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Application of GIS and Multi-Criteria Decision Analysis for Locating Suitable Rainwater Harvesting Zones in Kabul Metropolitan Area, Afghanistan

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Abstract

In recent years, Afghanistan has been suffering from water shortages, and around one-third of the population lacks access to stable water sources. The Kabul Metropolitan Area (KMA) in particular has faced increasing water scarcity challenges due to rapid urbanization and the absence of adequate water conservation infrastructure. Alarmingly, UNICEF Afghanistan has issued a warning that Kabul's groundwater could run dry by 2030. To address this critical issue, this study aimed to identify potential Surface Rainwater Harvesting (SRWH) sites within the KMA using an integrated approach combining the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS). In this study, rainwater harvesting refers specifically to the collection of surface runoff from natural catchments rather than rooftop systems. The proposed methodology was implemented at a large urban metropolitan catchment scale in KMA with an area of 1629.2 km^2, located in the existing Kabul city and the Kabul New City areas of Dehsabz and Barikab in the northeast. Based on the comprehensive literature reviews, FAO guidelines, and the expert opinions of Afghan professionals with field experience in the region, Six biophys-ical criteria were selected such as precipitation (average annual), slope (derived from DEM), soil type (based on soil texture), land use/land cover, lithology (classified based on rock types), and drainage density (calculated as total stream length per unit area). The experts provided pairwise comparisons and feature ratings to determine the weights. Then, in ArcGIS Pro, the weighted overlay analysis was applied, assigning the highest weight to rainfall (24%) due to its critical influence on RWH suitability, and the lowest to drainage density (11%). The weighted overlay results indicate that approximately 40.5% of the study area falls within the high suitability class, 30.9% within moderate suitability, and 28.5% within low suitability, based on the classification of the composite suitability index. These results highlight the application of a GIS-AHP model that may be used to determine potential areas for harvesting rainwater, not only in this region but also in other semi-arid urban areas with restricted information.

Keywords

Kabul Metropolitan Area, Water Scarcity, Rainwater Harvesting, MCDA, AHP

1. Introduction

The 2019 UNICEF report says that around one-third of Afghanistan's population, roughly 12.5 million people, lack access to reliable water sources, like groundwater, stream flow diversion, and reservoir storage [1]. Urban areas in arid and semi-arid regions, like Kabul, face double challenges such as urban flooding and water scarcity, both of which threaten sustainability [2]. Kabul, the capital of Afghanistan, is suffering from severe water shortages as rapid urban growth has outpaced the development of water infrastructure, and this has led to overuse of groundwater, frequent urban flooding, and a growing risk to the city's population [2]-[4]. UNICEF Afghanistan issued an urgent warning in October 2024 that the capital Kabul's groundwater could run dry by 2030 due to the combined impacts of speedy urbanization and climate change [5]. Previous research has shown that groundwater quality and quantity are declining in the Kabul Plain [2]. Between 1964 and 2009, land use change analysis in north Kabul identified a 15% reduction in green area, a 27% reduction in bare soil, and a 51% rise in impermeable surfaces [6].

According to Mahmoud *et al.* (2014), rainwater harvesting (RWH) is widely used in arid and semi-arid regions to supply water for domestic and other uses [7]. Today, RWH is promoted in many Asian and African countries as a low-cost, decentralized option for improving water security [8]-[13]. In urban contexts, RWH and managed aquifer recharge (MAR) have been recommended for Kabul to reduce pressure on overburdened aquifers [14]. However, previous studies, such as Rahmani (2019), have focused on soil surface treatment and RWH at the watershed level in the Paghman District of Kabul, while comprehensive suitability assessments at the metropolitan scale remain limited [15].

Selecting RWH locations in semi-arid regions requires consideration of multiple biophysical factors (*i.e.*, precipitation, slope, soil type, land use/land cover, lithology, and drainage density) and environmental factors, yet the lack of comprehensive data presents challenges [16]. According to recent studies, combining GIS and Multi-Criteria Decision Analysis (MCDA) enables structured, transparent site suitability assessments. Similarly, the Analytical Hierarchy Process (AHP) is widely applied within MCDA to determine the relative importance of factors based on expert judgement [17]-[22].

The present study applies MCDA using an integrated GIS-AHP approach to identify surface RWH potential zones in the Kabul Metropolitan Area (KMA) (**Figure 1**). This study is about runoff-based RWH from natural land surfaces and catchments, not rooftop rainwater collection systems, which are more common in cities.

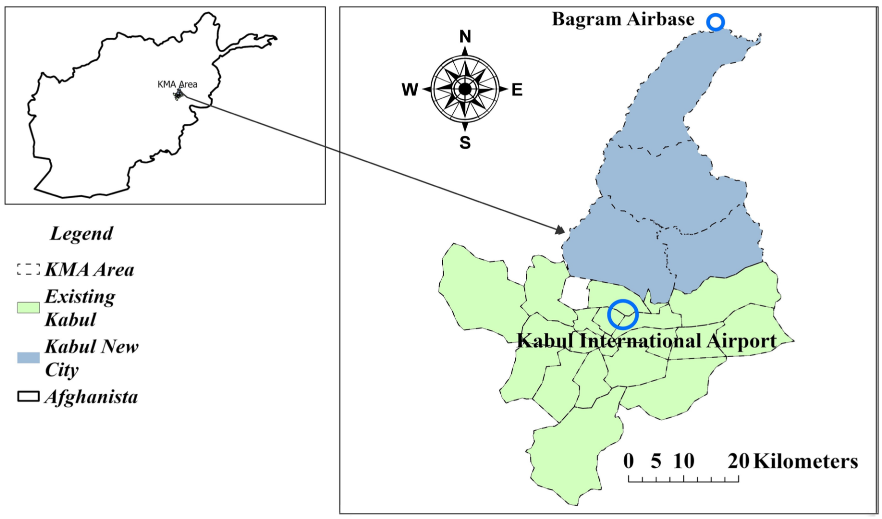

Figure 1. Location of KMA.

This research seeks to tackle water scarcity in KMA by identifying suitable zones for surface rainwater harvesting through the integration of GIS and MCDA, and by developing a GIS-based decision-support framework to guide the selection of appropriate catchment areas for RWH implementation. As little research has been done on RWH at the metropolitan scale in Afghanistan, particularly in Kabul, this is the first attempt to investigate potential surface RWH sites in the metropolitan area.

The findings of the research are intended to provide planners, local authorities, and development partners with a decision-support framework to prioritize interventions that can enhance water security.

2. Materials and Methods

The methodology used in this study is shown in **Figure 2**. The first step in the procedure is to collect the relevant satellite-based and hydrological data, such as study area administrative borders, soil maps, DEM, satellite imagery, and precipitation records.

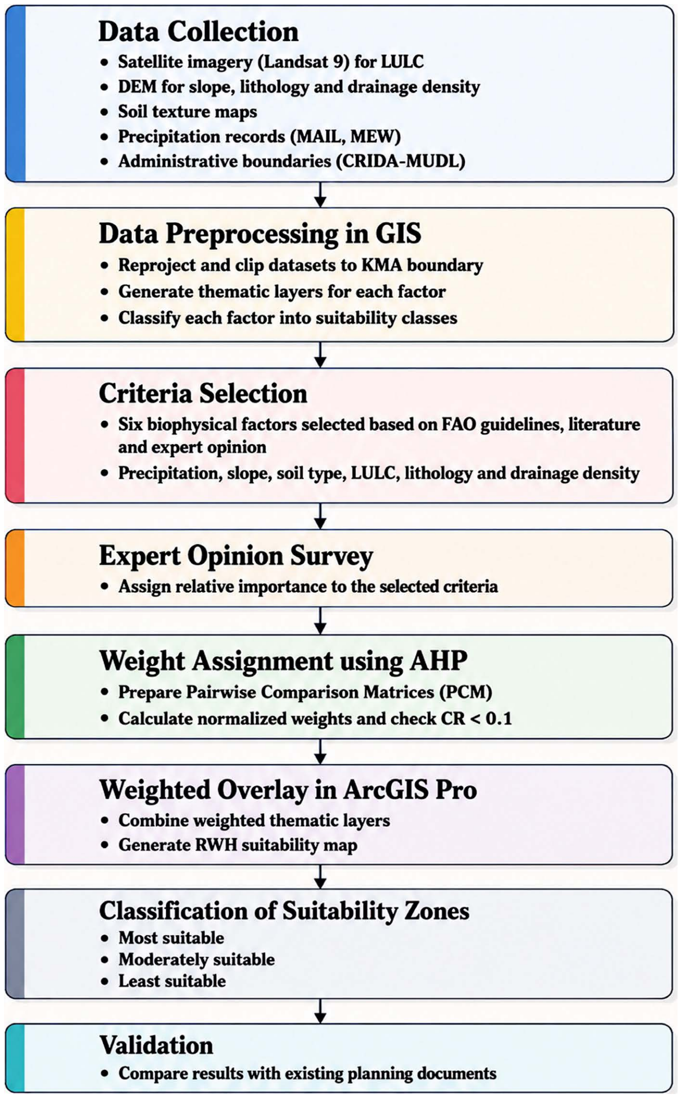

Figure 2. Methodology framework used to identify RWH potential zones.

Six biophysical factors, such as precipitation, slope, soil type, land use/cover (LULC), lithology, and drainage density, were selected based on FAO guidelines and a comprehensive literature review and were approved by Afghan experts through an opinion survey. Then, these factors were used to create thematic layers, which were then preprocessed in a GIS.

Following a consistency check, each factor is assigned a weight using Pairwise Comparison Matrices (PCM) and the Analytical Hierarchy Process (AHP) based on the expert's opinion survey results. Then, the RWH suitability map is created by integrating the weighted thematic layers using a weighted overlay in ArcGIS Pro. It is then divided into three suitability classes using the natural breaks (Jenks) method in ArcGIS Pro and then validated against strategic planning documents.

2.1. Study Area and Climate

Kabul is the largest and the capital city of Afghanistan. The Ministry of Urban Development (MOUD) defines the National Capital Region of Kabul (NCRK) as the Kabul Metropolitan Area (KMA) [23]. The total area is about 1629.2 km^2, with a population exceeding 4 million in 2024, double that of 1999 [24]. Projections estimate 6.5 million residents by 2025 [24]. The project area consists of the existing Kabul city and the Kabul New City areas of Dehsabz and Barikab in the northeast, as shown in **Figure 1**. The northern districts of KMA Dehsabz and Barikab are surrounded by Khwaja Rawash, Safi, and Marko mountains, and these watersheds with steep slope topography frequently lead to floods and soil erosion in the rainy season [24]. On the other hand, the water situation in Kabul city is serious, and the water availability will be the most critical constraint to the KMA development [23]. Kabul's semi-arid climate is characterized by a mean annual temperature of 12.1˚C, average annual rainfall of 327 mm, potential evapotranspiration of 1173 mm, and mean relative humidity of 62% at the Kabul airport station [2] [24].

2.2. Data Collection and Processing

This study used satellite-based data to map selected biophysical factors in GIS, with precipitation data sourced from the Afghan Ministry of Agriculture and Livestock (MAIL) and the Ministry of Energy and Water (MEW). Study area division boundary files were obtained from the Capital Region Independent Development Authority under the Ministry of Urban Development and Land (CRIDA-MUDL). Most of the data used in this analysis is open access, and the expert opinion survey was created in KoboToolbox, an open-source data collection platform. A complete view of the survey form is available in **Table 1**. The criteria of the study area have been processed by using ArcGIS Pro.

Table 1. Used data and their sources.

No	Data	Derived Map	Source
1	Landsat 9	Land Use/Land Cover	https://earthexplorer.usgs.gov/
2	Study Area	Study Area Division Boundary	CRIDA-MUDL
3	DEM	Slope, Drainage Density	https://earthexplorer.usgs.gov/
4	Soil	Soil Texture	https://www.isric.org/
5	Precipitation	Precipitation Map	MAIL and MEW
6	Expert Opinion Survey	-	https://ee.kobotoolbox.org/x/paKYgPAV
7	Geologic Shapefile	Lithology	https://isric.org/

2.3. Criteria Selection

Based on the Food and Agriculture Organization (FAO) advice, extensive literature review, and expert opinion, this study considers six key biophysical factors, such as Rainfall/precipitation, soil type, slope, lithology, LULC, and drainage density, into the analysis. Similarly, to represent the FAO parameters, this study used rainfall for climate/atmosphere, drainage density for hydrology, slope for topography, lithology and land cover for agronomy, and soil texture or type for soils [1] [25] [26].

The above-mentioned biophysical factors used in this study have also been successfully applied in similar research conducted in arid and semi-arid regions (ASAR), demonstrating their effectiveness in selecting suitable sites for rainwater harvesting systems [1] [17] [21] [26]-[28].

1) Precipitation/Rainfall

Rainfall is the most influential factor in determining high RWH potential, and average annual rainfall data is a key requirement for planning rainwater harvesting structures [17] [29]. In addition, according to previous studies in ASAR, a minimum annual rainfall of 200 mm has been recommended for effective and practical rainwater harvesting [21].

The Ministry of Agriculture Irrigation and Livestock (MAIL) and the Ministry of Energy and Water (MEW) have been measuring the precipitation in the Kabul area. This study uses data from 2006-2019 for Darulaman, Gul Khana, Badambagh, Sarobi, and Paghman stations from MAIL. Similarly, data for Wapika (2016-2022), Qala-e-Malik (2008-2022), and Shakardara (2009-2022) were obtained from the MEW. All rainfall records were converted to mean annual rainfall (mm/year) to make stations with different observation periods comparable. The locations of each rain gauge station are shown in **Figure 3**.

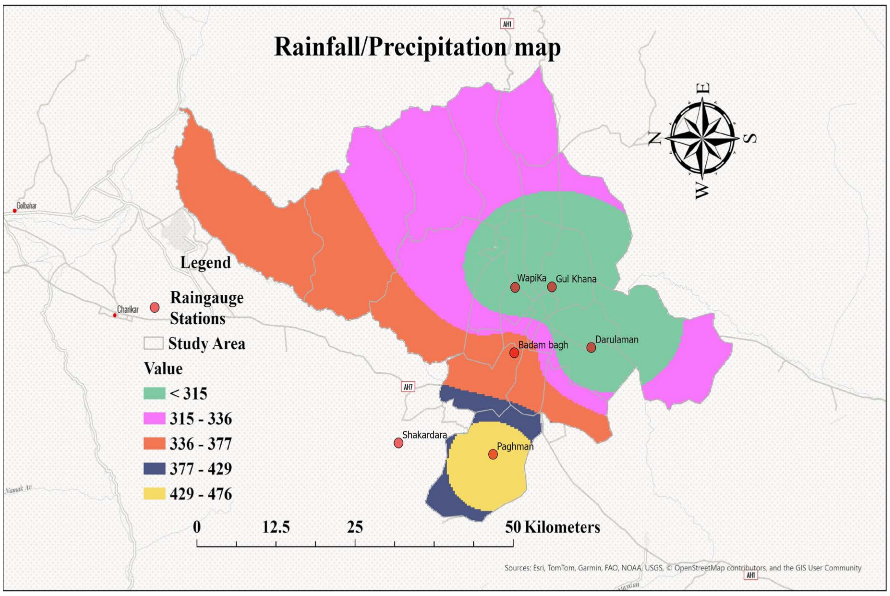

Figure 3. Precipitation map with rain gauge stations.

2) Slope

Slope is a crucial factor in selecting suitable locations for rainwater harvesting, as it directly influences runoff generation [17] [30]. Based on 48 reviewed studies, slope was identified as the most commonly used criterion in rainwater harvesting studies in ASAR, applied in 83% of them due to its direct influence on runoff generation and erosion potential [21]. Previous studies have used 30-meter resolution DEMs to generate slope maps and classify them into five suitability classes, as demonstrated by [19]. Similarly, in this study, slope maps were created in ArcGIS Pro using 30-meter DEMs, with slopes expressed in degrees and reclassified into five categories.

3) Soil Type

Soil is a key factor in RWH planning, as poorly drained clayey soils tend to generate more runoff, while sandy soils produce less runoff [17]. Based on previous studies in ASAR, soil type is one of the most commonly used criteria in rainwater harvesting, applied in 75% of the 48 reviewed studies because it directly controls infiltration and runoff generation [21].

In the present work, the soil texture map was created in ArcGIS Pro using Soil Grids 250 m Texture class United States Department of Agriculture (USDA) system data, and it was then reclassified into five suitability classes for rainwater harvesting.

4) Land Use and Land Cover

Dense vegetation, forests, and covered areas tend to enhance water infiltration and retention, whereas urban and pasture-covered areas increase surface runoff [17]. For this reason, LULC is widely recognized as a relevant criterion in rainwater harvesting suitability assessments, and it has been applied in the majority (75%) of 48 reviewed studies in ASAR [21].

For the research area, the LULC map was developed in ArcGIS Pro using Landsat 9 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) data from the United States Geological Survey (USGS) Earth Explorer, released in January 2025, with a spatial resolution of 30 meters. Three bands, 5, 4, 3, were used as a true color composite in ArcGIS Pro, and a supervised method was followed.

Similarly, a supervised classification was performed using Maximum Likelihood and Support Vector Machine (SVM) classifiers. Training polygons for seven land cover classes (Water, Developed, Barren, Shrubland, Planted/Cultivated, Snow, and Mountains) were manually digitized using high-resolution Google Earth imagery as reference. However, quantitative accuracy assessment (e.g., kappa) was not conducted due to the absence of field validation data, which is acknowledged as a limitation.

5) Drainage Density

Drainage density is an important geomorphological factor influencing catchment runoff and is calculated by dividing the total stream length by the basin area, a process that can be efficiently done using GIS [31]. In this analysis, the stream network was extracted from a Digital SRTM DEM, and the drainage density was classified into five suitability classes.

6) Lithology

Lithology influences the rainwater harvesting process primarily through the permeability of the underlying rock layers beneath the topsoil, and low-permeability lithology tends to yield a greater volume of harvested rainwater [31]. According to the JICA groundwater report, the uppermost layer at KMA comprises reworked loess (loam), which is semi-permeable to impermeable in nature [32]. Hence, from the above observation, it can be concluded that even when there is the presence of soil, low permeability will lead to less infiltration, thus lithology becomes important for forming runoff. However, soil thickness data were not available for this study. Future research should incorporate soil thickness data where possible.

The lithological layer was prepared in ArcGIS Pro using the South Asia geology shapefile [33]. The original polygon feature class was clipped to the KMA boundary and converted to raster format. In the present case, Lithological units were categorized and reclassified into five suitability classes based on their relative permeability and influence on runoff generation.

2.4. Multi-Criteria Decision Analysis (MCDA)

A Pairwise Comparison Matrix (PCM) is a structured tool used in the Analytic Hierarchy Process (AHP) to compare criteria in pairs and assign relative weights based on expert judgment. Based on a previous study, PCM involves comparing all possible pairs of criteria to determine which ones have higher priority [34]. The AHP is a well-known MCDA tool that provides decision-making under complex conditions with the help of combining the expertise opinions through pairwise comparisons with mathematical modeling approaches [18] [35]. The AHP method is based on building a series of PCMs that compare all the criteria to one another to establish their relative importance [34].

This paper applies the AHP within ArcGIS Pro for generating the potential Rainwater Harvesting (RWH) suitability map. After selecting the criteria for site suitability, an expert opinion survey was carried out for each identified biophysical factor to collect expert judgments and assign relative importance to each criterion. All consulted experts are Afghan professionals with experience in implementing water management projects in the study area. They have backgrounds in hydrology and environmental sciences and possess specialized knowledge in GIS and remote sensing tools. Their professional experience ranged from 5 to 14 years and included affiliations with the MEW Afghanistan, UNFAO, academic institutions, and international development projects.

In total, four participants were involved. The questionnaire was created using KoboToolbox, and the survey questions were also sent through email and WhatsApp. Individual pairwise comparison responses were aggregated by averaging the corresponding matrix values from all experts to produce the final AHP comparison matrix. Due to the complexity of the pairwise comparison procedure in AHP, obtaining a larger number of responses was challenging. This small sample size is acknowledged as a limitation of the study. In addition to the pairwise comparison weights, the same experts rated the suitability of individual features within each criterion using a 1 - 3 scale (1 = least suitable, 2 = moderately suitable, 3 = most suitable). These feature ratings are presented in **Table 2**. Saaty, T.L., 1980 [35] proposed a scale from 1 to 9 for elements in PCM, where 1 means the criteria are equally important and 9 means one criterion is extremely more important than the other, with the values in between representing varying degrees of importance as shown in **Table 2**.

Table 2. Scales for the pairwise comparisons method (Adapted from Saaty, T.L., 1980).

Scale	Definition	Explanation
1	Equal Importance	Two criteria contribute equally to the objective
3	Moderate Importance	Judgment and experience slightly favor one criterion over another
5	Strong Importance	Judgment and EXPERIENCE strongly favor one criterion over another
7	Very Strong Importance	Judgment and experience very strongly favor one criterion over another
9	Extreme Importance	The evidence favoring one criterion over another is of the highest possible validity
2, 4, 6, 8	Intermediate Values	When compromise is needed

In our analysis, the relative importance of each criterion was determined with an expert opinion survey to explore the opinions of the experts on the relative importance of the criteria selected for water harvesting. The results of the questionnaire are summarized in **Table 3**.

Next, this work prepared the normalized pairwise comparison matrix (**Table 4**) by dividing each value in the column of the pairwise comparison matrix by the sum of the column.

Table 3. The pairwise comparison matrix of experts' opinions.

Factors	Rainfall	Slope	LULC	Lithology	Soil Type	Drainage Density
Rainfall	1	1	2	3	2	1
Slope	1	1	1	2	2	3
LULC	1/2	1	1	1	3	2
Lithology	1/3	1/2	1	1	2	1
Soil Type	1/2	1/2	1/3	1/2	1	3
Drainage Density	1	1/3	1/2	1	1/3	1
Column Sum	4.33	4.33	5.83	8.50	10.33	11.00

Table 4. Normalized pairwise comparison matrix.

Factors	Rainfall	Slope	LULC	Lithology	Soil Type	Drainage Density	Sum	Criteria Weights
Rainfall	0.23	0.23	0.34	0.35	0.19	0.09	1.44	0.24
Slope	0.23	0.23	0.17	0.23	0.19	0.27	1.33	0.22
LULC	0.11	0.23	0.17	0.11	0.29	0.18	1.10	0.18

Continued

Lithology	0.07	0.11	0.17	0.11	0.19	0.09	0.76	0.12
Soil Type	0.11	0.11	0.05	0.05	0.09	0.27	0.71	0.11
Drainage Density	0.23	0.07	0.08	0.11	0.03	0.09	0.63	0.10

In the third stage, the weight of each criterion/factor was computed by dividing the sum of each row in the normalized pairwise comparison matrix (**Table 4**) by the number of criteria/factors.

Similarly, to check whether the comparison is correct/consistent or not, the consistency check can be performed using Equation (1), as given by [34].

$$CI = \lambda \max - n/n - 1 \quad (1)$$

where CI is the consistency index, n is the number of criteria or factors compared in the matrix, and λmax is the maximum eigenvalue of the pairwise comparison matrix. As suggested by saaty, 1980 [35], the λmax value can be calculated by multiplying each value in the column of the table which is not normalized by the criteria weight, then computing the weight sum value by adding the values in the row, then calculating the ratio of each weighted sum value to the respective criteria weight and then averaging the ratio of the weighted sum to the Criteria weight, as shown in **Table 5**.

Table 5. Calculating consistency, λmax.

Criteria Weight	0.24	0.22	0.18	0.12	0.11	0.10			
Factors	Rainfall	Slope	LULC	Lithology	Soil Type	Drainage Density	Weighted Sum Value	Criteria Weight	WSV/CW
Rainfall	0.24	0.22	0.36	0.38	0.23	0.10	1.55	0.24	6.49
Slope	0.24	0.22	0.18	0.25	0.23	0.31	1.45	0.22	6.56
LULC	0.12	0.22	0.18	0.12	0.35	0.21	1.22	0.18	6.63
Lithology	0.08	0.11	0.18	0.12	0.23	0.10	0.84	0.12	6.64
Soil Type	0.12	0.11	0.06	0.06	0.11	0.31	0.79	0.11	6.64
Drainage Density	0.24	0.07	0.09	0.12	0.03	0.10	0.67	0.10	6.43
								λmax.	**6.57**

Finally, consistency ratio (CR) was computed by using Saaty (1980) [35], below Equation (2).

$$CR = CI/RI \quad (2)$$

where CR is the consistency ratio, CI is the consistency index, and RI is a random consistency index, which is 1.24 for 6 criteria. On the other hand, AHP theory recommends that the CR must be equal to or smaller than 0.1 [35] to obtain acceptable results, and in case of a consistency ratio > 0.1, the subjective judgment needs to be revised by revisiting the pairwise comparisons weights [17]. The resulting CR in this work was <0.09; thus, consistency is considered acceptable.

Before weighted overlay analysis, all thematic layers were projected, clipped to the KMA boundary, and converted to raster format in ArcGIS Pro. LULC, DEM, slope, and drainage density were prepared at 30 m resolution. The SoilGrids 250 m soil raster was resampled to approximately 210 m. All layers were then harmonized to a common resolution of 210 m for weighted overlay analysis. Categorical layers (soil type, lithology, LULC) were resampled using the Nearest Neighbor method to preserve class integrity. The same raster extent and alignment settings were applied to minimize spatial inconsistencies between layers. After assigning weights to the criteria, the potential rainwater harvesting (RWH) sites were identified by overlaying all the weighted layers in the ArcGIS Pro environment.

3. Results and Discussions

3.1. Results of Individual RWH Criteria

1) Precipitation

According to the precipitation map in **Figure 3**, precipitation in the study area ranges from 315 to 476 mm per year, with the Paghman area receiving the highest amounts. This pattern, visualized using the Inverse Distance Weighting (IDW) interpolation method, shows that approximately 49.2% of the total area receives an average annual rainfall of about 326 mm, followed by 40.4% receiving about 360 mm. Smaller areas, 7.2%, receive over 389 mm, and the smallest area, 2.8%, also receives over 400 mm. The IDW interpolation method was selected because it assumes that locations closer to each other have more similar precipitation values than distant locations, which is appropriate for a semi-arid region with limited station density. On the other hand, IDW does not require assumptions about data distribution and has been successfully applied in similar rainwater harvesting studies in ASAR. The 14-year data show that most of the precipitation in the study area occurs during the winter and spring months, specifically from November to May.

2) Slope

According to the slope map in **Figure 4**, approximately 62.03% of the study area has a slope ranging from 0˚ to 5˚, 8.10% has a slope between 5˚ and 8˚, 12.3% has a slope between 8.6˚ and 18.4˚, 8.23% has a slope between 18.4˚ and 29.6˚, and 3.7% has a slope greater than 30˚. The study area is predominantly surrounded by steeper mountains, while the central region features gentler slopes, making it more suitable for RWH.

3) Soil Type

Figure 5 presents the classification of the study area's soil map into four suitability classes based on texture. Loam dominates about 76.28% of the area, offering moderate infiltration with balanced texture [17]. Sandy clay loam covers just 0.01%, with low infiltration due to fine structure and restrictive layers. Clay loam, making up 0.77%, has high runoff potential and limited infiltration. Sandy loam accounts for 22.82% and supports high infiltration with low runoff [30]. The absence of silty soil overall lowers the region's suitability for rainwater harvesting due to its less favorable texture.

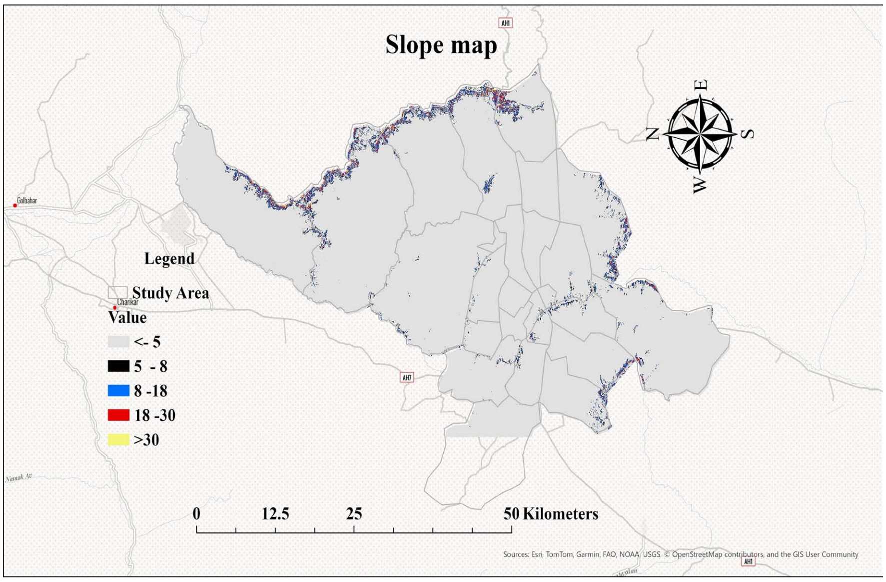

Figure 4. Slope map.

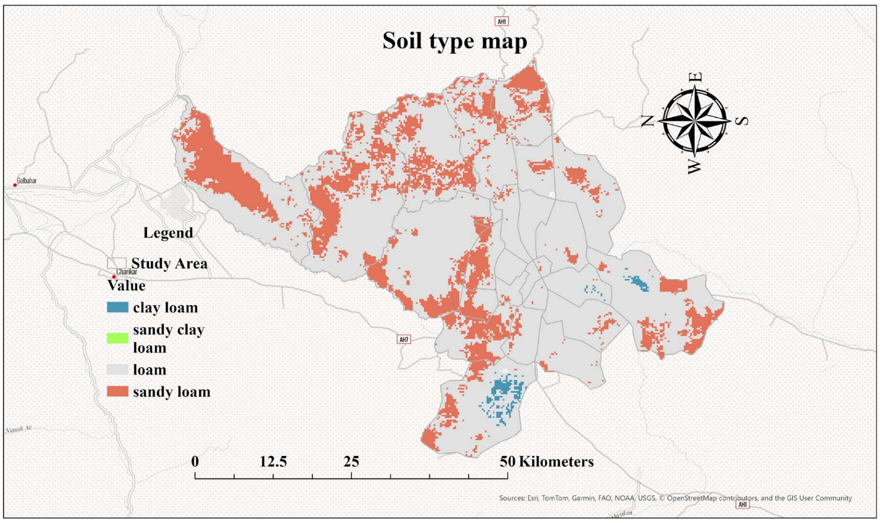

Figure 5. Soil map.

4) Land Use/Land Cover

The LULC of the study area was categorized into seven classes: Water bodies, developed land, Barren, Shrubland, Planted, Snow, and Mountains. As shown in Figure 6, water bodies cover 3.3% of the area, while urban or developed land accounts for 31.2%. Barren land makes up 29.7%, and shrubland, characterized by sparse vegetation, covers 2.01%. Planted or cultivated areas represent 23.8%, and around 27.7% of the area is covered by snow and mountainous terrain.

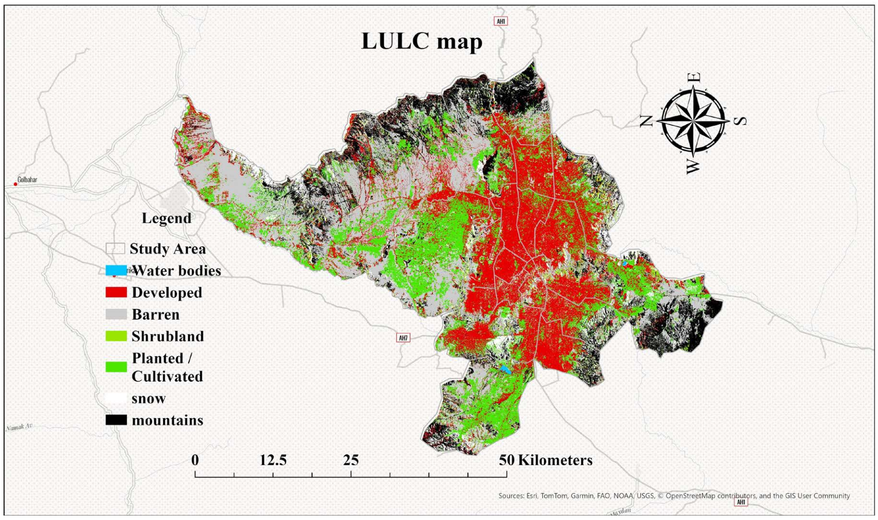

Figure 6. Land use land cover map.

5) Drainage Density

The drainage density map, shown in **Figure 7**, highlights the spatial distribution of drainage patterns across the study area. According to the analysis, 42.31% of the area has a drainage density ranging from 0.01 to 13.96 km/km^2, 23.16% falls between 13.96 and 37.2 km/km^2, 18.27% between 37.2 and 61.6 km/km^2, 10.62% between 61.6 and 92.5 km/km^2, and 5.59% exceeds 92.5 up to 148.4 km/km^2. Overall, more than 90% of the area has a drainage density above 0.05 km/km^2, indicating a generally favorable drainage density in the study area.

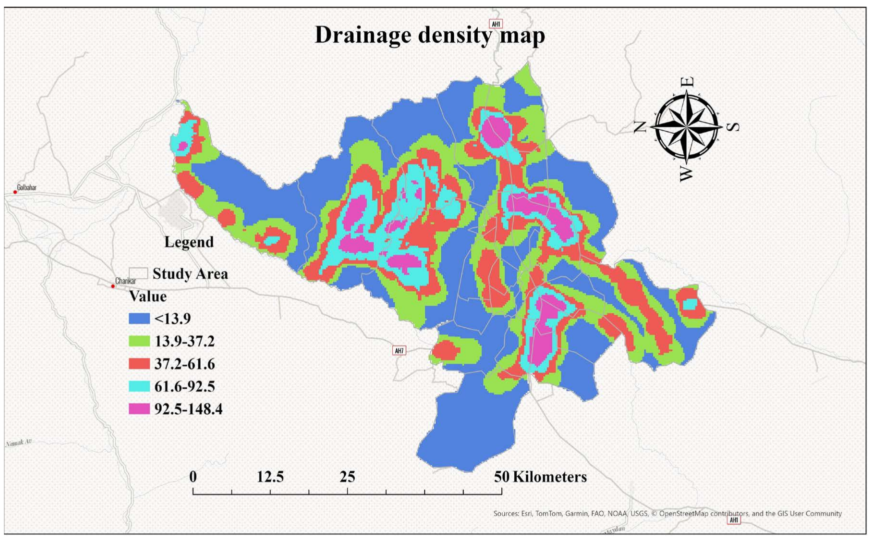

Figure 7. Drainage density map.

6) Lithology

The lithology map, presented in **Figure 8**, illustrates the spatial distribution of surface rock types across the study area. Lithological units were categorized based on their hydrological properties and then reclassified into five suitability classes for RWH. According to the analysis, 2.9% of the area consists of sandstone and shale. Sandstone and gravel formations are highly permeable, allowing more infiltration and thus are less suitable for surface RWH [31]. Granite and gneiss cover 35.9% of the area, sand and gravel account for 16.7%, limestone and shale 30.9%, and granite with schist 13.4%. The most dominant lithology is granite and gneiss, followed by limestone and shale. Notably, limestone formations are generally impermeable, restricting water infiltration and promoting surface runoff, which makes them highly suitable for surface rainwater harvesting [31].

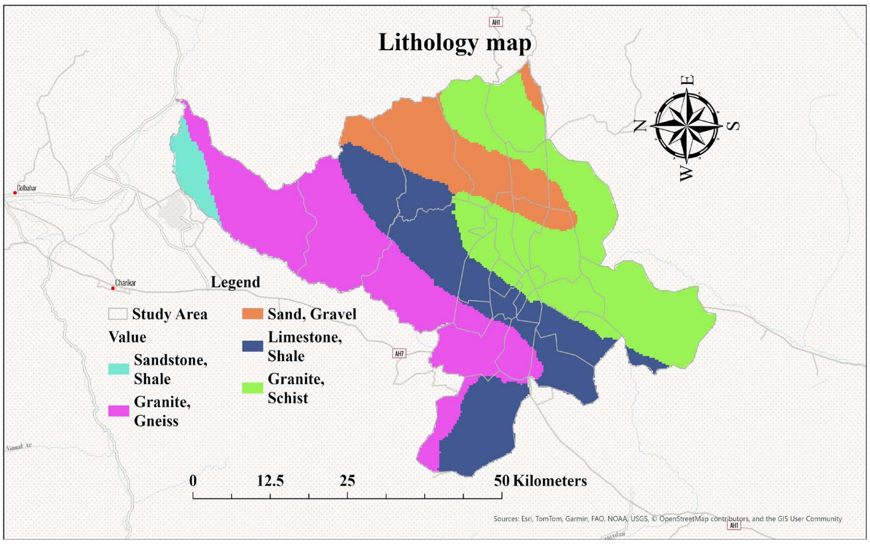

Figure 8. Lithology map.

7) Site Suitability Final Map

Six biophysical layers were combined using their assigned weights and classified features to produce the rainwater harvesting potential map shown in **Figure 9**. Based on the analysis, the study area has been classified into three zones: least

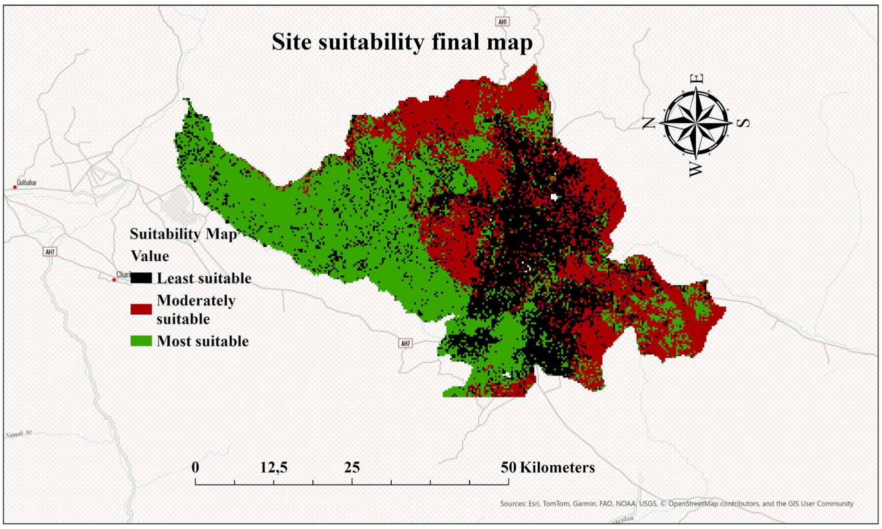

Figure 9. Site suitability final map.

suitable, moderately suitable, and most suitable for RWH. The least suitable zones are primarily concentrated in the central part of the study area, which includes the developed urban core of Kabul city, covering approximately 430.5 km^2, 28.5%. The moderately suitable zones are mainly located around eastern, southern, and south-western areas, accounting for about 466.5 km^2, 30.9%. The most suitable RWH zones are predominantly found in the northern and western parts of the study area, as well as in some smaller western districts, covering around 610.9 km^2, 40.5%.

3.2. Weighting Results and Suitability Classification

Rainfall was assigned the highest weight of 24% among the biophysical factors, as described in **Table 6**. This reflects the expert survey results and is consistent with the literature, which indicates its strong influence in identifying suitable RWH sites. In contrast, the drainage density layer received the lowest weight of 11%. The consistency ratio of the comparison matrix was 9%, which is below the acceptable threshold of 10%, indicating satisfactory consistency in the weighting process [18] [31]. Based on these assigned weights, a weighted overlay analysis was conducted to identify suitable catchments within the study area. The continuous suitability index was classified into three zones (least, moderate, and most suitable) using the natural breaks (Jenks) method in ArcGIS Pro, which minimizes within-class variance and maximizes between-class variance.

Table 6. The weights of each primary factor.

Factors	Class Value	Rating	Weights %	Justification/References
Rainfall	<315	1	24	Rainfall is a critical factor in any water collection system, and it stands as the most significant criterion in assessing rainwater harvesting (RWH) potential [17] [31].
	315 - 336	2		
	336 - 377	3		
	377 - 429	3		
	429 - 476	3		
Slope (˚)	<5	3	22	For RWH potential, gentler slopes are preferred; however, in steeper catchment areas, erosion control measures must be considered [17] [19] [31].
	5 - 8.6	3		
	8.6 - 18.4	2		
	18.4 - 29.6	1		
	>30	1		
Soil Type	Clay Loam	2	12	Loam soil offers moderate infiltration due to its balanced texture, while clay loam has limited infiltration and high runoff potential. Sandy loam supports high infiltration with minimal runoff, but both sandy loam and sandy clay loam are considered to have low suitability for [17] [19] [30].
	Sandy Clay loam	1		
	Loam	2		
	Sandy Loam	1		

Continued

Lithology	Sandstone, Shale	1	13	Lithology influences permeability and infiltration rates at RWH sites, with low-permeability rock types typically yielding higher volumes of harvested rainwater [31].
	Granite, Gneiss	3		
	Sand, Gravel	1		
	Limestone, Shale	3		
	Granite, Schist	2		
LULC	Water Bodies	Restricted	18	Rainwater harvesting (RWH), whereas barren lands are regarded as highly suitable due to their greater runoff potential [1] [17] [30] [31].
	Developed Land	Restricted		
	Barren	3		
	Shrubland	2		
	Planted	2		
	Snow	3		
	Mountains	1		
Drainage Density	0.01 - 13.96	1	11	Areas with higher drainage density are considered more suitable for rainwater harvesting (RWH), as they offer an efficient network for runoff to flow and be captured promptly [31].
	13.96 - 37.2	2		
	37.2 - 61.6	3		
	61.6 - 92.5	3		
	92.5 - 148.4	3		

Note: This table is original content created by the authors for this study.

The results showed that 40.5% of the area was classified as highly suitable for RWH, with favorable rainfall, topography, lithology, and soil texture that naturally support water retention and require minimal intervention. Approximately 30.9% of the area was classified as moderately suitable, representing most of the study area, where the implementation of RWH technologies would require improvements in physical and technical conditions such as water availability, slope, LULC type, and soil characteristics. Around 28.5% of the study area was classified as less suitable or unsuitable for RWH. From an economic perspective, RWH is most effective in flat terrains where runoff can be harvested with minimal earthwork. However, the study area is characterized by mountainous topography, and runoff tends to flow towards the flatter, central regions **Figure 4**, making the weight assignment process more complex. Nevertheless, the prioritization of rainfall and slope in this study is consistent with previous findings [17] [30].

3.3. Validation of Suitability Mapping Results

Currently, no functional RWH structures exist in KMA to facilitate direct validation of the results. Therefore, comparison with the master plan is not intended as a scientific validation, but rather as a consistency check to ensure that the most suitable zones identified in this study do not contradict major planning documents. Due to the absence of existing RWH infrastructure in the study area, direct scientific validation remains unfeasible, and this limitation is acknowledged.

Nevertheless, in the Conceptual Design of the Drainage and Sewerage System for Kabul New City [36], the site located at coordinates 69.2810688˚E, 34.7332252˚N, designated as a natural water reservoir for diverted stormwater and effluent disposal, coincides with the "most suitable" zones identified by this study's RWH suitability map, as shown in **Figure 10**.

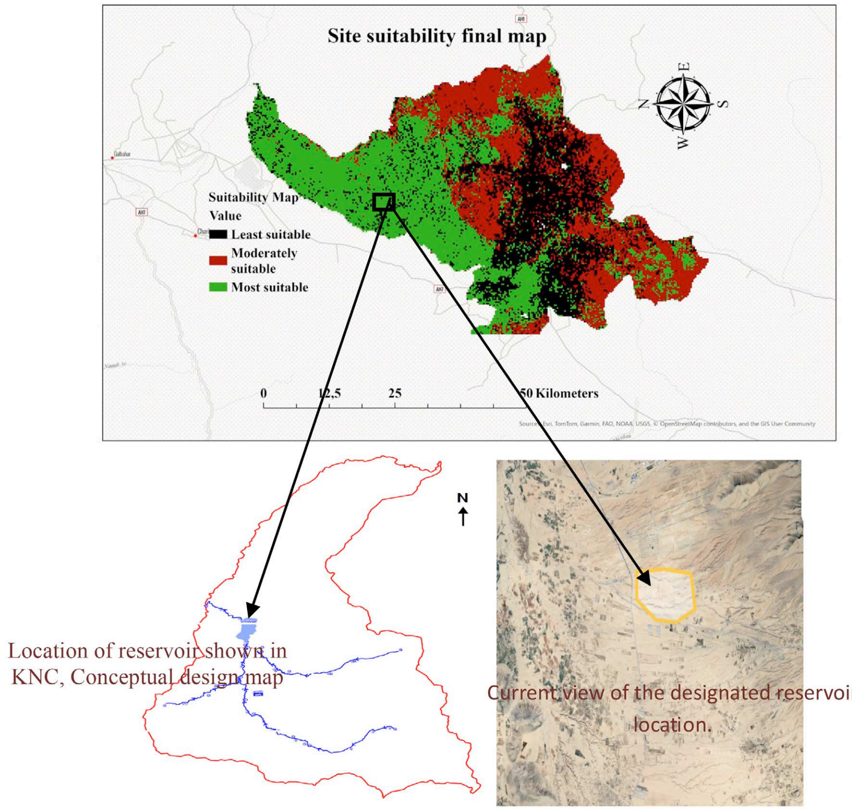

Figure 10. Validation map of potential RWH site.

To determine suitable RWH locations, this research integrated multiple criteria, including biophysical factors and expert knowledge. Afghan professionals with experience in implementing water management projects in the study area contributed their insights to enhance the reliability of the analysis. The selection of RWH suitability criteria was guided by existing literature, FAO recommendations, and practitioner expertise. The main objective was to develop a GIS-based decision-support framework for identifying suitable catchment zones for surface rainwater harvesting using key biophysical factors. It is essential to note that combining all selected layers is critical for accurate site selection. However, when applying this framework to other regions, local expert input is necessary to review and adjust the weighting of the criteria. Additionally, should any parameter be excluded, the remaining weight must be recalibrated to ensure the model remains valid and consistent.

3.4. Sensitivity Analysis

To evaluate the sensitivity of the RWH suitability classification, the one-at-a-time sensitivity analysis was conducted using the varying weight of the criterion of maximum sensitivity (rainfall), +10%, −10%, +20%, and −20%, with weights of other criteria, such as slope, LULC, lithology, soil and drainage density being varied in proportion to the total weight of 100%. Weighted overlay in ArcGIS Pro was then recalculated using the new criteria weights. For comparison purposes, all raster maps were classified using the same class breaks as the base case. Based on the previous studies, sensitivity analysis through variation of criteria weights has been widely applied in GIS-based AHP suitability studies to evaluate the robustness of spatial decision-making results [37]. **Table 7** presents the area percentages classified as Least, Moderate, and Most suitable under the different scenarios.

Table 7. Sensitivity analysis results for rainfall weight variations.

Scenario	Least Suitable (%)	Moderate Suitable (%)	Most Suitable (%)
Base	28.5	30.94	40.51
Rainfall +10%	28.5	39.36	32.08
Rainfall −10%	28.5	30.94	40.51
Rainfall +20%	28.5	36.93	34.52
Rainfall −20%	28.5	30.96	40.49

As can be seen in **Table 7**, the area classified as Least Suitable showed very little variability (around 28.55%) under the different scenarios, implying that the least suitable area is not sensitive to variations in rainfall weight. The Most Suitable area percentages ranged from 32.08% to 40.51% under different scenarios, showing moderate sensitivity to rainfall weight variations. Decreasing rainfall weight by 10% and 20% produced results nearly identical to the base case (40.51% and 40.49%, respectively), while increasing rainfall weight reduced the Most Suitable area to 32.08% (+10%) and 34.52% (+20%).

The low sensitivity to negative rainfall weight variations is explained by **Table 6**, where rainfall in KMA (315 - 476 mm/year) was rated as highly suitable (rating 3) for all classes above 315 mm by experts. Thus, even with reduced weight, rainfall remained in the highest suitability category for most of the study area.

Importantly, the spatial distribution of high-suitability zones, particularly in the northern and western parts of the KMA, remained generally consistent across all scenarios. These findings suggest that the overall suitability pattern is reasonably robust despite moderate variations in expert-assigned weights.

4. Conclusions

In KMA, water scarcity has become a serious issue due to speedy urbanization and heavy reliance on groundwater resources. On the other hand, the absence of functioning RWH structures has deepened the challenge, which highlights the urgent need for alternative water sources. The main purpose of this research was to identify suitable catchment areas where rainwater harvesting structures can be constructed to enable effective and efficient management of rainwater resources. Internationally, there have been a lot of studies about RWH site suitability mapping. However, studies to address this issue are not known to have been conducted in KMA, Afghanistan.

This study addressed the above-mentioned gap by applying a GIS-based MCDA approach, using the AHP to determine the relative importance of six selected biophysical factors: rainfall, slope, soil type, LULC, drainage density, and lithology. These six factors were selected based on comprehensive literature reviews and FAO advice, and their relative importance was determined through an expert opinion survey of Afghan professionals familiar with the study area. A weighted overlay analysis was applied in ArcGIS Pro to identify possible suitable RWH zones by allocating weight to each factor. The consistency ratio (*CR*) of the pairwise comparison matrix was 0.09, which is below the acceptable threshold of 0.1, indicating reliable expert judgments.

Based on the integrated weighted overlay analysis, the study area was classified into three zones of suitability for RWH. Approximately 40.5% of the area was identified as most suitable, 30.9% moderately suitable, and 28.5% of the research area was classified as least suitable. These percentages are dependent on the chosen classification method and should be interpreted as relative indicators rather than absolute values. The classification of the least suitable area was mainly due to steep slopes, developed areas, and unsuitable soil textures or lithological characteristics.

For validation, no existing RWH structures are available in the project area. Direct scientific validation is not possible due to the absence of existing RWH infrastructure, and this limitation is acknowledged. The comparison with the master plan is not intended as scientific validation, but as a consistency check. Nevertheless, the designated natural water reservoir falls within the most suitable zone identified by this study, confirming its practical relevance. Similarly, a sensitivity analysis varying the rainfall weight (±10%, +20%) confirmed that the spatial pattern of suitable zones remained stable, demonstrating the robustness of the results.

The methodology presented in this study (GIS + AHP) is transferable to other semi-arid regions. It does not depend on Kabul-specific data. Any ASAR with basic satellite data (DEM, soil, Landsat, rainfall stations) can apply the same steps. The weighting can be adapted, and this paper provides a framework. Additionally, the data sources used (DEM, Landsat, soil grids) are open access and freely available worldwide, making replication easy. To apply this framework to other similar regions, revision and adjustment of the weights for each factor are essential with input from local experts. If any factor or parameter is excluded, the weights of the remaining layers must be re-evaluated to maintain consistency and reliability.

Overall, this research provides a practical framework for locating suitable areas for RWH in KMA. Recommended future studies include identification of RWH storage structures, hydrological simulations, cost-benefit analysis, and incorporation of soil thickness data and water quality checks where available. The framework can be refined and adapted for broader applications in developing countries with similar climatic conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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