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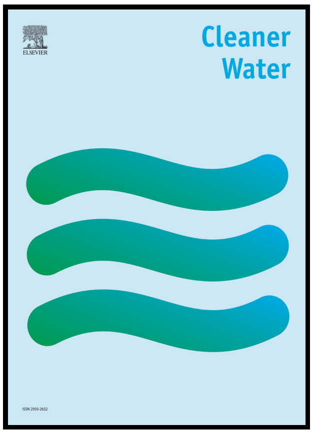

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Targeting Runoff Hotspots for Sustainable Rainwater Harvesting in Arid Regions

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Abstract

Rainwater harvesting (RWH) is a crucial strategy for enhancing water availability in arid regions and supporting local livelihoods, including those of Bedouin communities. Rainwater. This study focuses on Wadi Sudr, located opposite Ras Sudr city in the Sinai Peninsula, to identify optimal RWH sites and recommend suitable harvesting techniques. A weighted spatial probability model (WSPM) was developed within a Geographic Information System (GIS) framework, incorporating eight morphometric parameters. Two scenarios were evaluated: 1) equal weighting of all factors and 2) analytical hierarchy process (AHP) based weighting. The resulting maps classified the watershed into five RWH potential categories. Scenario 1 (equal weighting) identified 49.6% of the area as high or very high potential. In contrast, Scenario 2 (AHP-based) refined this to 18.2%, emphasising the role of basin shape, slope, and valley floor area. High- and very high-priority zones guided recommendations for two surface storage dams in Al-Mleha, with capacities of 25,000–30,000 m³, and Al-Athamy, with capacities of 70,000–80,000 m³, sub-catchments, complemented by cisterns to support remote communities. By integrating GIS, WSPM, and AHP into a unified framework, this study delivers a replicable methodology for prioritising RWH in arid regions, balancing efficiency with accessibility to strengthen sustainable water resource management.

Keywords: Climate change, Floods, Nature-Based, Rainwater harvesting, Water scarcity.

1. Introduction

Water scarcity is one of the most pressing environmental and socio-economic challenges in arid and semi-arid regions, where irregular rainfall and limited surface water supplies constrain sustainable development. In such areas, rainwater harvesting (RWH) has long been recognised as a practical and sustainable solution for augmenting water resources. Rainwater harvesting has long been recognised as a practical and sustainable approach for managing scarce water resources, particularly in arid and semi-arid regions. The practice involves capturing and storing surface runoff for domestic, agricultural, and groundwater recharge purposes, thereby reducing dependence on conventional water supplies (Halder and Bose, 2024; Hassan et al., 2025). Historically, RWH has been widely applied in dryland civilisations through the construction of cisterns, reservoirs, and small-scale dams, many of which remain functional (Aklan et al., 2025). The RWH not only mitigates the impacts of flash floods and water scarcity but also supports climate adaptation by enhancing water availability, improving agricultural productivity, and sustaining local communities (Dharmarathne et al., 2024; Siphambe et al., 2024). When combined with hydrological modelling and geospatial tools, RWH emerges as a cost-effective and strategic solution for managing water in regions experiencing growing rainfall variability (Jha et al., 2014).

Globally, several studies have applied GIS and hydrologic models to assess flash floods. Ramadan et al. (2022) evaluated the geomorphological characteristics of Wadi Sudr in South Sinai, Egypt, to assess flash flood risks and identify effective mitigation strategies. Rahaman et al. (2015) and Javed et al. (2009) integrated GIS and decision-making approaches for flood risk assessment. Other research highlighted persistent flood hazards in urban areas (Chatzichristaki et al., 2015; Diakakis, 2022). Advanced modelling approaches have also been used, including random forest-based assessment (Wang et al., 2015) and GIS–AHP integration for flood susceptibility mapping (Agaj, 2025; Stefanidis and Stathis, 2013).

In Egypt, situated within the vast hot desert belt, occasional torrential rains—particularly across the Sinai Peninsula—can trigger flash floods that, although short-lived, are extremely destructive due to their sudden peaks and rapid flow velocities (El Afandi et al., 2013). Despite their destructive nature, these floods also offer a valuable source of freshwater if properly managed (Opperman and Galloway, 2022). In the case of Egypt, and more specifically the Sinai region examined in this study, flash floods generate substantial runoff; however, most of this water is lost to the sea or lowland areas without being utilised, while simultaneously causing damage to infrastructure and local communities. The lack of integrated approaches for harvesting and managing floodwater has hindered efforts to address both flood risks and chronic water shortages in the region. While most studies in Sinai have focused primarily on floods as hazards—using morphometric analysis (Ramadan et al., 2022) or hydrological modelling (El-Rawy et al., 2022), little attention has been given to their potential as a valuable water resource. Approaches that integrate modelling, spatial analysis, and decision-support tools to identify suitable rainwater harvesting sites remain limited.

While numerous studies have assessed flood hazards in Wadi Sudr, few have focused on harnessing this runoff as a supplementary water resource. This persistent gap highlights the necessity for an integrated approach that simultaneously mitigates flood risks and enhances water availability. The present study seeks to address this research gap by developing a novel, integrated framework that links flood hazard mitigation with sustainable water resource development. Specifically, it combines hydrological modelling, GIS-based morphometric analysis, and spatial decision-making approaches to evaluate the potential for RWH in Wadi Sudr. This integrated approach not only mitigates the destructive impacts of flash floods but also enhances water resource availability, offering a practical, replicable strategy for arid regions facing similar challenges.

The main objective of this study is to evaluate the potential for rainwater harvesting (RWH) in Wadi Sudr by integrating morphometric watershed analysis with the WSPM GIS model. Specifically, the study aims to (i) identify and prioritise suitable zones for RWH using both equal-weighting and expert-weighted (AHP) approaches, (ii) compare the performance of these weighting scenarios in capturing optimal and moderately suitable sites, and (iii) propose a practical strategy for implementing water harvesting infrastructure, including dams and cisterns, within priority sub-catchments. By accomplishing these objectives, the study seeks to develop a replicable framework that balances flood hazard mitigation with sustainable water resource management in arid regions. The remainder of the paper is organized as follows: Section 2 provides a brief description of the study site, data collection, and methodological approaches; Section 3 presents the main findings and discusses their practical relevance; and Section 4 summarizes the main conclusions.

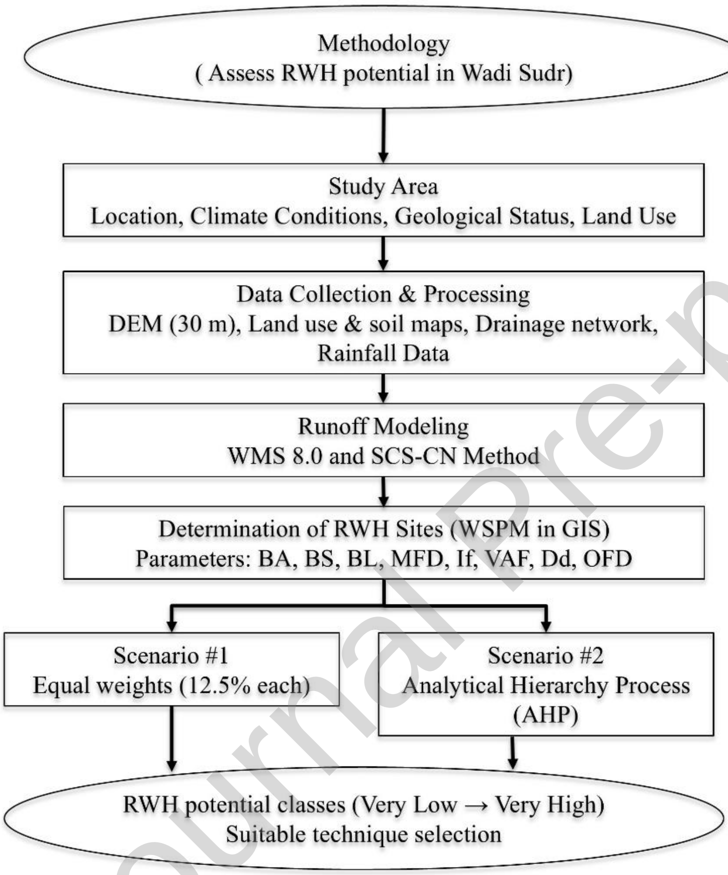


Figure 1: Methodology flowchart

2. Materials and Methods

2.1 Study Area

Wadi Sudr, positioned in the southwestern sector of the Sinai Peninsula between latitudes 29°35′–29°55′ and longitudes 32°40′–33°20′ (Figure 1), extends over an estimated area of 600 km².

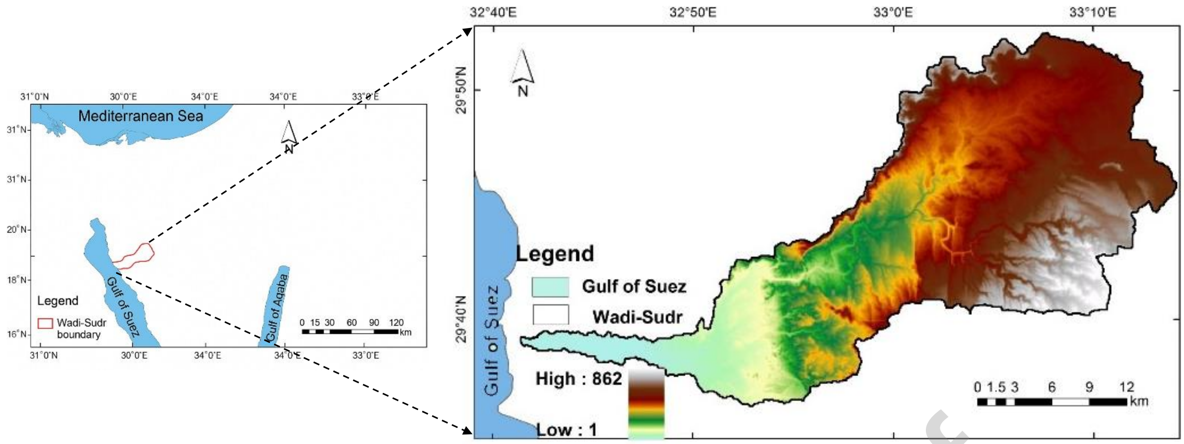


Figure 2: Geographical Location of Wadi Sudr.

The Sinai Peninsula shares climatic features with other desert regions, characterised by prolonged hot, arid summers, mild winters, and minimal rainfall. Although infrequent, winter precipitation can trigger severe flash floods that pose significant risks to infrastructure and human safety (Badreldin and Goossens, 2015). Wadi Sudr lies within a semi-arid climate zone, with relative humidity ranging from 60% to 70%. Precipitation is predominantly generated by localised convective activity, which frequently results in brief yet intense storms, especially under unstable atmospheric conditions associated with low-pressure systems (Awadallah and Younan, 2012).

2.2 Geological Formation and Land Use

The geology of Sinai and Wadi Sudr has been widely investigated by several researchers (Hammad, 1980; Said, 1962; Sherief, 2008). Quaternary deposits dominate the wadi floors, consisting mainly of gravel, loose sediments, and sabkha deposits formed by carbonates, evaporites, and marine or fluvial materials. Pleistocene and Holocene sediments cover much of the main channels, while older formations, such as the Cretaceous Matulla and Sudr formations, are composed of shale, marl, chalk, and dolomitic limestone. The Miocene stratigraphy includes the Gharandal and Ras Malab groups, represented by sandstone, limestone, gypsum, and evaporite formations, as well as basaltic intrusions. Eocene (Egma) and Palaeocene (Esna) formations are characterised by calcareous limestone, flint, chert, and green shale. These geological units play a significant role in controlling infiltration, runoff, and groundwater recharge, making geological characterisation essential for assessing flash flood risks and identifying potential sites for water harvesting (Figure 2).

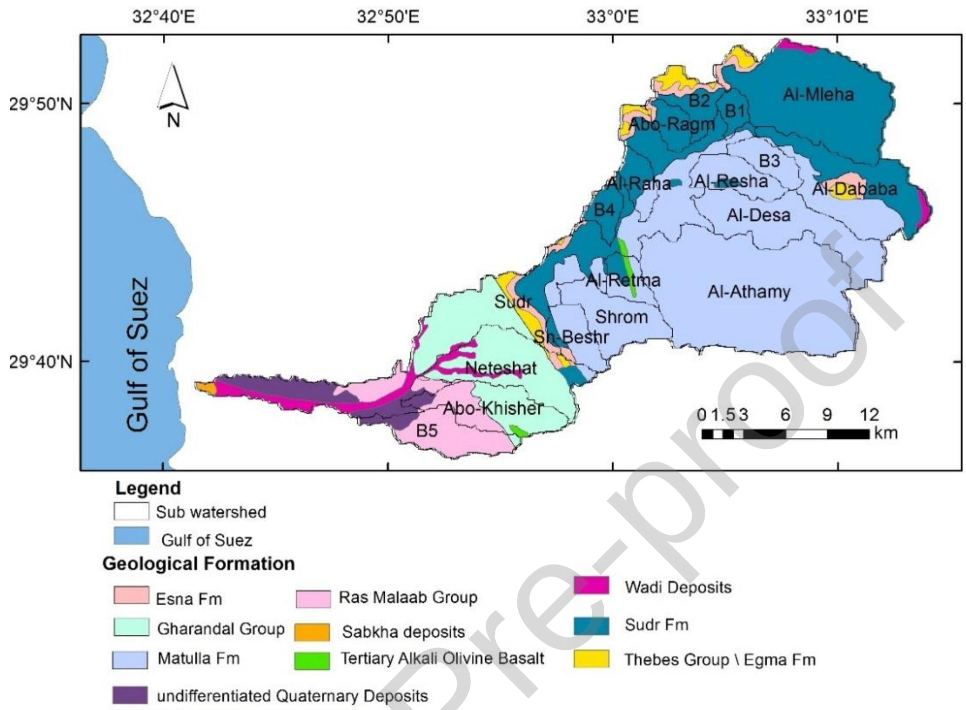


Figure 3: Geological map of the study area.

Wadi Sudr lies directly opposite Ras Sudr town and is mainly inhabited by Bedouin communities. More than 95% of the wadi area is desert land, with limited agricultural or urban development. However, its proximity to Ras Sudr enhances its strategic significance for both water management and socio-economic development.

2.3 Data Collection and Processing

2.3.1 Digital Elevation Model

For this study, a 30 m ASTER-derived digital elevation model (DEM) was used to delineate the drainage network of Wadi Sudr. Land-use and soil-type maps were incorporated to estimate the curve number for runoff modelling.

2.3.2 Rainfall Data

A total of twenty-two meteorological stations distributed across the Sinai Peninsula and its surroundings were utilised for runoff calculations (Table 1).

Table 1. Summary of rainfall and evaporation data for stations located in the vicinity of the Sinai Peninsula.

No.	Station Name	Mean Annual Rainfall (mm)	Minimum Seasonal Rainfall (mm)	Maximum Seasonal Rainfall (mm)	Maximum Daily Rainfall (mm)	Mean Daily Evaporation (mm)
1	Port Said	79.0	44.0	165.0	58.0	5.3
2	Ismailia	37.7	----	-----	50.8	7.6
3	Fayed	25.5	----	-----	32.4	----
4	Suez	24.7	Trace	82.0	31.0	9.2
5	Abu Rudeis	21.5	----	----	32.9	10.0
6	El-Tor	10.4	0.0	52.0	37.4	9.5
7	Sharm El-Sheikh	23.8	----	----	20.4	----
8	St. Catherine	62.0	----	----	76.2	-----
9	Ras El-Naqab	27.7	0.0	97.0	15.0	-----
10	El-Kuntella	23.3	2.0	76.0	32.0	----
11	El-Themed	29.0	0.0	80.0	30.0	----
12	Nakhl	22.1	0.0	68.0	32.0	11.4
13	El-Hassana	27.9	10.0	77.0	32.0	----
14	El-Maghara	43.7	----	----	9.0	----
15	El-Arish	99.7	Trace	214.0	59.0	4.6
16	Abu Aweigila	57.8	----	----	49.0	----
17	El-Quseima	63.4	25.0	123.0	24.2	9.0
18	Rafah	304.1	----	----	49.0	----
19	Gaza	336,5	237.0	497.0	84.2	4.9
20	Shivta	86.0	26.0	153.0	----	-----
21	Avdat	83.0	25.0	161.0	----	-----
22	Eilat	50.0	6.0	98.2	----	-----

While most of these stations provide continuous records spanning over three decades, some contain gaps due to technical issues or human-related factors. Missing data were filled using a linear interpolation technique (Kornelsen and Coulibaly, 2014). The mean annual precipitation used in the runoff simulations was calculated by averaging the records from the nearest stations—Fayed, Abu Rudeis, Nakhl, Suez, and El-Hassana (Figure 4)—resulting in an estimated annual average of 24.34 mm.

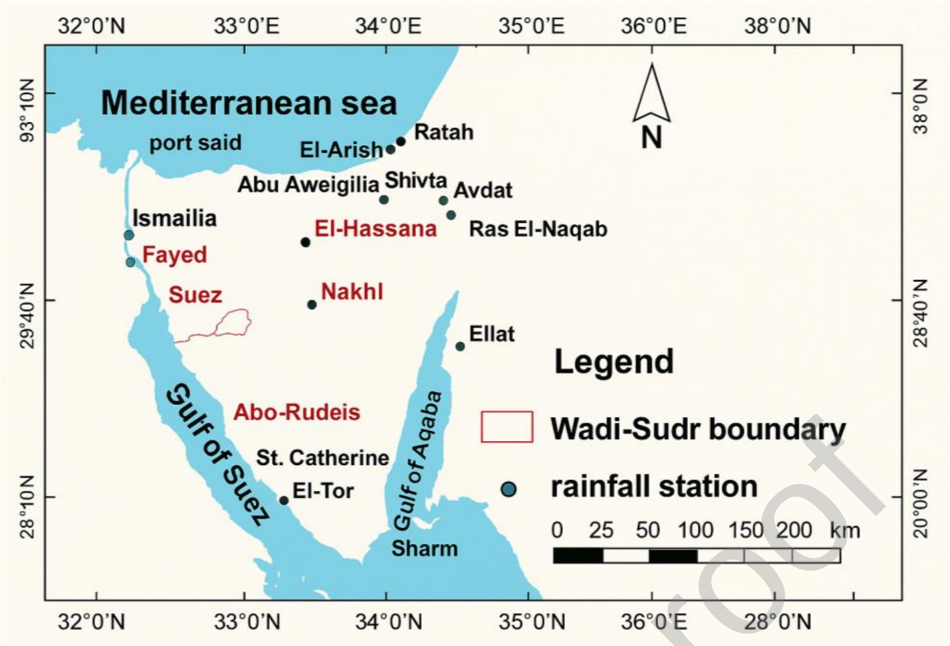


Figure 4: Meteorological stations situated within and in the vicinity of the Sinai Peninsula.

2.4 Runoff Calculations and Watershed Modelling

The drainage network was extracted using the Watershed Modelling System (WMS 8.1©), specifically the Main Drainage Module and the ''TOpographic PArameteriZation'' (TOPAZ) program. After delineating the watershed, morphometric parameters, including catchment area, slope, and maximum flow path length, were automatically calculated in WMS. Subsequently, the drainage network was exported as a shapefile into ArcGIS 9.8, where the weighted spatial probability model (WSPM) was applied to assess the potential for rainwater harvesting.

The runoff simulation was conducted in the Watershed Modelling System (WMS 8.0©) using the HEC-1 model and the Soil Conservation Service Curve Number (SCS-CN) method (Ibrahim-Bathis and Ahmed, 2016; SCS, 1972; USDA, 1986). This method estimates runoff volume based on precipitation depth and curve number (CN), relying on the water balance principle and two assumptions: the proportionality between actual and potential retention, and the linear relationship between initial abstraction and maximum retention, as expressed in Equations (1) and (2).

$$P = Ia + F + Q \quad (1)$$

The proportional relationship is defined as in Eq. (2):

$$\frac{Q}{P-I_a}=\frac{F}{S} \qquad (2)$$

For simplification, the following condition is defined as Eq. (3):

$$Ia=\lambda\ S \qquad (3)$$

The effective precipitation for runoff is expressed as (P − I_a), with runoff potential determined by the Curve Number (CN), which ranges from 0 (high infiltration) to 100 (impermeable surfaces). CN values, derived from watershed characteristics such as soil type, land use, and antecedent moisture, indicate that higher CN values correspond to greater runoff potential (SCS, 1972), Eqs. 4 and 5.

$$S=\frac{25400}{CN}-254 \qquad (4)$$

$$Q=\frac{(P-I_a)^2}{(P-I_a)+S}=\frac{(P-0.25)^2}{(P-0.80S)} \qquad (5)$$

P is total precipitation (mm); I_a is initial abstraction; Q is direct runoff (mm); F is cumulative infiltration (excluding I_a); S is maximum potential soil retention (mm); and λ (0.2) is the default initial abstraction ratio at runoff onset.

2.5 Identification of Potential Runoff Water Harvesting Sites

Catchment characteristics derived from WMS 8.1 were applied in a GIS environment to identify optimal runoff water harvesting (RWH) sites using the weighted spatial probability model (WSPM), based on parameters such as: basin area (BA), basin slope (BS), basin length (BL), maximum flow distance (MFD), infiltration number (If), volume of annual flood (VAF), discharge density (Dd), and average overland flow distance (OFD). These criteria were mapped into five potential classes (i.e., very high to very low) using Spatial Analyst, enabling the selection of suitable RWH techniques under two different scenarios. The WSPM was carried out using two scenarios.

i. *Equal weights to each criterion (scenario #1)*

In the first scenario, it was assumed that all eight thematic layers of the WSPM contribute equally to the prioritisation of RWH sites, with each assigned a weight of 12.5%.

ii. Justified weights using the Analytical Hierarchy Process (scenario #2)

In the second scenario, the analytical hierarchy process (AHP), developed by Saaty (1987), was applied to assign justified weights to the parameters. AHP is a widely used multi-criteria decision-making technique that addresses complex problems through a structured, flexible framework. The method relies on constructing a hierarchy of decision factors and conducting pairwise comparisons among parameters. The results are recorded in a weighting index matrix, where each parameter is assigned a weight along with a consistency ratio (CR).

2.5.1 Computation of the Pair-wise Comparison Matrix

The pairwise comparison matrix is constructed by assigning weights based on expert judgment. These weights are scored on a scale from 1 to 9 to reflect the relative importance of alternatives (Saaty, 1987). When a factor on the vertical axis is considered more significant than that on the horizontal axis, a value between 1 and 9 is assigned; conversely, less important factors are represented by reciprocal values ranging from 1/2 to 1/9 (Table 2). The assignment of values for parameter comparisons ultimately depends on the decision makers. In this study, the weights were automatically computed in Microsoft Excel.

Table 2. Pair-wise comparison of a 9-point rating scale.

Importance	Degree of preference	Explanation
1	Equal	Two activities contribute equally to the objective
3	Moderate	Experience and judgment slightly to moderately favour one activity over another.
5	Strong	Experience and judgment strongly or essentially favour one activity over another.
7	Very strong	An activity is strongly favoured over another, and its dominance is shown in practice.
9	Extreme	The evidence of favouring one activity over another is of the highest degree possible of an affirmation.

2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7, and 9.
Reciprocal	Opposites	Used for inverse comparison.

2.5.2 Normalise the Pairwise Comparison Matrix

Normalisation involves dividing each element of a column in the pairwise comparison matrix by the column's total. The average of each row in the normalised matrix is then calculated, which represents the criteria weights {W}. To ensure reliability, a consistency check is subsequently performed by computing the weight-sum vector {Ws}.

Determined a weight sum vector {Ws}.

$$Ws = [c] \times [w] \quad (6)$$

Find the consistency vector {consist}.

$$[Consist\,] = [Ws\,] \times [1/w] \quad (7)$$

Determine the averages of the column of consist; call this eigen vector (λ_{max}).

Determine the consistency index, CI

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (8)$$

Determine the consistency ratio, CR

$$CR = \frac{CI}{RI} \quad (9)$$

Where: [*C*] represents the pairwise comparison matrix; {*W*} denotes the criteria weighting matrix; *n* is the number of criteria; and *RI* is the random index, which varies depending on the number of elements (*n*) being compared. The standard *RI* values are presented in Table 3. A consistency ratio (*CR*) of less than 0.1 indicates an acceptable level of consistency, whereas a CR greater than or equal to 0.10 suggests inconsistency among the criteria.

Table 3. Order of matrix and random index.

Order of Matrix	Random Index	Order of Matrix	Random Index
01	0	09	1.45
02	0	10	1.49
03	0.58	11	1.51
04	0.90	12	1.48

05	1.12	13	1.56
06	1.24	14	1.57
07	1.32	15	1.59
08	1.41		

3. Results and Discussion

Eight thematic layers, including catchment area, catchment slope, catchment length, annual flood volume, runoff frequency density, maximum runoff distance, overland flow distance, and infiltration number, were used to run a weighted spatial probability model to identify potential areas for rainwater harvesting in Wadi Sudr. The output layers were converted to a raster format and categorised into five classes using the extension program "Spatial Analyst": very high, high, moderate, low, and very low. The resulting map divided the area into five RWH potential classes, ranging from very low to very high. Consequently, the appropriate RWH techniques can be selected.

3.1. Weighted Spatial Probability Model (WSPM) Thematic Layers

3.1.1. Basin Area

The basin area (BA) represents the total surface enclosed within a watershed boundary and is a key morphometric parameter that influences drainage patterns (Horton, 1941). Larger basins capture more rainfall, resulting in higher peak discharges, as they are strongly correlated with other runoff-related characteristics, such as basin length and flow distance. In Wadi Sudr, BA analysis shows very high to high values (118,613–56,274 km²) in parts of the Main-Sudr, Al-Athamy, and Al-Mleha sub-catchments, while central sub-catchments such as Al-Raha, Al-Retma, and Abo-Ragm exhibit low to very low values (38,453–7,909 km²), with the remaining areas falling in the middle range (Table 4 and Figure 5).

3.1.2. Basin Slope

The gradient of the catchment area is a very important factor in selecting water catchment sites to achieve the maximum channel storage capacity. It is the average gradient of the triangles that make up the catchment. The thematic layer of basin slope showed that the very high and high classes (0.189-0.104) were represented by Al-Raha, B4, Sn-Beshr sub-catchments, and some parts of B2, Main-Sudr, Al-Athamy, Shrom, and Neteshat due to the mountainous terrain in the mountains of Sn-Beshr and Om-Hamas (Table 4 and Figure 5a). In contrast, the BS decreased in the eastern parts (0.082-0.035).

3.1.3. Basin Length

The catchment gradient is a key factor in selecting water harvesting sites, as it influences the channel's maximum storage capacity. It represents the average slope of the triangular facets forming the catchment. The basin slopes thematic layer revealed that very high to high gradients (0.189–0.104) occur in Al-Raha, B4, Sn-Beshr, and parts of B2, Main-Sudr, Al-Athamy, Shrom, and Neteshat, largely due to the rugged topography of the Sn-Beshr and Om-Hamas mountains. Conversely, lower slopes (0.082–0.035) dominate the eastern regions, as shown in Table 4 and Figure 5b.

3.1.4. Volume of Annual Flood

The annual flood water volume (VAF), indicating the potential water available for harvesting, was estimated using the USDA SCS-CN method (USDA, 1986). High to very high VAF values (441,223,563–218,270,281 m^3/year) occur mainly in the far west and east of Wadi Sudr, including parts of the Al-Mleha, Al-Dababa, and Al-Athamy sub-catchments in the west, and the Sudr and Neteshat sub-catchments in the east. Moderate values (218,270,281–148,270 m^3/year) are distributed in sections of the same sub-catchments, while low to very low values (148,270,281–19,812,842 m^3/year) dominate the central watershed, represented by sub-catchments such as El-Kharoba, El Hamma El Hassana, El Bruk, Yarqa Abu Taryfya, El Fetahy El Aqaba, Geraia, and Heridien.

3.1.5. Stream Frequency

Stream frequency, defined as the number of streams per unit area, is influenced by factors such as rock erosion resistance, soil infiltration capacity, and climate. Higher stream frequency indicates a greater potential for rainwater harvesting (Musaed et al., 2022). In Wadi Sudr, very high to high values (1.491–1.167) are concentrated in the north, while very low to low values (1.039–0.666) are found in the Main-Sudr, Shrom, and Sn-Beshr sub-catchments, as well as parts of Al-Athamy, Al-Retma, Neteshat, and B5 (Table 4 and Figure 5d).

3.1.6. Maximum Flow Distance

The maximum flow distance (MFD) of a catchment encompasses both overland flow and channel flow. It is the maximum length of the waterway in the catchment (m). The higher the MFD, the greater the RWH opportunities, which is why it is considered very important in determining a catchment's RWH capability. The thematic map of the MFD criterion showed that the very high and high classes (63,840-29,661 m) were present in parts of the Main-Sudr sub-catchment. The very low and low classes (19,482-4,477m) occupied most of Wadi Sudr (Table 4 and Figure 5f).

3.1.7. Overland Flow Distance

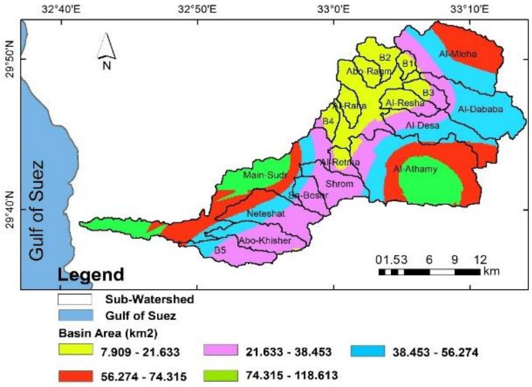
Horton's definition of overland flow length (L_g) relates it to drainage density: longer Lg favours infiltration and reduces flash flood risk, while shorter L_g enhances rapid runoff (Horton, 1941). In Wadi Sudr, most of the basin falls within the low to very low Lg range (358,260–386,352 m), indicating fast runoff and higher flood susceptibility. Moderate values (386,352–399,699 m) occur in sub-watersheds such as Al-Mleha, Al-Desa, Al-Resha, and Al-Athamy, suggesting locally improved infiltration potential. High to very high values (399,699–434,489 m) are limited to small areas in the western part of the basin (Al-Mleha, Al-Dababa, Al-Desa, Al-Athamy) (Table 4 and Figure 5g). This distribution implies that while some sub-catchments support water retention, much of Wadi Sudr is prone to rapid runoff, reinforcing the need for strategically placed RWH structures.

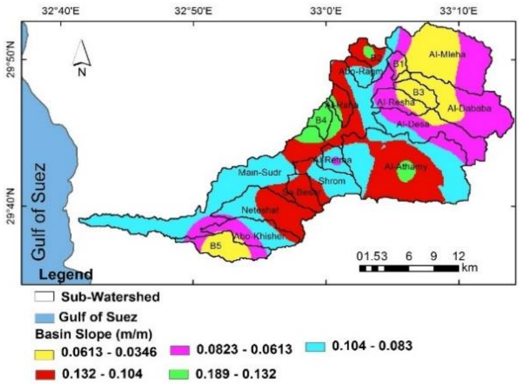
3.1.8. Infiltration Number

The infiltration coefficient (I_f), defined as the product of drainage density and stream frequency, provides insight into watershed infiltration capacity (Horton, 1941). Higher values indicate reduced infiltration and greater runoff (Masoud, 2015). In Wadi Sudr, the western sub-catchments fall within the high to very high If range (1.854–1.532), highlighting their limited infiltration and strong runoff potential (Table 4 and Figure 5h). Moderate values (1.492–1.532) occur in localised areas, suggesting intermediate conditions. Conversely, the eastern sub-catchments are dominated by low to very low If values (1.492–1.260), indicating favourable infiltration rates and greater potential for groundwater recharge. This spatial variation emphasises the contrast between western runoff-prone areas and eastern recharge-prone zones, underscoring the need for differentiated water harvesting strategies across the basin.

Table 4. Ranges of input criteria used for the WSPMs.

Watershed RWH Criteria	Very High	High	Moderate	Low	Very Low
Basin Area (BA)(km^2)	118.61-74.32	74.32-56.27	56.27-38.45	38.45-21.63	21.63-7.91
Basin Slope (BS)(m/m)	0.19-0.13	0.13-0.10	0.14-0.03	0.08-0.06	0.06-0.04
Basin Length (BL)(m)	44089.24-30944.36	30944.36-20944.25	20944.25-13719.94	13719.94-8800.22	8800.22-3718.64
Volume of annual flood (VAF) (m^3/year)	441223.56-297320.56	297320.56-218148.80	218148.80-148270.28	148270.28-84813.59	84813.59-19812.84
Drainage frequency (Fs)(m^{-2})	1.49-1.32	1.32-1.17	1.17-1.04	1.04-0.92	0.92-0.67
Maximum flow distance (MFD) (m)	63840-44222.05	44222.05-29660.80	29660.79-19482.33	19482.33-12223.75	12223.75-4477.21
Overland flow distance (Lg)(m)	434.48-414.73	414.73-399.70	399.70-386.35	386.35-372.94	372.94-358.26
Basin infiltration number (If)	1.85-1.60	1.59-1.53	1.53-1.49	1.49-1.45	1.45-1.26





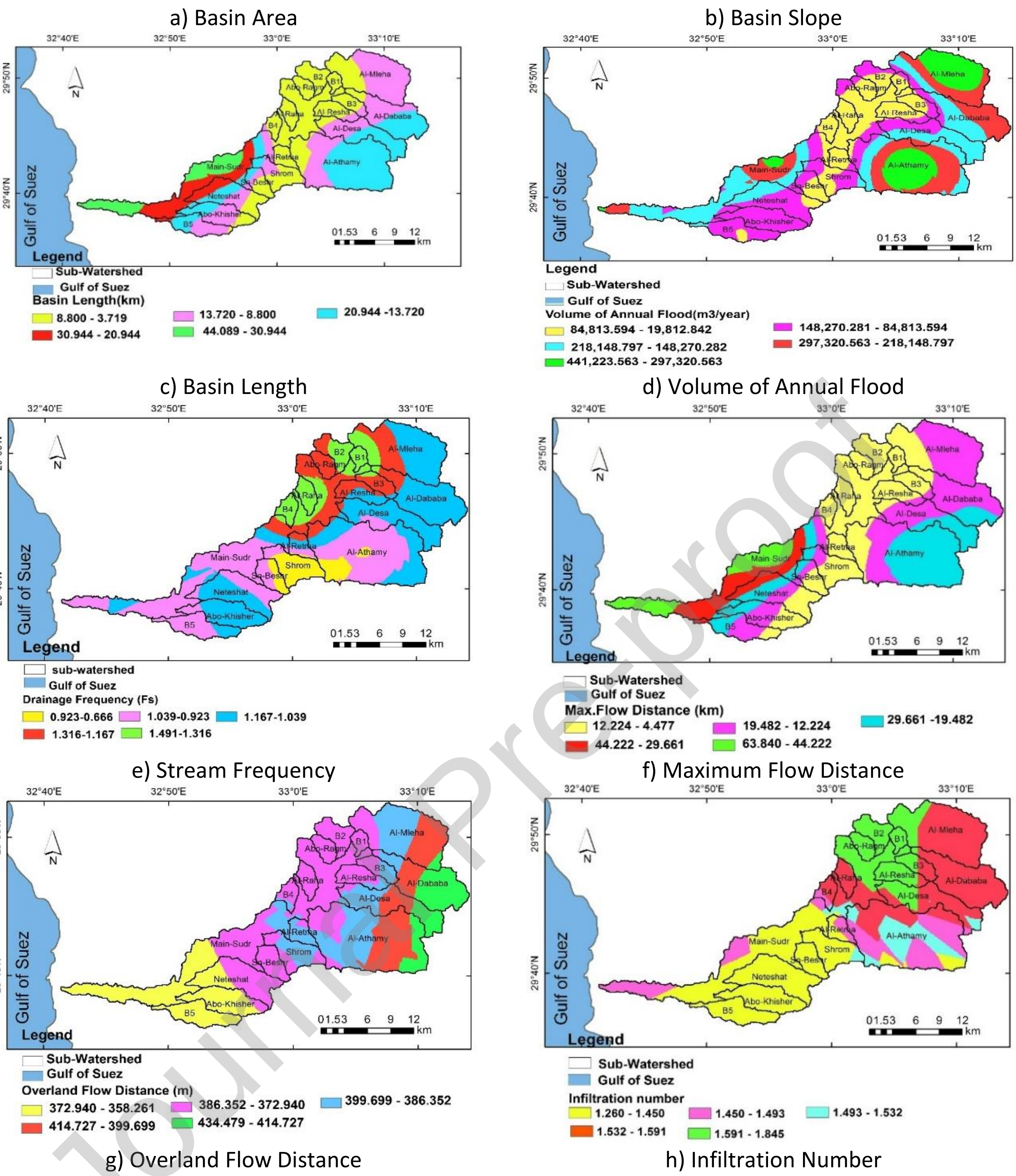


Figure 5: Thematic parameters for the Wadi Sudr basin.

3.2. Weighted Spatial Probability Model

The multi-criteria decision support system (MCDSS), constructed from eight morphometric and hydrological thematic layers, was classified according to their relative contributions to RWH, ranging from very high to very low. These same categories were applied in delineating the spatial distribution of RWH potential (Table 4). The weighted spatial probability model (WSPM) was executed under two distinct scenarios: (1) uniform weighting of all parameters, and (2) expert-derived weighting calibrated through the analytical hierarchy process (AHP). The resulting WSPM outputs stratified the watershed into five priority classes of RWH potential: very high, high, moderate, low, and very low.

3.2.1. Scenario I (equal weights to criteria)

In the first scenario, all eight thematic layers within the WSPM were assumed to contribute equally to RWH prioritisation, with each assigned a uniform weight of 12.5%. Certain factors, including VAF, BS, BA, DFD, and MFD, exerted a positive influence on RWH potential, whereas BL and OFD exerted negative influences. The watershed was classified into five potential categories: very high, high, moderate, low, and very low corresponding to rank intervals of 100–80, 80–60, 60–40, 40–20, and 20–0%, with mean rank values of 0.90, 0.70, 0.50, 0.30, and 0.10, respectively (Table 5). The degree of effectiveness (E) for each parameter was then determined by multiplying its weight (W_c) by the average rank (R_c). For instance, with a VAF of 12.5%, its effectiveness in Class I equals 11.25 (E = 0.125 × 90 = 11.25).

Table 5. Ranks and weights for each criterion, along with their influencing classes, are used to map RWH potentiality.

Thematic layers	RWH potentiality	Average rate (Rank) (R_c)	Weight (W_c)	Degree of Effectiveness (E)
Volume of annual flood (VAF) Drainage frequency (Fs) Maximum flow distance (MFD)	I (Very high)	0.9		11.25
Overland flow distance (Lg)	II (High)	0.7	12.5	8.75
Basin infiltration number (If)	III (Moderate)	0.5		6.25
Basin Area (BA)	IV (Low)	0.5		3.75
Basin Length (Bl) Basin Slope (Bs)	V (Low)	0.1		1.25

Spatial analysis (Table 6; Figure 6a) revealed that areas of very high and high potential collectively represent 49.57% of the basin. These are primarily concentrated in the Al-Mleha, Abo-Ragm, Al-Raha, B1, B2, B4, and parts of Al-Resha, B3, Main Sudr, and Al-Athamy sub-catchments. Such zones are characterised by moderate slopes, favourable lithology, and well-organised drainage systems that facilitate surface runoff retention, rendering them suitable for RWH interventions. Conversely, low and very low potential zones (25.04% combined) were predominantly found in Al-Retma, Shrom, Sn-Beshr, B5, and parts of Abo-Khisher, Neteshat, and Al-Dababa sub-catchments, where steep slopes, permeable substrates, or fragmented drainage patterns reduce their water harvesting capacity.

The equal-weight approach shows that nearly half of Wadi Sudr has strong RWH potential, even without prioritising specific factors. However, it also underscores the spatial disparity in suitability, while some sub-catchments consistently emerge as high-potential zones, others remain unsuitable due to inherent physical constraints. For decision-makers, this suggests that investment in RWH infrastructure should be spatially targeted, focusing resources on naturally favourable zones to maximise efficiency, while considering alternative water management strategies for areas with persistently low potential. The equal-weight scenario provides an unbiased baseline, revealing each factor's natural influence and enabling a fair comparison with weighted approaches.

Table 6. Areas of RWH priority classes represented by figure 6 (scenario I; equal weights to criteria).

RWH Class	Very high	High	Moderate	Low	Very low
Area km^2	60.81	237.45	152.80	131.41	19.23
Area (% relative to the total study area of 601.7 Km^2)	10.11	39.46	25.39	21.84	3.20

3.2.2. Scenario II (justified weights using AHP)

In this scenario, the eight thematic layers were weighed according to their relative importance, determined through a pairwise comparison matrix informed by expert knowledge and supported by findings from previous studies on runoff potential and soil erosion (Aher et al., 2014; Lawal et al., 2012; Rahaman et al., 2015). The pairwise and normalised matrices were calculated in Microsoft Excel to derive the final weights (Tables 7 and 8). The calculated consistency ratio (CR) was 0.04, well below the acceptable threshold of 0.1, confirming a high level of reliability in the weight assignments.

Table 7. Pair-wise comparison matrix.

Pair-wise Comparison	VAF	FS	MFD	Lg	BA	BL	BS	IF
VAF	1	5	7	7	1	5	1	1
FS	1/5	1	3	3	1/5	3	1/7	1/3
MFD	1/5	1/3	1	1	1/7	1	1/7	1/5
Lg	1/7	1/3	1	1	1/7	1	1/7	1/3
BA	1	5	7	7	1	5	1	3
BL	1/5	1/3	1	1	1/5	1	1/7	1/3
BS	1	7	7	7	1	7	1	5

IF	1	3	5	3	1/3	3	1/5	1
SUM	4.74	21.99	31.99	29.98	4.02	25.99	3.77	11.20

Table 8. Normalised matrix and check of consistency.

Normalised Matrix	VAF	FS	MFD	Lg	BA	BL	BS	IF	Weight	Consistency
VAF	0.21	0.23	0.22	0.23	0.25	0.19	0.27	0.09	0.21	8.42
FS	0.04	0.05	0.09	0.10	0.05	0.12	0.04	0.03	0.06	8.16
MFD	0.04	0.02	0.03	0.03	0.04	0.04	0.04	0.02	0.03	8.19
Lg	0.03	0.02	0.03	0.03	0.04	0.04	0.04	0.03	0.03	8.31
BA	0.21	0.23	0.22	0.23	0.25	0.19	0.27	0.27	0.23	8.62
BL	0.04	0.02	0.03	0.03	0.05	0.04	0.04	0.03	0.04	8.25
BS	0.21	0.32	0.22	0.23	0.25	0.27	0.27	0.45	0.28	8.84
IF	0.21	0.14	0.16	0.10	0.08	0.12	0.05	0.09	0.12	8.56
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	λ=	8.42
									CI=	0.06
									RI=	1.41
									CR=	0.04

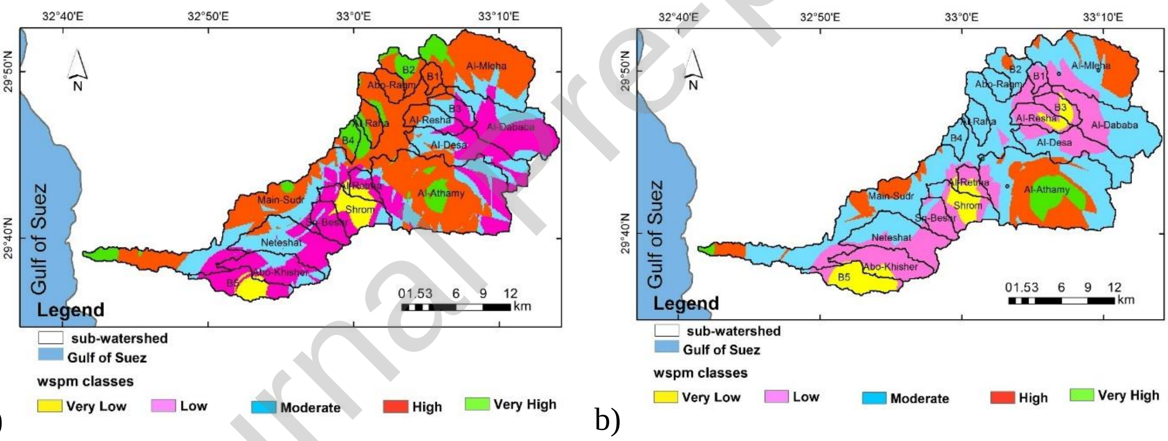
The resulting weights reflect a strong emphasis on BS (27.6%), BA (23.3%), and VAF (21.1%), indicating that basin shape, basin area, and volume of annual flood are considered the most influential factors for RWH potential. Moderate influence was assigned to IF (11.9%), while FS (6.4%), BL (3.5%), MFD (3.1%), and Lg (3.1%) received lower weights, reflecting their comparatively lesser but still relevant role in determining suitability.

Applying these weighted criteria in WSPM produced a spatial distribution that was markedly different from that in the equal-weight scenario. The results (Table 8, Figure 6b) show that very high- and high-potential zones cover only 3.45% and 14.78% of the basin, respectively, for a combined total of 18.23%. These areas are concentrated in parts of Al-Mleha, Al-Athamy, and Main Sudr sub-catchments, where favourable geomorphological characteristics align strongly with the highest-weighted factors. Conversely, low and very low potential zones account for 26.75% and 6.97% (33.72% combined), primarily in Al-Retma, Shrom, Sn-Beshr, B5, and portions of Abo-Khisher, Neteshat, and Al-Dababa, where less favourable physical conditions dominate. The remaining 48.08% of the basin falls into the moderate category, representing transitional areas where some favourable factors are offset by limiting conditions.

This weighted criterion highlights the influence of prioritising key physical parameters over equal treatment. The reduction in very high- and high-class coverage compared to the equal-weight scenario suggests that strict prioritisation narrows the spatial focus of potential RWH zones, potentially improving efficiency by targeting only the most physically suitable locations. However, it also underscores the trade-off between selectivity and overall coverage, which must be carefully considered in planning decisions.

Table 9. Areas of RWH priority classes, as represented by Figure 6 (scenario II), were justified by the sensitivity analysis.

RWH Class	Very high	High	Moderate	Low	Very low
Area km^2	20.77	88.91	289.28	160.95	41.94
Area (% relative to the total study area of 601.7 Km^2)	3.45	14.78	48.08	26.75	6.97



a) b)

Figure 6: The weighted spatial probability model map showing the potential areas of RWH in Wadi Sudr according to: a) scenario #1 and b) scenario #2.

3.3. Potential Runoff Water Harvesting Techniques

Water harvesting, a practice used for millennia in arid regions, is primarily employed for irrigation and to support human and livestock consumption. Techniques are typically classified by catchment size into micro-catchments—small areas that collect runoff for direct agricultural use or small reservoirs—and macro-catchments—larger areas, often beyond farm boundaries, that capture water via wadi bed or off-wadi systems (Mbilinyi et al., 2005).

In Wadi Sudr, rainfall occurs only in winter, with dry summers limiting the use of micro-catchment methods. Therefore, macro-catchment techniques such as dams and cisterns were deemed more suitable.

The selection of these sites was guided by the results of Scenario 2 (expert weighting) rather than those of Scenario 1, which used equal weighting. This choice was made to ensure that infrastructure targets only the most promising locations where multiple high-priority factors coincide. While Scenario 1 identified a broader range of potential sites, including many moderately suitable areas, Scenario 2’s weighting reduced the risk of overestimating suitability by excluding marginal zones. This focused approach is expected to enhance the efficiency of resource allocation, ensure more reliable water yields, and improve long-term performance, even during years of below-average rainfall.

Based on the high runoff-harvesting potential, two above-ground storage dams were proposed in the Al-Mleha and Al-Athamy sub-catchments, along with additional cisterns.

The water-harvesting sites were selected based on areas classified as having very high or high runoff-harvesting potential in the second scenario (Figure 6). Consequently, it was proposed to build two above-ground storage dams in the Al-Mleha and Al-Athamy sub-catchments, along with several cisterns, as illustrated in Figure 7.

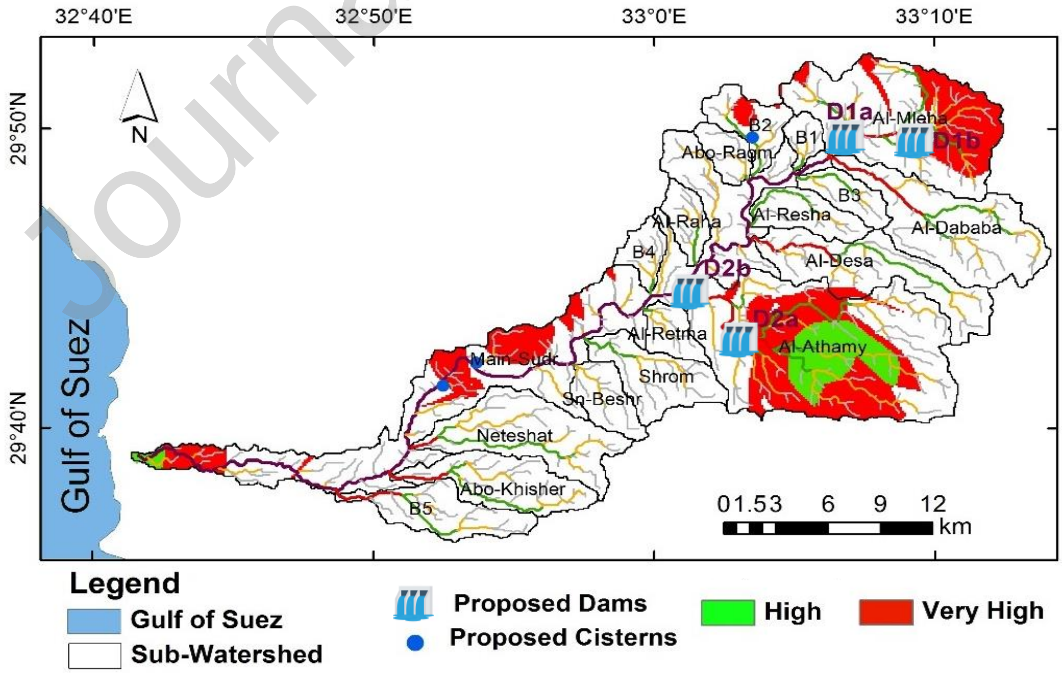


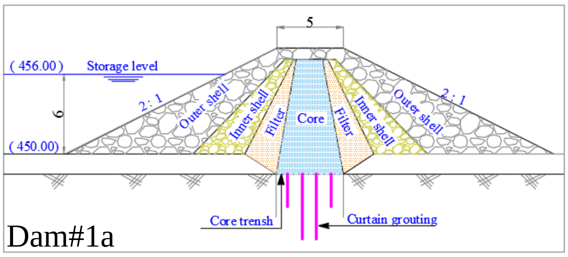
Figure 7: Map illustrating the potential rainwater harvesting (RWH) areas within Wadi Sudr and the proposed sites for dam and cistern construction.

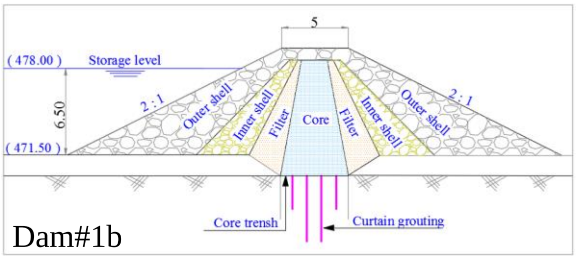
3.3.1. The Proposed Dams

When selecting suitable sites for the proposed dams, several key criteria were carefully considered to ensure both technical feasibility and long-term effectiveness. First, the Water Storage Potential Map (WSPM) results were used to identify zones within the very high and high runoff harvesting classes, as these areas offer the greatest likelihood of consistent water capture. Second, soil characteristics were evaluated, with priority given to alluvial and wadi deposits that provide fertile conditions for agriculture, thereby supporting the development of new cultivation areas. Third, existing land use was examined to avoid conflicts with currently inhabited zones, ensuring that intercepted water can stimulate the establishment of new settlements rather than disrupt existing ones. Fourth, local topography was assessed, favouring locations with side slopes that provide natural shoulders for dam placement, thereby enhancing stability and reducing construction complexity (Wang et al., 2021).

The selected structures are rock-fill type dams, chosen for their durability and adaptability to rugged terrain. These dams feature multiple layers of rock material, with an impermeable core to minimise seepage (Chen, 2015). A filter zone is incorporated to prevent soil particle loss due to seepage-induced erosion. At the same time, the outer shell and transition zones provide the main structural resistance against hydraulic and geotechnical stresses (Figure 8).

In the Al-Mleha sub-catchment, two dam sites were selected (Figure 6): Dam #1a (29°49’50.73”N, 33°06’51.6”E) with a 300 m length, 5 m crest width, 2:1 side slopes, 6 m height, 450 m base elevation, and 30,000 m³ storage capacity, designed to capture an annual flood volume of 348,365.7 m³ (Figure 8); and Dam #1b (29°50’4.8”N, 33°09’39.1”E) with similar dimensions but a slightly greater allowable height of 6.5 m, providing 25,000 m³ storage for an annual flood volume of 135,130.5 m³.





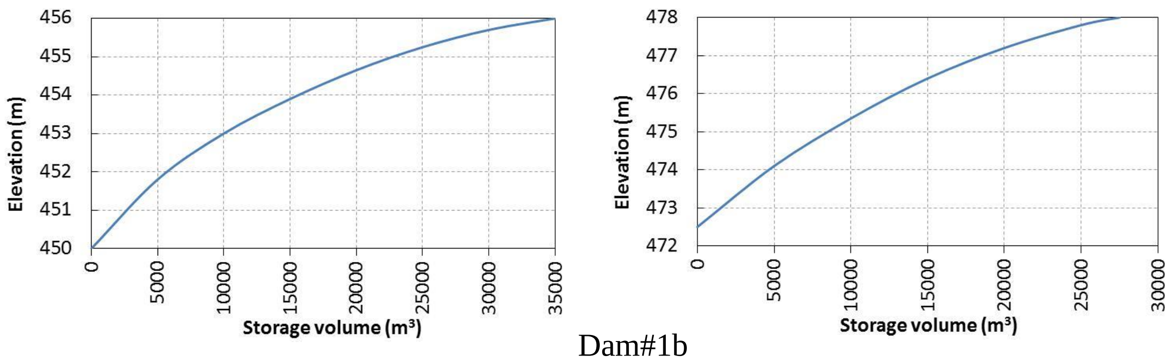


Figure 8: Cross-sectional view of storage dams and corresponding water storage volumes.

In the Al-Athamy sub-catchment, Dam #2a (Figure 6) (29°42′56.48″N, 33°03′12.46″E) is designed with a length of 200 m, a crest width of 5 m, 2:1 side slopes, a height of 12 m, a base elevation of 424 m, and a capacity of 80,000 m³, capturing 331,998.3 m³ annually. In contrast, Dam #2b (29°44′38.02″N, 33°01′27.98″E) has dimensions similar to those of Dam #2a, with a height of 11 m, a base elevation of 313 m, a capacity of 70,000 m³, and an annual flood volume of 441,754.2 m³ (Figure 9).

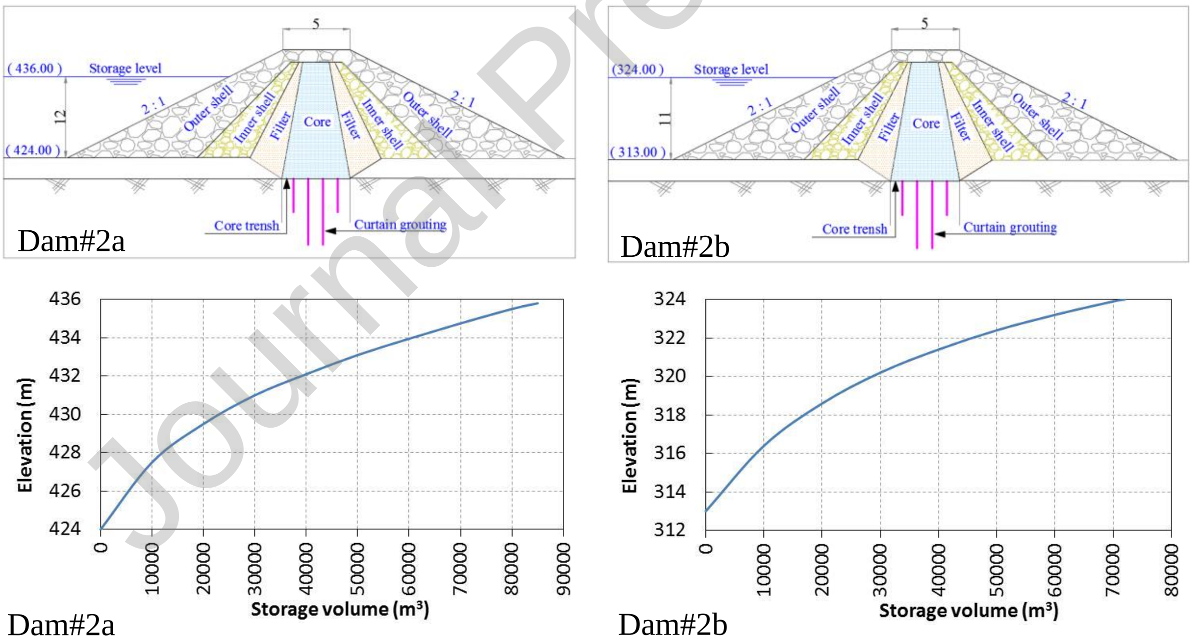


Figure 9: Cross-sectional profile of storage dams and their corresponding water storage capacities.

By integrating hydrological potential, soil suitability, land-use compatibility, and topographic stability into the site selection process, these proposed dams are strategically positioned to optimise water-harvesting efficiency, support agricultural expansion, and encourage sustainable settlement growth in Wadi Sudr.

3.3.2. Cisterns

Cisterns are traditional structures used to capture and store runoff at small catchment scales, typically built at the lowest point of a basin (Mays et al., 2013). They include a settling basin, inlet, mouth opening (50–75 cm), and an underground storage chamber often protected by a natural rock roof. Common in semi-arid regions such as Egypt, Syria, and Jordan, cisterns range from small unicellular types (100–300 m³) to larger multicellular systems (>300 m³), with capacities extending 1,500 m³ in ancient Roman designs (Ortloff, 2005) (Figure 10).

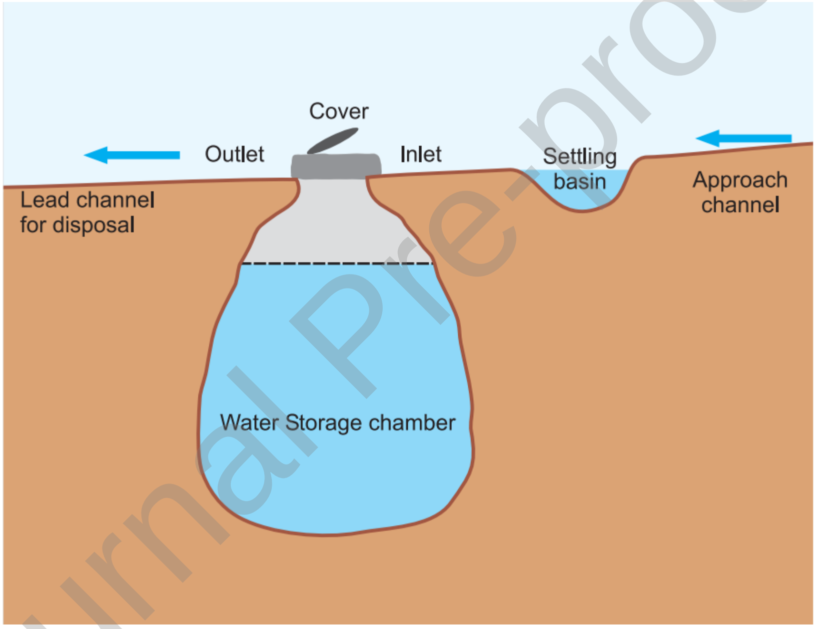


Figure 10: Components of a typical single-cell cistern, as described by Ali et al. (2009).

A hybrid strategy integrating top-priority locations with selected moderate-potential zones could balance efficiency with broader water accessibility. In practice, this means dams can secure large, reliable water volumes for irrigation and settlement expansion. At the same time, strategically placed cisterns can serve smaller communities and remote locations, creating a diversified water storage network that is both resilient and adaptable to variable rainfall conditions (Owusu et al., 2022). By aligning infrastructure planning with scientifically derived priority zones, the research provides a scalable decision-support tool for improving water security in arid and semi-arid landscapes. Beyond Wadi Sudr, the methodology offers a transferable framework that can inform sustainable water resource management strategies in other regions facing similar scarcity challenges.

The results of this study, which identified 18.23% of Wadi Sudr as highly suitable for RWH under the expert-weighted AHP scenario, align with findings by Rahaman et al. (2015), Ramadan et al. (2022), and Javed et al. (2009), who also emphasised the importance of morphometric parameters such as slope and drainage density in watershed prioritisation. However, unlike these studies, which primarily focused on catchment ranking, our framework integrates hydrological modelling to estimate potential storage volumes, thereby providing direct guidance for infrastructure design. In Egypt, Elsiad et al. (2017) applied GIS and WMS for morphometric assessment of Wadi Sudr but did not extend the analysis to site-specific RWH structures. In contrast, this study bridges that gap by proposing both large-scale dams and localised cisterns, thus offering a more comprehensive strategy for floodwater utilisation in arid environments.

This study's findings align with Agaj (2025), who identified morphometric factors as dominant in flood susceptibility in Kosovo using GIS–AHP frameworks. While Agaj focused on flood-risk mitigation in humid regions, our work applies similar methods to optimise rainwater harvesting (RWH) in arid environments, demonstrating the adaptability of these tools to support both hazard management and sustainable water resource development. Another study by Aklan et al. (2025) highlighted the decline of indigenous RWH systems and advocated integrating traditional practices with modern technologies. While their study drew insights from historical and literature-based evidence, our research applies a GIS–AHP framework to identify optimal RWH sites in arid regions. Together, these approaches underscore the value of combining traditional knowledge with modern analytical tools to enhance water security and climate resilience.

The weighted site-selection method significantly enhances efficiency for both dams and cisterns by targeting the highest-priority areas; however, it reduces high-potential coverage from 49.57% to 18.23%, potentially overlooking moderately suitable zones, making it one of the study's limitations. Additional constraints include reliance on moderate-resolution data, assumption-based weighting, and omission of socioeconomic and environmental considerations.

4. Conclusions

This study highlights the potential of combining morphometric watershed analysis with the WSPM GIS model to identify and prioritise rainwater harvesting (RWH) zones in arid regions. The novelty of this work lies in integrating quantitative geomorphological parameters with expert-based multi-criteria decision-making, thereby providing a robust, replicable framework for site selection of water-harvesting infrastructure. Two weighting scenarios were tested. The equal-weighting approach (Scenario 1) classified nearly half of the watershed (49.57%) as high or very high RWH potential, while the expert-weighted AHP approach (Scenario 2) refined this to 18.23% by emphasising critical factors such as basin shape, slope, and valley floor area. Although Scenario 2 offers superior precision by targeting only the most optimal zones, it reduces overall spatial coverage, potentially excluding moderately suitable areas. To address this limitation, a hybrid strategy is recommended that combines top-priority sites with selected moderate-potential zones. Such an approach balances efficiency with broader water accessibility, ensuring both large-scale irrigation and settlement expansion through dams, while providing small-scale, localised supply through strategically placed cisterns.

Based on the final prioritisation, this study proposes constructing two above-ground storage dams and several cisterns within the Al-Mleha and Al-Athamy sub-catchments. The proposed dams, with capacities ranging from 25,000 to 80,000 m³, would secure substantial water volumes for agricultural and domestic use, while cisterns would enhance resilience for smaller or remote communities. This diversified storage network strengthens adaptive capacity against rainfall variability, maximises resource efficiency, and minimises risks associated with marginal site development.

To further strengthen this framework, future studies should integrate socioeconomic and environmental criteria into the site-selection process, incorporate higher-resolution data, and validate model outputs through extensive field surveys. Coupling the WSPM approach with climate variability projections and stakeholder engagement would further enhance its applicability for long-term planning, ensuring that water-harvesting infrastructure remains adaptive, equitable, and resilient in the face of climate change.

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Availability of data and material

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(Upon request)

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Amal Magdy, Atef Elsaiad, El-Sayed M. Ramadan, Alban Kuriqi, Ashraf A Ahmed, and Ismail Abd-Elaty: Conceptualisation, Methodology, Investigation, Formal analysis, Data curation, Visualisation, Writing-original draft, Writing-review & editing, Resources; **Alban Kuriqi and Ismail Abd-Elaty**: Supervision.

Ethics approval

(Not applicable)

Consent to participate

(Yes)

Consent for publication

(Yes)

AI Statement

During the preparation of this paper, the authors employed ChatGPT 5.0 to improve solely the clarity, structure, and language of the manuscript, followed by a thorough review and manual editing of the content.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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