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Article

Geospatial-based AHP approach for rainwater harvesting sites in semi-arid areas: a case study of Wadi Abu Ghraibat

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ABSTRACT

Rainwater harvesting is becoming an important method of water management in semi-arid areas characterized by seasonal and perennial water scarcity. The investigation demonstrates a novel Analytic Hierarchy Process technique based on geospatial methods, applied to assess site suitability for rainwater harvesting in the semi-arid Wadi Abu Ghraibat area. Elevation, slope, precipitation, and drainage density were the four variables considered important in this respect. Each of these criteria was processed using both GIS and remote sensing data and weighted by the Analytic Hierarchy Process, which assigned 24% to elevation, 10% to slope, 22% to precipitation, and 44% to drainage density, with a consistency ratio of 0.06, which was acceptable. Therefore, the suitability map can be considered the area's most suitable for implementing rainwater harvesting practices. Although it is limited to water-stressed environments, interesting findings on water resource management lessons emerge. GIS-based integrated approach combining MCDA with GIS for sustainable water management in drought-prone regions.

1. Introduction

Water scarcity one of the most serious problems occurring in semi-arid areas around the world, and it impacts ecosystems as well as people [1]. As regions with low and unpredictable rainfall, high evaporative rates, and increasing water demand, semi-arid areas need new approaches to water resources management to ensure sustainability [2]. Rainwater harvesting (RWH), a traditional practice undergoing technological development, has been identified as a new water source and an effective means of supplementing water supplies, especially in water-stressed ecosystems [3]. The application of RWH systems should be carried out in the most efficient and cost-effective manner [4]. The site selection techniques involve considerable data collection and surveys, which are time-consuming and sometimes prone to bias [5]. RWH system sites can now be selected using a combination of GIS and Multi-Criteria Decision Analysis (MCDA) techniques, thanks to a novel approach that has emerged in recent decades [6]. Despite the critical need for sustainable water management in the semi-arid region of Wadi Abu Ghraibat, the area suffers from acute, escalating water scarcity driven by erratic seasonal rainfall, high evaporation rates, and rising demands from an expanding population and agricultural sector. Traditional water management techniques in this basin rely heavily on uncoordinated groundwater extraction and minor surface water sources, which are rapidly depleting and vulnerable to the accelerating impacts of climate change. Moreover, the identification of suitable sites for RWH interventions has traditionally relied on qualitative or monofactorial, localized assessments. These traditional methods do not account for the highly heterogeneous landscape characterized by fluctuating topography, varied soil infiltration capacities, and complex drainage networks. Current site selection methods are time-consuming, susceptible to cognitive bias, and often lead to suboptimal engineering placements that result in structural failures or low water-collection efficiencies. The absence of a transparent, quantitative, and spatially continuous framework that integrates multiple controls simultaneously prevents decision makers from systematically identifying hydrological hotspots, leaving the region highly vulnerable to recurrent water deficits and ecological stress. The Analytic Hierarchy Process (AHP), proposed by Saaty [7] in 1980, has attracted considerable attention in the field of MCDA for its effectiveness in integrating quantitative and qualitative variables in decision-making. The AHP process [8] facilitates the measurement of the relative importance of various criteria to inform the decision during the evaluation process itself. When combined with geospatial technology, AHP facilitates spatial analysis of criteria to identify the best sites for specific interventions [9]. Wadi Abu Ghraibat is a semi-arid area facing severe water shortages. It can be identified in regions with no access to fresh water, high dependence on rainfall, and rising demand due to population growth and the agricultural sector [10]. In such an area, RWH can potentially mitigate such levels of scarcity and ensure higher agricultural productivity and water security.

The objective of this research is twofold: to develop a reproducible, GIS-integrated MCDA framework specifically tailored to the geomorphology of Wadi Abu Ghraibat, and to systematically quantify and map macro-scale suitability zones to minimize decision-making bias in regional water infrastructure development. This research will develop an AHP framework that uses geospatial data to identify optimal rainwater-harvesting locations in Wadi Abu Ghraibat. AHP-GIS will ensure the rationality of decisions made for water resource management at Wadi Abu Ghraib, which could help increase the existing literature on the rational use of water. Unlike conventional site-selection approaches that rely on qualitative judgment or single-factor analysis, this research provides a transparent, quantitative, and reproducible GIS-based AHP workflow that explicitly links topographic controls, hydrological behavior, and rainfall variability.

2. Materials and methods

2.1 Study area

Wadi Abu Ghraibat is located in a semi-arid area. The study area is geographically situated within the Maysan Governorate in southeastern Iraq, bounded by latitudes 32°05′00″ N to 32°25′00″ N and longitudes 47°05′00″ E to 47°25′00″ E. Geomorphologically, the structural setup of Wadi Abu Ghraibat yields a highly heterogeneous terrain characterized by elevated structural plateaus, intermediate steps, and low-lying alluvial basins.

This distinct topographic configuration directly controls the region's dendritic drainage network, thereby concentrating surface runoff and defining the region's hydrological suitability for localized water-harvesting initiatives. This distinct topographic configuration dictates the region's dendritic drainage network, thereby directly influencing the concentration of surface runoff and defining the region's hydrological suitability for RWH [11]. It is a place characterized by harsh environmental conditions and extreme water scarcity. The study area includes a variety of landscape features that are intrinsically related to its topography, drainage network, and climatic regime, as shown in Figure 1.

The climate of the region is semi-arid, with sparse, erratic rainfall, most of which falls during specific seasons. Annual precipitation is quite low, thus triggering recurrent water deficits [12]. The terrain is highly heterogeneous, comprising low-lying basins, mid-level depressions, and elevated plateaus, and hence provides a variety of sites with potential to effectively harvest rainwater [13,14]. The drainage system of Wadi Abu Ghraibat is well developed due to the presence of several seasonal watercourses. The surface lithology of Wadi Abu Ghraibat is predominantly characterized by Neogene sedimentary successions, including the silty sandstones and mudstones of the Injana Formation, overlain by pebble conglomerates and sandstones of the Mukdadiya Formation. The soil stratum primarily comprises calcaric fluvisols and gypsic regosols, characterized by sandy loam to clay loam textures. These soil profiles exhibit highly variable infiltration capacities, where the exposed, compacted sandstone units yield low infiltration and high surface runoff coefficients, whereas the alluvial valley fills facilitate rapid transmission into shallow groundwater zones [15].

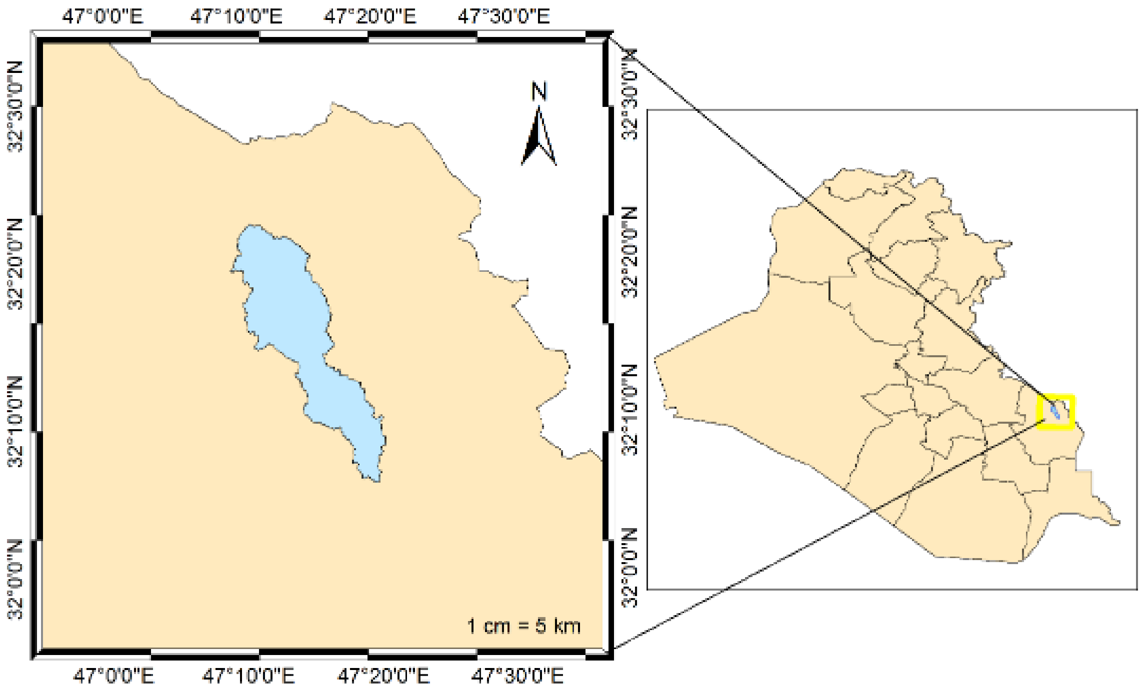

Figure 1. Location of the study area

Land use across the region is characterized by agriculture, with vegetation and small settlements. The major sources of water for the local population are groundwater and small surface water sources. Water demand has increased over the years due to climate change, which affects rainfall patterns. These factors make Wadi Abu Ghraibat a preferred candidate for applying geospatial AHP methodologies to identify potential rainwater-harvesting sites that could provide a sustainable solution to the region's water problems.

2.2 Data acquisition and processing

A geospatial dataset was created by combining multiple datasets to analyze RWH site suitability in the Wadi Abu Ghraibat region. Selection criteria were developed through reviews and consultations with experts to ensure that all factors significantly influencing RWH in semi-arid zones were considered. Topographic parameters, specifically elevation, slope, and drainage network density, were modeled in ArcGIS Pro 3.1 using a 1-arc-second USGS Digital Elevation Model (DEM). Preprocessing of the elevation dataset involved executing the Wang and Liu [16] algorithm to eliminate spurious sinks, thereby securing hydrological continuity. Then the drainage networks were delineated using the D8 flow model along the maximum descending slope. This provided the accumulation vectors for computing final drainage densities. Precipitation data were obtained from the Global Precipitation Measurement (GPM) mission, which provides spatially continuous rainfall estimates for semi-arid environments. Daily precipitation data were retrieved from the GPM Integrated Multi-satellite Retrievals for GPM (IMERG) Final Run product (Version 06) to evaluate the precipitation patterns. The dataset has 20 years of temporal coverage from January 2005 to December 2025, capturing long-term climate variability and seasonal anomalies in this semi-arid ecosystem.

The IMERG Final Run has a spatial resolution of 0.1 degrees (~10 km) and is calibrated using gauge analysis to achieve the best accuracy in arid and drought-prone regions [17]. All datasets were projected to the WGS 1984 coordinate system, resampled to a common spatial resolution, and subjected to quality control, gap filling, and normalization before analysis; all data details are shown in Table 1. The Topographic data were derived from the US Geological Survey (USGS) 1-arc-second-resolution DEM. The elevation and slope themes were derived using spatial analysis in the GIS environment using this dataset [18]. The hydro analysis tools for drainage mapping and drainage parameter derivation were also used to create the drainage density theme from the DEM. The precipitation data were obtained according to the GPM mission. It is a high-resolution rainfall dataset for the study region, enabling fine-grained quantification of annual and seasonal rainfall variability (an essential parameter for assessing RWH potential) [19]. All datasets were converted to the WGS 1984 coordinate reference system and resampled to a common spatial resolution, thereby ensuring compatibility across analytical workflows. Pre-processing steps such as rigorous quality checks, gap filling, and normalization were implemented to enhance data integrity for subsequent multi-criteria evaluation.

2.3 Criteria selection and standardization

Criteria selection: Moderate-elevation sites are considered optimal for Rainwater Harvesting (RWH) because they facilitate gravity-based distribution systems. Very high altitudes can produce excessive runoff, while low-lying areas may be prone to flooding, reducing harvesting efficiency [20]. The second criterion is the slope, which should be a gradient of between (5-15) %, which is optimal in RWH. Steeper slopes increase runoff speed, reducing the likelihood and extent of water pooling, whereas flatter slopes may lead to poor drainage and subsequent waterlogging. Recent hydrological assessments in arid catchments (e.g., Sayl et al [20]; Al-Kakey et al. [21]) strongly support the emphasis on slope ranges of 5–15% as highly suitable. Slopes less than 3% generally lack the hydraulic head to induce significant channel flow into structural storage reservoirs, while slopes greater than 20% generate velocities that lead to excessive channel-bed erosion and high structural risks of siltation. Precipitation had greater weight in the area of study that received higher precipitation levels, since under such conditions, the chances of successful harvesting are high. Assessments of regional precipitation distribution delineated specific geographic sectors capable of producing sufficient rainfall to justify developing rainwater collection infrastructure [21]. Finally, high drainage density regions indicate a well-functioning drainage system and represent areas where harvesting rainfall is beneficial.

Table 1. Data sources for the study

Dataset	Data Source	Spatial Resolution	Processing Methods / Derived Layers	Coordinate Reference System
DEM	USGS	1 arc-second (~30 m)	Sink Filling, Flow Direction Elevation, Slope, Drainage Density	WGS 1984 UTME Zone 38N
Precipitation	NASA GPM (IMERG V06)	0.1 *0.1 Degree	20-year Mean Annual Aggregation & Kriging Interpolation.	WGS 1984

Certain parameters, such as LULC and soil texture, were deliberately excluded from this regional macroscale mapping due to the Wadi Abu Ghraibat's extreme environmental homogeneity. The area consists almost exclusively of barren, unmanaged soil and sparse seasonal shrublands, resulting in negligible spatial variations in LULC roughness coefficients. Similarly, regional soil maps indicate a predominantly uniform sandy loam texture across the central wadi floor. Consequently, spatial variations in runoff generation are overwhelmingly dictated by topographic controls (elevation and slope) and structural drainage routing networks rather than variations in vegetation or soil properties. Each criterion layer was then normalized to a common scale (1-5) via reclassification, with higher values indicating greater suitability for harvesting. Such standardization facilitates comparability of the criterion layers.

2.4 Analytic hierarchy process (AHP)

The AHP was used to establish the relative weight of the criteria relevant to the selection of appropriate RWH sites [22]. A pairwise comparison matrix was developed following a thorough review of the relevant literature, enabling systematic comparison of the criteria [23,24]. The qualitative pair-wise evaluations were established via a structured expert consultation workflow involving a panel of seven experts selected through purposive sampling. The panel comprised three senior hydrogeologists specializing in hyper-arid watersheds, two GIS/remote sensing professors, and two regional water resources engineers from the Ministry of Water Resources, Iraq. A Delphi-based consensus procedure was conducted over three iterative rounds of surveys to harmonize individual pairwise matrices, culminating in final weights once the panel's average Kendall's Coefficient of Concordance (W) reached an acceptable consensus threshold of 0.82. A pairwise comparison matrix for the four thematic layers is illustrated in Table 2.

Table 2. Pairwise comparison matrix for the four thematic layers

Theme	Elevation	Slope	Precipitation	Drainage density	Weight %
Elevation	1	3	1	1/2	24%
Slope	1/3	1	1/2	1/5	10%
Precipitation	1	2	1	1/2	22%
Drainage density	2	5	2	1	44%
C.R.=6%					
CI = 0.027			RI = 0.90		

The subsequent matrix explains the relative importance of each criterion. For instance, the elevation factor is evaluated as three times more important than slope, but it is of equal value to precipitation. The factor that carries the greatest weight is drainage density, at 44%, followed by elevation at 24%, precipitation at 22%, and slope at 10%. The Consistency Ratio (C.R.) of 0.06 is below the threshold of 0.1, indicating acceptable consistency in the pairwise comparisons and the accuracy of the assigned weights. The mathematical consistency of the AHP matrix was validated using Saaty's framework. The consistency index (CI) was computed using the Equation:

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

where λ_{max} is the maximum principal eigenvalue (calculated as 4.081), and n is the number of evaluation criteria (n = 4). The Consistency Ratio (CR) was determined using Equation:

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

where RI represents Saaty's Random Index (RI = 0.90 for 4 *4 matrix). This yielded a CR of 0.06, well below the standard 0.10 threshold, verifying matrix stability.

2.5 Suitability analysis

The relative weights derived from the Analytical Hierarchy Process (AHP) governed the weighted overlay analysis, merging the normalized spatial criteria into a comprehensive suitability index map [25]. The suitability analysis can be mathematically modeled as:

$$\text{Suitability Index} = (\text{Elevation} \times 0.24) + (\text{Slope} \times 0.10) + (\text{Precipitation} \times 0.22) + (\text{Drainage density} \times 0.44) \tag{3}$$

Then classified into five categories of very low, low, moderate, high, and very high suitability, thus fully indicating the potential RWH sites across the study area. The spatial analysis output provides a basis for decision-makers to plan for priority areas and hotspots in RWH implementation based on scientific criteria.

3. Results and discussion

3.1 Criteria analysis

The four criteria layers identified characteristic patterns within the Wadi Abu Ghraibat area using Spatial analysis that can affect RWH potential in the study area, as shown in Figure 2. According to the topographic map, there is a gradual change between the center and the eastern section of the study area, where elevations range from 200 m to 800 m above sea level. Territories with an average altitude between 300 m and 500 m were identified as the most suitable sites for RWH. The slope percentage analysis revealed that about 35% of the study area has gentle slopes (0 to 5%), whereas 40% have slopes (5 to 15%). The other 25% is steep, with slopes greater than 15%. The relatively flat terrain, which was mostly along natural drainage systems, was highly conducive to RWH systems. Drainage density was highest in the mid and western regions of the study area. These regions are characterized by a dense stream network and are the most preferred for harvesting the rainfall due to their natural ability to concentrate the runoff. The importance of the analysis of drainage density was reflected in the higher weight assigned in AHP (44%). Patterns of precipitation showed an overall east-to-west trend, with heavier rainfall in the eastern highlands and lighter rainfall in the western lowlands. The amount of rainfall per year ranged from 150mm to 350mm, with the majority recording 200-250mm. Regions with heavier rainfall were clearly more conducive to RWH, although combining this criterion with other parameters enabled the identification of better locations.

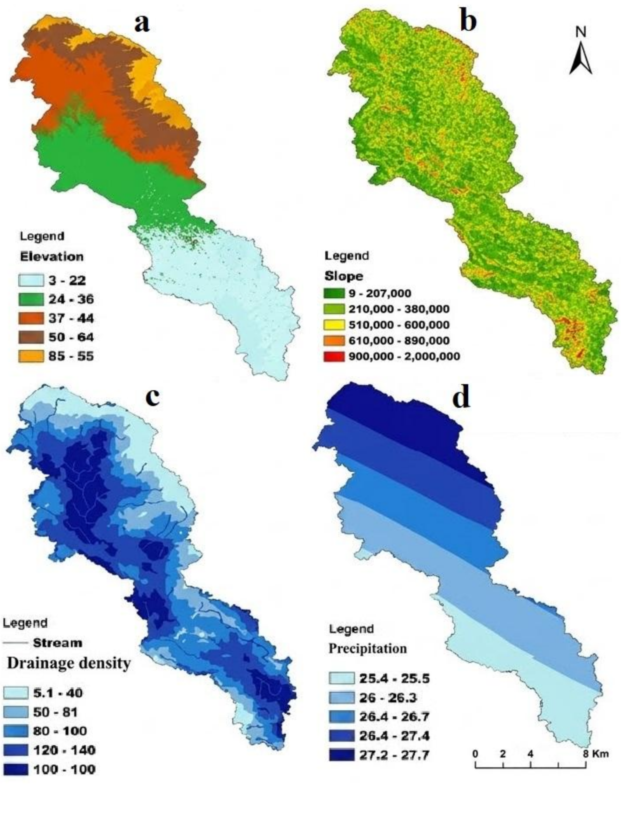

Figure 2. Criteria layers across the study area

3.2 Reclassified criteria

The original criterion layers were rescaled to suitability classes (1-5) to normalize them for conducting weighted overlay analysis, as shown in Figure 3. This reclassification process enabled an easy transition from continuous data to discrete suitability classes. Under elevation, 300-500m was assigned the highest degree of suitability with an index score of 5, while very high regions (>700m) and low regions (< 250m) were assigned lower scores. Regarding slope, the 5-15% category received the highest suitability rating (5) because this range is ideal for water collection and incurs little to no erosion costs. Very steep slopes in the >25% category received the lowest rating (1) because they receive little to no water. Drainage density received suitability ratings based on the density of stream networks per unit area, with densely populated networks receiving the highest suitability rating. Precipitation was reclassified based on annual rainfall and ranked as follows: above 300mm as very suitable (5) and below 200mm as least suitable (1). Table 3 summarizes the class threshold.

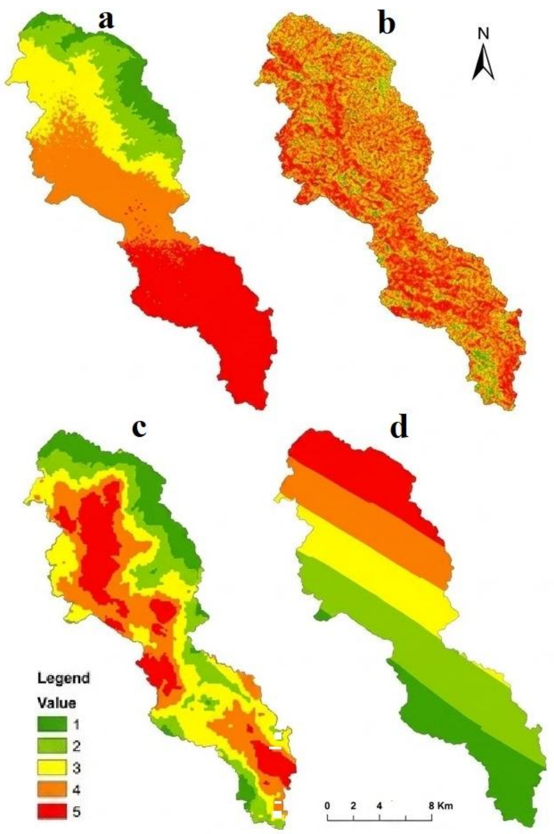

Figure 3. The reclassified raster. A) Elevation; B) Slope; C) Drainage density; D) Precipitation. (Values 1-5 represent increasing suitability for RWH).

3.3 Final suitability map

The integration of the four reclassified criteria layers using AHP-derived weights produced the final RWH suitability map for Wadi Abu Ghraibat, as shown in Figure 4. From the final suitability map, 12% of the study area has very high suitability for RWH, followed by 23% with high suitability, 30% with moderate suitability, 25% with low suitability, and 10% with very low suitability. The zone of most suitable areas (Very High & High) largely encompasses the middle and western part of the study area. Moderate elevation, gently sloping landscape, very dense drainage pattern, and moderate precipitation levels are among the predominant factors in these areas. The High and Very High suitability zones are predominantly clustered along the central-western geomorphological flank where drainage density values apex between 150 and 190 km/km^2. Indeed, such areas have a well-developed drainage network that concentrates run-off water. This makes these areas the most suitable for developing check dams or RWH structures. The spatial distribution of the moderately suitable sites is scattered around the study area, usually at the boundary between highly suitable and less suitable regions. In some cases, these regions will need more detailed examination before rainfall harvesting schemes are developed. The regions where the suitability for RWH schemes is (low and very low) are generally where there are steep slopes, drainage density is low, and rainfall can be considered low.

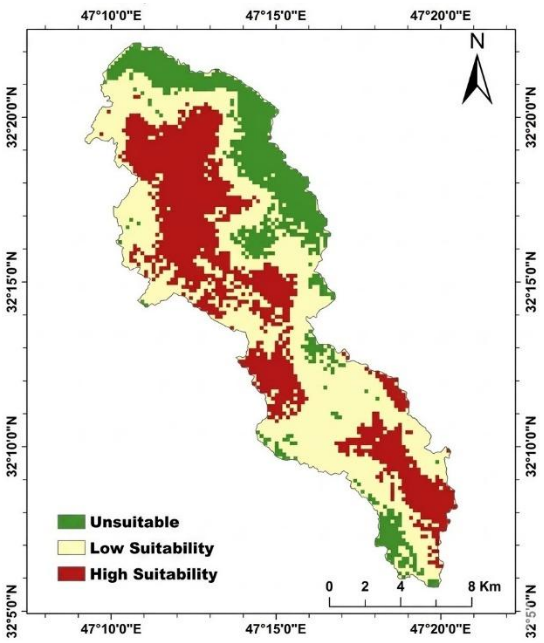

Figure 4. Final suitability map for the study area

Table 3. The four-class threshold

Criterion	Layer Unit	Class 1 (Very Low)	Class 2 (Low)	Class 3 (Moderate)	Class 4 (High)	Class 5 (Very High)
Drainage Density	Km/Km^2	5.1 – 49	50 – 81	82 – 110	120 – 140	150 – 190
Elevation	m	<250	250 – 300	500 – 700	700 – 800	300 – 500
Precipitation	mm/ year	<200	200 – 230	230 – 260	260 – 300	>300
Slope	%	>25	15 – 25	0 – 3	3 – 5	5 – 15

4. Discussion

The results of this study demonstrate the efficiency of integrating geospatial technologies with AHP for selecting suitable RWH sites in semi-arid regions. The technical novelty of this research lies in the development of an integrated open-source geospatial decision matrix specifically tailored to data-scarce transboundary desert basins. By demonstrating how macro-scale terrain models and satellite GPM engines can circumvent restricted access to physical field data, this workflow provides a template for water resource planning that is easily adaptable to other drought-prone zones worldwide. Deploying harvesting structures within the high-suitability zones of Wadi Abu Ghraibat presents distinct operational challenges, most notably the high atmospheric evaporation rates characteristic of the Maysan Governorate. To mitigate substantial surface water losses, structural designs should prioritize sub-surface sand-storage dams or check dams configured to accelerate localized infiltration into shallow alluvial aquifers. This strategic integration with local groundwater systems transforms ephemeral surface runoff into reliable subsurface reserves, mitigating atmospheric losses while providing sustainable agricultural supply channels for local agrarian communities.

The high weight assigned to drainage density (44%) reflects its critical importance in selecting the best site for rainwater harvesting, as areas with a well-developed drainage network tend to concentrate surface runoff, thereby increasing the efficiency of harvesting structures. The heavy weighting assigned to drainage density (44%) relative to precipitation (22%) is a deliberate reflection of regional hydro-meteorological controls. In hyper-arid catchments such as Wadi Abu Ghraibat, ambient annual precipitation is uniformly low (150–350 mm) throughout the bounding box. Because rainfall volumes alone are rarely sufficient to trigger widespread soil saturation, successful RWH relies entirely on natural geomorphological conduits that can concentrate massive volumes of ephemeral surface runoff into central collectors. The geographical distribution of such sites aligns with hydrological concepts, with the most suitable sites being those where surface topography and rainfall patterns are most conducive to RWH. The identified RWH sites in the central and western areas of Wadi Abu Ghraibat provide a very promising setting for the development and implementation of such a project. Compared with conventional methods, the geospatial-AHP approach to site selection is more systematic and comprehensive in evaluating RWH sites. The approach is less biased towards decision-making than conventional methods and enables the simultaneous assessment of several factors of varying significance.

The results achieved in this study have several implications for the management of water resources in Wadi Abu Ghraibat and other similar semi-arid regions. The locations identified as suitable could be considered high-priority for implementing any rainfall-harvesting project. Our finding that 35% of the catchment area exhibits high or very high suitability for RWH aligns closely with model structures developed for semi-arid environments in Iraq and neighboring regions. For instance, Al-Hasani et al. [13] found that moderate-elevation alluvial zones acting as drainage sumps offered the highest efficiency for check-dam placement. However, our model deviates from the broader literature regarding the slope parameter; while global templates frequently favor flat terrains (0-5%), our consultation framework explicitly classified the 5-15% slope class as optimal (Score 5) to ensure sufficient velocity for flash-flood routing into collection structures without triggering localized low-lying waterlogging. It must be explicitly stated that the final suitability map currently lacks direct empirical validation via historical runoff accumulation data or field verification of existing check dams. This represents a limitation of the study due to limited access and the lack of automated hydrometric stations within Wadi Abu Ghraibat. Consequently, the output map is presented as an exploratory planning tool. Future research will focus on a secondary validation campaign utilizing high-resolution radar imagery to map actual ponding zones following storm events to validate our AHP classifications.

4.1 Limitations and future perspectives

Several inherent limitations must be considered when interpreting our findings. First, the spatial resolution of the USGS DEM (30 m) may obscure localized microtopographical depressions that can pool water. Second, the satellite-derived GPM precipitation products are prone to systematic underestimation during intense, short-duration, localized convective storms typical of semi-arid zones. Lastly, the AHP criteria weighting incorporates inherent expert subjectivity. Despite these uncertainties, the framework establishes a solid spatial foundation for targeted field evaluations.

5. Conclusion

In this study, the proposed method was efficiently used to implement the AHP technique via a geospatial approach to determine RWH regions in the semi-arid Wadi Abu Ghraibat. The method laid the foundation for producing the final map using GIS software. The methodology used to consider the four main factors, which include elevation, slope, precipitation, and drainage density, with weights of 24, 10, 22, and 44, respectively. The analysis shows an appropriate harvest area that is determined by the layer. The results show that about 35% of the area is highly suitable for harvesting, especially on the mid-western flank, where the hydrological features create an ideal habitat. These results highlight the significant role of drainage density in locating RWH sites, as it carries the greatest weight in the AHP. The location pattern of the identified harvesting sites is consistent with established hydrological principles. The paper consequently offers a systematic model of water-resource planning in semi-arid areas and outlines a clear strategy that can be replicated in similar situations worldwide. It is expected that the RWH interventions at the identified sites would significantly contribute to the water security of Wadi Abu Ghraibat. Further studies can include more variables to improve the site-selection procedure. Moreover, testing the identified suitable locations in the field may further enhance the applicability of the results.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest

The authors declare no potential conflict of interest.

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