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# Spatial Multi-Criteria Analysis for Rainwater Harvesting Site Suitability Using GIS and AHP: A Case Study of Hababah Sub-Watershed, Amran Governorate, Yemen

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## Abstract

Rainwater harvesting (RWH) has become a necessity rather than a luxury in addressing increased water scarcity. However, identifying suitable locations for RWH systems remain a significant challenge, particularly in data-scarce and resource-limited contexts. This study aims to determine optimal sites for surface rainwater harvesting using GIS and AHP by integrating both biophysical and socioeconomic criteria for RWH site selection. A mixed-methods approach was employed, where KII's and FGD's played a central role in validating the top six biophysical and the top three socioeconomic criteria influencing site suitability. Expert-based PWC were used to assign weights to these criteria, supporting the development of a spatial decision-making model. The generated suitability map reveals that 7.6% of the study area is highly suitable, 23% suitable, 22% moderately suitable, 14% marginally suitable, and 33.4% unsuitable for rainwater harvesting. Model field validation was conducted by overlaying 26 existing rainwater harvesting systems onto the suitability map, which showed that 61.5% of the current systems are located in highly and moderately suitable areas, while 38.5% are situated in low-suitability zones, demonstrating the strong predictive performance of the adopted approach and its sensitivity to change in any of the influenced criteria. The study concludes that the integration of multidisciplinary biophysical and socioeconomic criteria through GIS and AHP provides an effective and cost-efficient approach for sustainable resource planning, especially in arid, semi-arid, and data-scarce areas. The study recommends extending this approach to other watersheds, and strengthening the integration of socioeconomic aspects with modern geospatial techniques to enhance sustainable water resource management.

## Article Info

**Keywords:**
Rainwater Harvesting (RWH), Site Suitability, Spatial Analysis, GIS, APH, Hababah sub-watershed.

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**ABBREVIATIONS:** GIS, Geographic Information Systems; AHP, Analytical Hierarchy Process; KII, key informant interview; FGD, focus group discussion; PWC, pairwise comparison; MCDA, multi-criteria decision analysis; FAO, Food and Agriculture Organization of the United Nations; WGS-84, World Geodetic System 1984



## 1. INTRODUCTION

Yemen is one of the most water-scarce nations in the world, facing a major challenge represented by shortages of renewable water resources, where water consumption and use exceed the renewable water supply [1]. The amount of renewable water resources is approximately 2,5 BCM whereas the total demand is estimated to be 4.4 BCM in 2025. This represents a 1.9 BCM deficit, which is covered by deep aquifers, resulting in the alarming depletion of groundwater in several basins that eliminate food production and other utilizations in many locations [2, 3]. The adaptation practices of rainwater harvesting systems play an important role in droughts and floods, enhance water security, achieve the implementation of the Sustainable Development Goals (SDGs), and increase the resilience of children and women during wars and droughts [4]. The success of RWH management depends heavily on identifying suitable sites for rainwater harvesting systems, which leads to increased water availability and improved water resource planning [5].

Three major sets of guidelines exist for selecting suitable rainwater harvesting (RWH) sites. The first was developed by the Integrated Mission for Sustainable Development (IMSD, 1995), which focused solely on biophysical criteria and was flexible with soil textures and slopes, but was limited in land-use applications and lacked socio-economic criteria. The second was developed by [6], who introduced socio-economic criteria, included specific requirements for different agricultural types, and provided detailed specifications for RWH structures, but still had a limited socio-economic scope. The third and most comprehensive guideline was developed by the FAO (2003), which incorporated extensive biophysical and socio-economic criteria, offering broader and more flexible parameters for RWH techniques, making it widely accepted in arid and semi-arid regions [7].

Various approaches have been developed to identify suitable sites and techniques for RWH [8, 9]. [10] In their review paper, four main approaches for selecting suitable sites for rainwater harvesting (RWH) were illustrated: (1) GIS combined with remote sensing (RS), (2) hydraulic modeling (HM) integrated with GIS/RS, (3) multi-criteria decision analysis (MCDA) integrated with HM and GIS/RS, and (4) MCDA integrated with GIS [10]. Each approach has its own advantages and limitations and is largely dependent on data availability and geographical context [10]. In recent years, the integration of GIS and AHP-based MCDA has emerged as the most widely applied technique in arid and semi-arid regions (ASARs) owing to its flexibility in adjusting evaluation criteria and applicability in areas with limited data availability [10].

In the Hababah Sub-Watershed of Amran Governorate, traditional water supply systems are often inadequate to meet the needs of the local population. Surface rainwater harvesting presents a viable alternative for enhancing water availability and promoting population well-being. However, the successful implementation of RWH systems requires careful selection based on various technical, environmental, social, and economic criteria. This study aimed to identify suitable rainwater harvesting sites within the Hababah Sub-Watershed by employing Geographic Information System (GIS) technology combined with an analytic hierarchy process (AHP)-based multi-criteria decision analysis (MCDA) technique. The integration of these methodologies will facilitate the systematic identification of potential sites, considering factors such as topography, drainage density, land cover, land use, soil type, geology, and proximity to existing infrastructure. Ultimately, this study seeks to provide actionable insights that can guide experts, decision-makers, local authorities, and stakeholders in optimizing rainwater harvesting strategies to improve water resource management.

The primary objective of this study was to identify suitable rainwater harvesting sites using GIS- and AHP-based MCDA. The primary objective was achieved through the following sub-objectives: 1) Identification and prioritization of the key biophysical and socioeconomic factors that influence the identification of suitable sites for RWH systems, establishing a foundation for GIS and AHP integration. 2) To develop a robust and iterative approach that integrates GIS and AHP to identify and evaluate suitable surface RWH storage sites, ensuring that critical factors and local contexts are dynamically incorporated into the analysis. 3) To develop actionable insights and decision-support tools, including georeferenced maps and customized reports, that empower experts, policymakers, and local stakeholders to plan, implement, and manage sustainable RWH strategies while promoting water accessibility and enhancing climate resilience.

## 2. STUDY AREA

This study focused on the Hababah Sub-Watershed, located in Amran Governorate, Yemen, between latitudes 15.51°/15.59° North and longitudes 43.81°/43.89° East, covering an area of $\sim$ 82.5 $km^2$ (Figure 1). The area experiences chronic water scarcity, which is further intensified by increasing climate variability, making it a suitable case for rainwater harvesting and water resource management research.

## 3. MATERIALS AND METHODS

### 3.1. Preparation of criteria

The success of rainwater harvesting systems depends not only on appropriate engineering and biophysical conditions but also on socioeconomic factors, which play a critical role in ensuring their effectiveness, sustainability, and community acceptance. Therefore, the selection of the suitability criteria was informed by a systematic review of the recent literature on GIS–MCDA applications for rainwater harvesting site selection in arid, semi-arid, and data-scarce regions. Based on this review, the initial set of criteria was adopted from studies with similar objectives and methodological approaches. These criteria were refined and validated through community participation.

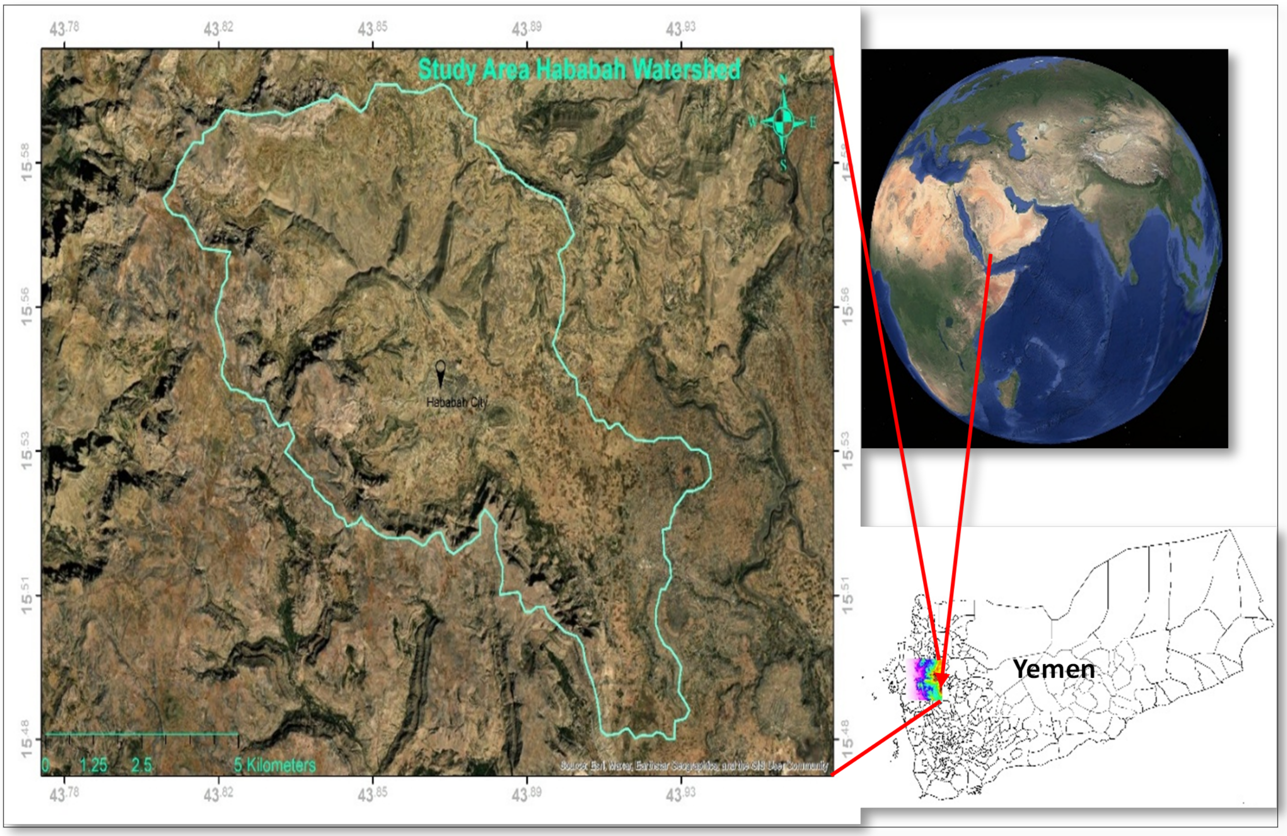


**Figure 1.** Location of the Hababah sub-watershed (Study Area).

## 3.2. Data Sources

To obtain qualitative insights into community rainwater use patterns, needs, perceptions, attitudes, barriers, socioeconomic conditions, and cultural factors influencing the adoption of surface rainwater harvesting (RWH) systems and site selection, eight Key Informant Interviews (KIIs) and three Focus Group Discussions (FGDs) were conducted.

Qualitative data were used to verify and contextualize the biophysical and socioeconomic criteria identified through a systematic review of recent GIS–MCDA literature, ensuring that the selected criteria reflected local environmental conditions and stakeholder perspectives.

The secondary data primarily comprised spatial datasets used in GIS analysis. These datasets were obtained from national and international institutions and processed to generate thematic layers for assessing rainwater harvesting suitability. A Digital Elevation Model (DEM) and satellite imagery were acquired from the Yemen Remote Sensing and GIS Center (YRSC), rainfall data were obtained from the National Water Resources Authority (NWRA), and soil type and geological maps were obtained from the Geological Authority. The data sources and spatial resolutions of each dataset are presented in (Table 1).

**Table 1.** Spatial data acquisition methods and sources used in this study.

| No | Data Type | Resolution/Scale | Data Source* |
|---|---|---|---|
| 1 | Rainfall Data | Two stations | [11, 12] |
| 2 | DEM | (12.7 m × 12.7 m) | [13] |
| 3 | Satellite image | (30 cm × 30 cm) | [14] |
| 4 | Geological map | (20 m × 20 m) | [15] |
| 5 | Soil type map | (30 second) | [16] |
| 6 | Land Cover / Land Use | (10 m × 10 m) | [17] |
| 7 | Roads network map | 1:100,000 | [18] |
| 8 | Yemen grid Map | 1:3,000,000 | [19] |

*All data were projected to WGS 84 / UTM Zone 38N for consistency.

## 3.3. Research methodology

A conceptual framework was developed to illustrate the methodological workflow through which the identified biophysical and socioeconomic criteria were synthesized using thematic analysis and subsequently integrated into the GIS overlay analysis for rainwater harvesting site suitability assessment (Figure 2).

## 3.4. Rainfall Data

Rainfall data from two meteorological stations, Thula and Shibam, located outside the study area boundary

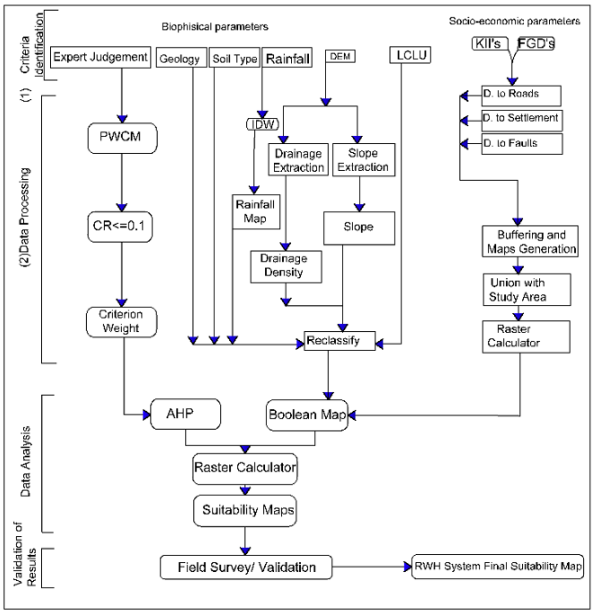


**Figure 2.** Flowchart of the methodology used to identify suitable sites.

(Figure 3), were analyzed to estimate annual precipitation. The results indicate that the mean annual rainfall ranges from approximately 642 mm in the northeastern highlands to approximately 271 mm in the southern part of the sub-watershed. The average annual rainfall values from both stations were processed in ArcGIS to generate an isohyet map representing rainfall distribution using the Inverse Distance Weighting (IDW) interpolation method.

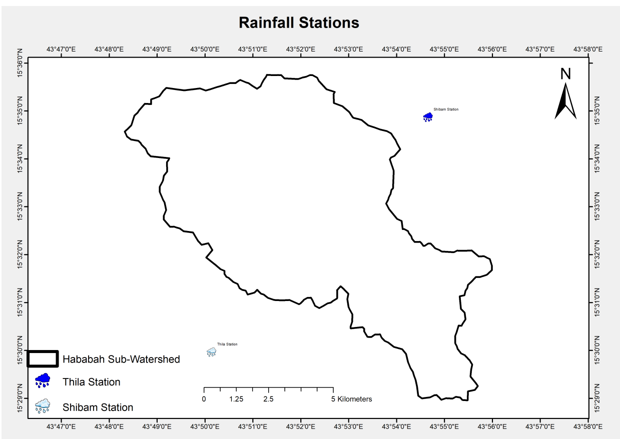


**Figure 3.** Location of the rain gauge stations in the study area.

## 3.5. Slope

The slope was derived from the ASTER Digital Elevation Model (DEM) with a spatial resolution of 12.7 m. The DEM was processed in ArcGIS using Spatial Analyst tools, where sinks and flat areas were filled to ensure a continuous hydrological flow. A slope map was generated using the planar slope algorithm. Based on the suitability criteria adopted in this study, slopes of less than 5° were assigned the highest suitability rating, whereas slopes greater than 30° were classified as unsuitable because of their high runoff velocity, increased erosion potential, and reduced capacity for surface rainwater storage.

## 3.6. Drainage Density

A drainage density map was developed using ArcGIS based on the DEM previously utilized for slope analysis. Mapping drainage density ($D_d$) allows for the strategic identification of regions with abundant water flow, aiding in the optimal placement of RWH infrastructure such as check dams and retention basins. This practice not only maximizes water collection efficiency but also guides sustainable water resource management in diverse geographical contexts.

## 3.7. Land Cover / Land Use

LCLU significantly influences the performance and suitability of RWH systems, as it directly affects key hydrogeological processes, including groundwater recharge, evapotranspiration and surface runoff. Variations in land use modify rainfall–runoff relationships by influencing interception capacity and regulating the distribution of precipitation between infiltration and overland flow.

## 3.8. Soil texture

Soil texture plays a critical role in effectiveness of RWH site selection because of its influence on the infiltration rate and water-holding capacity [20]. It determines the suitability of the base soil for the foundations of RWH systems and influences sediment probability, which affects the quality of collected rainwater and the potential for sediment accumulation within the RWH system, impacts the cost of filtration structures prior to the RWH system's inlet, and assesses erosion risk in downstream channels when there is overflow or a change in the direction of excess rainwater.

## 3.9. Geology

Geology is a key factor in RWH site suitability analysis because of its influence on the permeability, groundwater occurrence, and structural stability of storage facilities. To evaluate both water storage potential and leakage risks, low-permeability formations, such as igneous rocks and clay layers, are considered suitable for surface storage structures, whereas highly permeable formations, including fractured limestone and sandstone, are considered favorable in groundwater recharge studies [21, 22]. Geological structures, particularly faults, were mapped to identify zones that may either enhance subsurface recharge or pose structural and seepage risks for surface RWH systems.

### 3.10. Proximity to Faults

Proximity to faults was controlled through a 500-meter buffer zone from the fault location for the RWH storage systems. Fault zones were treated as exclusion areas because of their structural instability and associated risks [13].

### 3.11. Proximity to Road

Proximity to roads significantly influences regional accessibility and affects the socioeconomic dynamics of an area. Buffer zones were determined based on the distance indicated by [23] and were tailored to the characteristics of the study area. These zones were spatially integrated with the study area using the raster calculator tool in GIS, followed by a comprehensive raster reclassification of all maps [20, 22].

### 3.12. Proximity to Settlements

Settlement maps were extracted from the land use map and validated using satellite imagery. Buffer zones extend 250 meters from the settlement [13, 24]. A distance of 250 m was considered sufficient to mitigate the potential socio-environmental impacts of the constructed RWH systems and to avoid affecting future urban development.

### 3.13. Model Validation

To strengthen the accuracy of the GIS–AHP-based MCDA model, field validation was performed by conducting field visits to 26 existing RWH. The model's suitability levels were compared to the locations of the current RWH systems.

## 4. RESULTS AND DISCUSSIONS

### 4.1. Data Analysis

Qualitative data analysis was performed to validate the criteria selected from similar studies. This analysis captured community-level perceptions, needs, and practices and highlighted the technical and institutional perspectives influencing RWH management and site suitability. The most effective biophysical criteria were rainfall, soil type, slope, drainage density, land cover, land use, and geology, in addition to socioeconomic criteria represented by distance to roads, settlements, and faults.

### 4.2. Analytical Hierarchy Process (AHP) Weighting Results

Expert judgment helps determine the relative importance of different criteria based on practical experience and contextual knowledge. The pairwise comparison matrix was used to determine the relative weight of each criterion compared to the other criteria, as shown in (Table 2).

#### *4.2.1. Consistency Ratio (CR):*

Checking the consistency of the pairwise comparison matrix is critical to measure the errors of the eigenvalue ($\lambda_{max}$) caused by the incompatibility of the matrix. The consistency index (CI) is expressed as (Equation 1):

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

where $\lambda_{max}$ is the average eigenvalue of the comparison matrix, which is produced by summing the products of each priority value element and the number of columns in the reciprocal matrix (Table 3). $n$ represents the number of criteria used in this study. The corresponding average random consistency index (RI) is found according to [24] the (RI) table. In this case, the six evaluation criteria led to the corresponding Random Consistency Index (RI), which was selected as (1.24). The consistency ratio (CR) was calculated using the Saaty equation (Equation 2), resulting in (0.01). CR $\leq$ 0.1 indicates acceptable consistency as shown in (Table 3) which indicate a strong consistency between the criteria influence the RWH site suitability.

$$CR = \frac{CI}{RI} \tag{2}$$

### 4.3. Comparison criteria weightage with similar studies

The results of the AHP expert judgment for the selected biophysical criteria were compared with the geometric mean weights derived from 12 similar studies conducted under similar environmental and aridity conditions. The comparison results indicated that the expert opinion was closely aligned with the geometric average weights, as shown in (Figure 4). The analysis of expert judgments indicated a convergence with similar studies regarding the weights of slope, rainfall, and drainage density, highlighting their consistent importance across studies of RWH site suitability. However, a divergence was observed in terms of land cover, land use, soil type, and geology, indicating that these factors are particularly relevant to the specific study area. This divergence reflects the unique local significance of these elements, which should be evaluated in relation to site-specific conditions. Furthermore, it has been observed that experts and professionals in Yemen have a high level of confidence in the general geology of the region, which further influences their judgment.

The relative importance of the six criteria is summarized in (Table 4) with their Interpretation influencing the RWH site suitability in terms of run of availability.

 

**Table 2.** Pairwise comparison matrix of the main biophysical criteria (AHP method).

| Criteria | Rainfall | Soil Type | Slope | Drainage Density | LULC | Geology |
|---|---|---|---|---|---|---|
| Rainfall | 1 | 2 2/7 | 2 | 2 | 2 3/4 | 3 |
| Soil Type | 3/7 | 1 | 1 1/9 | 8/9 | 1 2/9 | 1 1/4 |
| Slope | 1/2 | 8/9 | 1 | 1 2/5 | 1 6/7 | 1 3/5 |
| Drainage Density | 1/2 | 1 1/9 | 5/7 | 1 | 1 5/8 | 1 2/3 |
| LULC | 3/8 | 4/5 | 1/2 | 3/5 | 1 | 1 3/8 |
| Geology | 1/3 | 4/5 | 5/8 | 3/5 | 3/4 | 1 |
| Sum | **3.11** | **6.92** | **6.09** | **6.52** | **9.20** | **9.91** |

**Table 3.** Pairwise comparison matrix used to determine the dominant eigenvalue ($\lambda_{max}$).

| Criteria | Rainfall | Soil Type | Slope | Drainage Density | LULC | Geology | vector sum | priority weights % | Division |
|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 0.32 | 0.33 | 0.36 | 0.32 | 0.30 | 0.30 | 1.93 | 31.81 | 6.05 |
| Soil Type | 0.14 | 0.14 | 0.19 | 0.14 | 0.14 | 0.12 | 0.87 | 14.41 | 6.06 |
| Slope | 0.15 | 0.13 | 0.17 | 0.22 | 0.21 | 0.16 | 1.04 | 17.09 | 6.06 |
| Drainage Density | 0.16 | 0.16 | 0.12 | 0.16 | 0.18 | 0.17 | 0.95 | 15.67 | 6.04 |
| LULC | 0.12 | 0.12 | 0.09 | 0.10 | 0.11 | 0.14 | 0.67 | 11.07 | 6.03 |
| Geology | 0.11 | 0.12 | 0.11 | 0.09 | 0.08 | 0.10 | 0.60 | 9.94 | 6.04 |
| CR $\leq$ 0.1 indicates acceptable consistency | | | | Average Dominant Eigenvalue | | | | $\lambda_{max}$ | 6.05 |
| | | | | Number of criteria | | | | $n$ | 6 |
| | | | | Consistency Index (ci) | | | | $ci$ | 0.01 |
| | | | | Random Consistency Index (RI) [24] | | | | $Ri$ | 1.24 |
| | | | | Consistency Ratio | | | | $CR$ | 0.01 |

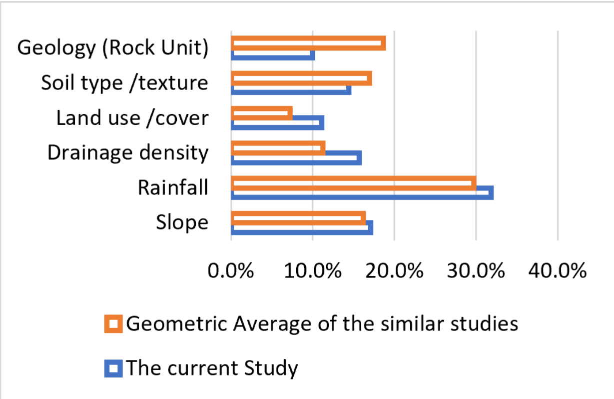


**Figure 4.** Comparison of criteria weights (%) between the current study and similar studies.

**Table 4.** Selected criteria weights (%) with interpretations.

| Criteria | Weight (%) | Interpretation |
|---|---|---|
| Rainfall | 31.8% | Highest determinant of runoff availability |
| Slope | 17.1% | Controls runoff speed and sediment delivery |
| Drainage density | 15.7% | Reflect flow accumulation and runoff concentration |
| Soil type | 14.4% | Governs infiltration and storage potential |
| Land use/cover | 11.1% | Influences runoff, vegetation cover, and human activity |
| Geology | 9.9% | Affects subsurface storage and structural feasibility |
| Total | 100% | |

## 4.4. Citeria's processing and analysis

### 4.4.1. *Rainfall*

The rainfall isohyetal map was classified into five equal-interval classes, as shown in (Figure 5). Areas receiving higher rainfall exhibit greater runoff potential and are therefore more suitable for medium- to large-scale RWH systems. The relatively high weight assigned to rainfall (31.8%) reflects its dominant influence on RWH suitability and aligns with the findings of [25], who identified rainfall as a primary factor affecting harvesting feasibility.

Suitability thresholds were established based on the observed rainfall distribution and were supported by previous studies. Areas receiving more than 558 mm/year were classified as highly suitable (S5), whereas areas receiving less than 369 mm/year were categorized as having low suitability (S1).

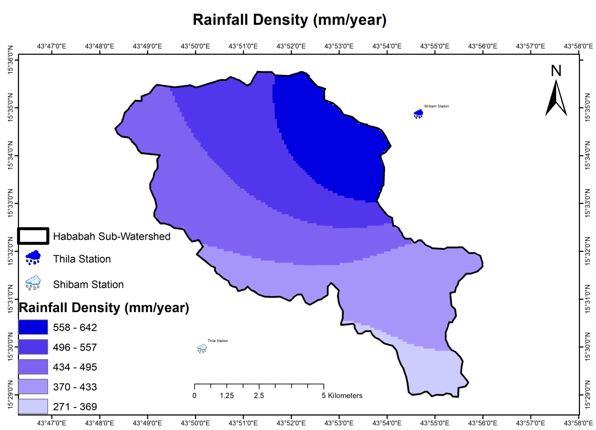


**Figure 5.** Spatial distribution of annual rainfall (mm) in the study area based on NWRA data.

These classifications highlight the critical role of rainfall variability in determining the spatial potential for effective RWH.

#### *4.4.2. Drainage density*

Drainage density analysis revealed that the watershed is dominated by first-order streams, which account for approximately 52.95% of the total stream length (8,954 km), indicating widespread infiltration zones and dispersed-runoff generation. Second-order streams constitute 24.47% (4,138 km), while third-order streams represent 12.33% (2,085 km); both categories offer moderate suitability for small- to medium-scale RWH interventions.

In contrast, higher-order streams, including fourth-order (4.61%, 779 km) and fifth-order (5.64%, 954 km) channels, were assigned higher suitability rankings because of their greater runoff accumulation capacity and enhanced potential to support larger RWH structures (Figure 6). These results suggest that lower-order streams are more appropriate for localized water harvesting and groundwater recharge, whereas higher-order streams represent priority zones for large-scale RWH infrastructure. This differentiation supports a more strategic watershed-level approach to water resource management by aligning intervention types with hydrological characteristics.

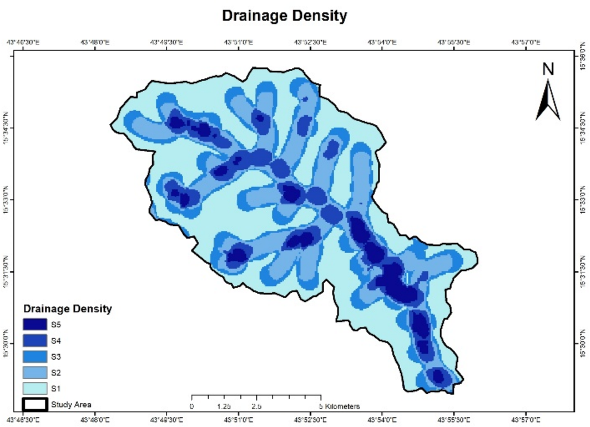


**Figure 6.** Drainage density (km/km$^2$) distribution map of the study area.

#### *4.4.3. Slope Suitability*

The derived slope layer (Figure 7) was classified into five suitability classes based on RWH structural requirements, previous studies, and expert judgment: highly suitable (S5) (0–5%), moderately suitable (S4) (5.1–10%), marginally suitable (S3) (10.1–20%), of low suitability (S2) (20.1–30%), and not suitable (S1) (>30%) [26].

This classification corresponds to the recommended RWH structures, where tanks and ponds are most appropriate for nearly flat terrain, percolation tanks and nala

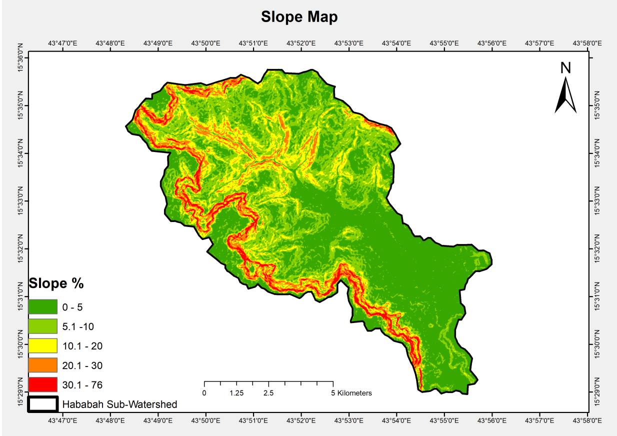


**Figure 7.** Slope map of the study area based on gradient classification (%).

bunds are suitable for moderate slopes, and terracing is recommended for steeper slopes [22].

Spatial analysis indicated that gentle slopes dominated the study area, with 44.19% classified as highly suitable (S5) (0–5%) and 30.08% as moderately suitable (S4) (5.1–10%), demonstrating the strong potential for implementing a wide range of RWH structures. Areas with marginal suitability (S3) (10.1–20%) account for approximately 27% of the area, providing additional opportunities for RWH interventions with appropriate design considerations.

In contrast, areas with slopes between 20.1% and 30% (S2) represent approximately 20% of the study area and are considered less favorable because of increased runoff velocity and erosion risks. Slopes exceeding 30% (S1) constitute approximately 13% of the area and are generally unsuitable for conventional RWH structures without significant engineering changes.

#### *4.4.4. Soil Type*

The dominant soil texture in the study area is sandy clay loam, covering approximately 65.85% ($\sim$54 km$^2$) of the total area, followed by firm sedimentary bedrock/pararock, which accounts for 25.61% ($\sim$21 km$^2$) of the total area. The latter is not classified as a soil texture because of its coarse structure and lack of a defined grain-size distribution. Sandy loam represented the remaining 8.53% ($\sim$7 km$^2$), as illustrated in (Figure 8).

The relationship between soil texture and hydrologic soil groups (HSG) was consistent with the established classifications (Table 5).

The study area is primarily characterized by soil groups B and C, where group B indicates moderate infiltration rates and relatively low runoff potential, and group C reflects slower infiltration rates and higher runoff potential. Owing to the limited variability of soil types across the study area, soil was assigned a relatively lower weight (14.4%) compared to other criteria in the suitability analysis. Nevertheless, its influence remains

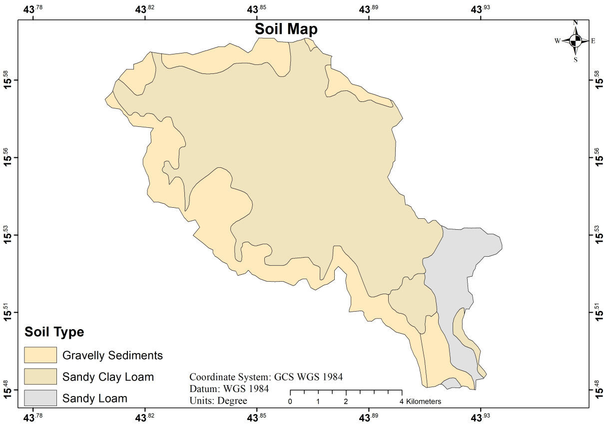


**Figure 8.** Soil type classification map of the study area.

**Table 5.** Hydrologic Soil Group (HSG) classification.

| Soil Group | Texture Class | Description Texture Class |
|---|---|---|
| A | Sand and loamy sand | Lowest overflow possibilities because of high penetration rate |
| B | Sandy loam and loam | Moderately low overflow possibilities and moderate penetration rate |
| C | Silt loam, silt, and sandy clay loam | Moderately high overflow possibilities due to slow infiltration rate |
| D | Clay loam, silt clay, sandy clay, and clay | Highest overflow possibilities with very low infiltration rate |

Source: [27]

important in determining the infiltration capacity and runoff behavior for RWH planning.

### *4.4.5. Land cover/land use (LCLU)*

The land use/land cover (LULC) map (Figure 9) shows that the study area is predominantly characterized by bare land and exposed rock, which accounts for 53.3% of the total area. These surfaces exhibit high runoff potential but low infiltration capacity, making them suitable for surface storage systems, such as ponds and tanks. Croplands, which cover 15.4% of the area, generate moderate runoff; however, harvested water may require treatment due to potential agrochemical contamination. Sparse shrubland represented 24.2% of the study area and contributed relatively little to runoff generation because of the partial vegetation cover. Settlements and rural areas (6.7%) offer opportunities for rooftop rainwater harvesting. The minimal presence of water bodies (0.2%) reflects existing water scarcity and underscores the importance of rainwater harvesting interventions. Although road networks occupy a very small proportion of the area (0.2%), they can enhance runoff collection efficiency if they are properly integrated into drainage and harvesting systems.

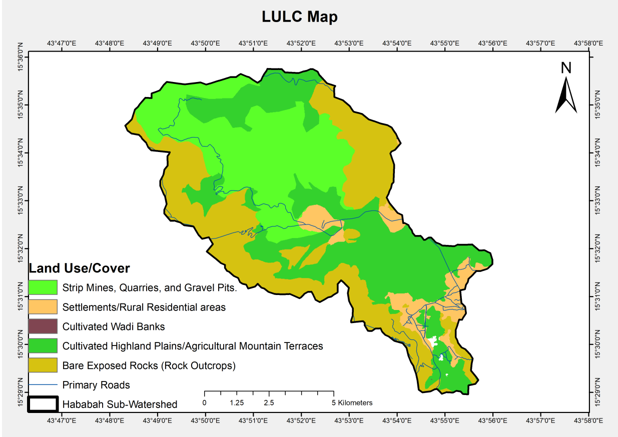


**Figure 9.** Land cover and land use classification of the study area.

### *4.4.6. Geology and Faults*

The geological characteristics of the study area, as illustrated in (Figure 10), were classified based on rock units and the presence of faults. The geological diversity was grouped into three suitability classes and assigned a weight of 9.9%, indicating a moderate yet significant influence on RWH site suitability.

The Tawilah and Amran Groups (S3) exhibited moderate potential, likely influenced by variations in lithology and permeability constraints. In contrast, the Nayfa and Al Hajur Formations (S2) show lower suitability due to geological properties that limit water retention and reduce infiltration efficiency. The least suitable units are represented by ignimbrite and ash flow deposits (S1), primarily due to their poor structural stability and unfavorable hydrological behavior.

These findings highlight the importance of geological conditions in controlling subsurface water movement and storage, thereby influencing the effectiveness and sustainability of RWH interventions.

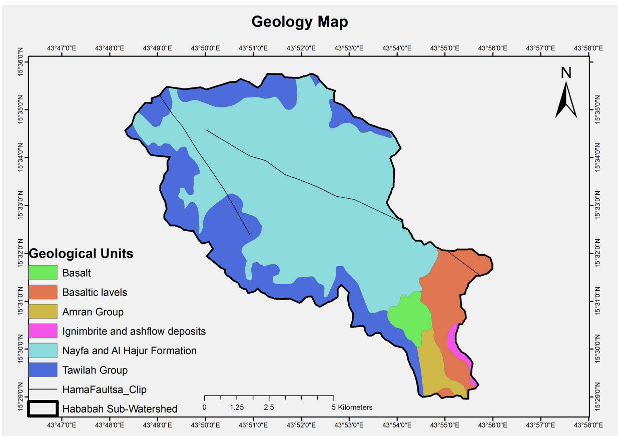


**Figure 10.** Geological units and fault map.

#### 4.4.7. Proximity to Roads

Road buffer zones were defined based on the distance thresholds reported in [23] and adapted to the characteristics of the study area. As illustrated in (Figure 11), approximately 2.28 km$^2$ (2.78%) of the total area was excluded from the suitability analysis, while 79.72 km$^2$ (97.22%) remained suitable for rainwater harvesting (RWH). Buffer zones were generated and spatially integrated into the analysis using raster-based processing, followed by the reclassification of all thematic layers. Areas located within 0–75 m on both sides of roads were classified as unsuitable to account for potential future land use expansion and to minimize environmental impacts associated with RWH implementation.

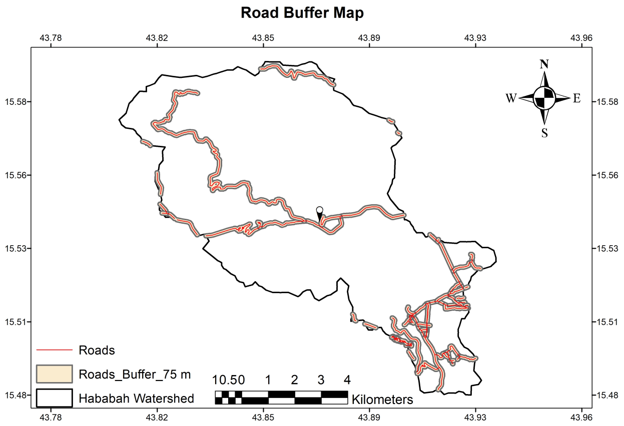


**Figure 11.** Roads with a 75 m buffer zones.

#### 4.4.8. Proximity to settlement

A 250 m buffer zone around settlements was established based on the recommended distance reported in [10] and adapted to the characteristics of this study area. As illustrated in (Figure 12), settlement areas and their associated buffer zones cover approximately 21 km$^2$ (25.5%) of the total study area, whereas the remaining 61 km$^2$ (74.5%) is available for suitability analysis. Settlement areas were designated as exclusion zones on the land use/land cover (LULC) map. The buffer zones were subsequently integrated into the analysis using raster-based processing, followed by the reclassification of all the thematic layers.

Areas located within 0–250 m of settlements were classified as unsuitable for rainwater harvesting (RWH) systems to minimize potential conflicts with human activities and to ensure environmental and public safety.

#### 4.4.9. Surface Runoff

Surface runoff is a critical parameter for assessing rainwater harvesting (RWH) potential. However, its explicit estimation using methods such as the Rational Method, the SCS–Curve Number (CN) approach, or other hydrological modeling tools was beyond the scope of this study.

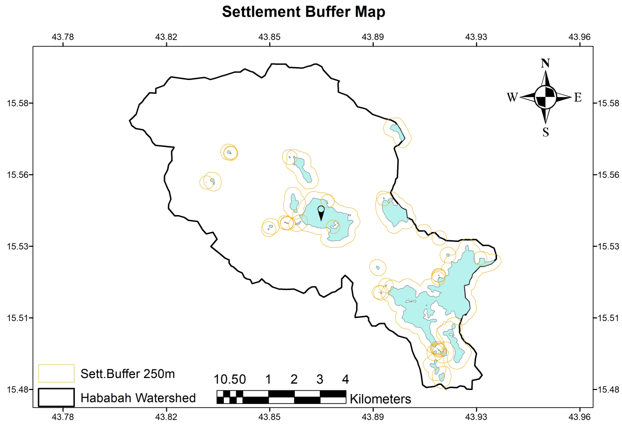


**Figure 12.** Settlements with a 250 m buffer zone.

Such approaches could further enhance the accuracy of site suitability assessments but require detailed hydrological data and field-based calibrations. Instead, runoff-related conditions were represented indirectly through key influencing factors, including rainfall, drainage density, land use/land cover (LULC), and soil type, which were assigned weights of 31.8%, 16%, 11%, and 14%, respectively. These variables are widely recognized as the primary determinants of runoff generation and accumulation within a sub-watershed.

Given the study's focus on site suitability assessment using available spatial datasets within a GIS-MCDA framework, the use of these surrogate indicators was considered appropriate. Moreover, to avoid redundancy among interrelated hydrological variables, the selected criteria were deemed sufficient to represent the runoff potential within the study area.

#### 4.4.10. Overlay Analysis and Suitability Map Generation

The final RWH suitability analysis model revealed spatial variability in site potential across the study area (Figure 13). Approximately 7.6% (6.24 km$^2$) of the sub-watershed was classified as very highly suitable, representing priority zones characterized by optimal biophysical and socioeconomic conditions for RWH implementation. An additional 23% (18.9 km$^2$) was identified as highly suitable, indicating strong potential for effective RWH system development with minimal technical constraints. A large portion of the watershed (22%; 18.8 km$^2$) was categorized as moderately suitable, suggesting that RWH interventions remain feasible but may require adaptive design or supplementary management measures. Areas classified as low suitability accounted for 14% (11.5 km$^2$), where limiting factors such as unfavorable slope, geology, or accessibility reduce RWH efficiency. As shown in (Table 6), 33.4% (27.44 km$^2$) of the watershed was identified as not suitable/excluded, primarily due to hydrological, geological, or infrastructural constraints that significantly hinder RWH implementation.

These findings highlight that although a substantial proportion of the watershed demonstrates favorable conditions for RWH development, targeted planning and structure selection are necessary to maximize water harvesting efficiency and ensure sustainable resource management.

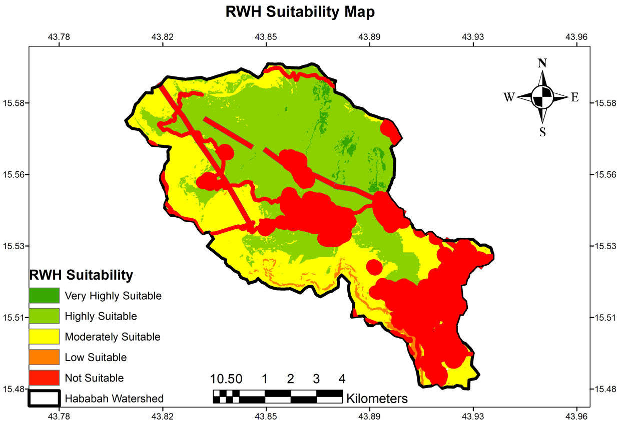


**Figure 13.** Rainwater harvesting (RWH) suitability map.

**Table 6.** Rainwater harvesting (RWH) site suitability map.

| Suitability Class | Area (km$^2$) | Percentage% |
|---|---|---|
| Very Highly Suitable | 6.24 | 7.6 |
| Highly Suitable | 18.90 | 23.0 |
| Moderately Suitable | 18.08 | 22.0 |
| Low Suitable | 11.50 | 14.0 |
| Not Suitable | 27.44 | 33.4 |

#### *4.4.11. Model Validation for existing RWH Systems suitability*

The locations of the suitability levels obtained by the model were compared with the locations of the existing RWH systems, as shown in (Figure 14).

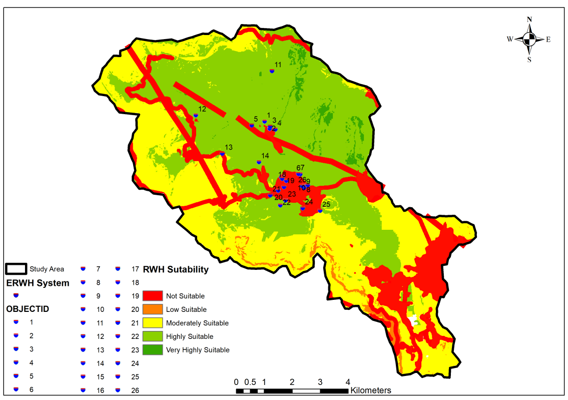


**Figure 14.** Validation of existing rainwater harvesting (ERWH) suitability.

Field validation results reveals both convergence and notable discrepancies in the evaluation of existing rainwater harvesting (RWH) systems (Table 8) and (Figure 15). The model classified (46.2%) of the systems as highly suitable, closely aligning with the field validation result of (42.3%), indicating a generally acceptable predictive performance in identifying optimal locations. However, the model failed to identify any systems within the moderately suitable category (0.0%), whereas field observations recognized (11.5%) of systems as moderately suitable. This discrepancy suggests that the model may oversimplify real-world conditions by imposing rigid classification thresholds, thereby under-representing transitional suitability zones. Furthermore, while the model categorized a majority (53.8%) of systems as unsuitable, field validation showed a slightly lower proportion (46.2%), implying that some sites deemed unsuitable by the model may still function under practical conditions owing to their location within settlement area boundaries, mainly due to land use development that has occurred in recent years, in close proximity to road networks, or are significantly affected by pollution from solid waste or sewage. Overall, these differences highlight the limitations of the model's sensitivity to on-the-ground complexities and emphasize the need to refine the criteria weighting, improve the data resolution, and integrate local knowledge.

The findings underscore that while GIS-MCDA models are valuable decision-support tools, their outputs should be interpreted with caution and complemented by field verification to ensure contextually appropriate and sustainable RWH site selections. The buffer threshold applied to the road network, set at 75 m on each side [23], was found to be excessive for mountainous environments such as those in Yemen. Field validation results indicate that future research and practical applications should consider reducing this buffer distance to approximately one-third (25 m) to enhance the reality and applicability of the suitability model for future studies and resource management. Furthermore, this study supports the exploration of road rainwater harvesting (RRWH) potential for agricultural use [28]. Roads can act as effective catchment surfaces that contribute to water collection and redistribution. According to [28], road networks represent a viable source for rainwater harvesting and can be utilized for both groundwater recharge and irrigation purposes. Similarly, the buffer threshold applied to residential areas, set at 250 m [10, 29], was also identified as overly conservative for mountainous terrain conditions such as those in Yemen. Although a distance of 250 m is generally considered sufficient to mitigate the potential socio-environmental impacts of constructed RWH systems and to avoid interference with future urban development, field validation findings suggest that this threshold may be unnecessarily restrictive in the study context. Therefore, it is recommended that future analyses consider reducing this buffer distance to

**Table 8.** Validation of existing rainwater harvesting (ERWH).

| ERWH ID | RWH Name | Model Suitability | Field Validation | Model Validity |
|---|---|---|---|---|
| 1 | Alrawnatin Tank | Highly Suitable | Highly Suitable | Yes |
| 2 | Alrawnah Alsofla Pond | Highly Suitable | Highly Suitable | Yes |
| 3 | Alrawnah Alalia careef | Highly Suitable | Highly Suitable | Yes |
| 4 | Alaridhah careef | Highly Suitable | Highly Suitable | Yes |
| 5 | Alrawnah Dam | Not Suitable | Not Suitable | Yes |
| 6 | Alsafa Alsifla Pond | Highly Suitable | Highly Suitable | Yes |
| 7 | Alsafa Alalia Pond | Highly Suitable | Highly Suitable | Yes |
| 8 | AlHajar Pond | Not Suitable | Not Suitable | Yes |
| 9 | Aldihdahi Pond | Not Suitable | Not Suitable | Yes |
| 10 | Mahdi Pond | Not Suitable | Not Suitable | Yes |
| 11 | Alw Wadi Ashim Pond | Highly Suitable | Highly Suitable | Yes |
| 12 | Bait Hibah Majil | Highly Suitable | Highly Suitable | Yes |
| 13 | Watar vilage dam | Not Suitable | Moderately Suitable | No |
| 14 | Mazin Alsadi Pond | Highly Suitable | Highly Suitable | Yes |
| 15 | Ain Shibar Alsifla Pond | Not Suitable | Not Suitable | Yes |
| 16 | Ain Shibar Alalia Pond | Not Suitable | Not Suitable | Yes |
| 17 | Ain Shibar Pond | Not Suitable | Not Suitable | Yes |
| 18 | Aljern Kareef | Not Suitable | Not Suitable | Yes |
| 19 | Alsafawi Pond | Not Suitable | Not Suitable | Yes |
| 20 | Alqasr Mosque Pond | Not Suitable | Not Suitable | Yes |
| 21 | Sawran Pond | Not Suitable | Moderately Suitable | No |
| 22 | Asaqieef Pond | Highly Suitable | Highly Suitable | Yes |
| 23 | Ain Omer Pond | Highly Suitable | Moderately Suitable | No |
| 24 | Aladhlaa Pond | Highly Suitable | Highly Suitable | Yes |
| 25 | AlHarawah Pond | Not Suitable | Not Suitable | Yes |
| 26 | AlDa'alai Spring | Not Suitable | Not Suitable | Yes |

improve the accuracy and practicality of the suitability models.

In addition, this study supports the investigation of rooftop rainwater harvesting (RTWH) as a viable option for domestic water supply [1]. Rooftops in residential areas can serve as effective catchment surfaces for collecting rainwater. According to [30], rooftop rainwater harvesting is a potential and safe source of water for domestic use, provided that appropriate hygiene and water quality-control measures are implemented. This adjustment contributes to a more realistic and applicable suitability model for future studies and planning.

## 5. CONCLUSION AND RECOMMENDATIONS

This study successfully identified suitable sites for rainwater harvesting (RWH) in the Hababah Sub-Watershed, Amran Governorate, Yemen using an integrated GIS-AHP-based MCDA approach. The results revealed that rainfall distribution plays a critical role, with the northeastern parts of the sub-watershed exhibiting the highest suitability owing to relatively higher precipitation, whereas the western and southern regions showed limited potential. Topographic analysis indicated that areas with gentle slopes (less than 10%), covering approximately 34% of the watershed, are highly favorable for RWH development, whereas steeper slopes are constrained by runoff instability and erosion risks. Soil characteristics further influenced site suitability, as loam and sandy clay loam soils in the central areas demonstrated good infiltration capacity, supporting both surface and subsurface harvesting systems. In contrast, rocky and shallow soils were found to be unsuitable for most RWH applications. Land use and geological conditions also played a significant role, with agricultural and barren lands offering high runoff potential, alluvial deposits supporting groundwater recharge, and basaltic formations being less suitable. Additionally, proximity to roads and settlements enhances the practicality and socio-economic benefits of implementing RWH structures.

The spatial suitability analysis showed that approximately 30.6% of the watershed fell within the highly to very highly suitable categories, highlighting the strong potential for RWH development, while a considerable portion remained unsuitable owing to limiting environmental conditions. Overall, this study demonstrates that integrating biophysical and socioeconomic criteria using GIS and AHP-based MCDA provides a robust, cost-effective, and replicable framework for sustainable water resource planning. This approach is particularly valuable for arid and semi-arid regions such as Yemen, where data scarcity and water stress necessitate efficient decision-support tools. Furthermore, this study represents the first comprehensive RWH suitability assessment for the Hababah Sub-Watershed and offers a scalable methodology that can be applied to other sub-watersheds across the country.

In conclusion, this study delineated the most promising zones for rainwater harvesting in the Hababah Sub-Watershed and established a scientifically grounded decision-support framework that bridges data limitations and practical planning needs. By integrating hydrological, topographic, and socioeconomic factors, this approach enhances the precision of site selection while reducing


**Figure 15.** Field Validation of existing rainwater harvesting (ERWH) suitability.

uncertainty and cost. Although further field verification is essential prior to implementation, the findings provide a strategic foundation for policymakers, planners, and development agencies to prioritize interventions. Ultimately, this study contributes to advancing sustainable water resource management in Yemen and offers a scalable model capable of supporting climate-resilient water security strategies in other arid and semi-arid regions.

Based on the study findings, the following recommendations are proposed to enhance the suitability of rainwater harvesting (RWH) systems in the Hababah Sub-Watershed and similar environments in Yemen:

- Priority should be given to the development of RWH systems within highly suitable zones, particularly in the northeastern parts of the watershed, through the construction of medium- and large-scale structures, such as check dams, farm ponds, rainwater harvesting tanks, and small earth dams. In moderately suitable areas, the adoption of small-scale techniques, including contour bunds, infiltration trenches, and micro-catchments is recommended to maximize local water retention and utilization.
- Rainwater harvesting interventions should be avoided in areas identified as having low or unsuitable potential owing to steep slopes, limited rainfall, rocky terrain, and high erosion susceptibility. Integrating RWH into watershed management plans is essential to strengthen local water security, reduce dependence on groundwater resources, and support sustainable water resource management.
- The active participation of local communities in site verification, construction, operation, and maintenance processes is recommended to enhance ownership and ensure the long-term sustainability of RWH systems. The GIS–AHP-based MCDA framework developed in this study should be adopted as a planning tool for assessing RWH suitability in other watersheds across Yemen.
- Greater investment in affordable and locally manage-

able RWH technologies is encouraged, particularly among smallholder farmers. In addition, the periodic monitoring and performance evaluation of existing RWH structures should be undertaken to improve system efficiency, identify design limitations, and inform future interventions.

- At the policy level, developing national guidelines and standards for the siting, design, implementation, and monitoring of RWH systems is recommended to ensure their sustainability. Strengthening meteorological and hydrological data collection, particularly rainfall, soil, and topographic datasets, will further improve the accuracy and reliability of suitability assessments.
- Future research should focus on integrating hydrological modeling tools, such as SWAT, HEC-HMS, and WEPP, with GIS–MCDA approaches, while incorporating additional criteria, including evapotranspiration, runoff dynamics, drainage density, and socioeconomic indicators. The use of high-resolution spatial datasets and long-term impact assessments is also recommended to better evaluate the contributions of RWH systems to groundwater recharge, agricultural productivity, climate resilience, and integrated water resource management.

## LIMITATIONS OF THE RESEARCH

This study has several limitations that should be acknowledged:

- Surface runoff was not explicitly modeled; instead, it was indirectly represented through selected hydrological criteria. Incorporating detailed runoff modeling could improve the accuracy of the suitability assessment and will be addressed in future research as a follow-up to this study.
- A degree of divergence was observed in the weighting of land cover, land use, soil type, and geology when compared with similar studies. This variation indicates that these factors are highly context-specific and particularly relevant to the characteristics of the study area's population. While this reflects their local significance, it also highlights the need for further verification and field-based validation to ensure their appropriateness for rainwater harvesting (RWH) site selection in the region.
- It must be emphasized that this study should not be used for selecting the RWH sites without conducting detailed on-site geotechnical investigations and environment impact assessment at the suggested locations. Nevertheless, by eliminating sites with serious constraints, the study identified sites that appear more suitable, where additional exploration should be conducted for the design and construction of the RWH system.

## ETHICS STATEMENT

This study used open, non-sensitive data, publicly available data, satellite imagery, and secondary geospatial datasets and did not involve human or animal subjects or identifiable personal data.

Ethics approval: Not applicable.

## CREDIT AUTHOR CONTRIBUTIONS

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Data curation: Khalid Allaith.

Formal analysis: Khalid Allaith. Investigation (field/context): Khalid Allaith.

Software (GIS/remote sensing): Khalid Allaith.

Visualization: Khalid Allaith.

Writing–original draft: Khalid Allaith

Writing–review & editing: Ahmed M. Al-Wadaey, Fadhl A. Al-Nozaily & Musaed Aklan

## CONFLICT OF INTEREST

The authors declare no conflicts of interest in relation to the publication of this study. All co-authors have approved the manuscript and concur with its submission to the journal.

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