate of Jordan). The low humidity also reduces absorption in specific radio frequency bands, improving the quality of received signals. Compared to northern and central Jordan, the area has a relatively low population density, which means there are fewer sources of light pollution and radio frequency interference (RFI) from human activities such as power lines, telecommunications networks, and cell towers. This is

one of the most significant international criteria for choosing locations for radio astronomy observatories. The International Telecommunication Union's (ITU) guidelines stress the need to select locations that are remote from cities and sources of dangerous electromagnetic radiation [26–28].

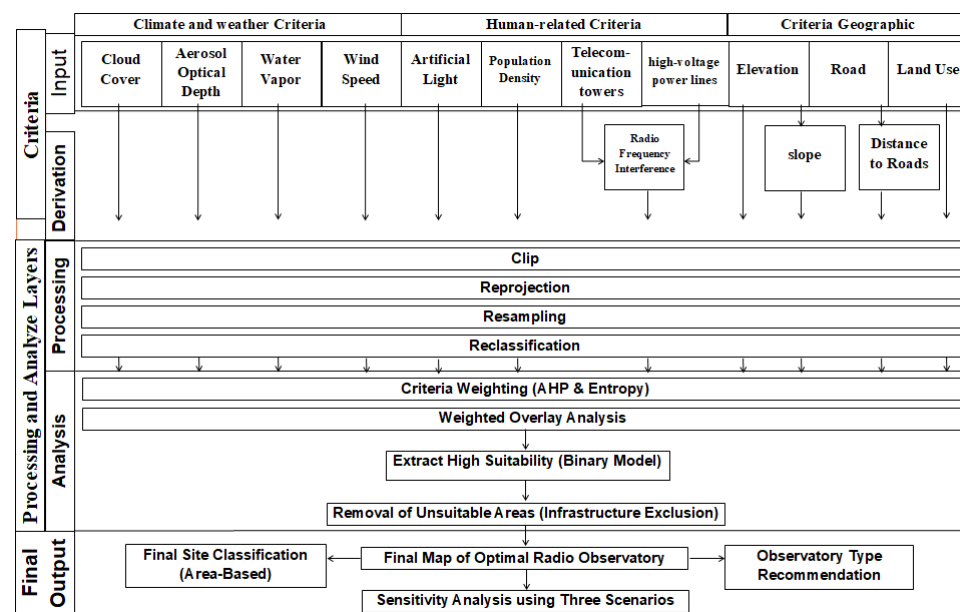
Additionally, southern Jordan has a relatively small road network that balances accessibility to possible locations without appreciably raising radio interference levels, according to an examination of the road map obtained from OpenStreetMap. Even with these advantages, there are some areas within the region with high-voltage power lines and telecom towers that could cause radio interference. As a result, these areas need to be thoroughly examined using a multi-criteria spatial analysis to rule out inappropriate sites in compliance with ITU-R RA.611 [26], ITU-R RA.2552-0 [27], and ITU-R RA.769 [28], which specify acceptable interference levels in radio frequency bands. As a result, southern Jordan was chosen as a study area based on a combination of human and climatic topographical factors, as well as the scientific and technological significance of opening a radio astronomy observatory there to support astronomy and space sciences in Jordan and the surrounding region.



**Figure 1.** Study area.

#### 4. Materials and Methods

This section presents the methodology for selecting the optimal radio astronomy observatory site in this study. The approach integrates GIS analysis techniques with a hybrid AHP and entropy method for assessing site suitability. The overall Methodology workflow is illustrated in Figure 2 below.



**Figure 2.** Research methodology.

#### 4.1. Criteria for Radio Astronomy Observatory Site Selection

Once a location for a radio astronomy observatory is selected, it is essential to thoroughly examine environmental, atmospheric, and human-related factors. As mentioned previously, the primary criteria affecting the determination of the best places for the radio astronomy observatory are RFI, atmospheric and climatic suitability, topography (altitude and terrain), environmental stability, accessibility, infrastructure, and legal protection. Such criteria have been determined relying on the scientifically proven correlations between RFI levels and observational efficiency. Every criterion is essential to ensure the observatory operates at its best with minimal interference. Table 1 presents the criteria for selecting radio astronomy observatory sites. Justification for selecting such criteria is discussed later in Section 4.4.3.

**Table 1.** Criteria for the selection of radio astronomy observatory sites.

| Criterion                          | Description                                                            | Should the Value Be High or Low | Notes                                                             |
|------------------------------------|------------------------------------------------------------------------|---------------------------------|-------------------------------------------------------------------|
| Aerosol Optical Depth (AOD)        | The number of suspended particles in the atmosphere affects the signal | Low                             | Lower values mean clearer air and better radio transmission       |
| Cloud Cover                        | Percentage of cloudiness in the sky                                    | Low                             | Clouds affect atmospheric stability and observation conditions    |
| Water Vapor                        | Amount of water vapor in the atmosphere                                | Low                             | Water vapor absorbs radio signals, so lower values are better     |
| Artificial Light (Light Pollution) | Light pollution indicates human activity                               | Low                             | Indicates low human activity and electromagnetic interference     |
| Wind Speed                         | Wind speed and its effect on equipment stability                       | Low                             | High wind speeds cause vibrations and reduce observation accuracy |

|                                              |                                                       |                                                |                                                                             |
|----------------------------------------------|-------------------------------------------------------|------------------------------------------------|-----------------------------------------------------------------------------|
| Population Density                           | Population density indicating electronic activity     | Low                                            | Lower population density means less radio frequency interference            |
| Land Use/Land Cover (LULC)                   | Type of land use and its effect on radio interference | Low in urban/industrial areas, high in deserts | Undeveloped and desert areas are better because of lower interference       |
| Elevation                                    | Site altitude above sea level                         | High                                           | Higher elevation reduces signal absorption and improves observation quality |
| Radio Frequency Interference (RFI) Proximity | Proximity to sources of radio interference            | Low                                            | Should be far from towers, power lines, and urban areas                     |

#### 4.2. Data Collection

The data for this project were collected from a variety of reputable global sources and advanced cloud-computing platforms. Some data have been obtained using GIS tools in ArcGIS Pro 3.5 (Esri, Redlands, CA, USA). The focus was on acquiring up-to-date, high-resolution datasets covering the period from 2020 to 2024 to accurately represent the climatic, environmental, and anthropogenic conditions in the study area, located in southern Jordan. Several layers were acquired from official and globally recognized platforms, including:

- USGS Earth Explorer: for extracting the Digital Elevation Model (DEM).
- World Pop: for obtaining the 2024 population density layer at 1 km resolution.
- NOAA VIIRS: for nighttime light pollution data.
- Global Wind Atlas: for wind speed datasets.
- MODIS (NASA): for water vapor, cloud cover, and Aerosol Optical Depth (AOD) data for the 2020–2024 period.

Furthermore, Google Earth Engine (GEE) was used to retrieve and evaluate satellite data on cloud cover, water vapor, and AOD. GEE offers a cloud computing environment that is useful for dealing with temporal and spatial data, improving the accuracy and precision of the retrieved data. Using tailored OpenStreetMap queries, the Overpass Turbo tool was used to extract the position of telecommunication towers and high-voltage power lines, both of which are regarded as important emitters of RFI. Layers were spatially harmonized to a common projection, and the layers resampled to 30 m to match the finest dataset to maintain consistency and reduce the loss of terrain details. The coarse resolution raster data layers were resampled to match the finest resolution datasets (from 500 m and 225 m to 30 m), not to enhance the intrinsic spatial accuracy of the original layers but to standardize their cell sizes for computational consistency, and to create a common analysis grid for the raster overlay analysis and integration. In ArcGIS Pro 3.5 (Esri, Redlands, CA, USA), the RESAMPLE tool was used to perform resampling. All layers were projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 36 N, based on WGS 84. All layers involved in the analysis were clipped, resampled, and categorized within ArcGIS Pro. Refer to Table 2 for the data and its related details.

**Table 2.** Data sources and details.

| Layer                       | Source              | Year(s)   | Resolution | Format | Notes                                    |
|-----------------------------|---------------------|-----------|------------|--------|------------------------------------------|
| Aerosol Optical Depth (AOD) | MODIS MCD19A2, NASA | 2020–2024 | 500 m      | Raster | Monthly averages were utilized           |
| Cloud Cover                 | MODIS MOD09GA, NASA | 2020–2024 | 500 m      | Raster | Extracted mean values during dry seasons |

|                                           |                                                   |           |                    |                    |                                                               |
|-------------------------------------------|---------------------------------------------------|-----------|--------------------|--------------------|---------------------------------------------------------------|
| Water Vapor                               | MODIS MOD05L2,<br>NASA                            | 2020–2024 | 500 m              | Raster             | Daily product combined with monthly averages                  |
| Artificial Light                          | VIIRS, NOAA                                       | 2024      | 500 m              | Raster             | Nighttime light imagery is used as a proxy for human activity |
| Wind Speed                                | Global Wind Atlas (GWA)                           | 2024      | 225 m              | Raster             | Wind speed statistics, averaged                               |
| Population Density                        | World Pop                                         | 2024      | 1 km               | Raster             | Reprojected and resampled to 30 m                             |
| Digital Elevation Model (DEM) (Elevation) | USGS SRTM                                         | 2014      | 30 m               | Raster             | Used to analyze slope, aspect, and elevation                  |
| Slope                                     | Derived from DEM                                  | 2014      | 30 m               | Raster             | Calculated in ArcGIS                                          |
| Euclidean Distance to Roads               | OpenStreetMap                                     | 2024      | 1 km (vector)      | Vector             | Roads rasterized and distance calculated                      |
| Land Use/Land Cover                       | Open Street Map                                   | 2025      | 100 m              | Vector             | Used to exclude urban/industrial areas                        |
| RFI Sources                               | Manually created from Cell Towers and Power Lines | 2024      | More details below | More details below | Integrated layer for RFI proximity                            |

#### 4.3. GIS Criteria Map Layer Production

This section shows how the spatial datasets are required for the radio observatory site suitability analysis and selection. The process involves integrating various GIS layers that represent environmental and human factors influencing site selection. Three main layers have been generated: the RFI layer identifies areas affected by radio frequency interference; the DEM characterizes terrain slope relevant to construction suitability and sky visibility; and the Euclidean distance from road network evaluates the site accessibility and proximity to infrastructure. Together, these layers form a spatial basis for multi-criteria evaluation (MCE) and decision-making within the GIS-based site selection framework.

##### 4.3.1. RFI as a Constraint for the Optimal Site Selection of a Radio Astronomy Observatory

RFI is a primary concern when identifying a site for radio astronomy observatories because radio telescopes are particularly sensitive to even minimal amounts of electromagnetic radiation from man-made sources. Because Jordan's key agencies were unable to provide direct RFI data, a proxy RFI model was developed using established scientific principles and extensive geographical research within a GIS framework. The following section gives a detailed overview of the approach used.

The RFI analysis began by detecting locations within the line of sight (LoS) of telecommunication towers and high-voltage power lines, which are known to be substantial emitters of radio emissions. The Viewshed 2 tool in ArcGIS Pro was used because it can process larger spatial datasets more effectively than the basic Viewshed tool. The analysis was based on the premise that radio waves in the Very High Frequency (VHF) and Ultra High Frequency (UHF) frequency bands travel predominantly in straight lines. Higher levels of interference are predicted to be at locations under direct LoS from these emission

sources, corresponding with ITU-R findings [29,30], which indicate that path loss at such frequencies is mostly determined by the presence or lack of direct visibility. The transmitter and receiver heights were adjusted to approximate typical tower and near-ground sensor heights (30 m and 1.5 m, respectively) to ensure accuracy. The analysis area was limited to a 50 km radius around each interference source.

Because the Viewshed tool applied to point features, not lines, the high-voltage power line dataset was transformed into points at 500 m intervals using the Generate Points Along Lines tool. This method enabled the precise depiction of continuous emissions along power line segments. In addition to visibility analysis, the Euclidean Distance tool was used to calculate the distance between each position and the nearest interference source. According to the standard path loss equation, this step accounts for the natural attenuation of radio signals as they travel further away. The typical free-space path loss (FSPL) equation is given in decibels (dB). It determines how much a radio signal is reduced (loses its strength) as it travels through free space [30].

$$FSPL(dB) = 147.55 - \log_{10}(f) 20 + \log_{10}(d) 20 \quad (1)$$

where  $FSPL$  (dB) = free-space path loss in decibels,  $f$  = frequency of the signal (typically in MHz), and  $d$  = distance between transmitter and receiver (typically in km). Constants like 147.55 are obtained by combining the standard FSPL formula with unit conversions (m/km, MHz/GHz) and logarithmic properties.

In essence, this equation predicts the amount of signal power lost over a specific distance at a particular frequency in free space, which is helpful in radio communications, RF planning, and GIS-based signal propagation studies [30].

Since frequency is assumed to be relatively constant in this context, distance alone serves as a suitable indicator for signal weakening.

Handling No Data Values:

The Viewshed analysis occasionally produces No Data cells. This happens especially in mountainous, steep, or impassable locations. These regions were classified as Class 5 (best) based on a rational physical assumption: if an area is not visible to the signal source, it is predicted to acquire minimal or no interference.

RFI Index Computation:

The final RFI index was created by combining the categorized Viewshed and Euclidean Distance with Raster Calculator and taking the average value of the two for each cell [31]:

$$\frac{Viewshed}{Distance} = RFI\ index \quad (2)$$

The resulting index captures the combined effect of visibility and proximity to interference sources. Higher values (closer to 5) refer to more radio-quiet areas, making them ideal for a radio astronomy observatory. Finally, the generated RFI index map shows places with high amounts of radio noise (low scores) and areas with little interference (high scores). This layer is then integrated into the Multi-Criteria Evaluation (MCE) framework, which identifies and orders the most suitable candidate sites for the observatory [32].

#### 4.3.2. Derivation of Slope Layer from Digital Elevation Model (DEM)

USGS (2024) DEM for the study area offered a precise depiction of the terrain and was chosen to represent the topography of the area and extract secondary layers essential to site suitability assessment. Using the Slope tool in ArcGIS Pro, a slope layer was created to indicate the steepness of each raster pixel based on elevation variations. Slope values were expressed in degrees for both topographic and astronomical assessments, as this unit

is more appropriate for analyzing criteria such as sky visibility, line-of-sight concerns, and the possibility of fog or cloud accumulation in steep or low-lying areas. The slope layer was then divided into five groups, with softer slopes considered more suitable for a radio astronomy observatory. Flatter sites provide many benefits, such as improved drainage, reduced erosion risk, enhanced structural stability, and simplified telescope facility installation and maintenance, all of which are essential to long-term operational reliability.

#### 4.3.3. Derivation of Euclidean Distance from Road Network

The road network for the study area was obtained in vector format from OpenStreetMap and converted to a raster layer at 30 m resolution to ensure consistency with the other spatial datasets used in the study. Using the Euclidean Distance tool, the proximity of each location to existing roads was estimated, producing a continuous raster layer showing the straight-line distance from each cell to the nearest road. This distance is a significant criterion for selecting sites for a radio astronomy observatory, as it must be as far away as possible from infrastructure and human activity. Proximity to transportation, automobiles, lines of power, and networks of communication can contribute to electromagnetic noise RFI, which can dramatically reduce observational accuracy. In contrast to many infrastructure projects, radio observatories benefit from their remote location. Thus, the resulting distance layer was categorized into five classes, with larger distances indicating greater suitability for minimizing RFI.

#### 4.3.4. Reclassification of GIS Layers

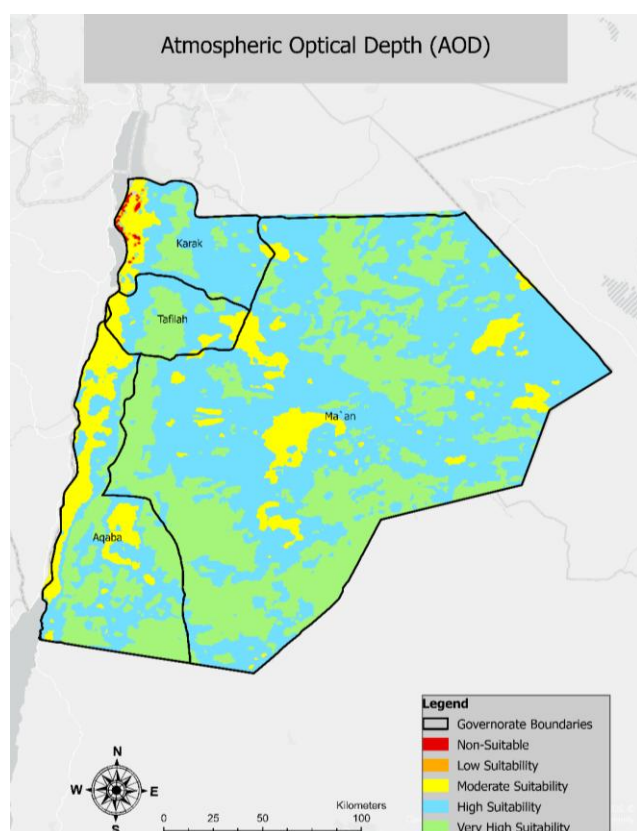
To identify the most suitable site for a radio astronomy observatory in southern Jordan, 11 raster layers that represent the suitability criteria were classified following the procedure outlined in this section. Each layer is classified into 5 suitability classes, in which 1 represents the least suitable and 5 represents the most suitable, using conventional observational research and international standards. Table 3 presents in detail the GIS data layer information and the classification equations employed in each. For each layer, five classes were designated to achieve an optimal balance between simplicity of interpretation and analytical precision. Figure 3 shows the reclassified GIS layers used in the site suitability assessment for the planned radio astronomy observatory, in addition to the value ranges for each class. These layers contain: (a) aerosol optical depth (AOD), (b) perceptible water vapor (PWV), (c) cloud cover (CC), (d) wind speed (WS), (e) artificial light pollution (ALP), (f) DEM, (g) slope, (h) Euclidian Distance from Roads (EDFR), (i) population density (PD), (j) land use (LU), and (k) RF. Appendix A presents the classification scheme for each layer.

**Table 3.** GIS data layer classification.

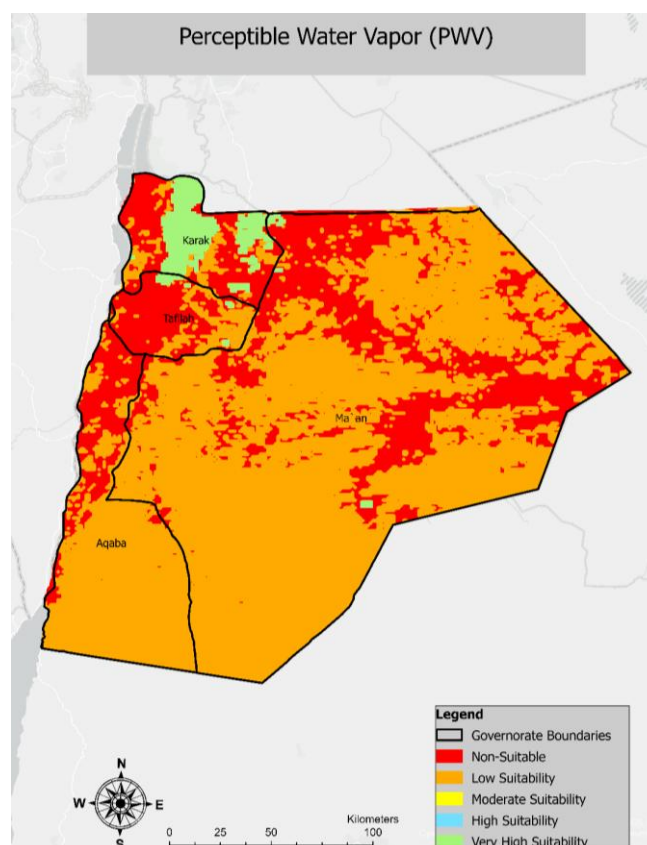
| Data                            | Classification Equation (Geometric)                                                                            | Rationale for Geometric Classification                                                                                                                                                                                                                    |
|---------------------------------|----------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Atmospheric Optical Depth (AOD) | $r = \left( \frac{AOD_{\max}}{AOD_{\min}} \right)^{1/N}, g_n = AOD_{\min} \times r^n, n =$                     | When compared to linear classification algorithms, this methodology better controls skewed data distributions. The usage of five classes guarantees that air turbidity levels are adequately differentiated while remaining manageable and interpretable. |
|                                 | $0, 1, \dots, N$                                                                                               |                                                                                                                                                                                                                                                           |
|                                 | Where                                                                                                          |                                                                                                                                                                                                                                                           |
|                                 | $AOD_{\max}$ and $AOD_{\min}$ represent the maximum and minimum values of aerosol optical depth, respectively. |                                                                                                                                                                                                                                                           |
|                                 | $r$ is a scaling factor that adjusts the AOD values.                                                           |                                                                                                                                                                                                                                                           |
|                                 | $g_n$ denotes the $n$ th value in the geometric progression of AOD values.                                     |                                                                                                                                                                                                                                                           |

|                               |                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                               |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                               | <p><math>N</math> is the total number of intervals or steps [33].</p>                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                               |
| Perceptible Water Vapor (PWV) | <p>Scale Conversion</p> $PWV_{mm} = \max(0, PWV_{raw} \times 0.01)$ <p>Where</p> <p><math>PWV_{raw}</math> is the raw measurement of perceptible water vapor.</p> <p>The factor of 0.01 converts the raw value into mm.</p> <p>The max (0, ...) function ensures that negative values are set to zero, as negative water vapor is not physically meaningful [34].</p> | <p>This classification aligns with global observational thresholds in the mm and sub-mm wavelengths. Employing five classes allows for meaningful differentiation of water vapor conditions across potential sites.</p>                                       |
| Cloud Cover                   | <p>Normalization Equation:</p> $CC_{\%} = \frac{CC_{raw} - CC_{min}}{CC_{max} - CC_{min}} \times 100$ <p>Where</p> <p><math>CC_{raw}</math> is the raw cloud cover measurement.</p> <p><math>CC_{min}</math> and <math>CC_{max}</math> are the minimum and maximum observed values of cloud cover, respectively [34].</p>                                             | <p>This classification is grounded in astronomical definitions of sky clarity to accurately represent observational conditions. The adoption of five classes facilitates a detailed distinction ranging from clear to fully overcast skies.</p>               |
| Wind speed                    | Quartile Classification [35]                                                                                                                                                                                                                                                                                                                                          | <p>This approach provides an approximately uniform distribution of data points, taking operational stability into account. The use of five classes enables precise differentiation of critical wind thresholds that influence mechanical performance.</p>     |
| Light Pollution               | Jenks Natural Breaks Classification [35]                                                                                                                                                                                                                                                                                                                              | <p>This classification highlights natural clusters in spatial radiance distribution to support accurate dark-sky assessments. Employing five classes facilitates clear identification of both extremely dark and heavily light-polluted areas.</p>            |
| DEM                           | Manual Breaks Based on High-Altitude Observatory Studies [36]                                                                                                                                                                                                                                                                                                         | <p>This classification is based on ALMA and Mauna Kea studies, which indicate optimal elevation ranges for minimal atmospheric water vapor. The use of five classes strikes a balance between ideal elevations and practical geographic feasibility [36].</p> |
| Slope                         | Manual Engineering-Based Classification [36]                                                                                                                                                                                                                                                                                                                          | <p>This classification accounts for infrastructure costs and structural stability. Employing five classes allows for a nuanced assessment of site buildability.</p>                                                                                           |
| Distance to Roads             | Jenks Natural Breaks Classification                                                                                                                                                                                                                                                                                                                                   | <p>This classification identifies natural clusters in proximity values to balance accessibility with interference mitigation. The use of five classes enables a</p>                                                                                           |

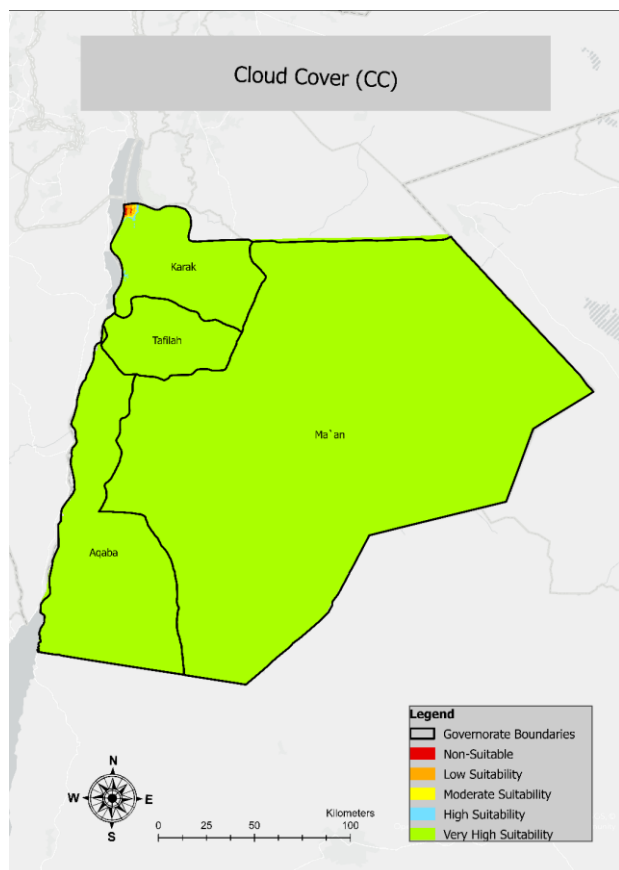
|                                          |                                     |                                                                                                                                                                                                  |
|------------------------------------------|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                          |                                     | refined evaluation of the trade-off between site accessibility and electromagnetic interference.                                                                                                 |
| Population Density                       | Jenks Natural Breaks Classification | Rationale for Jenks: Accurately reflects heterogeneous population distributions. Justification for Five Classes: Clearly distinguishes between rural and urban settings.                         |
| Land use                                 | Jenks Natural Breaks Classification | The Jenks classification method is employed to accurately represent heterogeneous population distributions. Utilizing five classes allows for a clear distinction between rural and urban areas. |
| Radio Frequency Interference (RFI Proxy) | Jenks Natural Breaks Classification | The Jenks method is applied to effectively capture hotspots of electromagnetic interference. Using five classes enables straightforward identification of critical interference zones.           |



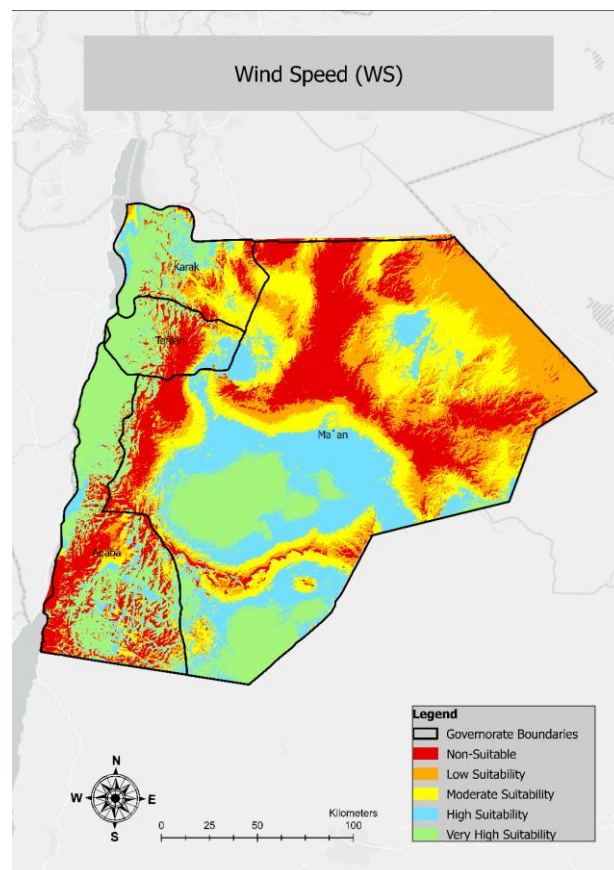
(a)



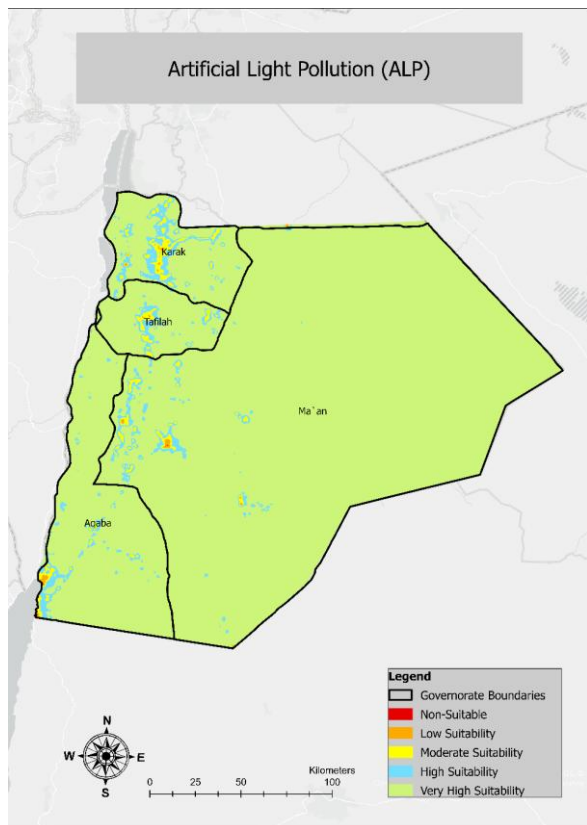
(b)



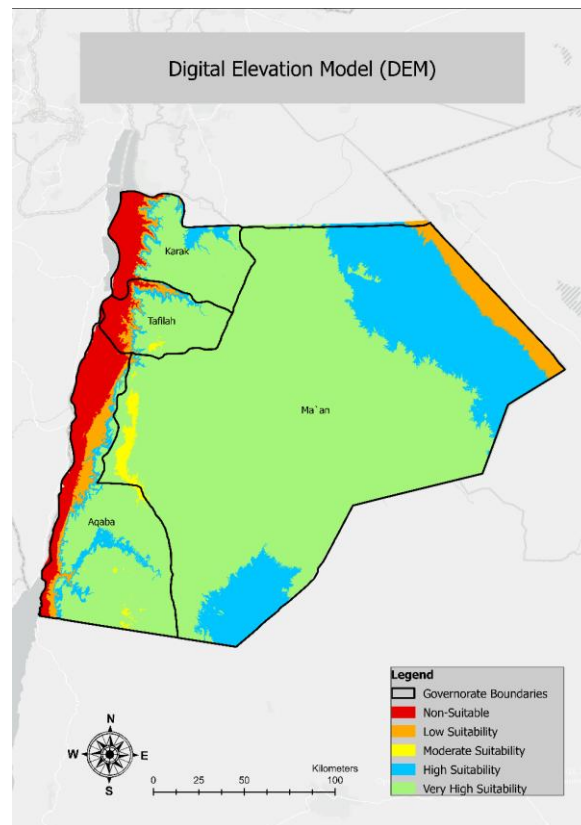
(c)



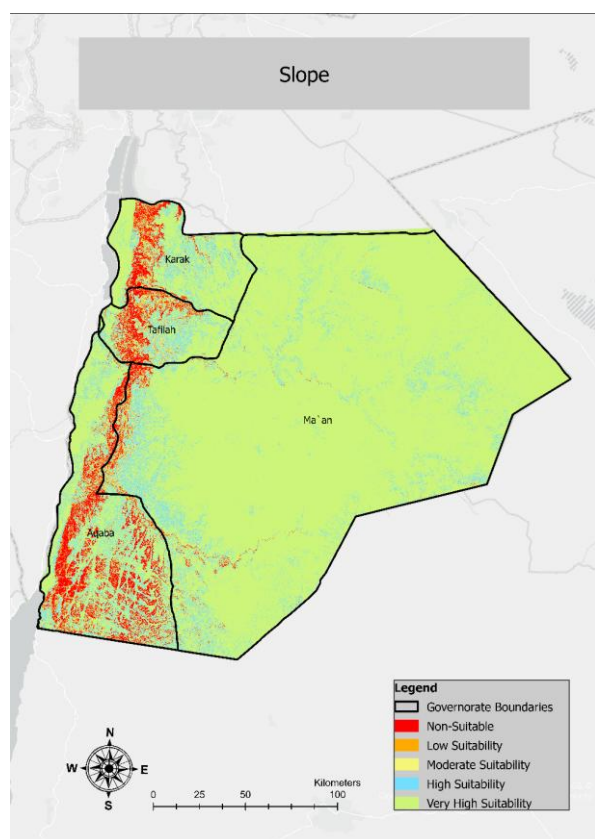
(d)



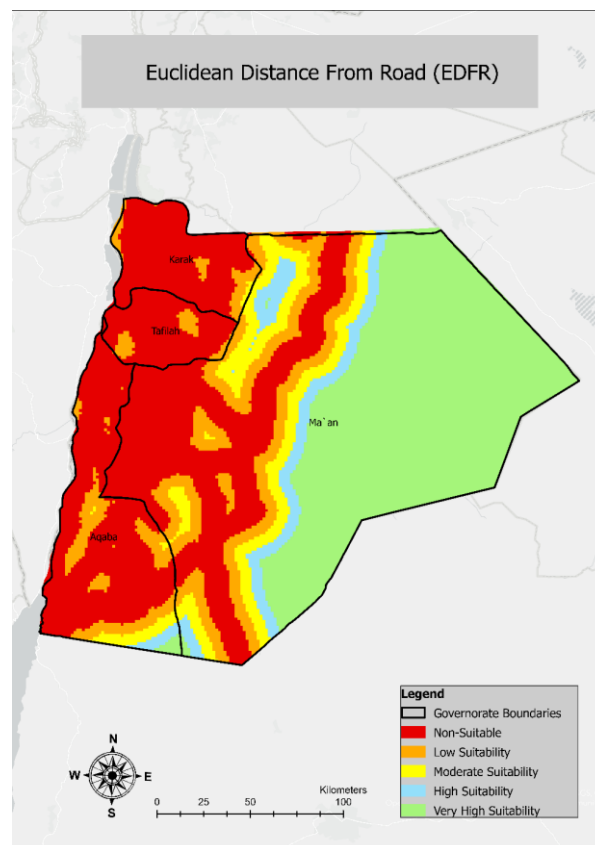
(e)



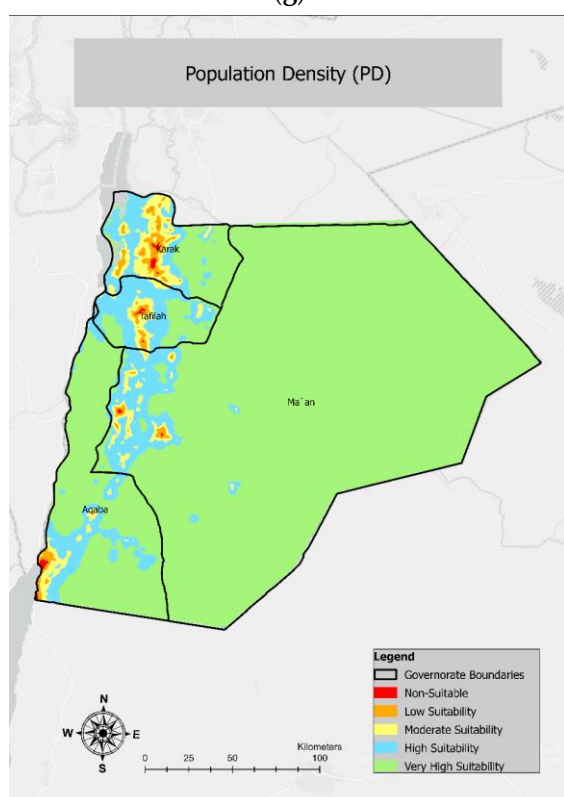
(f)



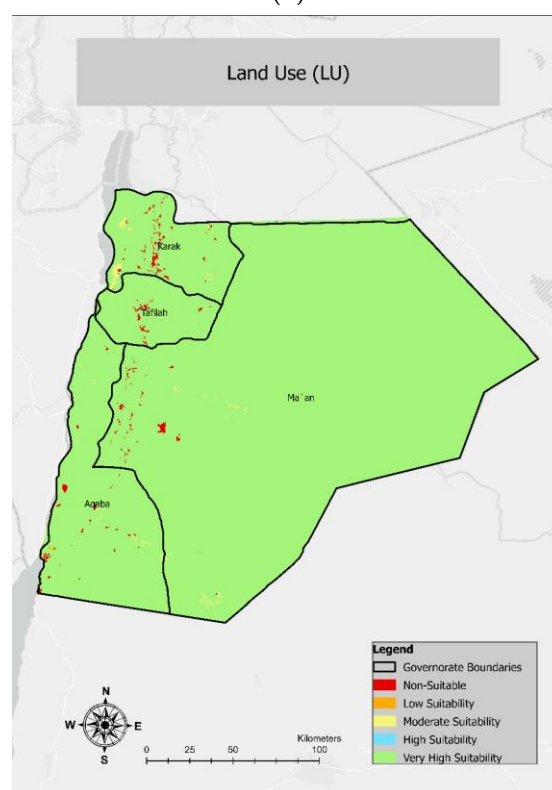
(g)



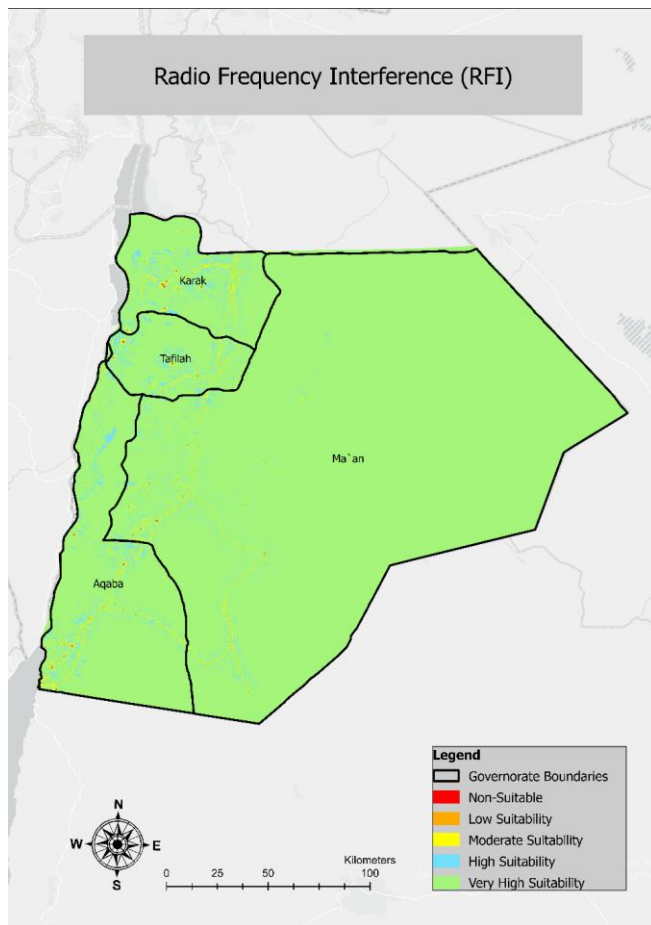
(h)



(i)



(j)



(k)

**Figure 3.** Reclassified GIS layers for the radio astronomy observatory location criteria: (a) AOD; (b) PWV; (c) CC; (d) WS; (e) LP; (f) DEM; (g) slope; (h) EDFR; (i) PD; (j) LU and (k) RFI.

#### 4.4. Research Methodology

This study proposes a GIS-based MCDA that uses AHP and entropy weighting techniques. The weights for the influencing factors were calculated using hybrid AHP–Entropy weighting, which balances subjective scientific knowledge with objective data variability. GIS capabilities are employed to spatially compute, map, and visualize these weighted elements, resulting in more robust geographical analysis and informed decision-making. Sensitivity analysis was applied to ensure that the results were robust and reliable. Infrastructure exclusion analysis and spatial classification of first-order candidate sites were also carried out.

##### 4.4.1. Analytic Hierarchy Method

AHP is used to evaluate the relative significance of each of the 11 criteria in selecting a suitable site for a radio astronomy observatory. AHP used pairwise comparison analysis to derive weights for each criterion, including AOD, CC, WV, AL, WS, LU, PD, DEM, slope, DistRd, and RFI. Through previous observatory studies, ITU-R recommendations, and physical radio astronomy considerations, the criteria weights were determined via AHP pairwise questionnaires, and the sub-criteria scores were ranked. The resultant weights are determined for each criterion.

#### 4.4.2. Shannon Entropy Weight Method (EWM)

As mentioned, AHP determines criteria weights based on expert judgments, while the entropy method is a quantitative tool based on the principle of information dispersion in datasets. Entropy weighting objectively assigns higher weights to criteria with more spatial variability, complementing the expert-driven AHP approach. Entropy weighting incorporation with AHP in the weighting procedure is thought to achieve equilibrium between expert-based judgments and data-oriented objectivity and reduce dependence on subjective evaluations. Entropy detects subtle differences and modifies the weight distribution accordingly. AHP may yield comparable weights for criteria as equally significant by experts, while the entropy approach distinguishes among them based on empirical data variability to aid in mitigating artificial uniformity and enhancing the robustness of the results.

Several previous studies have adopted integrating the entropy method with AHP. They supported such a hybrid method. Ding et al. (2018) [37] discuss the entropy's ability to capture subtle variations within data, layers that are often overlooked by conventional pairwise comparison techniques. At the same time, Xu et al. (2020) [38] demonstrated that combining AHP and entropy yields more stable and consistent results than employing either method independently. Umar et al. (2017) [39] successfully applied this hybrid weighting framework in Malaysia for radio observatory site selection and reported minimized bias caused by fluctuations in atmospheric parameters such as cloud cover and humidity.

In the present study, entropy was purposefully integrated. It is considered a methodological enhancement to produce a final suitability map. This combination ensures a more balanced and objective evaluation process, providing a rigorous scientific foundation for identifying the optimal observatory location.

The Shannon entropy principle determines the criteria involved weights in MCDA by assessing the degree of informational dispersion within each dataset. Layers exhibiting greater variability convey more information and thus merit higher weighting in the decision process. Consequently, entropy serves as an ideal complement to AHP, representing data-driven variability, whereas AHP encapsulates expert judgment—together achieving a comprehensive and impartial decision-making framework [37–40].

#### 4.4.3. Weighing Criteria

The AHP was used to assess 11 important criteria for radio observatory site selection. A pairwise comparison matrix was created, and relative weights were extracted for each criterion with consistency (CR) verification to guarantee the validity of the results [9]. Previous observatory studies, ITU-R recommendations, and physical radio astronomy considerations were used instead of experts' direct opinions to determine each criterion's relative importance in a AHP pairwise comparison matrix. Then, the weight of each criterion was determined. The relative importance of each criterion in comparison to other criteria against the radio observatory site suitability was determined based on Saaty's 1–9 scale. Such importance in the form of comparison values was determined, as mentioned, based on the previous literature, ITU-R recommendations, and the physical influence of each criterion on radio signal quality and telescope performance. The highest importance criteria were radio frequency interference (RFI) and water vapor (WV) because of their direct effect on radio observations, and hence they were assigned higher importance values. Engineering-related criteria (slope and road distance) received lower comparison scores. In the pairwise comparison matrix, reciprocal values were used for inverse comparisons, and the normalized eigenvector method was applied to derive the final criterion weights.

Prior research, including Koc-San et al. (2013) [41], and Aksaker (2020) [3], emphasized the significance of RFI and light pollution and the moderate value of cloud cover

and AOD, which served as the basis for the weighting. Umar (2017) [39] and Yılmaz (2023) [13] found that radio frequency interference (RFI) and water vapor (WV) had a significant impact on radio reception. Population density, land use, and road distance are all secondary considerations.

Subsequently, the entropy method was incorporated to add an objective dimension and reduce human bias. The approach involves calculating the entropy index for each criterion based on the relative frequencies of pixels inside each spatial layer and translating them into objective weights [17,37]. To normalize weights, a hybrid approach was taken, employing the formula

$$\text{Hybrid Weight} = 0.7 \text{ AHP weight} + 0.3 \text{ Entropy weight} \quad (3)$$

To balance expertise and data variability, RFI received a final hybrid weight of 0.3201 (32.01%), while cloud cover and water vapor received balanced weights in accordance with ITU-R Recommendation RA.769-2 (2015) [29]. This prevents weak parameters in one component from receiving excessive weight, while parameters that are important and exhibiting high data variability receive high weights [17,37,39]. The weights, scientific reasoning, and studies for some selected radio astronomy observatory site criteria are shown in Table 4 below. To avoid ambiguity, Table 4 presents percentage weights for readability, while the normalized decimal values used in all calculations are presented later in Section 5.1.

**Table 4.** Weights, scientific basis/justification and studies for selected radio astronomy observatory site criteria.

| Criterion | AHP Weight | Scientific Basis/Justification                                                                                                                                                                                                                               | Related Literature |
|-----------|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| AOD       | 0.0990     | High aerosol concentrations, including dust and smoke, increase atmospheric scattering and absorption, particularly in millimeter and sub-millimeter wavelength ranges, which can degrade radio signal transmission.                                         | [3,42,43]          |
| CC        | 0.0698     | Cloud cover affects atmospheric stability and contributes to the absorption and scattering of electromagnetic waves. Although radio waves can partially penetrate clouds, persistent cloudiness is often associated with unfavorable atmospheric conditions. | [3,13,41,44]       |
| WV        | 0.1923     | Atmospheric water vapor strongly attenuates radio signals at frequencies above 20 GHz, particularly near the 22 GHz water vapor absorption line, leading to a direct reduction in telescope sensitivity and signal quality.                                  | [3,41,45]          |
| AL        | 0.0172     | Although light pollution mainly affects optical astronomy, it is included here as a secondary indicator of human activity and infrastructure development.                                                                                                    | [3,41,46]          |
| WS        | 0.0397     | High wind speeds can induce mechanical vibrations and negatively affect telescope pointing accuracy, thereby reducing observational precision.                                                                                                               | [3,22,47]          |
| LU        | 0.0375     | Land use patterns influence electromagnetic noise levels, with urban and agricultural areas generally producing higher interference, while arid and sparsely inhabited regions are more suitable for radio observatories.                                    | [3,19,48]          |
| PD        | 0.0456     | Population density serves as an indirect indicator of human activity and the potential presence of electromagnetic interference sources associated with settlements and infrastructure.                                                                      | [19,29]            |

|         |        |                                                                                                                                                                                                                                                                                                                |                       |
|---------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| DEM     | 0.0459 | Higher elevations are associated with reduced atmospheric water vapor content and improved atmospheric transparency, which enhances the quality of received radio signals.                                                                                                                                     | [3,13,19,22–24,41,48] |
| Slope   | 0.0366 | Slope is primarily a technical and engineering consideration affecting construction feasibility and structural stability, and is therefore less influential than atmospheric and interference-related factors.                                                                                                 | [3,22,40,48]          |
| Dist Rd | 0.0257 | Proximity to roads reflects increased human presence and potential electromagnetic noise; however, its overall impact on radio observations is relatively limited compared to major interference sources.                                                                                                      | [13,39,41]            |
| RFI     | 0.3902 | Radio frequency interference is considered the most critical factor in radio astronomy site selection. For reliable observations, observatory locations must be sufficiently distant from artificial radio sources such as telecommunication towers, transmission networks, and densely populated urban areas. | [29,38,39,41]         |

#### 4.4.4. Integrating AHP and Entropy Weights to Produce a Balanced Hybrid Weight

With the entropy weight method, the weight is determined by fully utilizing the entropy of the index, which appears to be a more objective approach. This approach is actually limited as well; regardless of how significant the index is, as long as the index value difference is significant, the entropy is low, and the related weight is large, it is best suited for assessing the variations across various evaluation units. AHP relies only on the significance of each indicator. In this work, the entropy index's statistical objectivity and AHP's systematic human expertise were combined by merging the weights. Based on the following formula, a weighted integration model was selected, giving the AHP technique priority. AHP weight contributes 0.7 to the combination weight, whereas entropy weight only contributes 0.3, as previously mentioned in Equation (3).

#### 4.4.5. Spatial Suitability Analysis

Once the criterion weights were determined, the final suitability raster map was generated in ArcGIS Pro using the Weighted Sum tool. All values were standardized to a common scale, and layers were pre-scaled from 1 to 5. The scale has a positive semantic direction (higher values indicate better suitability). The Weighted Sum method was preferred over Weighted Overlay. This approach aligns with the criteria requirements for consistent weighting and semantic direction. The Weighted Sum method applies a simple mathematical formula:

$$\text{Suitability} = \sum_{j=1}^m (w_j \times x_i) \quad (4)$$

where  $x_i$  is the normalized value of criterion  $j$  at a given pixel, each pixel value is multiplied by its corresponding criterion weight, and the resulting values are summed to produce a composite suitability map [49].

This method offers several advantages, such as it does not require additional handling of value directions or layer classifications, reduces the potential for errors from conflicting value directions or manual classification, and performs efficiently with large datasets, such as the 11-layer set used in this study (ESRI). Once the suitability raster was created, the values were categorized into discrete classes using Natural Breaks (Jenks) classification. It was used for classifying the suitability zones because it minimizes distortions associated with arbitrary classification schemes like Equal Interval or Quantile, ensuring within-class variance is minimized while between-class variance is maximized. As

a result, it provides a more accurate representation of the data distribution. The effectiveness of this approach is supported by ESRI guidelines [35], and it is widely used in geographic analyses, including suitability, risk, and resource mapping.

#### 4.4.6. Sensitivity Analysis

Sensitivity analysis was conducted as the last step in the site suitability assessment, where input data (the suitability criteria and their associated weights) were altered/modified to some extent to observe the impact on the results. If the overall suitability patterns and rankings do not change and stay stable, the results are said to be robust and reliable. Three scenarios were used to evaluate the model's sensitivity. Firstly, the number of criteria was reduced from 11 to 7, and the relative relevance of each criterion was preserved by redistributing the weights proportionally. Only 3 criteria representing the most important factors were used in the second scenario, and their weights were renormalized to sum to 100%. In the third scenario, the impact of weights on the model was examined by swapping the highest and lowest weights, while keeping the remaining weights unchanged. Tables 5–7 show the chosen criteria and their weights for each scenario.

**Table 5.** Scenario 1 (7-criteria model).

| Criterion | Modified Weight |
|-----------|-----------------|
| RFI       | 0.3787          |
| WV        | 0.1926          |
| CC        | 0.1202          |
| AOD       | 0.1073          |
| PD        | 0.0776          |
| DEM       | 0.0641          |
| LU        | 0.0595          |

**Table 6.** Scenario 2 (3-criteria model).

| Criterion | Modified Weight |
|-----------|-----------------|
| RFI       | 0.5479          |
| WV        | 0.2786          |
| CC        | 0.1735          |

**Table 7.** Scenario 3 (weight reversal model).

| Criterion | Modified Weight |
|-----------|-----------------|
| AOD       | 0.0907          |
| CC        | 0.1016          |
| WV        | 0.1628          |
| AL        | 0.0597          |
| WS        | 0.0278          |
| LU        | 0.0503          |
| PD        | 0.0656          |
| DEM       | 0.0541          |
| Slope     | 0.0515          |
| RFI       | 0.0188          |
| Dist Rd   | 0.3201          |

## 5. Results

### 5.1. Subjective Weights from the AHP

Using the AHP method, an  $11 \times 11$  comparison matrix for all 11 criteria was established based on Saaty's 1–9 scale (see Table 8). The matrix obtained and its weights are presented in Table 9. For verifying that the judgments made by the experts were consistent and reliable, the Consistency Ratio (CR) was computed. According to Saaty, if the CR is below 0.1 then the comparison is reliable. The calculated CR in our research work was 0.00596.

The final AHP weights were validated using the Random Index (RI = 6.037) and Consistency Index (CI = 0.00739) obtained from the aggregated group judgments.

**Table 8.** Saaty scale (Saaty, 1987, 1980) [9,10].

| Value | Interpretation         |
|-------|------------------------|
| 1     | Equal importance       |
| 3     | Moderate importance    |
| 5     | Strong importance      |
| 7     | Very strong importance |
| 9     | Extreme importance     |

**Table 9.** AHP pairwise comparison matrix and weights.

| Criterion | AOD    | CC     | WV     | AL     | WS     | LU     | PD     | DEM    | Slope  | Dist Rd | RFI    | AHP Weight |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|--------|------------|
| AOD       | 1.0000 | 3.0000 | 0.2000 | 3.0000 | 3.0000 | 3.0000 | 5.0000 | 3.0000 | 5.0000 | 7.000   | 0.1111 | 0.0990     |
| CC        | 0.3330 | 1.0000 | 0.1420 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 5.0000  | 0.1111 | 0.0698     |
| WV        | 5.0000 | 7.0000 | 1.0000 | 9.0000 | 5.0000 | 5.0000 | 5.0000 | 5.0000 | 5.0000 | 7.0000  | 0.1429 | 0.1923     |
| AL        | 0.3330 | 0.3333 | 0.1110 | 1.0000 | 0.3333 | 0.3330 | 0.3330 | 0.3330 | 0.3333 | 0.2000  | 0.1111 | 0.0172     |
| WS        | 0.3330 | 0.3333 | 0.2000 | 3.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 3.0000  | 0.1111 | 0.0397     |
| LU        | 0.3330 | 0.3333 | 0.2000 | 3.0000 | 1.0000 | 1.0000 | 0.3330 | 1.0000 | 1.0000 | 3.0000  | 0.1111 | 0.0375     |
| PD        | 0.2000 | 0.3333 | 0.2000 | 3.0000 | 1.0000 | 3.0000 | 1.0000 | 1.0000 | 1.0000 | 3.0000  | 0.1111 | 0.0456     |
| DEM       | 0.3330 | 0.3333 | 0.2000 | 3.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 3.0000 | 3.0000  | 0.1111 | 0.0459     |
| Slope     | 0.2000 | 0.3333 | 0.2000 | 3.0000 | 1.0000 | 1.0000 | 1.0000 | 0.3330 | 1.0000 | 3.0000  | 0.1111 | 0.0366     |
| Dist Rd   | 0.1429 | 0.2000 | 0.1420 | 5.0000 | 0.3333 | 0.3330 | 0.3330 | 0.3330 | 0.3333 | 1.0000  | 0.1111 | 0.0257     |
| RFI       | 9.0000 | 9.0000 | 7.0000 | 9.0000 | 9.0000 | 9.0000 | 9.0000 | 9.0000 | 9.0000 | 9.0000  | 1.0000 | 0.3902     |

### 5.2. Objective Weights from Entropy

To complement the AHP results, the EWM was applied to provide an objective assessment of the criteria based on the inherent variability of the data. EWM measures the amount of knowledge or uncertainty associated with each criterion, minimizing subjective bias in the weighing process. Table 10 shows the calculated entropy values (Ej), degree of diversification (Dj), and resulting objective weights (Wj) produced using the Shannon entropy technique, which was used to help choose appropriate radio observatory sites.

**Table 10.** Entropy, degree of diversification and entropy weights.

| Criterion | Entropy (Ej) | Divergence (Dj) | Weight (Wj) |
|-----------|--------------|-----------------|-------------|
| AOD       | 0.5886       | 0.4114          | 0.0708      |
| CC        | 0.0078       | 0.9922          | 0.1708      |
| WV        | 0.4433       | 0.5567          | 0.0958      |
| AL        | 0.1338       | 0.8662          | 0.1491      |
| WS        | 0.9999       | 0.0000          | 0.0000      |

|         |        |        |        |
|---------|--------|--------|--------|
| LU      | 0.5207 | 0.4793 | 0.0825 |
| PD      | 0.3494 | 0.6506 | 0.1120 |
| DEM     | 0.5756 | 0.4244 | 0.0730 |
| Slope   | 0.5011 | 0.4988 | 0.0859 |
| Dist Rd | 0.9812 | 0.0188 | 0.0032 |
| RFI     | 0.0913 | 0.9086 | 0.1564 |

The original divergence value for wind speed is  $5.45128 \times 10^{-6}$ , which is rounded to 0.0000 to attain a four-decimal precision.

### 5.3. Integrated AHP–Entropy

To obtain the advantages of both weighting approaches, AHP and entropy, this study adopted a hybrid weighting approach to derive more balanced and reliable criterion weights for the site selection analysis. The integrated AHP–Entropy weights were calculated using the formula outlined in Section 4.4.3 (equation (3)), and the final combined weight values are summarized in Table 11.

**Table 11.** AHP, entropy and integrated AHP–Entropy weights of criteria.

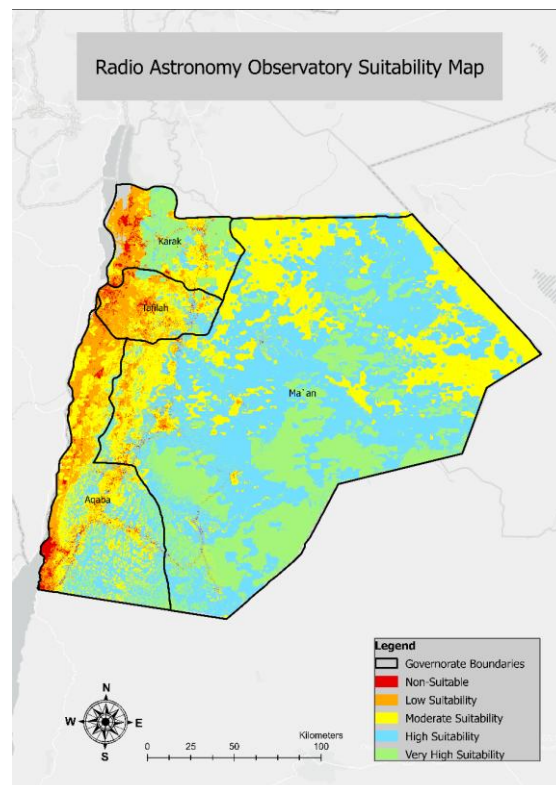
| Criterion | AHP (%)  | Entropy (%) | Hybrid Weight (%) |
|-----------|----------|-------------|-------------------|
| AOD       | 0.099048 | 0.070835    | 0.0907            |
| CC        | 0.069818 | 0.170873    | 0.1016            |
| WV        | 0.192313 | 0.095864    | 0.1628            |
| AL        | 0.017265 | 0.149174    | 0.0597            |
| WS        | 0.039790 | 0.000001    | 0.0279            |
| LU        | 0.037545 | 0.082529    | 0.0503            |
| PD        | 0.045657 | 0.112032    | 0.0656            |
| DEM       | 0.045918 | 0.073073    | 0.0541            |
| Slope     | 0.036661 | 0.085906    | 0.0515            |
| DistRd    | 0.025740 | 0.003221    | 0.0188            |
| RFI       | 0.390245 | 0.156492    | 0.3166            |

### 5.4. Radio Astronomy Observatory Suitability Assessment

Using the Weighted Sum approach described in equation [13]

$$\text{Suitability} = \sum_{j=1}^m (w_j \times x_i) \quad (5)$$

The 11 thematic raster layers illustrated in Figure 3 were integrated within ESRI ArcGIS Pro to generate the overall suitability map. The final criterion weights derived from the integrated AHP–Entropy model were applied to each thematic layer during the overlay analysis. Subsequently, the resulting composite map was reclassified into five suitability categories (ranging from 1 to 5) using the Natural Breaks (Jenks) classification method. In the final suitability map (refer to Figure 4), areas classified as 1 displayed in green indicate the most suitable locations, whereas areas classified as 5 displayed in red present the least suitable sites. The spatial resolution of the input datasets (30 m to 1 km) limits the positional and spatial precision of the suitability areas. The overall effective mapping accuracy is estimated to be approximately 500 m at the regional analysis scale, as most of the environmental and atmospheric layers were derived from MODIS products at 500 m spatial resolution. The suitability map is intended for strategic site screening and comparative suitability evaluation rather than for precise spatial delineation or engineering design purposes.



**Figure 4.** Final radio astronomy observatory suitability map of southern Jordan.

#### 5.5. Post-MCDA Results Analysis

After the step of the MCDA and finding the results, a statistical post-analysis was carried out. The analysis was done to interpret and validate the outcomes of the integrated AHP–Entropy model. This phase aimed to ensure that the derived suitability results were not only spatially coherent but also statistically consistent and meaningful. Various statistical measures were applied to evaluate the distribution, variability, and correlation among the criteria and the resulting suitability scores. By combining spatial interpretation with quantitative statistical evaluation, the post-MCDA analysis provided a deeper understanding of the factors influencing site suitability and strengthened the reliability of the final decision-making outcomes for identifying optimal radio observatory locations.

##### 5.5.1. Statistical Assessment

The three classes 3, 4, and 5 in the resulting classification implemented associated moderate, high, and very high suitability levels, respectively. In Table 12, the spatial extent of each suitability class was quantitatively assessed. These classes cover an area of 40,670.967 km<sup>2</sup>, predominantly located in the non-metropolitan regions of southern Jordan.

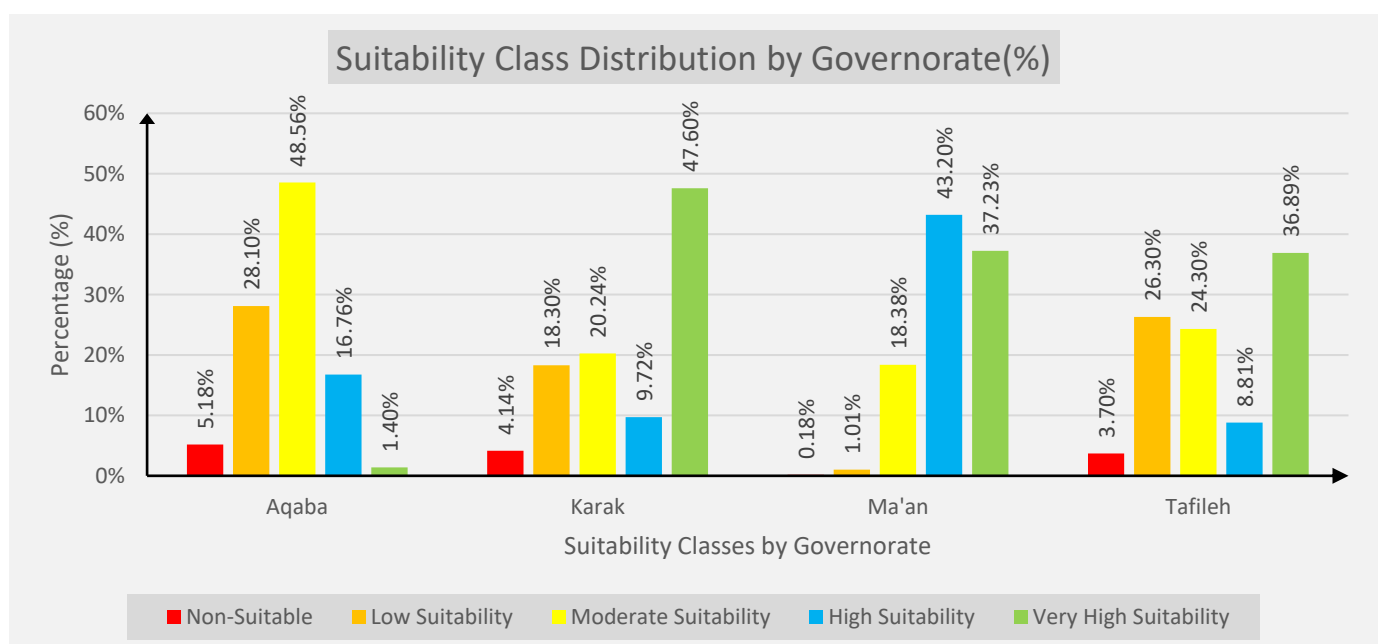
The final suitability raster map was spatially intersected with the administrative boundaries of the four southern governorates of Jordan using the Tabulate Area tool in ArcGIS Pro. The purpose of this analysis was to calculate the area (in km<sup>2</sup>) and the corresponding percentage of each suitability class within each governorate. See Table 13. Refer to Figure 5a for the spatial distribution of the suitability classes across the southern governorates; and Figure 5b illustrates the distribution of the very high suitability class within each governorate.

**Table 12.** Suitability land area coverage.

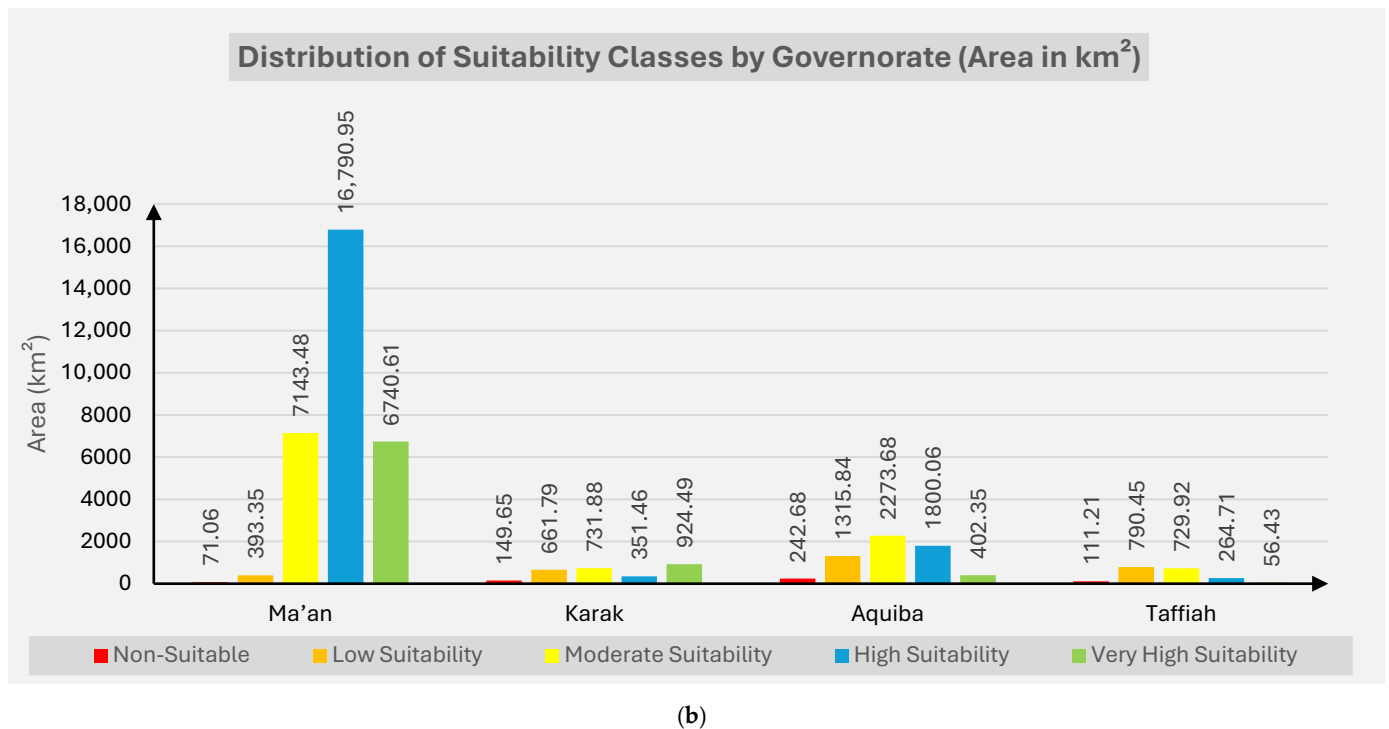
| Suitability Map Class  | Area (km <sup>2</sup> ) | Suitability (%) |
|------------------------|-------------------------|-----------------|
| 1 Unsuitable           | 641.8197                | 1.43%           |
| 2 Low Suitability      | 3524.6898               | 7.86%           |
| 3 Moderately           | 12,193.4556             | 27.19%          |
| 4 Suitable             | 19,447.5384             | 43.37%          |
| 5 Very Highly Suitable | 9029.9736               | 20.14%          |

**Table 13.** Suitability classes distribution across governorates of southern Jordan.

| Governorate | Category | Area (km <sup>2</sup> ) | Percentage (%) |
|-------------|----------|-------------------------|----------------|
| Aqaba       | 1        | 242.68653               | 5.18           |
| Aqaba       | 2        | 1315.84176              | 28.10          |
| Aqaba       | 3        | 2273.68215              | 48.56          |
| Aqaba       | 4        | 1800.06156              | 16.76          |
| Aqaba       | 5        | 402.35382               | 1.40           |
| Karak       | 1        | 149.65479               | 4.14           |
| Karak       | 2        | 661.79106               | 18.30          |
| Karak       | 3        | 731.88603               | 20.24          |
| Karak       | 4        | 351.46386               | 9.72           |
| Karak       | 5        | 924.49422               | 47.60          |
| Ma'an       | 1        | 71.06778                | 0.18           |
| Ma'an       | 2        | 393.35058               | 1.01           |
| Ma'an       | 3        | 7143.48963              | 18.38          |
| Ma'an       | 4        | 16,790.95188            | 43.20          |
| Ma'an       | 5        | 6740.61426              | 37.23          |
| Taffiah     | 1        | 111.21624               | 3.70           |
| Taffiah     | 2        | 790.45389               | 26.30          |
| Taffiah     | 3        | 729.92907               | 24.30          |
| Taffiah     | 4        | 264.71691               | 8.81           |
| Taffiah     | 5        | 56.43999                | 36.89          |

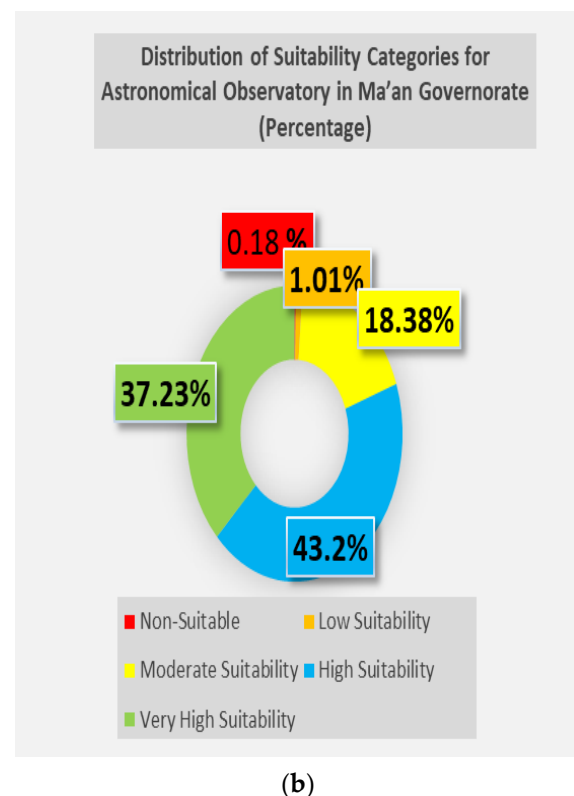
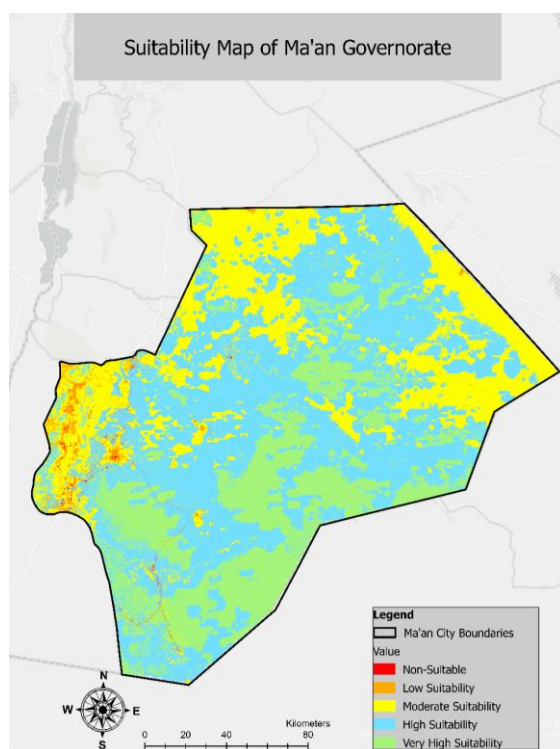


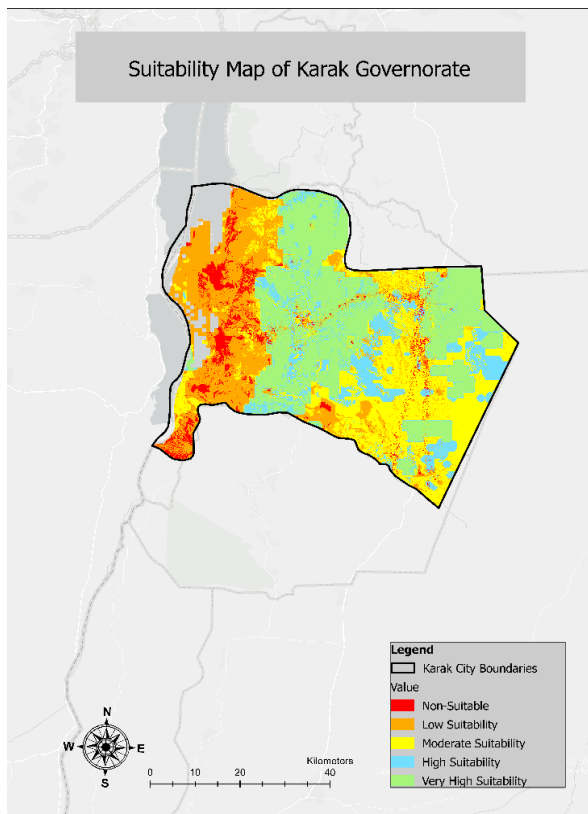
(a)



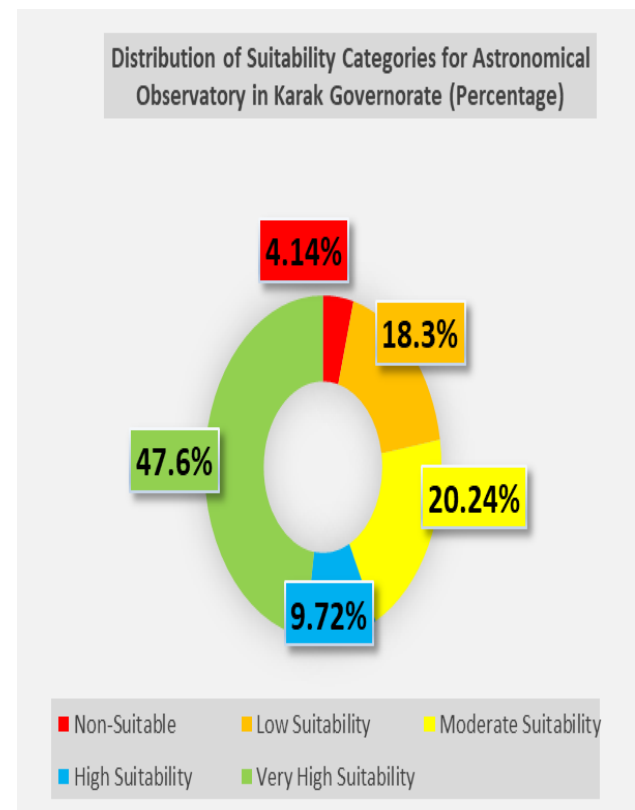
**Figure 5.** (a) The spatial distribution of the suitability classes across the southern governorates; (b) the distribution of the very high suitability class within each governorate.

Ma'an Governorate contained the largest absolute area of Class 5 land, totaling 6740.61 km<sup>2</sup>, which accounted for 37.23% of its total area. It also included 16,790.95 km<sup>2</sup> of Class 4 land. In contrast, Tafilah Governorate exhibited a much smaller absolute area of highly suitable land (56.44 km<sup>2</sup>) but a relatively high proportion (36.89%), which may constrain potential future development. Refer to Figure 6, which shows the spatial distribution of suitability classes for the astronomical observatory in each governorate.

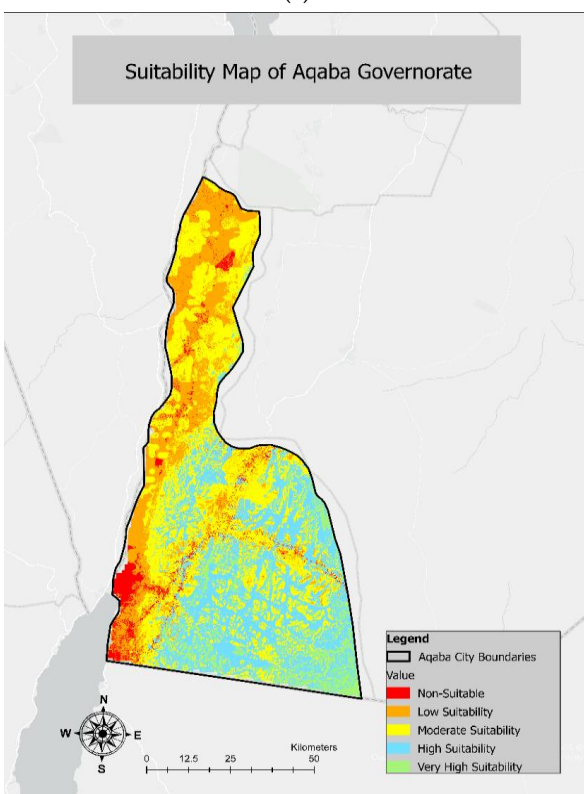




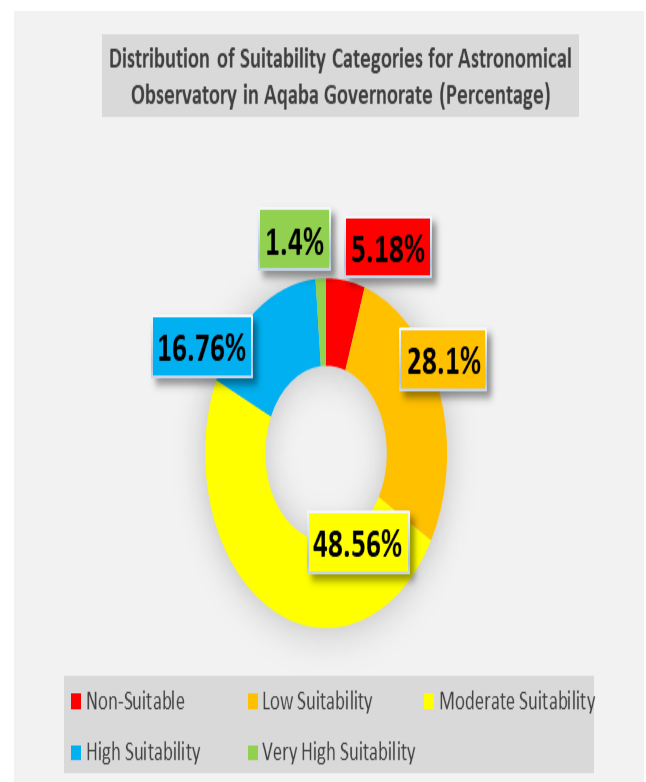
(c)



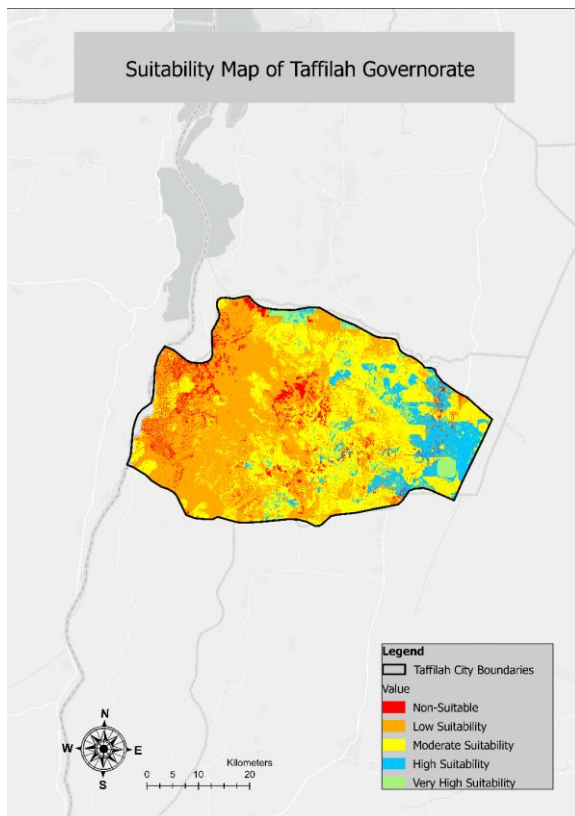
(d)



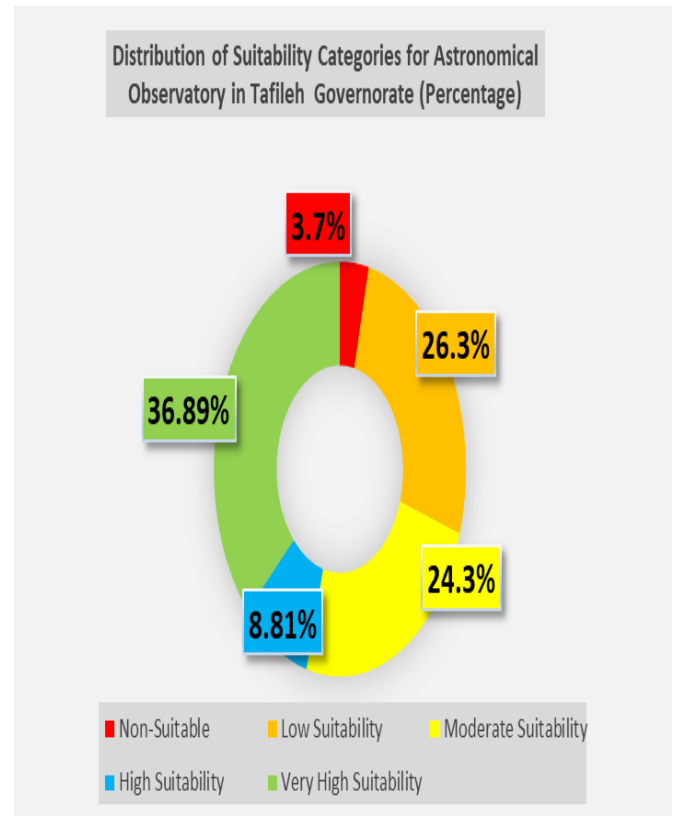
(e)



(f)



(g)

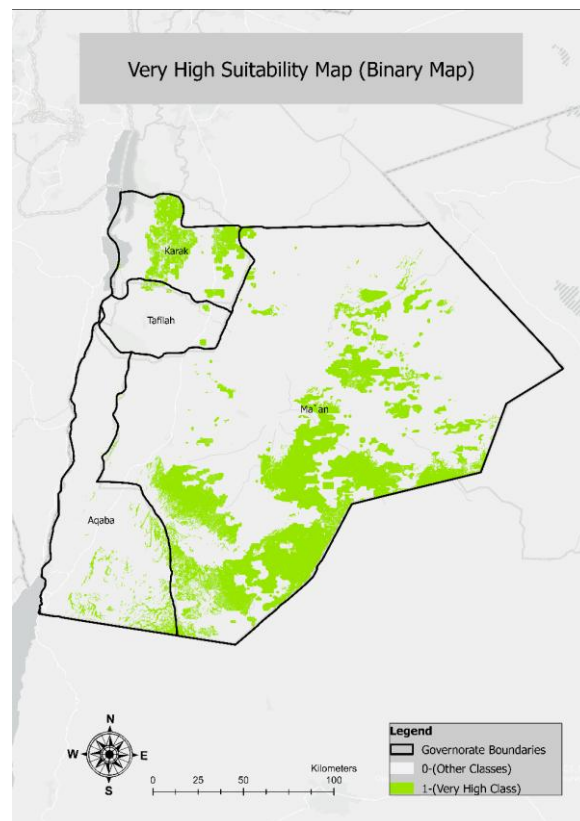


(h)

**Figure 6.** (a) Spatial distribution of suitability classes for the astronomical observatory in Ma'an Governorate; (b) percentage distribution of suitability categories for the astronomical observatory in Ma'an Governorate; (c) spatial distribution of suitability classes for the astronomical observatory in Karak Governorate; (d) percentage distribution of suitability categories for the astronomical observatory in Karak Governorate; (e) spatial distribution of suitability classes for the astronomical observatory in Aqaba Governorate; (f) percentage distribution of suitability categories for the astronomical observatory in Aqaba Governorate; (g) spatial distribution of suitability classes for the astronomical observatory in Taffilah Governorate; (h) percentage distribution of suitability categories for the astronomical observatory in Taffilah Governorate.

#### 5.5.2. Extracting the Highest Class (Very High Suitability)

From the final raster suitability map, only those regions having the highest suitability values were selected for further analysis using the Con tool in Raster Calculator in ArcGIS Pro. This process helped select those cells that have very high suitability values and extract them as a new layer. These binary classifications include assigning a value of 1 to all cells that satisfy very high suitability conditions and assigning a value of 0 or No Data to all other remaining cells. Then, this newly created binary raster map was converted into vector polygons, generating a clear layer showing the potential sites for a radio astronomy observation facility. Figure 7 shows the output map.

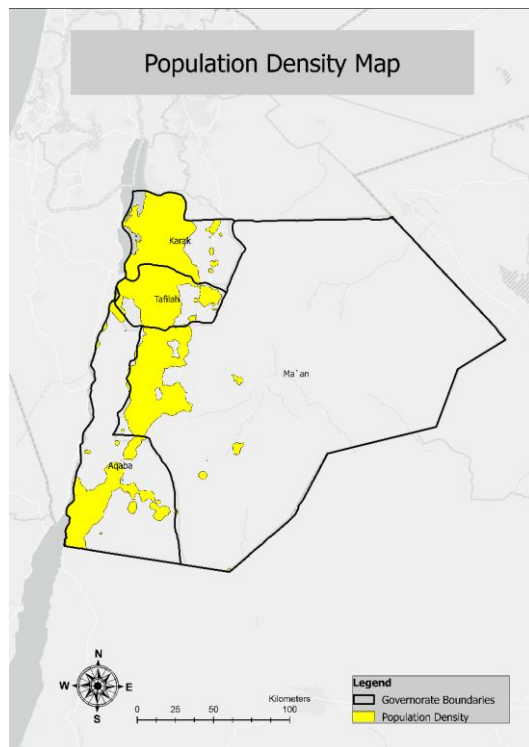


**Figure 7.** Very high suitability areas for a radio astronomy observatory in southern Jordan.

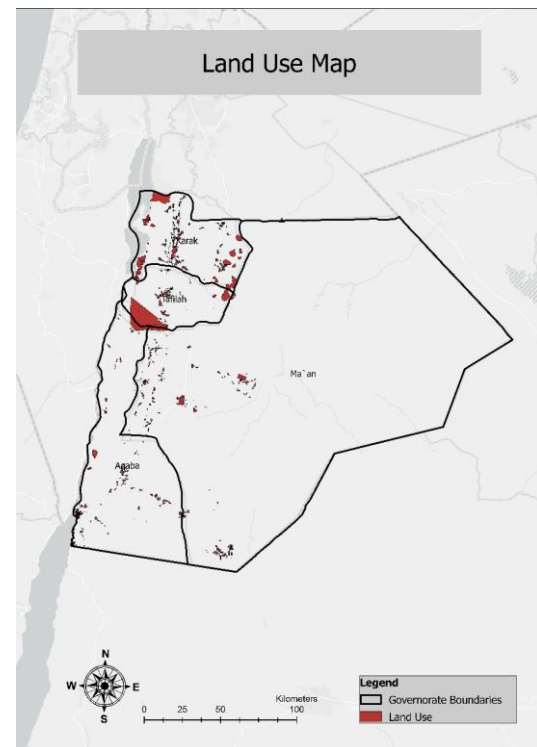
#### 5.5.3. Spatial Overlay and Buffering

Using ArcGIS Pro, a detailed spatial overlay analysis was conducted to further refine and identify the most suitable potential locations for the proposed radio astronomy observatory. The procedure started with incorporating multiple thematic layers to identify potential sources of interference and logistical constraints. These layers included infrastructure layers (major roads, high-voltage transmission lines, and communication towers) beside the demographic and land use layers (population density and land use classifications). Refer to Figure 8a–e.

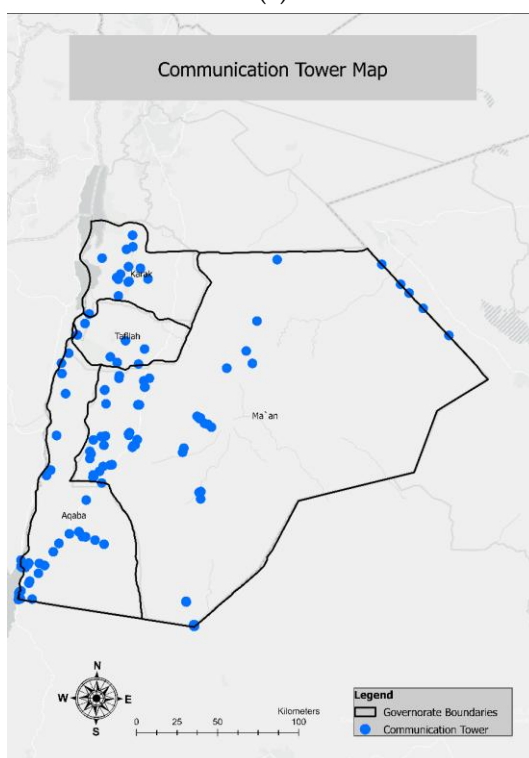
To minimize any possible risks of interference caused by the electromagnetic radiation from towers, power lines, and roads, buffer zones of 500 m around these areas were created. It should be noted that the 500 m buffer corresponds to international scientific engineering standards and ensures complete elimination of RFI while still providing operational accessibility for inspection and maintenance (Federal Communications Commission, FCC, 2023) [50].



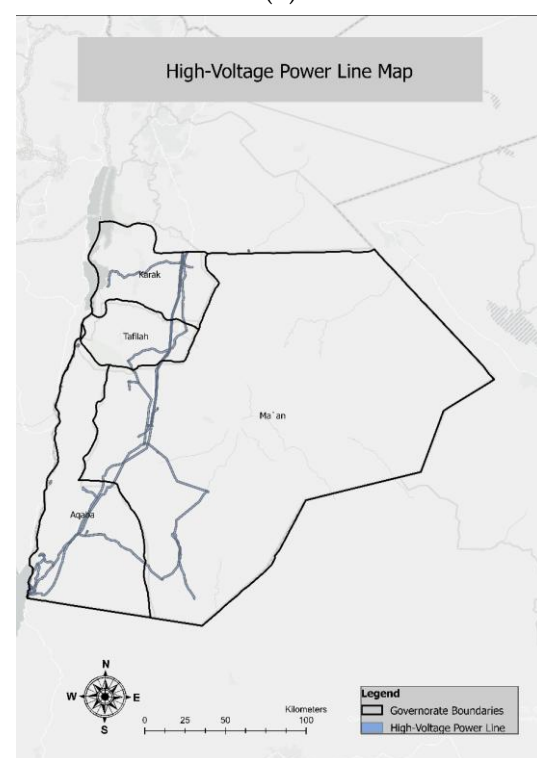
(a)



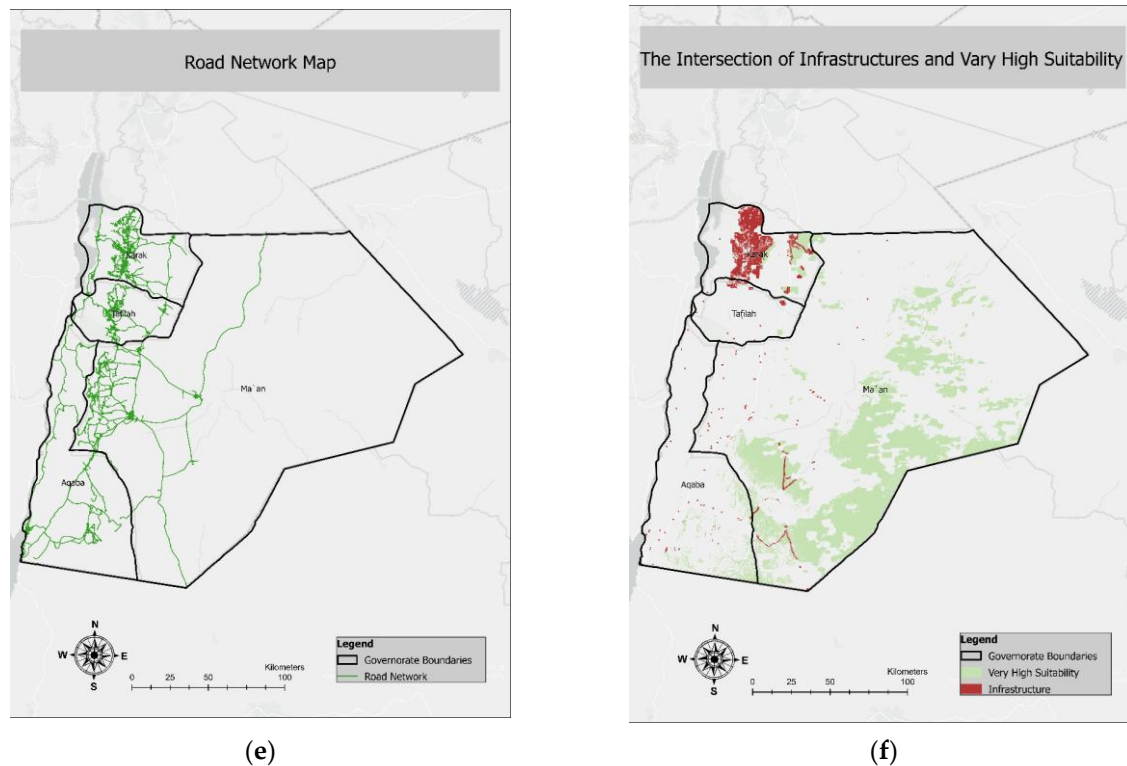
(b)



(c)



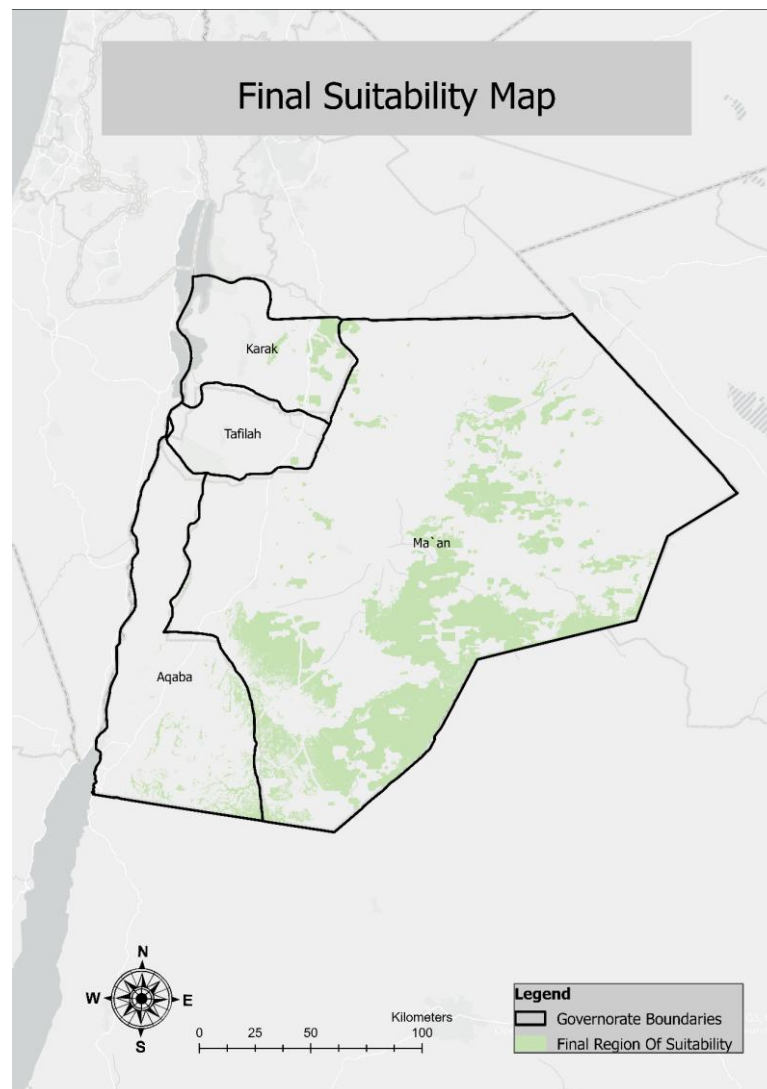
(d)



**Figure 8.** Thematic layers of infrastructures of possible interference sources for the construction of a radio astronomy observatory in southern Jordan: (a) population density; (b) land use; (c) communication towers; (d) high voltage line; (e) road and (f) infrastructure overlapping with very high suitability areas for establishing a radio astronomy observatory in southern Jordan.

The next procedure used after buffer creation involved applying the Intersect tool on areas classified as “Very High Suitability” (Class 5). In other words, the intersect analysis highlighted overlapping parts indicating potential conflicts. The results of the Intersect tool are illustrated below in Figure 8f.

After identifying the overlapping areas, all areas that overlap with buffered or restricted areas were erased through the use of the Erase tool. As a result, only such regions remained that did not overlap with conflicting factors such as undesirable land use or population density, along with potential sources of electromagnetic interference. The last step in this procedure entailed labeling each polygon with the name of the governorate to which it belongs, its area in km<sup>2</sup>, and the geographic coordinates of the center, enabling the scientific representation of the chosen sites for the radio astronomy observatory, as illustrated in Figure 9 below.



**Figure 9.** Final suitable locations for a radio astronomy observatory in southern Jordan.

#### 5.5.4. Classification of Suitable Sites According to the Type of Radio Observatory

For this study, each polygon representing potential observatory sites was systematically evaluated in ArcGIS Pro to derive key spatial attributes. The analysis involved calculating the area of each polygon in terms of square kilometers ( $\text{km}^2$ ), computing the coordinates of the centroids based on the UTM Zone 36N coordinate system, and identifying the name of the administrative area where the sites are located. Such spatial measurements were necessary for the integration of the results into an overall geographic evaluation within the GIS platform. To facilitate planning and decision-making, the sites were further categorized according to their total area into three distinct classes: small sites ( $0.01\text{--}0.5 \text{ km}^2$ ), medium sites ( $0.5\text{--}10 \text{ km}^2$ ), and large sites (exceeding  $10 \text{ km}^2$ ). Sites with areas less than  $0.01 \text{ km}^2$  were excluded from consideration due to insufficient size for practical development. This categorization provides a structured framework to compare and prioritize sites based on both spatial and administrative criteria, supporting strategic planning for the establishment of radio astronomy observatories.

In the results, five key sites meet the requirements to establish observatories according to international standards. These sites are distributed across the Aqaba and Ma'an districts, as well as the southeastern part of Amman, bordering Ma'an. See Table 14.

**Table 14.** Large observatory site characteristics.

| <b>Id</b> | <b>District</b> | <b>Area (km<sup>2</sup>)</b> | <b>X (m)</b> | <b>Y (m)</b>   | <b>Notes</b>                                                             |
|-----------|-----------------|------------------------------|--------------|----------------|--------------------------------------------------------------------------|
| 25024     | Aqaba           | 4146.6240                    | 831,139.7000 | 3,304,455.0000 | Ideal radio isolation and vast space near port and highways              |
| 13032     | Ma'an           | 918.6940                     | 775,987.9000 | 3,313,187.0000 | Flat desert terrain and sufficient safety distances                      |
| 3775      | Ma'an           | 558.3990                     | 870,995.5000 | 3,383,284.0000 | Open environment suitable for antenna array distribution                 |
| 7551      | Ma'an           | 227.6960                     | 911,685.2000 | 3,327,130.0000 | Adequate distance from settlements, allowing legal protection zone       |
| 2097      | Ma'an           | 199.2030                     | 797,026.5000 | 3,455,879.0000 | Southeastern Amman edge site with moderate isolation and legal potential |

The attributes of medium-sized sites are presented in the table below. Such sites are capable of supporting national or regional observatories with five to fifteen radio dishes and provide sufficient space to implement buffer zones of 1–5 km to mitigate potential interference. The characteristics of medium-sized observatory sites are summarized in Table 15.

**Table 15.** Medium observatory site characteristics.

| <b>Id</b> | <b>District</b> | <b>Area (km<sup>2</sup>)</b> | <b>X (m)</b> | <b>Y (m)</b>   | <b>Notes</b>                                             |
|-----------|-----------------|------------------------------|--------------|----------------|----------------------------------------------------------|
| 12485     | Aqaba           | 9.8750                       | 820,123.5000 | 3,295,013.0000 | Near the upper limit of the range, buffer setup feasible |
| 14230     | Ma'an           | 7.4320                       | 780,456.1000 | 3,321,005.0000 | Possible to establish a local protection zone            |
| 16892     | Amman           | 1.2000                       | 805,789.6000 | 3,462,789.0000 | Proximity to power and fiber-optic networks              |

Around university campuses and scientific facilities in Amman, Karak, and Tafileh, more than 20 tiny sites were found; these are perfect for academic research and teaching. The table below lists the largest of these locations as shown in Table 16.

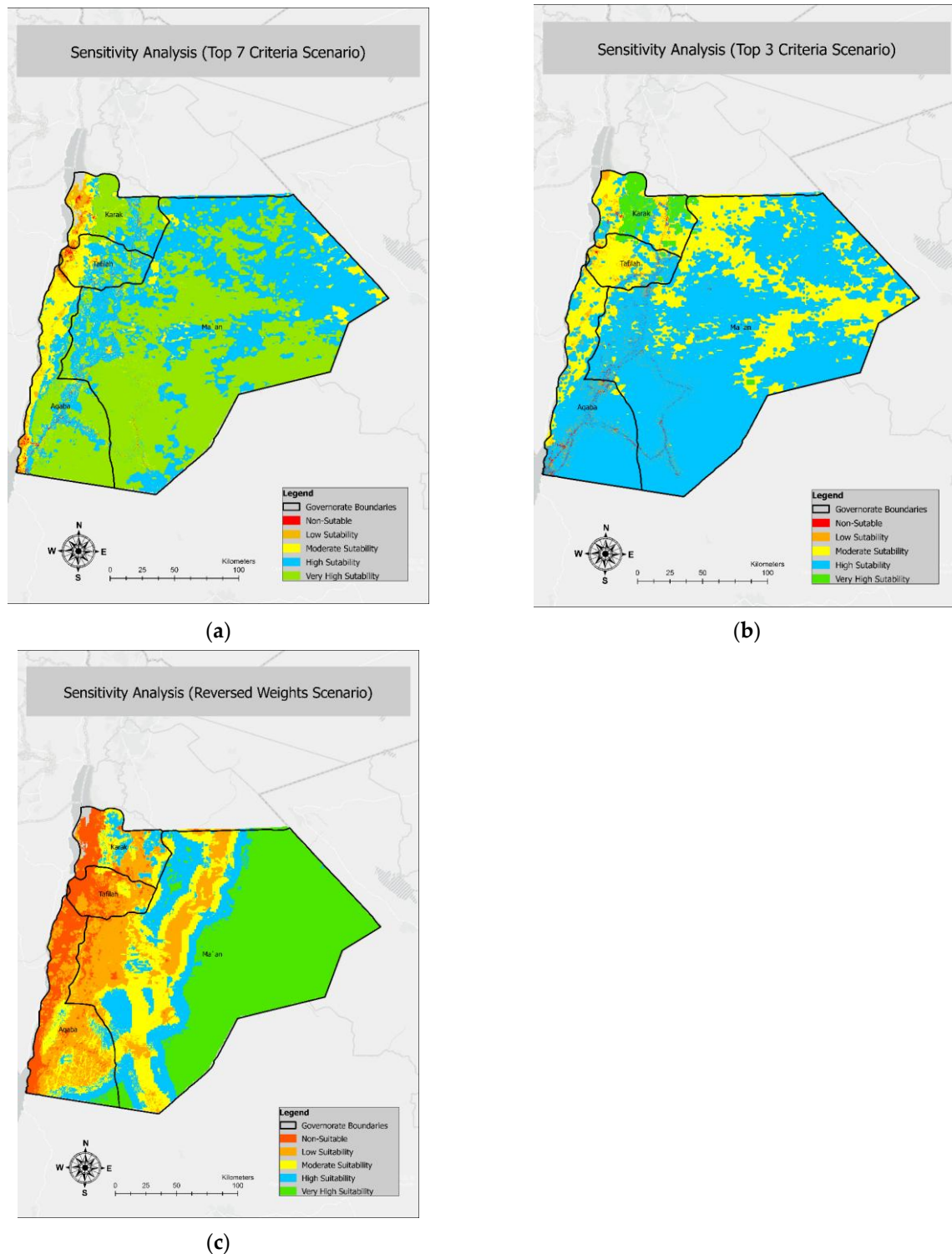
**Table 16.** Small observatory site characteristics.

| <b>Id</b> | <b>City</b> | <b>Area (m<sup>2</sup>)</b> | <b>X (m)</b> | <b>Y (m)</b>   | <b>Notes</b>                                        |
|-----------|-------------|-----------------------------|--------------|----------------|-----------------------------------------------------|
| 18567     | Amman/Ma'an | 498,700.0000                | 798,123.6000 | 3,456,789.0000 | Close to a university campus, suitable for training |
| 19345     | Karak       | 256,400.0000                | 745,987.2000 | 3,295,654.0000 | Integrated with a university electrical grid        |
| 20211     | Tafileh     | 12,300.0000                 | 734,567.9000 | 3,223,456.0000 | Suitable for limited academic experiments           |

#### 5.5.5. Sensitivity of Criteria

In this study, a sensitivity test was carried out by altering the site suitability parameters to 7 parameters, and in another test, to 3 parameters instead of 11 in the assessment of site suitability, and subsequently reversing the highest weight to the lowest weight factor and vice versa.

In order to find spatial variations in the five suitability categories (non-suitable, low suitability, moderate suitability, high suitability, and very high suitability), three new suitability maps, as shown in Figure 10a–c, were created based on each scenario and compared with the original suitability map that was produced prior to testing the model. To assess how each scenario differed, the Tabulate Area tool in ArcGIS Pro was used to calculate the area of each suitability class, as summarized in Table 17.



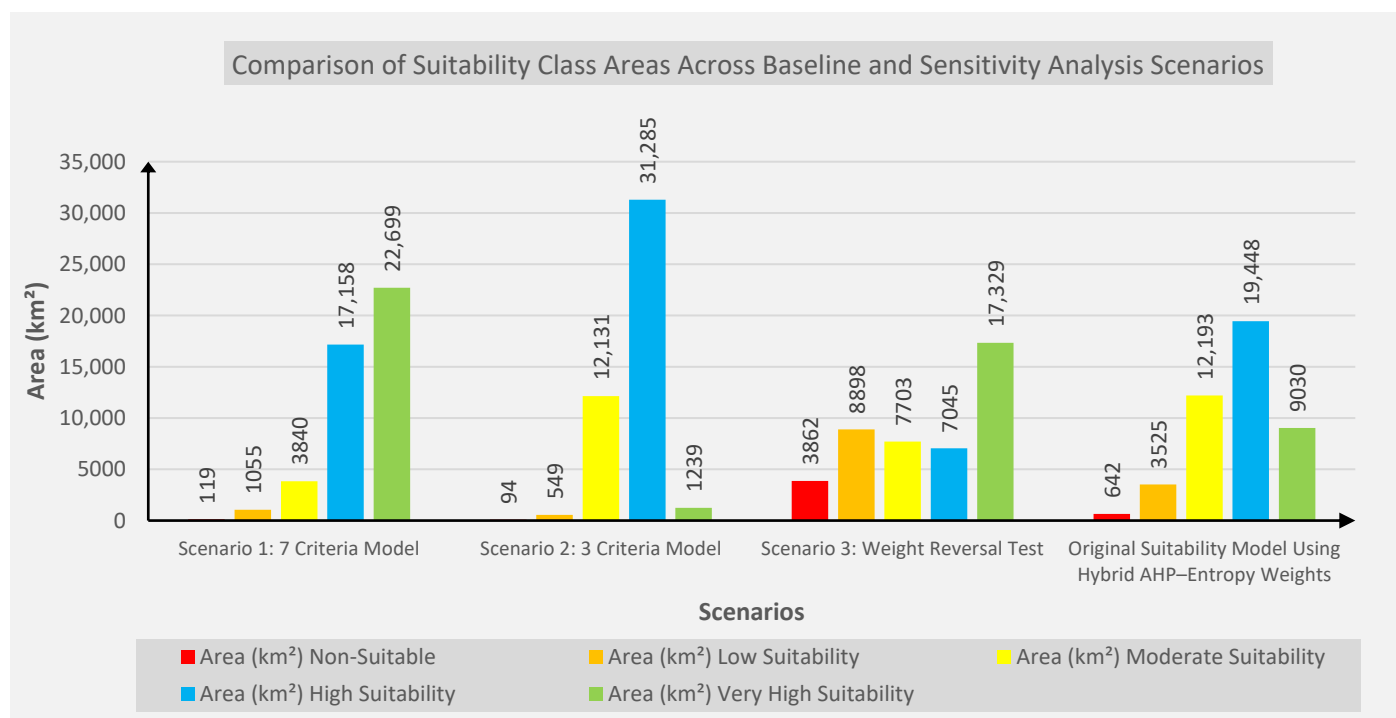
**Figure 10.** Sensitivity analysis maps generated using the (a) 7 most influential criteria, (b) 3 most influential criteria, and (c) reversed criteria weights (11 criteria scenario).

**Table 17.** Comparison of suitability class areas under sensitivity analysis scenarios.

| Suitability Class     | Scenario 1: 7 Criteria Model |       | Scenario 2: 3 Criteria Model |       | Scenario 3: Weight Reversal Test |       | Original Suitability Model Using Hybrid AHP–Entropy Weights |       |
|-----------------------|------------------------------|-------|------------------------------|-------|----------------------------------|-------|-------------------------------------------------------------|-------|
|                       | Area (km <sup>2</sup> )      | %     | Area (km <sup>2</sup> )      | %     | Area (km <sup>2</sup> )          | %     | Area (km <sup>2</sup> )                                     | %     |
| Non-Suitable          | 119.37                       | 0.27  | 3861.84                      | 8.61  | 93.51                            | 0.21  | 641.82                                                      | 1.43  |
| Low Suitability       | 1055.40                      | 2.35  | 8898.10                      | 19.85 | 548.60                           | 1.21  | 3524.69                                                     | 7.86  |
| Moderate Suitability  | 3840.27                      | 8.56  | 7703.45                      | 17.18 | 12,130.83                        | 26.79 | 12,193.45                                                   | 27.19 |
| High Suitability      | 17,158.39                    | 38.24 | 7044.65                      | 15.71 | 31,285.07                        | 69.07 | 19,447.53                                                   | 43.37 |
| Very High Suitability | 22,698.69                    | 50.58 | 17,329.41                    | 38.65 | 1238.53                          | 2.73  | 9029.97                                                     | 20.14 |

Figure 10a–c show that the spatial distribution of the high and very high suitability areas converged in the spatial structures of the three scenarios' maps. Table 17, in addition to Figure 10, shows that the resulting suitability classes were consistent with the original model, showing consistency in the selection of the most suited places. In contrast to the second scenario, the first and third scenarios' unsuitability zones were found to be more similar to those in the original model.

When compared to the original model, the areas and proportions of various suitability categories varied across all three scenarios, indicating that changing criteria and weights had varying effects on the spatial distribution of different categories while not significantly changing the overall pattern of the most appropriate areas. Refer to Figure 11. In the three scenarios, the model is considered stable in the very high and high suitability classes. Differences are more evident in the medium and low suitability classes, indicating the sensitivity of space distribution to changes in the number of criteria and their weights, without affecting the overall pattern of the most suitable areas.

**Figure 11.** Suitability areas under different scenarios.

## 6. Discussion

The issue of the lack of integration between multi-criteria decision-making techniques and Geographic Information System (GIS) technology in choosing locations for astronomical observatories was addressed in this work. The accuracy of geographic evaluation is decreased by the fact that much earlier research relied on sparse data or distinct analytical approaches. In order to improve the accuracy of identifying optimal locations and provide a more thorough assessment of environmental and astronomical factors, this study, in line with several earlier investigations like [3,13,39,41,43,51,52], presented an integrated framework that combines GIS data and multi-criteria evaluation techniques in order to identify potential suitable sites for astronomical observatories. These studies consider a few factors. Common criteria in the previous literature, such as cloud cover, DEM, artificial lights, perceptible water vapor, aerosol optical thickness, and wind speed, were considered in this study with five additional criteria.

Many prior studies based on expert-driven weighting (e.g., AHP) have been conducted without integrating an objective method like entropy [3,41,51,52] or have relied on objective approaches when establishing the weights of criteria when choosing radio observatory sites [38,43]. In order to achieve a better balance in criteria evaluation and increase reliability when choosing the best site, this study includes data-driven/hybrid approaches and goes beyond completely relying on expert judgments. It presents a combination of AHP (as a subjective method) and the entropy method (as an objective method) within a GIS environment. Several studies, such as those by Aksaker, N. et al. (2015, 2020) [3,52], Yilmaz (2023) [13,51], and Sakti et al. (2023) [43], did not determine the “absolute best”; instead, they produced a list of possible locations that must be tested in the field to confirm the true astronomical and climatic parameters before closure. However, in order to successfully reduce the risk of RFI while preserving operational accessibility for maintenance and observation, the best locations with very high suitability in this study were established by examining their intersection with infrastructure that may have an impact on the quality of radio astronomical observations, such as communication towers, power lines, and road networks. Additionally, the best sites were divided into three different classifications based on their overall area: small sites, medium sites, and large sites. Additionally, the locations were connected to nearby services and places, including scientific facilities and universities. Up to the end of this study, no prior research has addressed this link. Strategic planning for the construction of radio astronomy observatories is supported by this classification and integration, which offer an organized framework for comparing and ranking locations according to administrative and spatial criteria.

The process of multi-criteria spatial analysis used to select the most suitable site for a radio astronomy observatory in southern Jordan relies on several determinants. The accuracy of the final suitability map is related to the quality and precision of the input data, such as land use, elevation, and infrastructure. Additionally, some important factors, such as future urban expansion or undocumented sources of electromagnetic interference, may not be fully represented within the model.

Uncertainty in this study arises mainly from data variability, measurement errors, and model assumptions. Remote sensing and geographic information system data may contain spatial or classification errors. Temporal changes in land use and infrastructure development also increase the level of uncertainty when relying on static data. Similarly, differences in expert opinions in assigning weights to criteria lead to variability in suitability results.

The applicability of the model is limited by the geographical scope of the study, as the results mainly apply to southern Jordan and may not be generalizable to other areas with different environmental or geographical characteristics. Additionally, the assumption of constant input factors over time restricts the use of the model in the long term

without periodic updates. Furthermore, regulatory constraints such as land ownership and protected areas may pose an obstacle to the practical implementation of the proposed sites.

In future, studies, the accuracy and reliability of the model can be improved by using higher-resolution spatial data and integrating real-time monitoring of electromagnetic interference sources. Machine learning techniques can also be employed to reduce subjectivity in determining weights and to enhance prediction accuracy. Additionally, incorporating social, economic, and regulatory factors will contribute to providing a more comprehensive assessment. It is also recommended to periodically update geographic databases to ensure the continuity and reliability of results over the long term.

## 7. Conclusions

GIS and MCDA were integrated into this study's methodology and used to develop a scientifically rigorous framework for locating the radio astronomy observatories in southern Jordan. Expert opinion and the inherent unpredictability of geographical data were balanced through the deployment of a hybrid weighting technique that included AHP and entropy approaches.

Other findings from this study include that the RFI (radio frequency interference) was the most important because of its weight in both the AHP (39%) and entropy analysis. These findings agree with earlier research where the importance of RFI was considered in radio observations. Elevation, cloud cover, and water vapor were key environmental elements that contributed to site suitability, whereas slope, land use, and population density refined the final results. Using the integrated weights and the Weighted Sum tool in ArcGIS Pro, a thorough suitability map was created and classified into five suitability classes. Ma'an Governorate has the highest percentage of regions with extremely high appropriateness (37.23%), followed by Aqaba (20.14%). The "Very High" areas were converted into vector polygons and further modified by creating 500 m buffer zones around roads, power lines, and communication towers to eliminate regions influenced by human activity or infrastructure. The resulting high-resolution suitability map found numerous potential sites, classifying them by size. Five large observatories ( $\geq 10$  km<sup>2</sup>) are located in Ma'an, Aqaba, and southern Amman (near Ma'an). Medium observatories (0.5–10 km<sup>2</sup>; equivalent to 500,000–10,000,000 m<sup>2</sup>) are sites with potential for future expansion and development. Small observatories (0.01–0.5 km<sup>2</sup>) are academic sites near universities that are appropriate for research and training.

From this research, a scientific guide can be formulated to plan the radio astronomy facilities in southern Jordan based on their results. This process incorporates environmental criteria in addition to practical constraints, thus creating an adaptable structure that can help in future observatory projects by using the space and technology capabilities available.

For a number of reasons, including state security and changing anthropogenic conditions in neighboring states, it is crucial to stay away from areas that are close to international borders. This study does not account for these circumstances.

The study suggested conducting more RFI analyses at appropriate locations. To further the study, anthropogenic situations and national security should be taken into consideration. Additionally, the study suggests conducting additional research on this subject, which might include perceptible water vapor and atmospheric dust.

In conclusion, the proposed methodology in this study can become a crucial instrument for directing decision-making and the site-selection process of possible radio astronomy sites, especially those that require extensive territorial analysis, which frequently has information gaps or necessitates particular methods to handle the information that is available. Future work could involve field validation of the chosen sites, incorporation of

higher-resolution datasets, and development of the study to include additional environmental and technological variables such as seismic risk and electromagnetic interference.

**Author Contributions:** Conceptualization, Zubeida Aladwan; methodology, Alia Al-Mashaqbeh and Renad Abdulrahman; software, Alia Al-Mashaqbeh and Renad Abdulrahman; validation, Renad Abdulrahman; formal analysis, Zubeida Aladwan and Shatha Aldala'in; investigation, Zubeida Aladwan; resources, Renad Abdulrahman; data curation, Renad Abdulrahman; writing—original draft, Alia Al-Mashaqbeh; writing—review and editing, Zubeida Aladwan, Shatha Aldala'in and Shatha Al Rawashdeh; supervision, Zubeida Aladwan; project administration, Zubeida Aladwan. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** All data generated or analyzed during this study are included in this published article.

**Acknowledgments:** During the preparation of this manuscript/study, the authors used ChatGPT, GPT-5 mini for the purposes of rephrasing and enhancing the clarity of the text. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                            |
|------|--------------------------------------------|
| GIS  | Geographic Information Systems             |
| MCDA | Multi-Criteria Decision Analysis           |
| AHP  | Analytic Hierarchy Process                 |
| RFI  | Radio Frequency Interference               |
| RS   | Remote Sensing                             |
| SIAS | Suitability Index for Astronomical Sites   |
| ITUs | The International Telecommunication Unions |
| AOD  | Aerosol Optical Depth                      |
| LULC | Land Use/Land Cover                        |
| DEM  | Digital Elevation Model                    |
| GEE  | Global Earth Engine                        |
| GWA  | Global Wind Atlas                          |
| MCE  | Multi-Criteria Evaluation                  |
| LoS  | Line of Sight                              |
| VHF  | Very High Frequency                        |
| UHF  | Ultra High Frequency                       |

## Appendix A

### Appendix A.1

**Table A1.** Reclassification scheme for AOD.

| Class | AOD Range | Description |
|-------|-----------|-------------|
| 5     | 0.14–50   | Excellent   |
| 4     | 50–150    | Very Good   |
| 3     | 150–400   | Moderate    |
| 2     | 400–1000  | Poor        |
| 1     | >1000     | Very Poor   |

*Appendix A.2***Table A2.** Reclassification scheme for PWV.

| Class | PWV (mm) | Description |
|-------|----------|-------------|
| 5     | 0–5      | Excellent   |
| 4     | 5–10     | Very Good   |
| 3     | 10–15    | Acceptable  |
| 2     | 15–20    | Poor        |
| 1     | >20      | Unsuitable  |

*Appendix A.3***Table A3.** Reclassification scheme for CC.

| Class | Cloud Cover (%) | Description   |
|-------|-----------------|---------------|
| 5     | 0–20            | Clear         |
| 4     | 20–40           | Mostly Clear  |
| 3     | 40–60           | Partly Cloudy |
| 2     | 60–80           | Cloudy        |
| 1     | 80–100          | Overcast      |

*Appendix A.4***Table A4.** Reclassification scheme for WS.

| Class | Wind Speed (m/s) | Suitability |
|-------|------------------|-------------|
| 5     | 0.26–2.50        | Excellent   |
| 4     | 2.50–5.00        | Good        |
| 3     | 5.00–7.50        | Fair        |
| 2     | 7.50–10.00       | Poor        |
| 1     | >10.00           | Unsuitable  |

*Appendix A.5***Table A5.** Reclassification scheme for ALP.

| Class | Radiance (nW/cm <sup>2</sup> /sr) | Description |
|-------|-----------------------------------|-------------|
| 5     | 0.32–2.00                         | Excellent   |
| 4     | 2.00–10.00                        | Good        |
| 3     | 10.00–50.00                       | Moderate    |
| 2     | 50.00–150.00                      | Poor        |
| 1     | >150.00                           | Unsuitable  |

*Appendix A.6***Table A6.** Reclassification scheme for DEM.

| Class | Elevation (m) | Suitability |
|-------|---------------|-------------|
| 5     | 800–1500      | Excellent   |
| 4     | 600–800       | Good        |
| 3     | 1500–1800     | Fair        |
| 2     | 300–600       | Poor        |
| 1     | <300 or >1800 | Unsuitable  |

*Appendix A.7***Table A7.** Reclassification scheme for slope.

| Class | Slope (°) | Suitability                               |
|-------|-----------|-------------------------------------------|
| 5     | 0–5       | Easy construction, low geotechnical risk  |
| 4     | 5–10      | Acceptable with minor grading adjustments |
| 3     | 10–15     | Requires significant civil earthworks     |
| 2     | 15–20     | Major engineering challenges              |
| 1     | >20       | Impractical, high instability risk        |

*Appendix A.8***Table A8.** Reclassification scheme for EDFR.

| Class | Distance (m)  | Description |
|-------|---------------|-------------|
| 1     | 0–5000        | Very Close  |
| 2     | 5000–10,000   | Close       |
| 3     | 10,000–17,000 | Moderate    |
| 4     | 17,000–24,000 | Good        |
| 5     | >24,000       | Very Far    |

*Appendix A.9***Table A9.** Reclassification scheme for PD.

| Class | Density (People/km <sup>2</sup> ) | Suitability |
|-------|-----------------------------------|-------------|
| 5     | 0–10                              | Excellent   |
| 4     | 10–50                             | Good        |
| 3     | 50–200                            | Moderate    |
| 2     | 200–1000                          | Poor        |
| 1     | >1000                             | Unsuitable  |

*Appendix A.10***Table A10.** Reclassification scheme for LU.

| Original Class | Reclassified Suitability | Description                                   |
|----------------|--------------------------|-----------------------------------------------|
| 0              | 5                        | Natural, uninhabited areas                    |
| 1              | 3                        | Agricultural lands (low impact)               |
| 2, 3           | 1                        | Residential or industrial (high interference) |
| 4              | 2                        | Commercial (moderate activity)                |
| 5, 6           | 5                        | Forests or grasslands (low pollution)         |

*Appendix A.11***Table A11.** Reclassification scheme for RIF.

| Class | Normalized RFI | Description |
|-------|----------------|-------------|
| 5     | 0.0–0.2        | Very Low    |
| 4     | 0.2–0.4        | Low         |
| 3     | 0.4–0.6        | Moderate    |
| 2     | 0.6–0.8        | High        |
| 5     | >24,000.0      | Very Far    |

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