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GIS-Based Multi-Criteria Analysis for Identifying Suitable Rainwater Harvesting Sites to Enhance Groundwater Recharge: A Case Study of the Western Wellfield in Thaqban Area, Sana'a, Yemen

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Abstract

Groundwater depletion in the Sana'a Basin, Yemen, has intensified due to over-abstraction, rapid urbanization, and limited natural recharge. The Western Wellfield, which supplies a significant portion of Sana'a City's domestic water demand, has experienced substantial groundwater-level declines, highlighting the need for sustainable recharge interventions. This study evaluates the potential of rainwater harvesting (RWH) for enhancing groundwater recharge in the Thaqban area using a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) integrated with the Analytic Hierarchy Process (AHP). Ten thematic criteria were considered, including rainfall, runoff depth, slope, geological media, soil texture, land use/land cover, drainage density, distance to wadis, distance to groundwater wells, and groundwater depth. The criteria were weighted using AHP and combined through a weighted linear combination (WLC) approach to generate an RWH suitability map. The results show that 1.34% of the study area is highly suitable for RWH implementation, 37.60% is moderately suitable, 58.21% is marginally suitable, and 2.85% is unsuitable. Highly suitable areas are mainly associated with permeable geological formations, favorable topography, and proximity to production wells. This study demonstrates the usefulness of GIS-MCDA techniques for identifying priority recharge zones and supporting sustainable groundwater management in arid environments.

Article Info

Keywords:
Rainwater harvesting, Groundwater recharge, GIS, MCDA, Western Wellfield, Sana'a Basin, Yemen.

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1. INTRODUCTION

Yemen is among the most water-scarce countries in the world, characterized by low and highly variable rainfall, the absence of perennial rivers, and a heavy dependence on groundwater resources [1]. The country's renewable water resources are insufficient to meet the growing demands of domestic, agricultural, and industrial sectors. Agriculture alone consumes approximately 90% of the available water resources, while rapid population growth and urban expansion continue to increase water demand [2, 3]. Consequently, groundwater abstraction has significantly exceeded natural recharge rates in many basins, leading to continuous declines in groundwater levels and deterioration of water security.

The Sana'a Basin represents one of the most critical examples of groundwater stress in Yemen. Groundwater serves as the principal source of water supply for both domestic and agricultural uses within the basin [4]. Sana'a City, with a population exceeding 4 million [5], relies heavily on groundwater extracted from several well-

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fields operated by the Sana'a Water and Sanitation Local Corporation (SWSLC), including the Western, Eastern, Misik, Asr, and South Sana'a wellfields. Decades of intensive pumping, coupled with limited natural recharge and expanding urban development, have resulted in substantial groundwater-level declines, reduced well productivity, and the abandonment of several wells [6]. Among these wellfields, the Western Wellfield, located in the Thaqban area, has experienced significant groundwater depletion. Continuous abstraction, increasing water demand, and insufficient recharge have disrupted the natural groundwater balance, raising concerns regarding the long-term sustainability of water supplies [6]. Consequently, identifying practical and cost-effective approaches to enhance groundwater recharge has become a priority for water-resource management in the region.

The increasing frequency of droughts, along with the overuse and deterioration of natural water resources, has renewed interest in traditional rainwater harvesting (RWH) systems [7, 8]. **Today, the United Nations** and many non-governmental organizations (NGOs) support the study and use of these traditional systems because they are based on local knowledge, require little or no fossil fuel energy, and make use of locally available materials [9, 10]. Traditional RWH systems have been sustainable for centuries and are compatible with local lifestyles and socioeconomic regimes [11].

Rainwater harvesting (RWH) has been widely recognized as an effective strategy for improving water availability and augmenting groundwater recharge in arid and semi-arid environments. Recharge-oriented RWH structures, such as check dams, recharge basins, percolation ponds, and contour bunds, can capture surface runoff, reduce water losses, and increase infiltration to underlying aquifers. The identification of appropriate sites and structures for RWH is an important preliminary step for good RWH management [12]. Many RWH site suitability analyses have been carried out using different approaches. Forzieri et al., [13] analyzed sites using cost–benefit ratios, rainfall regime, and the volume of water that can be collected and stored. Previous studies have demonstrated the effectiveness of integrating geographic information systems (GIS) and multi-criteria decision analysis (MCDA) techniques for identifying suitable locations for RWH implementation [14–16]. Currently, GIS-multi-criteria decision analysis (GIS-MCDA) is widely regarded as the most promising and emerging alternative for identifying suitable sites for the implementation of MAR techniques [17]. The Analytic Hierarchy Process (AHP) is among the most widely used approaches for assigning relative importance to multiple environmental and hydrogeological factors involved in site selection [17]. Although several studies have applied GIS-based approaches for RWH site selection, limited research has focused on groundwater recharge enhancement in the Sana'a Basin, particularly in areas supplying municipal water systems. Furthermore, the integration of hydrogeological criteria such as groundwater depth and proximity to production wells remains insufficiently explored in previous studies conducted in Yemen.

This study aims to identify and prioritize suitable locations for rainwater harvesting structures designed to enhance groundwater recharge in the Thaqban area of the Western Wellfield, managed by the Sana'a Water and Sanitation Local Corporation (SWSLC).

2. MATERIALS AND METHODS

2.1. Study Area

The study area is located in the northwestern region of Sana'a, Yemen, covering approximately 100 km² within the Ma'ain, Al-Thawrah, and Bani Harith districts, including the villages of Thaqban and Jedar. Figure (1) shows the study area in the global coordinate system, spanning latitudes from 15°23'23.2"N to 15°27'47.7"N and longitudes from 44°09'00.6"E to 44°12'23.3"E. The area exhibits significant topographic variation, with elevations ranging from 2,200 m above sea level (m.a.s.l.) in the eastern plains to 2,800 m.a.s.l. in the western highlands. Mean annual temperatures range between 10°C and 25°C, while annual rainfall varies from 190 mm to 300 mm. This area encompasses the Western Wellfield, a critical groundwater source managed by the Sana'a Water and Sanitation Local Corporation (SWSLC), which supplies potable water to the capital city. Administratively, the area spans parts of the Ma'ain, Al-Thawrah, and Bani Harith districts.

2.2. Methodology

A 12.5 m resolution digital elevation model (DEM) was downloaded from the USGS Earth Explorer portal and used to generate the slope map and extract the stream network. The land use/land cover (LULC) map was derived from Sentinel-2 satellite imagery acquired in 2024 and further refined through field surveys and high-resolution satellite data. The stream network was re-digitized using GPS-tracked wadi paths, which revealed a 12% increase in total channel length due to altered surface runoff patterns caused by urban development. These updates significantly improved the accuracy of the drainage density and distance-to-wadis layers. Soil texture data were obtained from existing geological maps and previous studies. Long-term annual rainfall data (1990–2024) required for rainfall distribution and runoff depth estimation were collected from the National Water Resources Authority (NWRA) and the Civil Aviation and Meteorology Authority (CAMA). Groundwater level measurements were conducted in February–March 2025 from 14 operational wells managed by the Sana'a Water and Sanitation Local Corporation (SWSLC) in the Western Wellfield, supplemented by several privately owned

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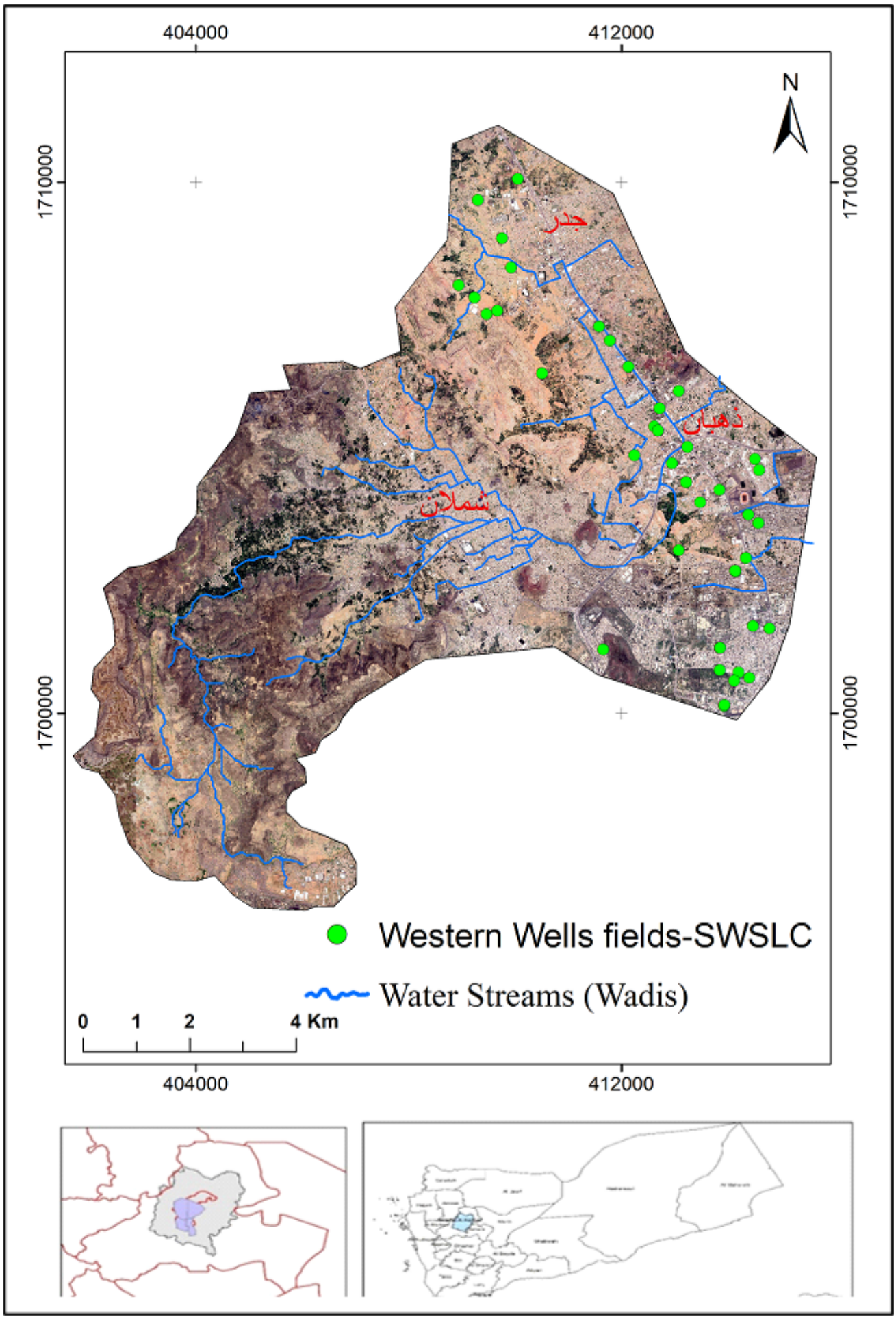

Figure 1. Geographical location of the study area

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Table[1]: Rainwater Harvesting Suitability Classification Standards

Factor	Suitability class				Source
	Highly suitable (1)	Moderately suitable (2)	Marginally suitable (3)	Unsuitable (4)	
Slope (%)	0–2	2–8	8–30	>30	[20]
Annual Rainfall (mm)	260–282	237–259	215–236	191–214	[22]
Land Use	Pastures	Agricultural	Rocky Terrain	Urban	–
Soil texture	Alluvial Soils (Fluvisols)	Sandy clay	Silty clay	clay loam	[23]
Geological Media	Sandstone & Alluvial	quaternary volcanic (Scoria and volcanic ash)	Fracture Volcanic rocks	Massive Volcanic rocks	–
Drainage density (km/km^2)	15-20	10-15	5-10	<5	[24]
Runoff depth potential (mm)	>230	205-230	185–205	<185	[19]
Distance to water stream (Wadi) (m)	≤100	100-500	500-1000	>1000	[25]
Distance to GW wells	<500	500-1000	1000-1500	>1500	[25]
Depth to groundwater level (m)	<100	100-150	150-200	>200	–

wells. These wells were strategically selected to ensure representative spatial coverage of groundwater depth across the study area.

Criteria selection and the preparation of thematic layers are crucial steps in any GIS-based multi-criteria modeling approach [18]. In this study, ten predictive criteria were selected as thematic layers for identifying suitable rainwater harvesting (RWH) sites. These criteria include slope, land use/land cover (LULC), soil texture, geological media, rainfall, runoff depth, drainage density, distance to water streams (wadis), distance to groundwater wells, and depth to groundwater level. The selection of these criteria was informed by previous studies [19–21]. The suitability classification standards for each criterion are presented in Table (1).

The conceptual framework for selecting suitable sites for rainwater harvesting (RWH) in the Thaqban area is illustrated in Figure (2). The framework follows a systematic multi-step process that integrates geospatial data and weighted analysis. This study adopted a GIS-based multi-criteria decision analysis (MCDA) approach combined with the analytic hierarchy process (AHP) technique [17]. The thematic layers were first reclassified into four suitability levels (highly suitable, moderately suitable, marginally suitable, and unsuitable) according to the standards presented in Table (1). Each layer was then assigned a suitability rating, and all layers were integrated using the weighted linear combination (WLC) method in ArcGIS to produce the final RWH suitability map.

3. RESULTS AND DISCUSSION

3.1. Criteria's processing and Geospatial analysis

Geospatial analysis plays a crucial role in identifying suitable sites for rainwater harvesting by integrating and analyzing multiple environmental, hydrological, and topographical factors within a geographic information system (GIS) environment. The application of geospatial techniques enables the assessment of spatial variability in parameters such as rainfall distribution, slope, drainage density, land use/land cover, soil characteristics, geology, runoff potential, and groundwater recharge conditions [19–21]. Potential RHW site identification and mapping using geospatial techniques and AHP is a new approach to tackling water shortage for various services, especially for improved groundwater recharge activity. Annual average rainfall, LULC, soil textural, aquifer media (geology), slope, runoff depth, drainage density, and distance to river (water stream) are the datasets employed for RWH site identification in the study area (Table 2).

3.1.1. Rainfall

Rainfall is one of the most important factors in identifying suitable sites for rainwater harvesting (RWH) and plays a critical role in large-scale RWH planning [22]. In addition to directly contributing to water availability, rainfall significantly influences watershed recharge and other hydrological processes, particularly in lowland areas [4, 26]. Figure (3a) presents the spatial distribution of average annual rainfall across the study area and the corresponding reclassified suitability map. Rainfall varies considerably within the region, with lower amounts concentrated in the central and northeastern parts and higher values

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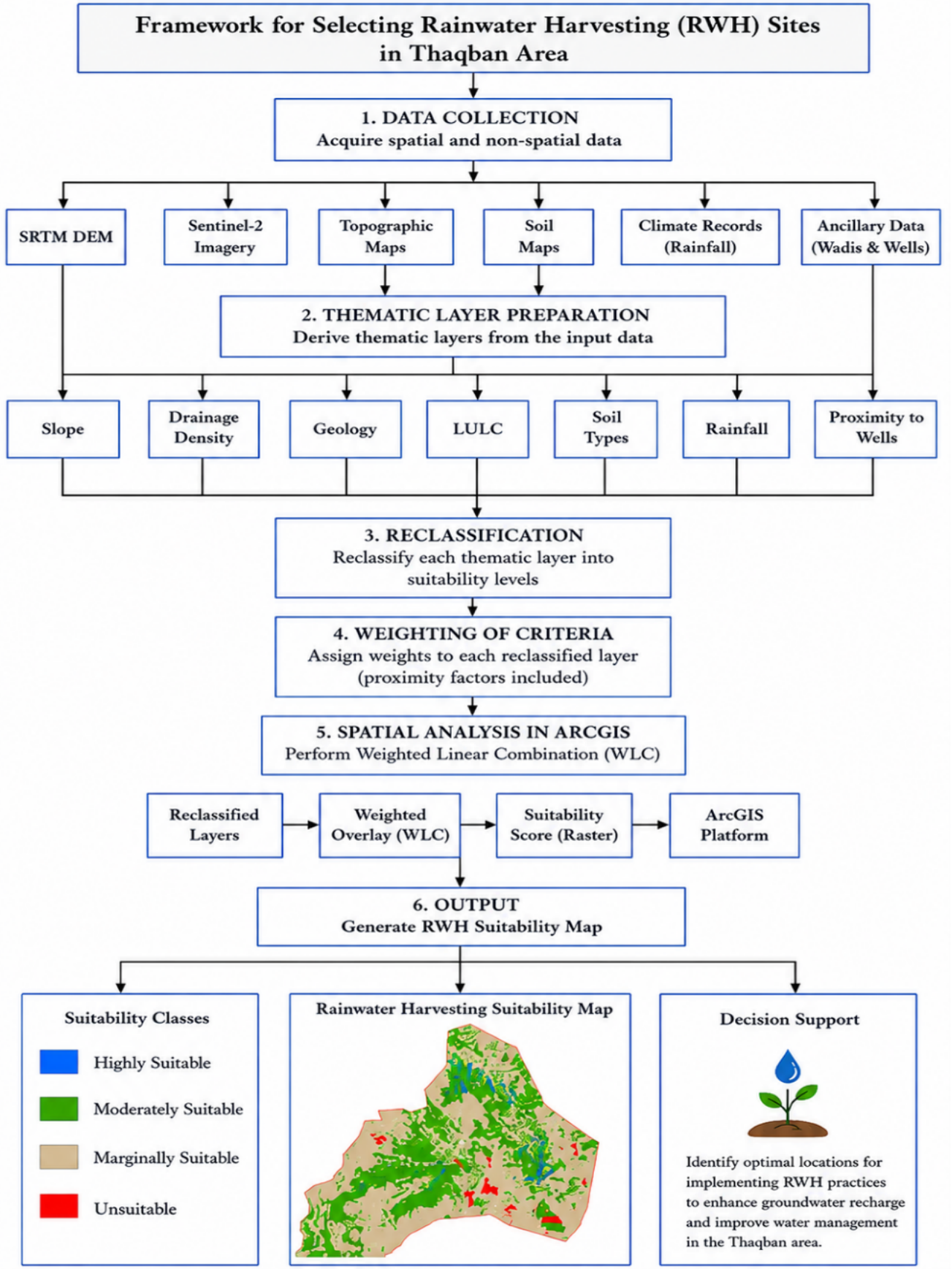

Figure 2. The general framework of the study

observed in the western highlands [27, 28]. Based on long-term rainfall records from stations managed by the National Water Resources Authority (NWRA) and the Civil Aviation and Meteorology Authority (CAMA), the

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Table[2]: Distribution of criteria suitability classes

Factor	Interval	Rate	Suitability	Coverage (km^2)	Coverage (%)
Rainfall (mm)	191–214	4	Unsuitable	18.05	18.12
	215–236	3	Marginally suitable	21.14	21.22
	237–259	2	Moderately Suitable	42.22	42.38
	260–282	1	Highly Suitable	18.28	18.35
Slope (degree)	>30	4	Unsuitable	18.4	18.49
	8.1 - 30	3	Marginally suitable	53.53	53.73
	2.1 - 8	2	Moderately Suitable	26	26.10
	0 - 2	1	Highly Suitable	1.6	1.69
Land use land cover (LULC)	Urban areas	4	Unsuitable	32.04	32.3
	Rocky terrain	3	Marginally suitable	34.7	35
	Agricultural land	2	Moderately Suitable	26.6	26.7
	Pastures	1	Highly Suitable	5.6	6
Soil texture	clay loam	4	Unsuitable	58.2	58.41
	Silty clay	3	Marginally suitable	4.7	4.71
	Sandy clay	2	Moderately Suitable	5.8	5.88
	Alluvial Soils (Fluvisols)	1	Highly Suitable	31.2	31
Geological Media	Massive Volcanic rocks	4	Unsuitable	41.2	41.2
	Fractured Volcanic rocks	3	Marginally suitable	6.15	6.15
	Quaternary Volcanics	2	Moderately Suitable	11.4	11.4
	Sandstone and Alluvial deposits	1	Highly Suitable	41.25	41.25
Drainage density	<5	4	Unsuitable	79.78	79.09
	5-10	3	Marginally suitable	10.81	10.81
	10-15	2	Moderately Suitable	8.5	8.5
	15-20	1	Highly Suitable	1.6	1.6
Runoff depth (mm)	<185	4	Unsuitable	22.4	22.48
	185–205	3	Marginally suitable	38.5	38.65
	205-230	2	Moderately Suitable	9.8	9.87
	>230	1	Highly Suitable	28.8	29
Distance to water stream (m)	>1000	4	Unsuitable	12.2	12.26
	500 – 1000	3	Marginally suitable	25.3	25.40
	100 - 500	2	Moderately Suitable	30	30.12
	≤100	1	Highly Suitable	32.1	32.22
Distance to GW wells (m)	>1500	4	Unsuitable	55.8	56.24
	1000 – 1500	3	Marginally suitable	8	8.03
	500 - 1000	2	Moderately Suitable	17.4	17.46
	<500	1	Highly Suitable	18.2	18.27
Depth to GW level (m)	>200	4	Unsuitable	2.4	2.4
	150 – 200	3	Marginally suitable	31.7	31.84
	100 - 150	2	Moderately Suitable	53.3	53.52
	<100	1	Highly Suitable	12.1	12.24

study area was classified into four suitability categories, as shown in Table (2): highly suitable (260–282 mm),

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moderately suitable (237–259 mm), marginally suitable (215–236 mm), and unsuitable (191–214 mm).

3.1.2. Slope

Slope is a key factor in rainwater harvesting (RWH) site selection because it affects runoff, infiltration, and groundwater recharge. The slope suitability classification criteria are detailed in Table (2), which defines four categories based on slope percentage (Figure 3b). Steep slopes (>30°), covering 18.4% of the study area, are unsuitable for RWH due to rapid runoff and limited infiltration, whereas flat areas (0–2°), covering 1.69 %, are highly suitable for water retention. Gentle slopes (2–8°) and moderate slopes (8–30°) constitute 26.10% and 53.73% of the study area, respectively.

3.1.3. Geological Media

The lithological formations identified include sandstone, alluvial deposits, Quaternary volcanics (scoria and volcanic ash), fractured volcanic rocks, and massive volcanic rocks. As detailed in Table (2) and Figure 3c, these units were classified based on their infiltration potential.

- High Suitability: Sandstone and alluvial deposits, accounting for 41.26%.
- Moderate Suitability: Quaternary volcanics (scoria and volcanic ash), representing 11.4%.
- Marginal Suitability: Fractured volcanic rocks, comprising 6.15%.
- Unsuitable: Massive volcanic rocks, covering 41.2% of the study area.

3.1.4. Land cover/land use (LCLU)

The study area comprised diverse land use types, as illustrated in Figure (3d): urban areas (32.3%), agricultural land (26.7%), rocky terrain (35%), and pastures (6%). Table (2) outlines the suitability classification for RWH interventions. Urban areas, despite their significant spatial coverage, are deemed unsuitable for RWH due to high runoff contamination risks. Rocky terrain was classified as marginally suitable. Agricultural land, representing 26.7% of the area, was considered moderately suitable, while pastures occupying 6% of the territory were identified as the most highly suitable sites for RWH implementation.

3.1.5. Soil Type

Soil characteristics, specifically texture and porosity, are fundamental determinants of the effectiveness of rainwater harvesting (RWH) systems for groundwater recharge, as they govern infiltration rates, water storage capacity, and surface runoff generation. The study area displays a diverse range of soil compositions, including alluvial soils (Fluvisols), sandy clay, silty clay, and clay loam. These classifications were categorized into four suitability levels (Figure 3e): high suitability (Fluvisols) covers of 31% of study area, moderately suitable (sandy clay) covers of 5.88% of study area, marginally suitable (silty clay) covers of 4.71% of study area, and unsuitable (clay loam) covers of 58.41% of study area, as shown in Table (2). The efficacy of rainwater harvesting (RWH) for groundwater recharge is fundamentally determined by the hydrogeological properties of geological units, specifically their porosity, permeability, and fracture density, which govern infiltration rates and subsurface storage capacity. Figure 3e illustrates a map of the suitability classification for geological media for RWH.

3.1.6. Runoff depth

The identification of suitable rainwater harvesting (RWH) sites is inherently dependent on the runoff generation capacity of a catchment area, which serves as the primary indicator of water potential [29, 30]. In this study, runoff depth was determined using the Soil Conservation Service Curve Number (SCS-CN) method, a widely accepted approach for estimating surface runoff [31, 32].

Runoff depth was estimated using the Soil Conservation Service Curve Number (SCS-CN) method. The required parameters included annual rainfall (P), Curve Number (CN), potential maximum retention (S), and antecedent moisture condition (AMC-II), which represents average soil moisture conditions (Soulis et al., 2009). CN values were assigned according to the combined land use/land cover and hydrologic soil group maps. The potential maximum retention (S) was calculated from the Curve Number using:

$$S = \frac{25400}{CN} - 254$$

and runoff depth (Q) was estimated using the standard SCS-CN equation:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

The total runoff depth (Q) for each pixel was calculated by integrating the annual average rainfall depth (P) with the corresponding Curve Number (CN) value. The estimated runoff depth was mapped using ArcGIS and classified into four standardized suitability zones, from low runoff depth to high runoff depth values (Figure 3f). An area with a high runoff depth value was rated as highly suitable, and low runoff depth-producing areas were rated as unsuitable considering the time taken to fill water in the RWH assembly. As shown in Table (2), the runoff depth analysis shows a mixed suitability pattern. While 22.48% of the area is unsuitable (<185 mm), 38.65% of the area is marginally suitable (185–205 mm), nearly 9.8% shows moderately suitability (205–230 mm), and another 29% is highly suitable (>230 mm). This means that approximately 40% of the region has adequate runoff conditions, although most areas face some water availability challenges.

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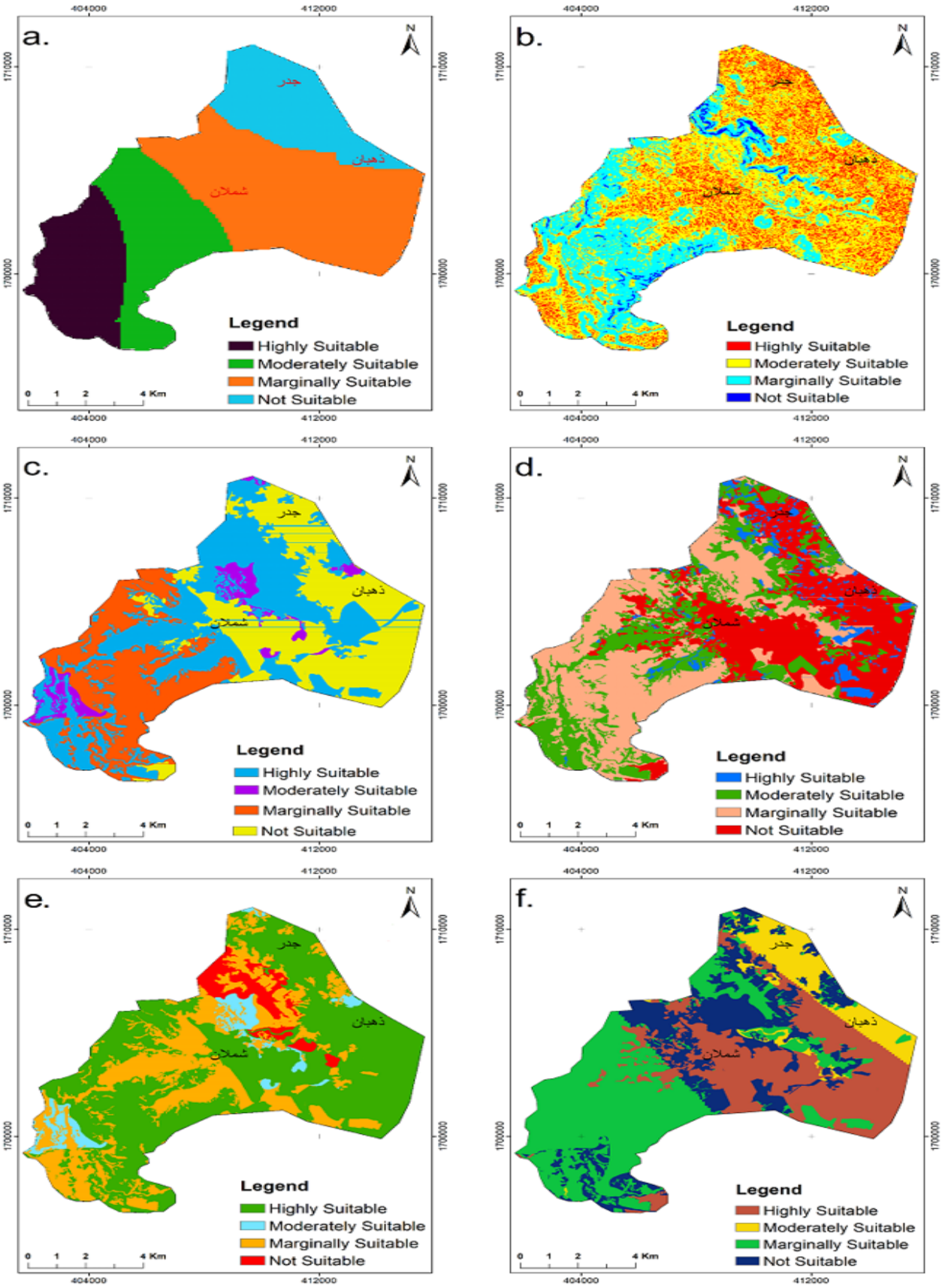

Figure 3. Criteria Suitability Maps in the Study Area: a. Rainfall; b. Slope; c. Geological Media; d. Land use; e. Soil Type; f. Runoff Depth

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3.1.7. Distance to water stream

The distance to drainage streams (wadis) was considered an important criterion because it controls runoff accessibility while minimizing flood hazards. Based on previous GIS-based RWH studies and local hydrological conditions, the distance-to-stream layer was reclassified into four suitability classes: <100 m (Highly Suitable), 100–500 m (Moderately Suitable), 500–1000 m (Marginally Suitable), and >1000 m (Unsuitable). These classes were adopted to balance runoff harvesting efficiency with structural safety and practical implementation. The Euclidean distance function was applied to calculate the distance to water streams, as illustrated in Figure (4a), with suitability classifications reclassified according to RWH standards (Table 2). The analysis reveals that the majority of the study area possesses favorable access to water sources. The suitability distribution is categorized as follows: Approximately 32.22% is especially well-placed within 100 m, which is highly suitable, and 30% of the land is within 500 m of streams, which is moderately suitable. While 25% is marginally suitable (500–1000 m away), only 12% is considered too far from water sources (unsuitable) (over 12km^2).

3.1.8. Drainage density

The drainage density for the study area was calculated within the ArcGIS 10.8 environment using a digital elevation model (DEM). Drainage density (DD) is defined as the total length of all stream segments per unit catchment area, as expressed in the following equation [32]:

$$DD = \frac{\sum_{i=1}^{n} L}{A}$$

where DD is the drainage density, n is the number of streams, L is the stream length (km), and A is the drainage area (km^2). Figure (4b) presents the suitability classification of drainage density for the study area. The DD standards for classifying RWH sites are listed in Table (1). The parts of the watershed with 15–20, 10–15, 5–10, and <5 are categorized as highly, moderately, marginally suitable, and unsuitable areas, respectively. As shown in Table (2), drainage density suitability. Areas with low density (<5) cover 79% but are unsuitable. Moderate density (5–10) makes up 11% and is marginally suitable, while medium density (10–15) accounts for 8.5% with moderate suitability. Only 1.6% has high density (15–20) and is highly suitable. Most of the area (90%) has poor to marginally suitable drainage, posing significant limitations for drainage-dependent uses.

3.1.9. Distance to Groundwater Wells

Locating RWH sites close to wells can enhance groundwater recharge and help reoperate dry and stopped wells in the western field managed by Sana'a Water Sanitation Local Corporation. This approach maximizes the benefits of rainwater infiltration, supporting aquifer recharge and improving the reliability of local water supplies [26]. Studies suggest maintaining an optimal distance that allows effective recharge while preventing potential pollutants from compromising well water quality [26]. The Euclidean distance function used to calculate the distance to GW wells, with suitability classifications reclassified accordingly based on suitability for RWH (Figure 4c). The distance to GW wells standards for classifying RWH sites are explained in Table (2). The parts of the area with <500, 500-1000, 1000-1500, and >1500 m are categorized as highly suitable, moderately suitable, marginally suitable, and unsuitable areas, respectively. Over half the area (56.24%) is too far from wells (>1,500m) to be suitable, while only 18.27% is within the ideal range (<500m) is highly suitable. Another 17% has Moderately suitability (500-1,000m).

3.1.10. Depth to Groundwater Level

Strategic RWH site selection in regions with moderate groundwater depths is essential for enhancing water sustainability and supporting the rehabilitation of depleted wells within the Western Wellfield, managed by the Sana'a Water and Sanitation Local Corporation (SWSLC). The classification criteria for groundwater depth in RWH site selection are presented in Table (2) and Figure 4d, where areas with depths of <100 m, 100–150 m, 150–200 m, and >200 m are categorized as highly suitable, moderately, marginally suitable, and unsuitable, respectively. Most of the area has good water access. Over half (53.3%) is moderately suitable (100-150m), while another 31.84% is Marginally suitable (150-200m). Only 12.24% is High Suitability (<100m) and just 2.4% is Unsuitable (>200m).

3.2. Multi-Criteria Decision Analysis (MCDA)

To enhance the geospatial analysis for identifying potential rainwater harvesting (RWH) sites, a multi-criteria decision analysis (MCDA) approach was employed, utilizing the analytic hierarchy process (AHP) to assign weights to the selected criteria. It was assumed that the parameters had an unequal contribution to the RWH suitable sites. The relative importance of each parameter was defined based on related theories, expert opinion, previous studies, and professional judgment [33, 34].
AHP [35] is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology. It facilitates the prioritization of factors by breaking down the decision problem into a hierarchy, comparing criteria pairwise, and deriving relative weights to reflect their importance to each criterion using Saaty's scale (1–9) (Table 3) in achieving the overall goal of optimal RWH site selection for groundwater recharge and water resource sustainability in the study area.

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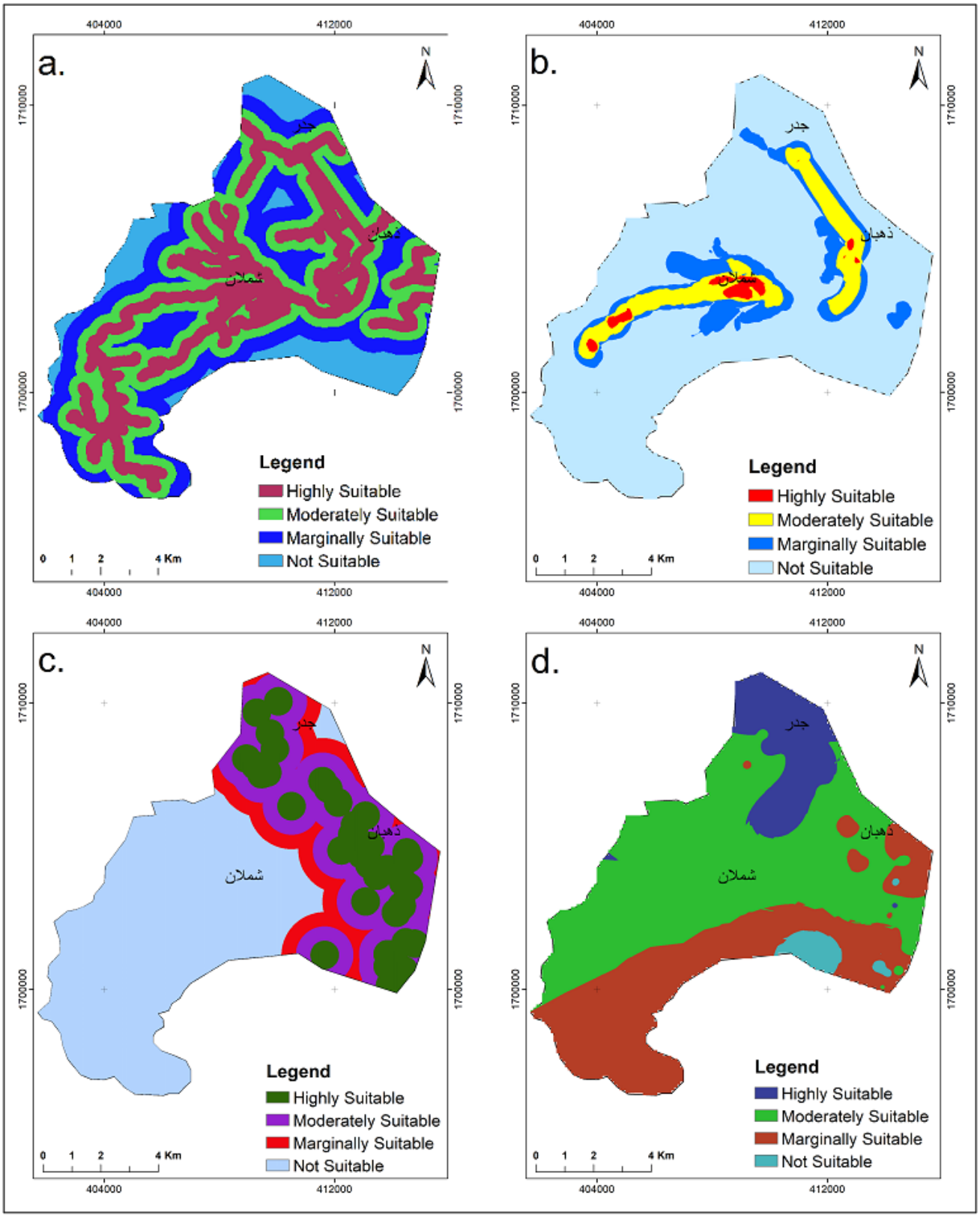

Figure 4. Criteria Suitability Maps in the Study Area: a. Distance to water stream; b. Drainage density; c. Distance to Groundwater Wells; d. Depth to Groundwater Level

3.3. Analytical Hierarchy Process (AHP) Weighting Results

The AHP approach provides a systematic and transparent method to balance multiple criteria, accounting for their relative importance in the context of the study area's unique challenges, such as rapid urbanization (30% urban area) and groundwater depletion. By combining AHP with geospatial techniques, this study ensures a robust, data-driven framework for RWH site selection, enhancing

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Table[3]: Pairwise comparison matrix of the main biophysical criteria (AHP method).

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1: Annual Rainfall	1	1.1	1.4	1.5	1.8	2.3	2.6	2.6	3.6	4.5
C2: Runoff Depth Potential	0.91	1	1.2	1.3	1.6	2	2.3	2.3	3.2	4
C3: Slope	0.71	0.83	1	1.1	1.3	1.6	1.9	1.9	2.6	3.3
C4: Distance to GW Wells	0.67	0.77	0.91	1	1.2	1.5	1.7	1.7	2.4	3
C5: Geological Media	0.56	0.63	0.77	0.83	1	1.3	1.4	1.4	2	2.5
C6: Soil Texture	0.43	0.5	0.63	0.67	0.77	1	1.1	1.1	1.6	2
C7: LULC	0.38	0.43	0.53	0.59	0.71	0.91	1	1	1.4	1.8
C8: Drainage Density	0.38	0.43	0.53	0.59	0.71	0.91	1	1	1.4	1.8
C9: Distance to Water Stream	0.28	0.31	0.38	0.42	0.5	0.63	0.71	0.71	1	1.3
C10: Depth to GW Level	0.22	0.25	0.3	0.33	0.4	0.5	0.56	0.56	0.77	1

decision-making for water resource management. An AHP pairwise comparison matrix is developed to assign relative importance to each criterion compared to other criteria using Saaty's scale (1–9) (Table 3). The matrix is constructed such that the weights (as percentages) guide the relative comparisons.

The matrix (Table 3) was based on the weights while ensuring consistency (Consistency Ratio, CR < 0.1). To measure the errors of the eigenvalue (λmax) caused by the incompatibility of the matrix, a consistency index (CI) expressed as follows was used:

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

where λmax is the major eigenvalue of the comparison matrix, which is produced by summing the products of each priority value element and the number of columns in the reciprocal matrix (Table 3). n represents the number of criteria applied in the study (Table 4). Higher values indicate greater importance. This matrix is based on the 10 criteria listed in Table (3).

Table (4) presents the normalized relative importance and final weight of the parameters. Divide each element in the matrix by its respective column sum to obtain the normalized matrix as follows:

$$Normal\ Value = \frac{Original\ Value}{Column\ Sum}$$

The final weight of each parameter was determined by averaging the normalized relative importance of each row. The pairwise comparison matrix was normalized by dividing each element by the sum of its corresponding column. The resulting normalized matrix ensured that the sum of each column equaled 1.000, thereby allowing direct comparison among criteria.

The priority weight for each criterion was obtained by averaging the normalized values across each row. The consistency of the pairwise comparisons was subsequently verified using the consistency ratio (CR), and the obtained value indicated acceptable consistency (CR $<$ 0.10), confirming the reliability of the assigned weights [35].

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

To ensure the reliability and consistency of the pairwise comparisons, we calculated the consistency index (CI) and consistency ratio (CR):

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

$$CI = \frac{10.1218 - 10}{10 - 1} \approx 0.0135$$

The Random Index (RI) for n=10 is 1.49.

The Consistency Ratio is:

$$CR = \frac{CI}{RI} = \frac{0.0135}{1.49} \approx 0.0091$$

Since CR$<$0.1, the matrix is consistent, confirming the reliability of the pairwise comparisons.

3.4. Weighted Linear Combination (WLC)

The weighted linear combination (WLC) method was applied in ArcGIS to identify suitable rainwater harvesting (RWH) sites by integrating multiple criteria into a single suitability map. Based on previous studies conducted in arid regions [36, 37], weights were assigned to the selected criteria. All thematic layers were then reclassified into four suitability classes according to the criteria presented in Figures (3,4) and assigned suitability scores ranging from 1 to 4. The weighted overlay analysis was performed using:

SI = Σ (Wi $\times$ Ri)

where SI = suitability index, Wi = weight of factors i, and Ri = reclassified score (1–4) denotes the corresponding suitability score. The resulting suitability index was classified into four categories: highly suitable, moderately suitable, marginally suitable, and unsuitable, thereby producing the final RWH suitability map for the study area.

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Table[4]: Pairwise comparison matrix of selected criteria and their corresponding weights

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Weight %
C1	0.181	0.176	0.183	0.18	0.18	0.182	0.182	0.182	0.18	0.179	18.05
C2	0.164	0.16	0.157	0.156	0.16	0.158	0.161	0.161	0.16	0.159	15.97
C3	0.128	0.133	0.131	0.132	0.13	0.126	0.133	0.133	0.13	0.131	13.08
C4	0.121	0.123	0.119	0.12	0.12	0.119	0.119	0.119	0.12	0.119	11.99
C5	0.101	0.101	0.101	0.1	0.1	0.103	0.098	0.098	0.1	0.099	10.01
C6	0.078	0.08	0.082	0.08	0.077	0.079	0.077	0.077	0.08	0.079	7.9
C7	0.069	0.069	0.069	0.071	0.071	0.072	0.07	0.07	0.07	0.071	7.02
C8	0.069	0.069	0.069	0.071	0.071	0.072	0.07	0.07	0.07	0.071	7.02
C9	0.051	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.052	5.01
C10	0.04	0.04	0.039	0.04	0.04	0.04	0.039	0.039	0.039	0.04	3.95
sum	1	1	1	1	1	1	1	1	1	1	100

3.5. Rainwater Harvesting Suitability Map

The final RWH suitability analysis model revealed spatial variability in site potential across the study area (Figure 5). The RWH suitability map classified the study area into four suitability classes: highly suitable, moderately suitable, marginally suitable, and unsuitable. Marginally suitable areas constituted the dominant class, covering 58.21% of the study area, followed by moderately suitable areas (37.60%). In contrast, highly suitable and unsuitable zones accounted for only 1.34 % and 2.85% of the total area, respectively (Figure 6).

The limited extent of highly suitable areas indicates that optimal conditions for rainwater harvesting are spatially restricted within the study area. These zones are mainly associated with favorable hydrogeological settings, including permeable alluvial deposits and exposed Tawilah Sandstone formations, which promote infiltration and groundwater recharge. Their occurrence near existing groundwater abstraction wells further enhances their strategic importance for recharge-oriented RWH interventions. Moderately suitable areas occupy a substantial portion of the study area and represent promising locations for future RWH implementation. Although these areas do not exhibit the same level of hydrogeological favorability as highly suitable zones, their suitability can be improved through engineering measures designed to increase runoff retention and infiltration efficiency.

The predominance of marginally suitable areas reflects the combined influence of topographic, geological, and land-use constraints. Steeper slopes reduce the residence time of surface runoff and limit infiltration opportunities, whereas volcanic formations with lower permeability restrict groundwater recharge. Furthermore, ongoing urban expansion has altered natural drainage processes and increased surface sealing, thereby reducing the effectiveness of natural recharge mechanisms.

The results demonstrate that the availability of runoff alone is insufficient for successful RWH site selection. Instead, effective groundwater recharge requires the simultaneous occurrence of favorable slope conditions, permeable geological formations, suitable soil characteristics, and proximity to recharge targets. This explains why only a small fraction of the study area was classified as highly suitable despite the presence of seasonal runoff and localized high rainfall zones.

From a water-resource management perspective, the findings highlight the importance of prioritizing recharge-focused RWH structures within highly suitable zones while adopting complementary measures in moderately suitable areas. Such an approach is particularly important in the Thaqban area, where continuous groundwater abstraction and declining groundwater levels have increased pressure on available water resources. Strategic implementation of RWH systems could therefore contribute to enhancing aquifer recharge, reducing dependence on groundwater extraction, and improving long-term water security.

3.6. Validation of the Suitability Map

To evaluate the reliability of the generated suitability map, the identified highly and moderately suitable zones were visually compared with the locations of the existing production wells managed by the Sana'a Water and Sanitation Local Corporation (SWSLC) and the mapped wadi network collected during field surveys. Most of the highly suitable zones were located close to productive groundwater wells and major drainage channels, indicating good spatial agreement between the GIS-MCDA model and existing hydrogeological conditions. This qualitative validation increases confidence in the suitability assessment and supports its applicability for groundwater recharge planning in the Western Wellfield.

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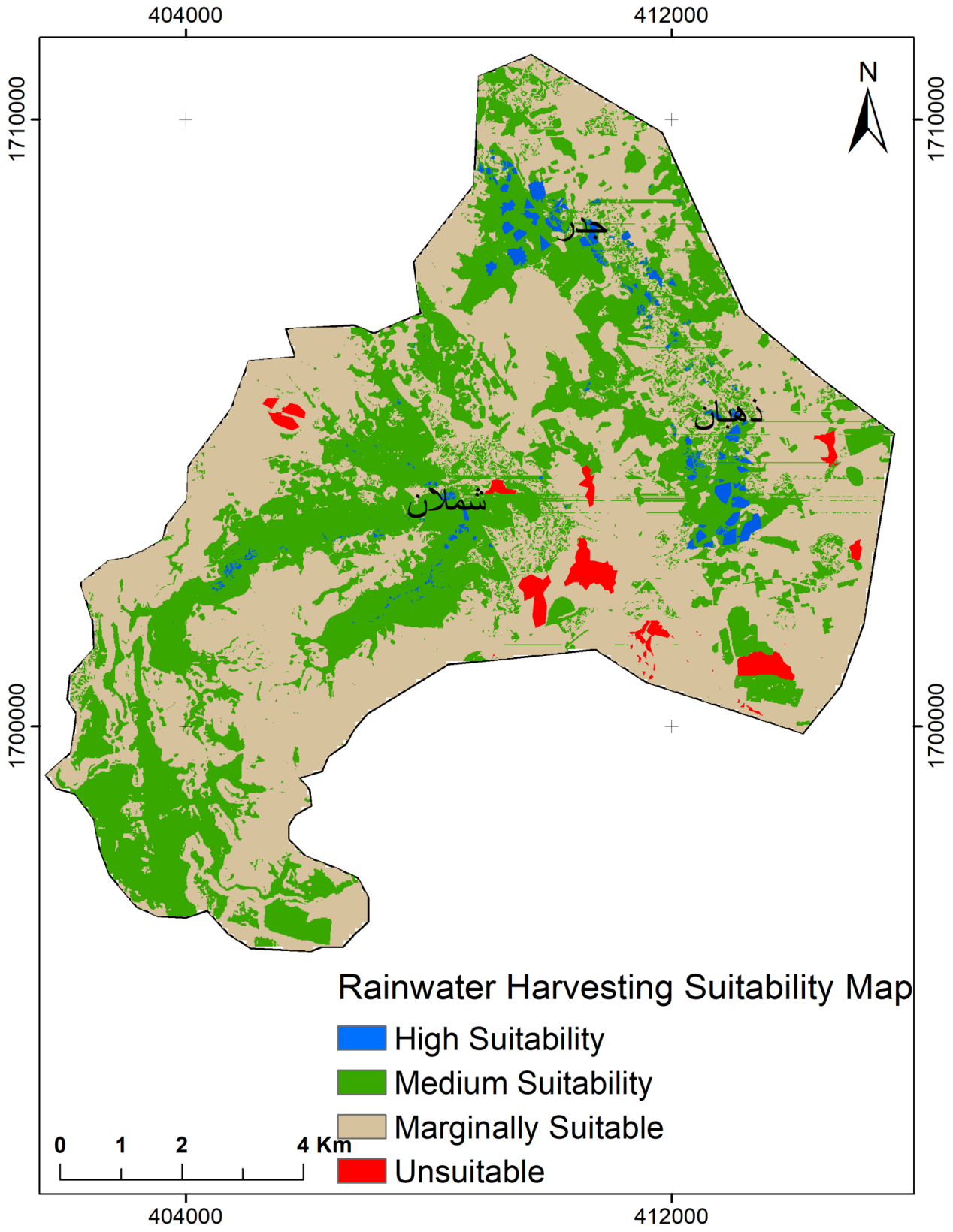

Figure 5. Rainwater harvesting (RWH) suitability map of the study area

4. CONCLUSION AND RECOMMENDATIONS

4.1. Conclusions

This study applied a GIS-based multi-criteria decision analysis (MCDA) integrated with the analytic hierarchy

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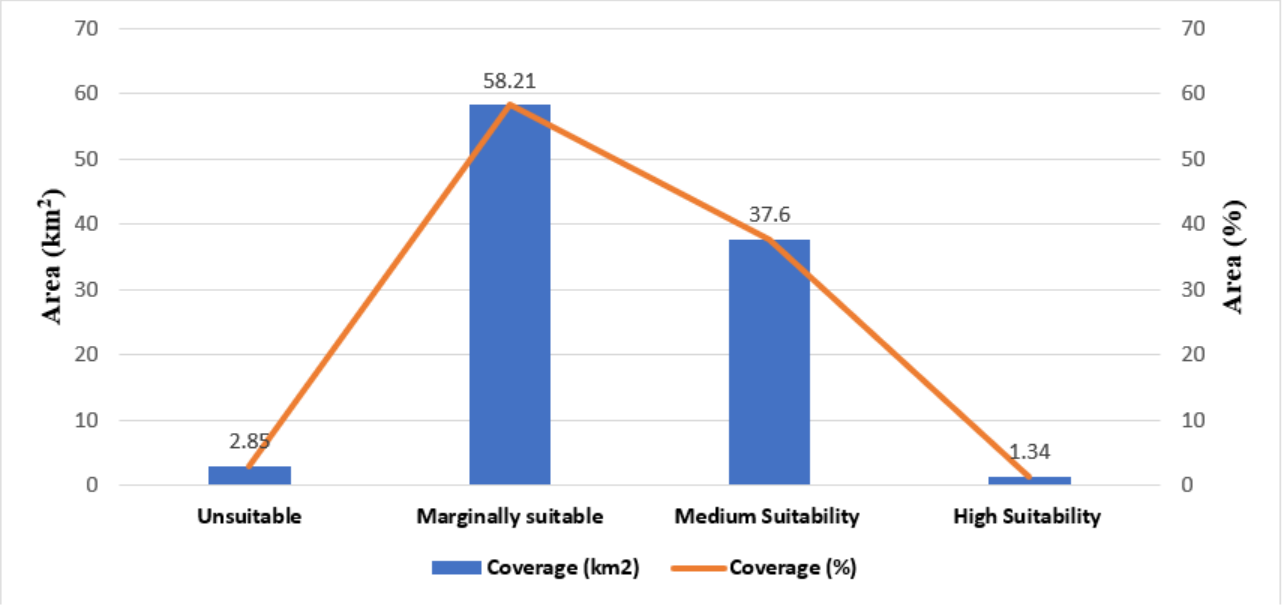

Figure 6. Distribution of areas covered by the RWH suitability classes

process (AHP) to identify suitable locations for rainwater harvesting (RWH) aimed at enhancing groundwater recharge in the Thaqban area, within the Western Wellfield of Sana'a Basin, Yemen. Ten hydrogeological, hydrological, and environmental criteria were incorporated into the analysis, including rainfall, runoff depth, slope, geological media, soil texture, land use/land cover, drainage density, distance to wadis, distance to groundwater wells, and groundwater depth.

The results revealed that only 1.34% of the study area is highly suitable for recharge-oriented RWH interventions, while 37.60% is moderately suitable, 58.21% is marginally suitable, and 2.85% is unsuitable. Highly suitable zones are primarily associated with permeable alluvial deposits, Tawilah Sandstone formations, favorable topographic conditions, and proximity to existing production wells. These characteristics enhance infiltration potential and provide favorable conditions for groundwater recharge.

The findings demonstrate that the effectiveness of RWH for groundwater recharge depends not only on runoff availability but also on the combined influence of geological, hydrogeological, and topographic conditions. The generated suitability map provides a practical decision-support tool for prioritizing locations for recharge structures, such as check dams, recharge basins, and percolation ponds, in the Western Wellfield.

Given the continuing decline in groundwater levels within the Sana'a Basin, the implementation of recharge-focused RWH systems in identified priority zones could contribute to improving aquifer replenishment and strengthening long-term water security. Future research should focus on field validation of the identified sites, estimation of recharge volumes, and assessment of the long-term impacts of RWH interventions on groundwater recovery and well productivity.

5. RECOMMENDATIONS

1. Prioritize the implementation of groundwater recharge structures in the highly suitable zones identified by GIS-MCDA analysis, particularly in areas underlain by alluvial deposits and Tawilah Sandstone formations.
2. Preparation of hydraulic studies, designs, and bills of quantities for suitable sites and construction of suitable rainwater harvesting structures, such as recharge basins, percolation ponds, and Karfan, to capture seasonal runoff and enhance aquifer recharge.
3. Direct seasonal floodwater and runoff from nearby wadis toward the identified recharge zones to maximize aquifer recharge and reduce water losses.
4. Protect identified recharge zones from uncontrolled urban expansion and land-use changes that may reduce infiltration and groundwater recharge.

Declarations

Ethical Approval

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

We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Conflict of interest

The authors declare no conflicts of interest regarding the publication of this study. All coauthors have approved the manuscript and concur with its submission to the journal.

Competing interests

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The authors have no financial or proprietary interests in any material discussed in this article.

Authors' contributions

All authors contributed to the study conception and design. All authors performed the simulations, data collection, and analysis, and commented on the present version of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

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Consent for publication

The authors confirm that informed consent was obtained for the publication of the data contained in the **article.**

Consent to participate

Informed consent was obtained from all authors.

Declaration of AI-Assisted Technologies

"The authors declare that artificial intelligence (AI) tools were used only for limited purposes, such as language editing, grammar improvement, and formatting assistance. All scientific content, data analysis, interpretations, conclusions, and final manuscript revisions were reviewed and verified by the authors, who take full responsibility for the integrity and originality of the work."

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