

A GIS-based multi-criteria framework for rainwater harvesting site selection in data-scarce semi-arid regions: Application to the Tafрата plain (Morocco)

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ABSTRACT

This study aims to identify the most suitable locations for rainwater harvesting (RWH) in the Tafрата plain, a semi-arid region of northeastern Morocco, to support sustainable agricultural development and optimize water resource management. Recognizing the pressing challenges of water scarcity and uneven rainfall distribution, the research adopts a comprehensive spatial multi-criteria decision-making approach, integrating the analytic hierarchy process (AHP) with geographic information systems (GIS) to systematically evaluate key environmental and socio-economic factors influencing site suitability. The study combines expert knowledge, field observations, and a thorough review of recent literature to select six primary criteria – rainfall, slope, soil type, drainage density, land use/land cover, and distance to roads – and assigns weights to each based on their relative hydrological and operational significance. High-resolution spatial datasets, including digital elevation models (DEM), rainfall records, soil surveys, and remote-sensing-derived land use data, were processed and analyzed in ArcGIS to generate reclassified thematic maps, which were subsequently integrated using the weighted linear combination (WLC) method. The analysis reveals that moderately suitable zones dominate the study area, covering approximately 80.7% of the total surface, while highly suitable and very highly suitable zones represent 9.3% and 4.9%, respectively. Validation of the model against existing in-field water harvesting structures demonstrates that 99% of operational installations coincide with areas classified as very suitable, confirming the accuracy and reliability of the proposed methodology. Despite limitations related to data resolution and the inherent variability of semi-arid climatic conditions, the results provide a scientifically robust and transferable framework capable of guiding medium- and long-term agricultural and water resource planning. The approach allows for informed prioritization of RWH interventions, minimizes risks associated with site selection, and enhances the potential for sustainable agricultural productivity in water-scarce environments. The originality of this study lies in its integrated application of AHP-GIS techniques tailored to semi-arid plains, offering a replicable model for similar regions facing hydrological constraints, and demonstrating a practical balance between scientific rigor and actionable planning.

Keywords: rainwater harvesting, geographic information system, multi-criteria decision-making approach, Tafрата plain, remote sensing.

INTRODUCTION

Multiple factors, including climate change, demographic growth, urban expansion, water-demanding agriculture, and industrial activities, are placing considerable stress on global water resources (Hassan et al., 2025). Many of the world's

populations suffer from malnutrition, especially in semi-arid regions where agriculture is the main source of livelihood for about 70% of the population (Rockström and Falkenmark, 2015). In addition to the issues of desertification and erosion, Water limitations weaken agricultural stability in arid regions (Preeti and Rahman, 2021). and

future climate changes will further exacerbate these issues. However, different regions of the world will not be affected to the same degree, as developed countries have human, financial, and technical resources that enable them to adapt to the phenomenon of climate warming, while developing countries will be more sensitive to climatic variability. Thus, it is expected that higher temperatures, different wind speeds, drier soils, and lower precipitation will lead to a decrease in the productivity and yield of agricultural land. Rising humidity, coupled with significant precipitation and severe flooding, will lead to loss of crops due to erosion and reduced soil fertility in many parts of the world.

Freshwater is a critical natural resource essential for life on Earth, yet only about 1% of the planet's total 2.5% freshwater is accessible for human use (Xing and Wang, 2024). Currently, the rising shortage of water represents a key barrier to sustainable development (Biswas et al., 2025). Growing population pressure and the growth of modern farming have substantially raised water demand, particularly in regions where surface water availability remains limited. Moreover, the impacts of climate change have further intensified water scarcity by reducing the reliability and supply of surface water resources. So, limited water availability poses a significant challenge, particularly in dry and semi-dry regions. Among the possible measures, implementing water harvesting technologies is crucial for collecting and storing rainwater to mitigate water scarcity. Nonetheless, rely heavily on their proper placement (Patel and Chaudhari, 2023). especially in a country with a Mediterranean and desert climate like Morocco, where Rainfall is weak and irregular, due to inadequate management, a large amount of water is lost to the desert or the sea, often leading to flooding in the lower basins.

Rainwater harvesting is a commonly employed technique for the storage of rainwater in countries experiencing drought conditions (Ibrahim et al., 2019). Consequently, understanding watershed features plays a key role in managing this vital resource effectively through the use of GIS and remote sensing tools, which are important tools for this purpose, by contributing to the systematic analysis of the various factors controlling the efficient and sustainable management of water resources (Lasage and Verburg, 2015). In semi-arid regions, water harvesting is widely adopted to increase the availability of water for

household and farming uses. Additionally, this technology contributes to both agricultural productivity and the management of soil and water resources (Sun et al., 2023).

The selection of appropriate locations for RWH is a complex process that considers multiple objectives and criteria, considering the physical, socio-economic, and environmental attributes of the target site (Nyirenda et al., 2021). Methods for identifying suitable RWH locations differ depending on the area and utilize tools such as GIS, RS, and digital mapping. Globally, many nations have adopted diverse solutions, including Rainwater Harvesting, to guarantee water supply for household, farming, and industrial needs (Aghad et al., 2021). RWH represents a proven and eco-friendly practice that captures and retains rainfall from sources such as rooftops or natural catchments (Al-Hasani et al., 2025). Rainwater harvesting provides relatively clean water for aquifer recharge, helping dilute contaminants and enhance groundwater quality (Gebreslassie et al., 2025). Moreover, Rainwater harvesting is an encouraging tool to augment surface and groundwater to alleviate the imbalance between water demand and supply, especially since the demand for water resources is increasing every year. Alternative water sources, such as rainwater captured via RWH and desalinated seawater, need to be retained for emergency use and to support socio-economic growth (Seif et al., 2024).

Water resource management in Morocco now represents a critical issue. The growing pressure on water resources reflects a complex interplay between climate variability, intensified agricultural modernization, and governance challenges, positioning water management as a pivotal concern in national development strategies (Boutagayout et al., 2025). Water has been identified as a fundamental priority within Morocco's national strategy for sustainable development. In addition to climate change, irrigation accounts for 90% of the country's water consumption (Fikri et al., 2024). Research indicates that arid and semi-arid areas in Morocco need to establish updated strategies to cope with the impacts of climate change (Kahil et al., 2015). Selecting optimal rainwater harvesting locations in countries at risk of water scarcity plays a vital role in securing water resources (Moumane et al., 2024). In Morocco, which suffers from acute water shortages, rainwater harvesting stands out

as one of the most effective methods for conserving water (Bourass et al., 2025). Despite the extensive research on water scarcity and rainwater harvesting in Morocco, significant knowledge gaps remain. Previous studies often focus on isolated sites and specific technologies, leaving broader regions, such as the area addressed in this study, relatively under-investigated in scientific literature. This study proposes a GIS-based approach to help water managers pinpoint optimal sites for rainwater harvesting the issue of water shortage is expected to affect important areas of Morocco, which is currently experiencing significant Water scarcity.

In the Moroccan Moulouya Basin, irrigated agriculture represents the main farming system. However, arid conditions and climate variability create serious difficulties, particularly for farmers who depend on rainfed agriculture (Amiri et al., 2025). Water resources are the main pillar on which agricultural exploitation is based in our studied area, especially since the latter is mostly irrigated, so they have become closely linked to water resources, which are affected by climatic changes that have intensified in recent decades. This is due to several factors, including Natural and human factors that make water resources more vulnerable to depletion due to increased pressure on them through agricultural intensification and agricultural expansion, which have sharply depleted groundwater. Since water is the most important driving factor for agricultural dynamism in the Tafrata plain, achieving the desired local development depends on mobilizing this vital resource to invest it in the agricultural sector within the framework of sustainable development based on good governance of natural resources. Leveraging available water resources allows for irrigation throughout the growing season and offers supplementary irrigation to mitigate losses in crop yield (Alene et al., 2022).

In the semi-arid landscape of the Tafrata Plain, northeastern Morocco, recurrent drought cycles and escalating climatic volatility have necessitated a strategic shift toward proactive water resource management. Given the significant scarcity of surface water, (RWH) emerges as a highly viable solution to bolster agricultural productivity and ensure long-term water security. However, identifying optimal collection sites presents a multifaceted challenge for planners, primarily due to fragmented spatial data, infrastructure

limitations, and complex environmental variables (Singhai et al., 2019). In tackling this issue, the research introduces a robust spatial optimization approach by effectively integrating GIS with MCDA techniques. This approach systematically evaluates six key parameters – rainfall patterns, topographic slope, soil characteristics, drainage density, land cover, and road network proximity – to provide a reliable and scientifically rigorous tool for prioritized RWH site selection in data-constrained, arid environments.

Despite the extensive research on water scarcity and rainwater harvesting in Morocco, significant knowledge gaps remain regarding the spatial prioritization of suitable harvesting sites under conditions of limited data availability and increasing irrigation demand. Previous studies have often focused on specific techniques or localized case studies, without integrating multiple environmental and hydrological criteria into a comprehensive, decision-support framework applicable to semi-arid agricultural systems. In particular, the Tafrata Plain remains insufficiently investigated in terms of its spatial potential for rainwater harvesting, despite its growing dependence on groundwater and increasing vulnerability to climatic variability

Furthermore, the lack of integrated approaches that combine geospatial analysis with multi-criteria evaluation limits the capacity to optimize rainwater harvesting site selection and improve the efficiency of water resource management under challenging environmental conditions. Addressing this gap is essential for improving water resource management and supporting sustainable irrigation practices in data-scarce semi-arid regions.

Therefore, this research aims to design and implement and apply a GIS-based multi-criteria framework for the spatial prioritization of rainwater harvesting sites in the Tafrata Plain (Morocco). The study seeks to (i) integrate key environmental and topographic factors influencing water harvesting suitability, (ii) generate a spatial suitability map for potential harvesting sites, and (iii) provide a decision-support tool to enhance water resource management under conditions of increasing water scarcity. It is hypothesized that the integration of multiple criteria within a GIS environment enables more accurate and operational identification of priority zones for harvesting rainwater compared to conventional single-factor approaches.

MATERIALS AND METHODS

In arid and semi-arid zones, the scarcity of water poses a significant challenge, highlighting the importance of efficient water management to sustain agricultural output. Among the various strategies in response to this issue, the implementation of rainwater harvesting (RWH) has emerged as a sustainable solution, capturing and storing precipitation for agricultural irrigation. Many researchers have proposed different criteria and methodologies to identify suitable dams and RWH sites (El Ghazali et al., 2021).

This study employs a combined (GIS) and analytical hierarchy process (AHP) approach to identify suitable sites for harvesting rainwater in the Tafrata Plain. AHP, one of the most widely used multi-criteria decision analysis (MCDA) methods in water management (Prieto-Jiménez et al., 2024), facilitates the systematic weighting and prioritization of multiple physical, environmental, and socio-economic factors. Moreover, AHP has been widely integrated with GIS to support spatial decision-making (Githinji et al., 2022), with GIS providing a robust framework to integrate, visualize, and analyze these factors across the landscape.

Study area

The study area is located within the Central Moulouya Basin, located in the central-eastern region of Morocco, spanning approximately 1.650 km² between 34°20' and 34°50' N latitude and 3°20' and 2°50' W longitude. The basin extends from west to northeast, bordered by the High Plateaus, the Middle Atlas, and the eastern Rif, and is fed by tributaries descending from the High Atlas. The Tafrata plain, situated on the right bank of the Moulouya River between Guerçif and Oued Za, is bounded to the south by the Debdou Massif and Sidi Lahcen Mountains, to the southwest by the Maârouf plain, and to the north by the Moulouya River (Figure 1).

Geologically, the study area lies between the Guercif Basin to the north-northwest and the Debdou Mountains to the south-southeast (Seghir et al., 2019). The region has a semi-arid climate, with recorded summer temperatures reaching up to 48 °C and winter temperatures around 7 °C. Long-term precipitation averages 310 mm/year in the Debdou Massif and 241 mm/year in the Tafrata Plain, based on meteorological data from the Taourirt, Guercif, and Debdou stations for the period 2000–2021. Frequent droughts and higher

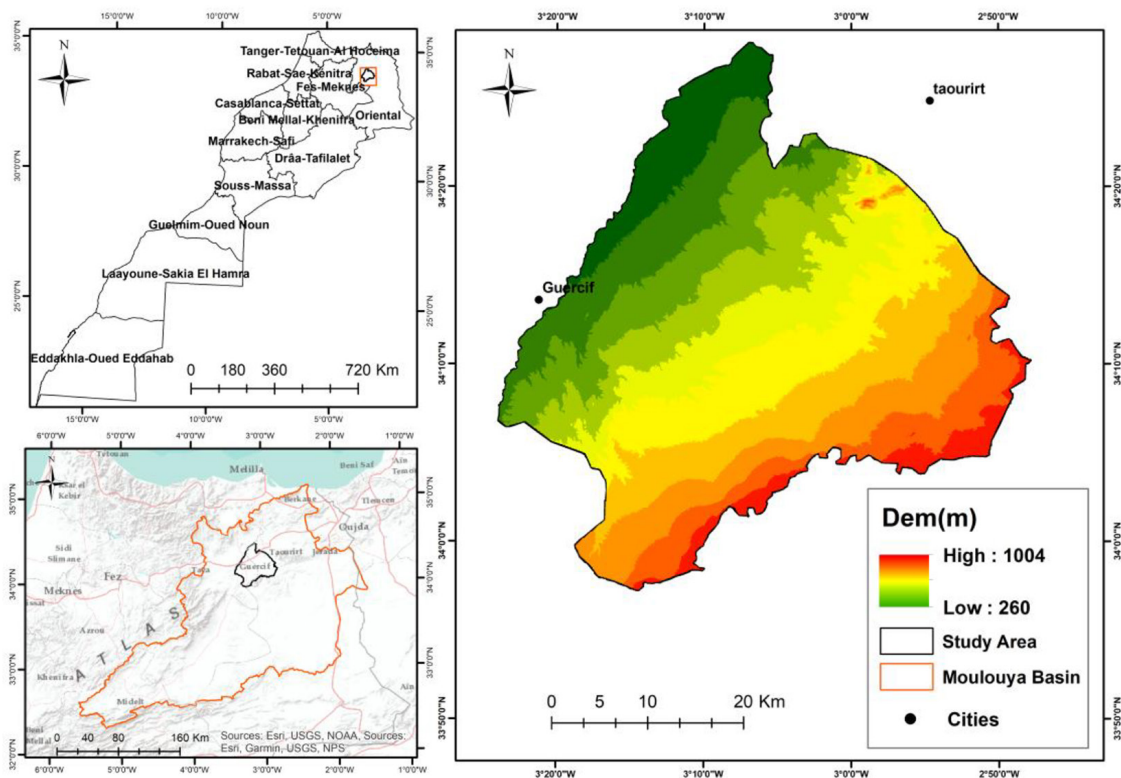


Figure 1. Geographical position of the Tafrata plain in northeastern Morocco

temperatures have increased the need for surface water and contributed to the overexploitation of groundwater, particularly for irrigated agriculture (Mustapha et al., 2026; Bouguelba, 2024). The study area has undergone substantial agricultural development, particularly for olive cultivation, increasing water management challenges. These climatic and anthropogenic pressures highlight the critical necessity of implementing sustainable approaches for water resource management.

Data collection and analysis

A multi-source database supported the assessment of potential sites for identifying suitable rainwater harvesting locations in the Tafrata Plain. Topographic parameters, including slope and drainage density, were derived from a 30-m resolution digital elevation model (DEM), providing essential information on surface runoff patterns and storage potential. Meanwhile, long-term rainfall data from the Taourirt, Guercif, and Debdou meteorological stations (2000–2021) offered critical insight into water availability and temporal precipitation variability. Land use and land cover were derived from high-resolution satellite imagery. LULC patterns provide insight into the surface. Distance to roads was incorporated as an accessibility criterion, ensuring that potential harvesting sites are practically reachable for construction, maintenance, and management activities. Using ArcGIS, the soil map for the Tafrata plain was extracted from the Harmonized World Soil Database provided by FAO, providing essential insights into permeability and water retention capacity. Together, these datasets form the foundation for evaluating the suitability of locations for rainwater harvesting structures, before integration into the decision-making model. This rigorous preprocessing pipeline was essential to mitigate discrepancies between multi-source

datasets and to establish a robust, spatially consistent foundation for the subsequent AHP-GIS analysis (Table 1) (Figure 2).

Selection of the criteria for targeting RWHS

Many researchers have developed or refined various MCDA methods over the past few decades, including the Analytic Hierarchy Process (AHP) and several others (Ahmed et al., 2023). Researchers selected a set of criteria affecting the study of the spatial suitability of water dams, reviewing previous studies and incorporating expert opinions. Researchers identified six major factors, widely used to select potentially suitable surface water areas, as identified by the United Nations’ Food and Agriculture Organization (FAO). These factors include climatic data, hydrological conditions, terrain, agricultural activities, soil, and socio-economic data (FAO, 2003; Kahinda et al., 2008). In the 1990s, research largely concentrated on biophysical criteria, including rainfall patterns, terrain slope, soil characteristics, sanitation, and land use. We mention as examples (Oweis et al., 1998, Padmavathy et al., 1993), Approaches have evolved from relying solely on biophysical indicators to more comprehensive methods that also consider socio-economic criteria, especially following the year 2000. The selection of suitable water harvesting sites primarily depends on slope, land use/cover, soil characteristics, precipitation levels, and proximity to settlements (Patel and Chaudhari, 2023). Across the literature, biophysical factors most often considered were slope (83%), land use/cover (75%), soil type (75%), and rainfall (56%). Socioeconomic considerations frequently included distance from cities (25%), water bodies (15%), roads (15%), and associated costs (8%) (Githinji et al., 2022).

In selecting criteria for the present study, this research is based on a comprehensive review of

Table 1. Data sources and databases employed for research

Data	Description	Source
Randall	Climate data Taourirt, Guercif, Mrija stations (2000–2021)	Moulouya Water Basin Agency (MWBA)
Slope	Download (DEM, 30-m resolution, 2024)	https://earthexplorer.usgs.gov/
Soil type	FAO Soil data	https://www.fao.org/
Drainage density	DEM, 30-m resolution (2024)	https://earthexplorer.usgs.gov/
LULC	Satellite imagery, Landsat 8 OLI/TIRS, 2024	https://earthexplorer.usgs.gov/
Distance to roads	The Euclidean distance tool was used to measure proximity to road networks) ArcGIS (2024)	Ministry of Equipment and Water (Shapefile 2024)

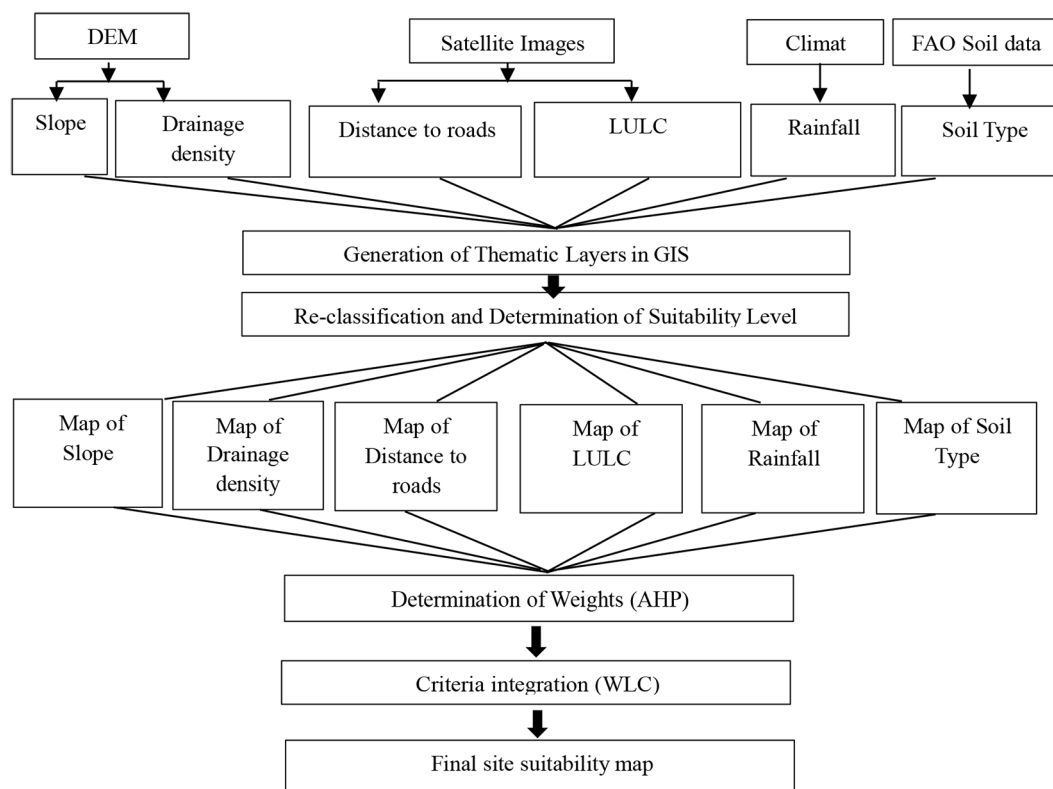


Figure 2. Flowchart illustrating the methodology applied to identify potential RWH sites

the latest literature concerning RWH in arid zones (Silva et al., 2025). This study focuses on current approaches for identifying suitable areas for rainwater harvesting (RWH) in arid regions. A total of 37 articles published between 2020 and 2025 were analysed. Among multi-criteria evaluation methods, AHP was the most frequently employed, followed by the FAHP and WLC approaches within multi-criteria decision analysis. The study by Tasiwuka, Silungwe, and Mbilinyi (2025) is among the most important in this field, aiming to aim to evaluate data sources, factor weights, and classification measures as an effective tool designed to determine optimal sites for on-farm rainwater storage structures. It was based on a systematic review of over 400 publications, from which 50 studies were carefully selected according to strict criteria related to factor identification, data sources, weights, and classification measures. The findings indicated that rainfall is the most influential factor, followed by slope, soil texture, and LULC, with variations depending on local site characteristics. The assigned weights ranged from 30–60% for rainfall, 10–38% for slope, 7–32% for soil texture, and 5–25% LULC, reflecting the relative importance of each factor. Additionally, the 1-to-5 classification scale was identified as the most suitable, offering a

balance between analytical precision and interpretability, thereby ensuring a robust, context-sensitive framework for site suitability assessment implementation, as shown in research by (Tasiwuka et al. 2025, Ahmad et al., 2024; Du et al., 2024, and Syarifuddin et al., 2024).

The Spatial analysis begins with identifying, collecting, storing, and organizing the data (variables), and then preparing them as layers (Couches). that form the cornerstone of the application of the process, these variables are the basis for the Spatial analysis to the topic, mainly related to determining the statistical characteristics of each variable, ensuring that the variables are consistent with the components of the field of study and their validity and suitability for addressing the issue, and the extent to which these variables are compatible with the statistical tools used. Incorporating AHP into ArcGIS – a leading GIS software worldwide – typically involves several steps: setting the study goal and selecting the criteria, gathering and preparing the data, digitizing and rasterizing the datasets, classifying the raster layers, developing a suitability matrix, determining criteria weights from the matrix, and ultimately calculating the combined weighted values of all criterion raster layers (Marinoni, 2004).

Digital elevation model (DEM)

A DEM provides a two-dimensional digital representation of the terrain, capturing the elevation of the Earth’s surface, typically generated from systematic elevation data derived from topographic maps and aerial imagery (Gavit et al., 2018). For this study, terrain characterization relied on high-resolution DEM data obtained from the NASA Shuttle Radar Topography Mission (SRTM) data, providing a spatial resolution of 30 m (NASA, 2015). DEMs enabled precise mapping of basin morphology, with slope-derived maps informing runoff behaviour and concentration timing.

Rainfall

Rainfall in the Tafrata exhibits high temporal and spatial variability. As a result, water scarcity significantly constrains agricultural activities across much of the area, particularly during drought periods. Considering the water crisis the plain is witnessing due to the weak and irregular annual rainfall and its uneven distribution, it was necessary to adopt the criterion of the spatial distribution of rainfall because of its importance in determining the appropriate places to collect rainwater in hydrological basins. The Moulouya Water Basin Agency (MWBA) provided data on average annual rainfall spanning the years 2000 to 2021 (Table 2).

Rainfall variability across the Tafrata plain was examined through IDW interpolation. Mean yearly precipitation varied from 185 mm to 275 mm, representing the minimum and maximum recorded values, respectively.

Slope

Watershed slope plays a decisive role in regulating surface runoff generation and infiltration potential. As slope steepness increases, the residence time of rainfall over the land surface decreases, leading to rapid flow concentration and reduced suitability for rainwater harvesting. Slope plays a key role in determining the suitability of

sites for rainwater harvesting structures, as it controls runoff dynamics and storage potential. The slope was derived from a DEM using the Slope tool available in ArcGIS 10.8 spatial analyst.

The selection of places (locations) for the construction of future for rainwater harvesting according to the criterion of degrees of topographic gradient is required to be slight, Steeply sloped areas are generally considered less suitable for rainwater harvesting storage structures when large water volumes are required for irrigation, due to the increased construction and earthwork costs associated with such terrains (Preeti et al., 2022). Sites characterized by low to moderate slope conditions are generally preferred for rainwater harvesting, as they help minimize construction costs associated with storage structures (Alwan et al., 2020). From a structural engineering perspective, steep slopes pose significant risks, primarily due to increased hydrostatic pressure and accelerated surface runoff, which threaten the stability of harvesting structures. Furthermore, gradients exceeding 5% are generally categorized as unsuitable; this is attributed to the erratic distribution of runoff and the prohibitive financial burden associated with the extensive earthmoving operations required in such topographies (Critchley et al., 1991).

Soil type

Soil characteristics, with particular emphasis on texture and permeability, exert a fundamental influence on hydrological behaviour by regulating water retention and downward percolation toward underlying aquifers. Infiltration is mainly controlled by LULC and soil physical characteristics, playing a critical role in water management (Mahapatra et al., 2020). The rate of water percolation and the quantity retained in the soil layers are largely controlled by soil permeability (Alene et al., 2022).

In the study area, five soil classes can be distinguished: weakly developed soils, raw mineral soils, rendzinas, and calcimines soils. Despite lithological diversity, dominant soils share similar characteristics due to scarce rainfall, undulating

Table 2. Station coordinates and elevations

Name	Longitude	Latitude	Elevation (m)
Guercif	-3.35731	34.21953	362
Taurirt	-2.87674	34.4151	358
Mrija	-3.27692	33.99508	667

terrain, and the long-term absence of vegetative cover, resulting in poor horizons and low organic matter content (Seghir et al., 2019). Soils characterized by moderate permeability provide favourable conditions for rainwater harvesting and groundwater recharge processes, whereas excessively permeable or poorly permeable soils may significantly reduce system efficiency, depending on the design and functional requirements of the adopted harvesting structures.

Drainage density

Surface runoff is part of the preliminary studies related to planning projects for the construction of water dams, as these studies focus on identifying optimal sites for the implementation of these projects. Grasping how rainfall translates into runoff is fundamental in surface water hydrology. Runoff reflects the intensity of hydrological processes on the surface and indicates the potential for its utilization as a natural water resource, especially for agricultural use in irrigation on the one hand, or working to prevent negative risks, on the other hand, such as floods, for example. Effectively storing floodwaters from precipitation events and river overflows is essential to address the challenges posed by drought (Ali et al., 2024). When the soil cannot absorb water after precipitation, it forms torrents and floods that rush according to the gradient towards the exit of the basin or valley, so the possibility of building a dam to collect this water to exploit it becomes feasible.

Drainage density is a morphometric indicator reflecting the spatial concentration of the drainage network, derived from the proportion between the aggregated stream lengths and the watershed surface area. Drainage density is a crucial factor in RWH planning, as it affects both surface runoff and the soil's infiltration capacity (Shams et al., 2025). While surface runoff is influenced by rainfall, soil, and slope, drainage density serves as a practical proxy, directly reflecting the catchment's ability to channel water toward harvesting structures. This approach allows conceptual acknowledgment of runoff dynamics while streamlining the analysis to a measurable, reliable parameter for arid region RWH assessments. The drainage density (DD) quantifies how densely a drainage network is distributed within a watershed, determined by dividing the total stream length by the basin area in square Km. It is calculated using the formula:

$$DD=L/A \quad (1)$$

where: *DD* – drainage density (km/km²), *L* – total length of all streams and rivers in the watershed (km), *A* – watershed area (km²).

The study evaluated the drainage density of the region by applying the Kernel Density tool within ArcGIS, facilitating the measurement of the distribution of the drainage network. Computed values of drainage density vary from 1.51 to 5.25 streams/km².

Land use/land cover

The assessment of LULC serves as a fundamental component in environmental modeling, offering critical insights into contemporary land utilization dynamics (Gavhane et al., 2023). To characterize the surface landscape of the study area, we utilized Landsat 8 OLI/TIRS satellite data acquired in January 2024. The classification process adhered to standardized hierarchical protocols, ensuring consistency and accuracy. Subsequently, these classifications were validated through rigorous field-based ground truthing, resulting in high-precision spatial maps that delineate the diverse land cover configurations across the Tafrata plain.

Distance to roads

Socio-economic criteria help ensure the feasibility and sustainability of RWH systems, community-aligned, and responsive to stakeholder priorities (Sayl et al., 2016). The existence of a dense road network means easy communication between population groups and the possibility of opening these groups. Thus, positioning potential dam locations near existing roads may offer advantages by minimizing transportation costs (Ahmad et al., 2024; Faisal and Abdaki, 2021; Othman et al., 2020).

Consistency analysis

A standardized pairwise comparison matrix is shown in Table 3, aimed at assessing the interrelationships and influence levels among six principal factors: precipitation, terrain slope, soil type, drainage density and land use, land cover, and proximity to roads. Each element in the matrix indicates the comparative significance of one factor relative to another, with normalized scores between 0 and 6, illustrating their estimated impact in the given context.

A summary of the criteria used in this research and their relative weights obtained via the analytic hierarchy process (AHP) results are summarized in Table 4. Six thematic layers were assigned weights based on their relative importance, established through a pairwise comparison matrix informed by expert judgment and supported by previous (Tables 3 and 4). The resulting consistency ratio was below 0.1, confirming the internal consistency and robustness of the assigned weight, demonstrating the robustness and reliability of the weighting scheme.

The relative weights of each criterion were determined using the analytic hierarchy process (AHP), considering the hydrological and topographical roles of each factor in relation to rainwater harvesting. The resulting λ max of the matrix was 6.13, yielding a consistency index (CI) of 0.026. When compared with the random index (RI = 1.24), with a consistency ratio (CR) of about 0.021, well under the 0.1 threshold, the pairwise comparisons show strong consistency are consistent, and the derived weights are reliable. Therefore, these weights can be confidently applied in spatial analysis to select the best sites for implementing rainwater harvesting system structures, ensuring an accurate numerical representation of each criterion’s importance. And so, the pairwise comparisons and their corresponding weights establish a solid methodological foundation for comprehensive analysis and informed decision-making in the context of rainwater harvesting.

Selection factors were identified based on an in-depth review of the literature, with their corresponding weights determined by each criterion, which is explained either by the different units of measurement that belong to these categories or by their varying impact from one criterion to another. The adopted weighting

scheme reflects the selected criteria’s relative importance for hydrological assessment in rainwater harvesting site suitability assessment. Precipitation (38.2%) was assigned to be the highest weight as it directly controls runoff generation and the overall volume of harvestable water. Slope (25.2%) follows in importance due to its strong influence on flow velocity, runoff concentration, erosion risk, and the feasibility of water retention structures. Soil type (16.4%) plays a critical supporting role by governing infiltration capacity, water storage potential, and groundwater recharge processes. Drainage density (10.0%) was given moderate importance as it indicates the efficiency of surface water flow and the catchment’s hydrological response. Land use/land cover (6.4%) exerts an indirect influence by modifying surface roughness, infiltration rates, and evapotranspiration, while road proximity (3.9%) was assigned the lowest weight since it primarily represents a technical and economic consideration rather than a direct hydrological control. Overall, this hierarchical distribution ensures a balanced integration of climatic, topographic, hydrological, and infrastructural factors, consistent with GIS-based MCDA and AHP frameworks commonly applied in arid and semi-arid environments.

In this study, suitability values were derived by integrating insights from prior research, field observations, and expert knowledge (Table 5). These qualitative assessments were converted into standardized numerical scores using reclassification, where each category was assigned a numerical value to allow integration into the suitability analysis, producing values between 1 and 5. Finally, the normalized data were integrated through the weighted linear combination (WLC) technique to generate the ultimate suitability map.

Table 3. Pairwise comparison matrix of the criteria

Criteria	Rainfalls	Slope	Soil type	Drainage density	LULC	Distance to roads
Item description	1	2	3	4	5	6
Rainfall	1.00	2.00	3.00	4.00	5.00	7.00
Slope	0.50	1.00	2.00	3.00	4.00	6.00
Soil type	0.33	0.50	1.00	2.00	3.00	5.00
Drainage density	0.25	0.33	0.50	1.00	2.00	3.00
(LULC)	0.20	0.25	0.33	0.50	1.00	2.00
Distance to roads	0.14	0.17	0.20	0.33	0.50	1.00
Total	2.43	4.25	7.03	10.83	15.50	24.00

Table 4. Standardized weights of key factors are used to determine appropriate zones for RWHS

Criteria	Rainfall	Slope	Type soil	Drainage density	Land use / land cover	Distance to roads	Weight	%
Rainfall	2.29	3.02	2.94	2.36	1.9	1.61	2.29	38.2
Slope	1.14	1.51	1.96	1.77	1.52	1.38	1.51	25.2
Type soil	0.76	0.75	0.98	1.18	1.14	1.15	0.98	16.4
Drainage density	0.57	0.75	0.49	0.59	0.76	0.69	0.59	10.0
Land use / land cover	0.45	0.37	0.32	0.295	0.38	0.46	0.38	6.4
Distance to roads	0.32	0.25	0.19	0.19	0.19	0.23	0.23	3.9

Table 5. Criteria, classes, and suitability for identifying suitable sites of RWH

Criteria	Class	Suitability	References	Weights
Rainfall (mm)	265–275 mm	1	Preeti et al. (2022), Alene et al. (2022) and Aghad et al. (2021)	0.38
	240–265 mm	2		
	215–240 mm	3		
	190–215 mm	4		
	185–190 mm	5		
Slope (%)	0–3%	1	Sarkar and Biswas (2022), IMSD (1995), and Critchley et al. (1991)	0.25
	3–5%	2		
	5–10%	3		
	10–15%	4		
	> 15%	5		
Soil type	Calcimines soils with inclusion of weakly developed soils Weakly developed fluvial soils Weakly developed eroded soils with inclusion of raw minerals	Very high suitability 1 Medium suitability 3 Low suitability 4	Alene et al. (2022) and Mahapatra et al. (2020)	0.16
Drainage density (km/km ²)	> 5	1	Fetene et al. (2025), Aghad et al. (2021)	0.10
	4–5	2		
	3–4	3		
	2–3	4		
	< 2	5		
Land use / land cover	Cover Bare land	1	Gavhane et al. (2023), Alene et al. (2022), and Ejegu and Yegizaw (2020)	0.06
	Agricultural and grazing-land	2		
	Mixed forest / Mixed tree	3		
	Cover built-up area	4		
	Water	5		
Distance to roads (m)	250–500	1	Ahmad et al. (2024) Sayl et al. (2016)	0.04
	500–1000	2		
	> 1000	3		
	100–250	4		
	< 100	5		

RESULTS AND DISCUSSION

Water harvesting suitability analysis

The spatial analysis processes applied based on the previously defined criteria allowed obtaining partial results to determine the places suitable for the rainwater harvesting in the sense that each result translates the suitability of these places according to the adopted criterion, and all maps were divided into 5 categories, and these categories are graduated according to their suitability by adopting a color gradient. Starting from 1, which

indicates the best and best areas suitable for rainwater harvesting based on the adopted criteria and their weights, to category number 5, which indicates the impossibility or poor possibility of rainwater harvesting, and these results will be the basis for reaching the result.

Gently sloping terrains provide more favorable conditions for effective rainwater harvesting by enhancing water retention and infiltration processes. The classification of slope suitability was carried out following the IMSD (1995) framework for sustainable watershed management.

Slope represents a key topographic factor extracted from the digital elevation model (DEM), as it directly governs surface runoff behavior. Areas with steep gradients promote rapid water movement, limiting infiltration and storage potential, whereas gently sloping or flat terrains favor runoff retention, making them more suitable for effective rainwater harvesting.

The slope suitability map of the study region, reclassified into five categories, is presented in Figure 3a. These categories include flat (0–3%), low (3–5%), moderate (5–10%), steep (10–15%), and very steep slopes (>15%). Figure 3a indicates the suitability of these places based on degrees of gradient, where the number 1 represents very favorable areas, while the number 5 represents areas unsuitable for rainwater harvesting. The data indicate that the degrees of slope in the study area are weak, which allowed the extraction of an important result that makes a large area of the Tafrata plain suitable for rainwater harvesting. A mere 0.31% of the research area falls under the very steep category, making it the least favorable for rainwater harvesting. Areas with moderate slopes cover 5.26% of the region (Figure 8). Slopes under 5% are optimal, indicating that approximately 93.80% of the study area is extremely suitable for RWH.

Bare or lightly vegetated surfaces favor water harvesting by maximizing infiltration and concentrating runoff. The land use of the Tafrata plain was divided into five separate classes, as follows (1) cover bare land; (2) agricultural and grazing-land; (3) mixed forest / mixed tree cover; (4) built-up area; and (5) water body (Figure 3b). The majority of the research area (about 60.56%) is bare ground which were about 997.59 km²; agricultural and grazing-land (34.31%) which were about 564.80 km² and mixed forest / mixed tree cover (3.80%) built-up (1.32%) areas. The total area covered by water bodies is around 0.10 km², equivalent to 0.01% of the study region.

The study area's soil map illustrates the distribution of different soil types, weakly developed fluvial soils (including alluvial), Calcimines soils with inclusion of weakly developed soils, and weakly developed eroded soils with inclusion of raw minerals. The Tafrata plain is primarily composed of sandy loam soils (55%), accompanied by a considerable deficiency in organic matter, observed in 61% of the region, which imposes significant limitations on water retention (Oubdil et al., 2025). These soil characteristics reduce

the effectiveness of rainwater harvesting systems (RWHS), as water infiltrates rapidly and is poorly stored in the soil profile. Soil permeability critically dictates rainwater harvesting efficiency: fluvial soils with high permeability favor groundwater recharge, calcimine soils offer balanced storage, while eroded mineral-rich soils require engineered retention to minimize losses. This nuanced classification informs targeted site selection for sustainable RWH. Following this, these species have been classified under three levels of suitability (Figure 2c): very high suitability, medium suitability, and low suitability. The calcimines soils are a major portion of the study area (50.60%), followed by weakly developed fluvial soils (30.98%), weakly developed eroded soils (18.42%)

The road network is one of the main pillars of development and breaking the isolation of the rural world to address the issue of developmental delay and marginalization from the center. Roads hold considerable socio-economic importance in the area. For safety purposes and to avoid interference with future road construction, a buffer distance of at least 250 m from roads is recommended for proposed dam sites (Ahmad et al., 2024; Karakuş and Yıldız, 2022; Al-Adamat et al., 2010). While proximity to roads reduces construction and maintenance costs, excessive closeness may pose safety risks and conflict with future expansions. Therefore, intermediate distances (250–500 m) were deemed optimal, balancing economic feasibility with structural safety requirements. The Euclidean distance tool was used to measure proximity to road networks, producing values ranging from 0 to 10,692 m. Figure 3d presents the reclassified suitability map of the study area based on the distance to roads criterion. The spatial analysis indicates that areas located within <100 m of roads are excluded due to safety concerns. The results further reveal a non-linear relationship between road distance and Rainwater harvesting suitability, with the 250–500 m range representing the optimal zone that minimizes access costs while ensuring structural stability. In contrast, more distant locations, despite their engineering suitability, exhibit reduced implementation feasibility owing to increased infrastructure and connectivity costs.

Surface runoff is defined as a part of the total rainfall on the water basin, which flows on the surface of the earth, following several paths according to the topography of a specific area

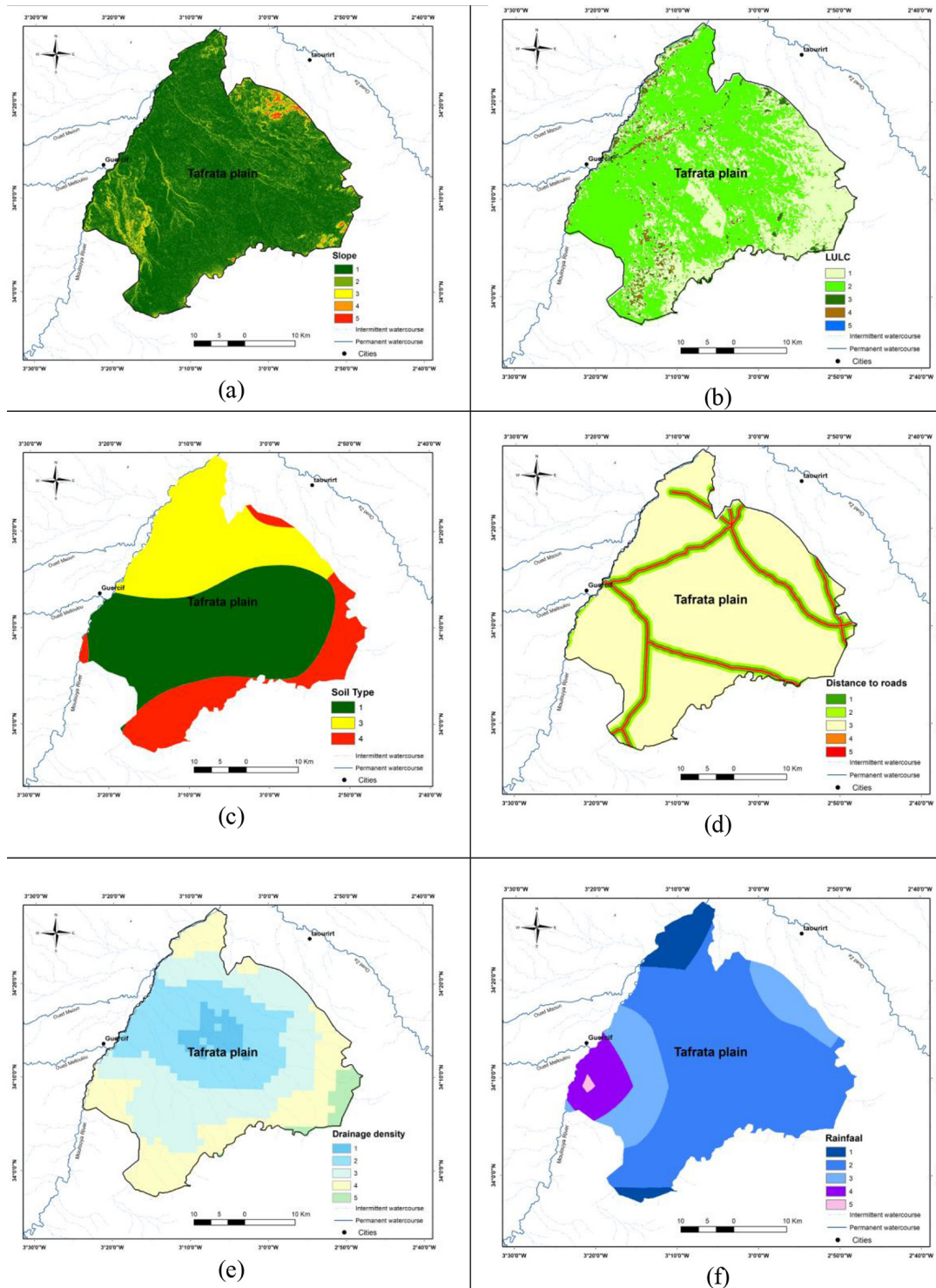


Figure 3. Maps RWH suitability based on spatial analysis: slope (a), LULC (b), soil types (c), distance to roads (d), drainage density (e), rainfall (f)

to reach the water estuary or river or a secondary stream that confines the water within its section, pouring into it and becoming part of it, Surface runoff occurs because of water saturation of the soil after rainfall or poor penetration and is of great importance because it constitutes one of the primary contributors to groundwater.

Rainfall-driven runoff serves as the main determinant for the effectiveness of rainwater harvesting structures (Chowdhury and Paul, 2021). Drainage density indicates a landscape’s inherent ability to direct and capture surface runoff (Fetene et al. 2025). Consequently, a universally fixed drainage density threshold does not exist; instead, it

should be assessed according to the runoff behavior of the study area (Sreedevi et al. 2005). It is advantageous to position RHSs in zones characterized by elevated drainage densities (Ouali et al., 2022). However, this preference depends on the type of structure; regions with low drainage density produce limited runoff, while areas with high drainage density generate more substantial surface flow (Patel et al., 2022). Therefore, sites with greater runoff availability are ideal for establishing water harvesting facilities, including check dams, retention ponds, and recharge wells (Patel and Chaudhari, 2023).

Using the ArcMap Arc Hydro tool, the hydrographic network was generated using the DEM representing the Tafrata Plain. The drainage density map was categorized into five levels, with areas showing the lowest density ($<2 \text{ km/km}^2$) being considered most favorable for rainwater harvesting, followed by those with low to moderate density ($2\text{--}5 \text{ km/km}^2$), whereas areas with the highest density ($>5 \text{ km/km}^2$) were deemed least suitable. The results indicate a heterogeneous distribution of runoff density across the Tafrata plain (Figure 3e). The very low density occupies only 81.37 km^2 , representing 4.94% of the total area. Class 2 covers 450.58 km^2 (27.36%), while Class 3, which corresponds to moderate runoff density, is the largest class with 598.90 km^2 , accounting for 36.36% of the total area. Class 4, representing high runoff density, occupies 461.19 km^2 (28.01%), and the highest density class (Class 5) covers the smallest area of 54.87 km^2 (3.33%).

Higher rainfall classes ensure sufficient runoff generation to offset infiltration and evaporation losses, thereby enhancing the efficiency and reliability of rainwater harvesting systems. Conversely, lower rainfall ranges limit runoff availability and reduce system performance. Rainfall was weighted as a primary driver of runoff potential but evaluated in conjunction with drainage density, slope, and soil. The Tafrata plain receives experiencing an average annual rainfall of 185–275 mm, reflecting significant temporal and spatial variability. This variability is primarily attributed to the influence of topography. Areas located near the Debdou escarpment receive relatively higher rainfall amounts due to the role of elevation in enhancing orographic condensation, making these zones more favored in terms of precipitation compared to the rest of the plain. In contrast, rainfall gradually decreases toward

the northwestern and southeastern parts of the plain, particularly in the direction of the cities of Taourirt and Guercif, where annual averages do not exceed 185 mm. This pattern reflects the semi-arid climatic character of these areas.

Figure 3f illustrates the reclassified map of the study area based on average annual rainfall. The results of this criterion were categorized using the same method as the previous criteria, and the result was as follows:

- Value (1): Corresponds to areas with significant precipitation, which are mainly distributed along the Zones adjacent to the edge of the Dabdou plateau and in the middle of the plain, in addition to the north-eastern part, which is the best location for rainwater harvesting.
- Value (5): Corresponds to areas with low precipitation; based on this factor, rainwater harvesting construction is deemed unsuitable in the plain's southeast and northeast regions.

The distribution of water harvesting suitability shows that the largest portion of the study area, 1113.84 km^2 (67.60%), falls under Class 2, indicating moderate suitability. The very suitable areas (Class 1) cover 111.22 km^2 (6.75%), representing limited but high-quality zones for water harvesting. Intermediate suitability areas (Class 3) span 300.71 km^2 (18.25%), while less suitable areas, Class 4, cover 116.93 km^2 (7.10%). The least suitable areas (Class 5) are minimal, totaling only 4.51 km^2 (0.27%).

Final suitability map for water harvesting

The spatial analysis of the adopted criteria revealed the extent of the influence of each criterion in determining the appropriate places of future rainwater harvesting according to their degrees of suitability in the field of study, but this was not sufficient to develop the general future picture of the identification of these sites, so it was necessary to collect and synthesize the results of the spatial analysis of these criteria, by performing the cumulative matching process by applying the account the weight of each criterion and its importance in percentage terms, The results of collecting and synthesizing the adopted criteria and their different weights resulted to produce a spatial suitability map indicating locations suitable for establishing rainwater harvesting systems within the study region. The identified zones correspond to potential RWH

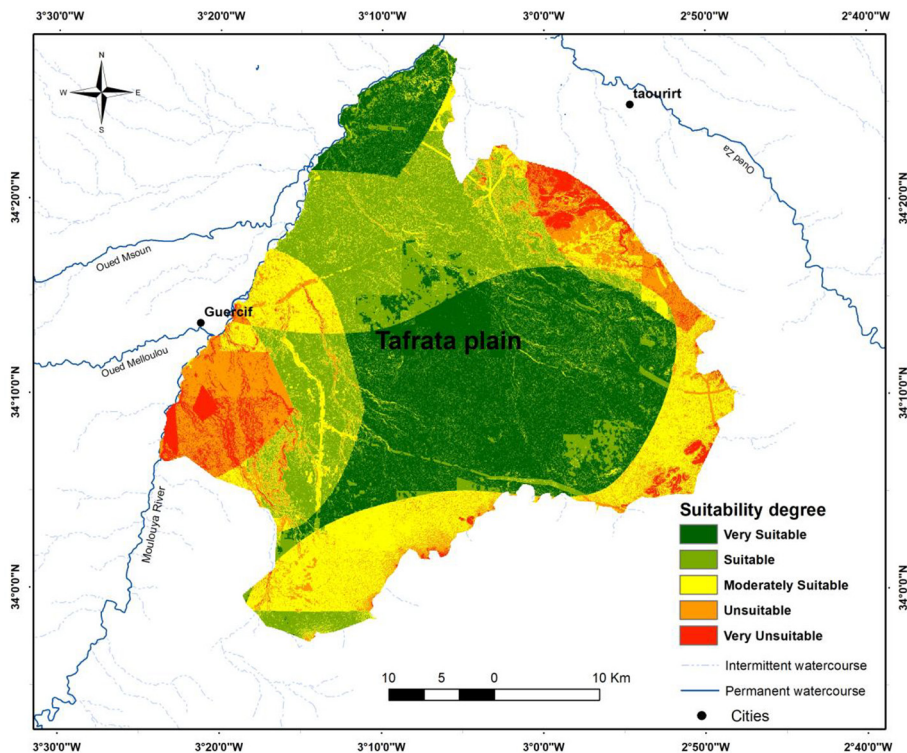


Figure 4. Classified potential Rainwater Harvesting (RWH) suitability map of the study area

sites, structures were spatially subdivided according to their degree of suitability. This classification was performed by assigning ranked suitability levels, namely very high, high, moderate, low, and unsuitable categories, as presented in Figure 4. These classes were quantified using a standardized ranking scale ranging from 1 to 5, where a value of 1 indicates optimal suitability and a value of 5 represents areas considered unsuitable or for RWH.

The spatial analysis shows that zones with moderate suitability dominate the study area, representing approximately 80.72% of its total extent. In contrast, unsuitable areas represent the smallest proportion, covering about 2.13%. Very highly suitable and highly suitable zones cover approximately 4.86% and 9.31% of the study area, respectively (Table 6). These priority zones were identified as the most favorable locations for RWH development, as they exhibit optimal combinations of key controlling factors.

To validate the suitability map, the proposed rainwater harvesting and multi-purpose dam sites were checked against existing IWH structures using ArcGIS proximity tools to see how closely they match (Abd-el-Kader et al., 2023). The results indicate that 99% of the current IWH structures are deemed successful (i.e., working efficiently

Table 6. Area of potential RWH classes

Suitability	Area (km ²)	%
Very suitable	79.90	4.86
Good	153.21	9.31
Moderate	1327.76	80.72
Very Weak	49.03	2.98
Highly Unlikely	35.01	2.13
Total	1644.91	100 %

in harvesting rainwater), were located within areas classified on the map as very suitable, which means that the model used to determine the locations was largely accurate, as the theoretical predictions matched reality. This study demonstrates the reliability of the proposed GIS-based framework, providing a precise spatial guide for identifying strategic rainwater harvesting locations.

CONCLUSIONS

The integration of GIS and AHP enabled the identification of optimal locations for implementing rainwater harvesting (RWH) in Morocco’s Tafrata plain, located in the north-east. The results demonstrate that the applied

methodology is robust, reliable, and capable of accurately prioritizing areas based on environmental and socio-economic criteria.

The generated suitability map classified the study area into five categories, highlighting that moderately suitable zones dominate (1,327.76 km², 80.72%), while very highly suitable areas occupy 79.90 km² (4.86%), and highly suitable areas cover 153.21 km² (9.31%). These priority zones represent optimal locations for implementing RWH systems, where favorable conditions of rainfall, slope, soil type, drainage density, land use, and proximity to roads converge.

The study confirms that GIS-AHP integration effectively supports the spatial prioritization of RWH sites, validating the hypothesis that a systematic, multi-criteria approach can accurately guide water resource management in semi-arid environments. The findings provide a practical decision-making framework for agricultural planning, territorial development, and sustainable water management. Moreover, the approach is cost-effective, transferable, and adaptable, offering significant potential for application in other regions facing similar climatic and infrastructural challenges.

The study successfully achieved a clear identification of high-priority zones for rainwater harvesting, grounded in rigorous quantitative analysis of spatial and hydrological factors. The reliability of these results was further confirmed through validation against existing in-field water harvesting structures, revealing that 99% of functional installations are located within areas classified as very suitable for rainwater harvesting. Consequently, the methodology developed provides a scientifically robust framework that can serve as a reliable tool for guiding medium- and long-term planning of agriculture and water resources in the Tafrata plain.

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