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RESEARCH ARTICLE - EARTH SCIENCES

A GIS-Based Integrated Fuzzy Logic and Analytic Hierarchy Process Model for Assessing Water-Harvesting Zones in Northeastern Maysan Governorate, Iraq

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Abstract Identifying potential sites for water harvesting (WH) is a crucial task for efficient water resources management in arid regions. In response, this paper proposes a geographical information system-based model that combines fuzzy logic and analytic hierarchy process (AHP) to delineate suitable areas for constructing WH structures in arid southern Iraq. Based on a literature review and available data, five influential factors were selected to develop the model: hydrological soil group, land cover, surface runoff depth, slope, and distance to an intermittent river. A fuzzy logic-based approach was used to standardize the factors, and AHP was used to derive weights. The total score for land suitability was obtained from a linear aggregation of the products of fuzzy standard criteria and AHP-derived weights. The WH suitability levels obtained were classified into five different classes: unsuitable, poor, moderate, good, and excellent. The study revealed that 393 km^2 (18% of the area) is unsuitable or poor, 538 km^2 (26%) is moderately suitable, and 1167 km^2 (56%) is good or excellent for WH in the study area. Field data revealed that the only existing WH dam in the area is situated within an excellent WH-suitable zone, which indicates the capability of the developed model to identify areas suitable for different WH structures.

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1 Introduction

Decades of war and mismanagement, increased demand due to population growth, the water policies of Iraq's upstream neighbors Turkey, Iran and Syria, and the worst droughts in recent memory have made water a scarce commodity in Iraq, particularly in the southern part of the country. In recent years, severe water scarcity in the region has forced thousands of marshland residents to abandon their homes, and the trend is likely to worsen as droughts in Iraq continue. There is thus an urgent need for alternative planning to mitigate Iraq's water scarcity.

Among the most effective options for irrigation in dry areas, water harvesting (WH) is the collection and management of surface runoff and flooded water to enhance water availability for different uses, especially domestic and agricultural ones [1]. Practically, the chief aim of WH is to collect runoff or groundwater from an area with ample water, store it, and make it available where and when a water deficit occurs [2]. WH techniques can be classified into different groups depending on the WH criteria in focus, among which the two most frequently used are the catchment type and size, and the water storage method used [3]. By catchment type, the four groups of WH systems are floodwater harvesting, macro-catchment, micro-catchment, and rooftop harvesting, a detailed description of which appears in [3, page 9]. In arid regions such as southern Iraq, WH can be an efficient approach to harness excess runoff that is often lost for later use during water deficit [4]. WH helps to increase the amount of water per unit of cropland, to improve groundwater levels [5], and thereby to mitigate water shortage problems, especially those affecting agricultural and domestic uses [6].

The effectiveness of any WH project depends on its ability to maximize the productivity of rainwater and increase the amount of water per unit of cropland [7]. To optimize those criteria, identifying potential sites for WH is critical; however, selecting potential areas for siting WH structures depends on several factors, including climate, hydrology, topography, soil types, and socioeconomic criteria. By extension, pinpointing such factors depends primarily upon the availability of data and in situ conditions.

In recent years, geographical information systems (GIS) have provided a flexible, powerful platform for integrating remote sensing data and runoff model outputs in order to optimally situate WH structures [4,7–10], typically by using spatial analysis tools [11]. Delineating suitable areas for WH structures is often performed by integrating different factors using GIS overlay and index-based multicriteria decision analysis (MCDA), which for GIS can provide a set of powerful techniques and procedures for making critical decisions [12].

Among MCDA approaches, the analytic hierarchy process (AHP) is a widely used method in decision-making processes in various fields [13]. It offers an adaptable, low-cost, and understandable output for complex decision making [14]. In reviewing the application of MCDA methods for water resource management, Hajkowicz and Collins [15] indicated that AHP is perhaps the most widely used technique over all other available methods. Indeed, the GIS-based AHP strategy has been broadly acknowledged by the global academic community as a powerful technique for analyzing spatial decision-making problems [16].

Fuzzy logic, by contrast, is an intelligent technique widely used to map an input space to an output space by using a list of *IF–THEN* rules. It provides a procedure for systemically calculating uncertain, imprecise, or incomplete information used in processing knowledge [17]. The preference of fuzzy logic stems from its simple application [18], as well as that it affords different fuzzy combination operators (*AND*, *OR*, *SUM, PRODUCT, and GAMMA*) for solving complex decision-making problems [19].

For the present study, a GIS-based model combining fuzzy logic and AHP was proposed to delineate suitable areas for constructing WH structures in the Teeb area of the northeastern Maysan Governorate in southern Iraq. Fuzzy set theory was used to standardize factors used to identify locations suitable for WH, whereas AHP was used to infer the weight of each influential factor. Ultimately, the factors were aggregated using weighted linear combination (WLC) technique. Despite its extraordinary significance, using remote sensing technology and GIS techniques in water resource management and its research remains quite limited in Iraq [20–25]. In particular, no research has been conducted to identify suitable locations for WH in the study area by using remote sensing and GIS. As such, the proposed approach using readily available data is expected to provide guidance for decision makers active in the region's water resource management.

2 Study Area

This study was conducted in the northeastern part of Maysan Governorate in southern Iraq (Fig. 1). Covering 2098 km^2, the study area exhibits ground surface elevation ranging from 0 to 266 m, with an average of 36 m (Fig. 1). Two intermittent streams—namely the Teeb and Dewereg—with a primary source in Iran run through the area; the Teeb enters Iraq in the north of the study area and runs southward until ending in the Al-Sanaf marsh [26], whereas the Dewereg flows east to northeast until disappearing in the Al-Rais wetland.

The study area's climate is characterized by hot, dry summers and cold, wet winters. The spring and fall seasons often last only 2 weeks. Temperature often differs between 23.74 and 26.43 °C with little variation across the area [27]. Tertiary rocks and Quaternary deposits are the primary geological features; the Quaternary deposits cover 72% of the area, whereas Tertiary rocks extend over the remaining 28% [28]. More particularly, the Tertiary rocks comprise up to 2000 m of fining upward cycles of gravely sandstone, sandstone, and red mudstone that become replaced almost entirely by conglomeratic facies in the high-folded zone of northeast but not northern Iraq [29]. By contrast, the Quaternary sediments are unconsolidated and usually finer grained than the underlying Tertiary rocks [30]. The aquifer system in the area contains three parts—a top shallow unconfined aquifer, an intermediate semiconfined major aquifer, and a deep confined aquifer—all separated by two less permeable aquitards with unknown hydraulic characteristics. The hydraulic connection between aquifer units is possible and the confined portion of the aquifer system is not fully separated. Table 1 presents the hydraulic characteristics of the main aquifer units. The hydraulic characteristic of the Tertiary rocks is greater than that of the Quaternary part of the aquifer system, meaning that the Tertiary part is more important for groundwater flow and storage than the Quaternary deposits.

3 Modeling Techniques

3.1 Weighted Linear Combination (WLC)

WLC is a simple additive weighting technique in which continuous criteria are standardized and aggregated accord-

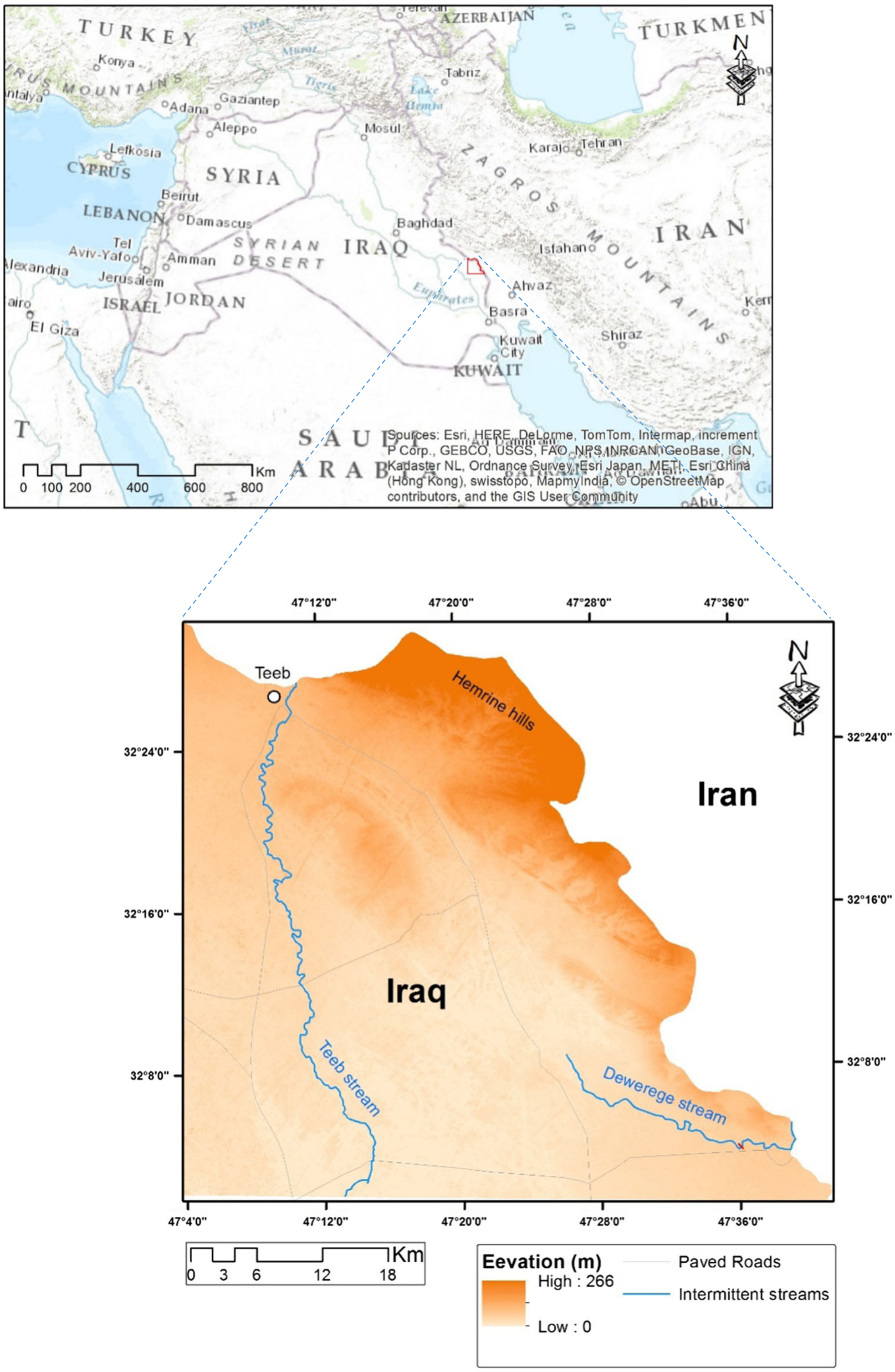

Fig. 1 Location map of the study area with ground surface elevation (m)

ing to a weighted average concept [31]. In the technique, the subjectively or objectively specified weights are used along with corresponding individual standardized criteria as input. The total score is obtained as follows [32]:

$$S = \sum_{i=1}^{n} w_i x_i \quad (1)$$

in which S is the suitability index, w_i is the weight of factor i, and x_i is the criterion score of factor i.

Table 1 Aquifer hydraulic characteristics in the study area (after Al-Abadi [28])

Aquifer lithology	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)
Quaternary deposits	0.5–15.5	12–290
Tertiary rocks	2–25	400–500

3.2 Fuzzy Logic

Whereas the classical theory of crisp sets can describe only the membership or non-membership of an item to a set [33], fuzzy logic permits partial membership, which can pose a value from 0 to 1:

$$\mu_A(x) : X \rightarrow [0, 1] \tag{2}$$

in which X refers to the universal set defined in a specific problem and $\mu_A(x)$ the grade of membership for element x in fuzzy set A. The crisp set is a special case of fuzzy sets, in which the membership function for each element takes one of only two values: 0 or 1 [34]. To build a fuzzy logic-based model, the proper types of membership function and its parameters should be carefully selected. The process of decomposing a given system input and/or output into fuzzy sets is called *fuzzification*. In this study, the "large" and the "small" fuzzification algorithms were used. These fuzzification operators were used here to indicate that small and large values of the crisp set are the larger membership of the fuzzy set [35]. The large fuzzification algorithm is written mathematically as [36]:

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f^2}\right)^{-f^1}}, \tag{3}$$

whereas the small fuzzification algorithm is written as [37]:

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f^2}\right)^{f^1}} \tag{4}$$

in which f^1 is the spread of the transition from a membership value of 0–1 and f^2 the midpoint.

In this study, the fuzzy logic approach was used for standardized factors in the range of 0–1. The fuzzy membership function tool in ArcGIS 10.2 was used to derive membership functions for factors used to derive spatial suitability levels.

3.3 Analytic Hierarchy Process (AHP)

AHP is a decision-support engine to identify optimal decision making in complex situations via a hierarchical structure made of targets, criteria, and alternatives [14]. The goal of the AHP is to distinguish the relative importance of multiple paired criteria to accomplish an expressed objective [38]. The initial step is to formulate the decision-making problem as a hierarchical structure, which presents an effective method for regulating complex natural systems. Once a hierarchy is developed, a priorization technique can be used to determine the relative importance of elements, all compared as pairs with respect to their importance in making the decision, at every level of the hierarchy. As part of the AHP, a verbal scale, or Saaty's scale (Table 2), is used to empower decision makers to consolidate subjective experience and knowledge in an instinctive, normalized way [39]. Once the comparison matrix is made, the relative weights of the different components against components in the adjacent upper level are figured as parts of the normalized eigenvector that is connected to the eigenvalue of their comparison matrix [40]. Composite weights are then dictated by aggregating the weights according to the hierarchy. The final result is a standardized vector of the overall weights of the system.

To examine the consistency of the comparison matrix, Saaty [14] proposed the following formula:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

in which CI is the consistency ratio and RI the consistency index of a comparison matrix. If CR is greater than 0.1, then the set of judgment is inconsistent; if CR equals 0, then the judgment is wholly consistent [14]. In Eq. (5), CI is computed as:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

in which $\lambda_{\max}$ is the largest eigenvalue of the comparison matrix and n the order of the comparison square matrix.

4 Results and Discussion

4.1 Generating Thematic Maps

Figure 2 illustrates the methodology used in this study. Although the selection of factors used to study an area's potential for WH varies from region to region, it primarily depends on available data [4,41]. In this study, five factors were used to investigate WH potential, all based on their importance and the data available: slope (%), hydrological soil group (HSG), land cover (LC), surface runoff depth, and distance to an intermittent river. All five factors were prepared as rasters with a spatial resolution of 30 × 30 m; each raster map contains 2054 columns and 1850 rows, for a total of 3,799,900 pixels.

Table 2 The fundamental scale of Saaty (after Saaty and Vargas [39])

Intensity of importance	Definition	Explanation
1	Equal importance	Two objective contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly factor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with j	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER-GDEM) was used to derive the thematic map of the slope (%) of the study area. The sinks in the raw DEM data were filled first. Slope (%) was directly derived from filled DEM and classified into four classes using a manual classification scheme [42]: <2% (flat), 2–8% (undulating), 8–15% (rolling), and 15–30% (hilly), as shown in Fig. 3a. The flat, undulating categories cover an area of about 2002 km^2 (95%), whereas the rolling, hilly categories encompass about 96 km^2 (5%). Since the slope affects runoff volume and infiltration, the location of WH depends highly upon slope [43]. For WH analysis, the dominant slope percentage was used, and to standardize the thematic layer of slope using fuzzy logic, the small fuzzification algorithm was used (Fig. 3b). According to Munyao et al. [43], the slope of WH in a macro-catchment should be between >2 and <30%.

HSG is highly useful in estimating the runoff in a watershed, since soil heavily influences runoff generation. The Natural Resource Conservation Service (NRCS) classified 3000 soil types into four hydrologic groups (Table 3) depending on infiltration, soil composition and other criteria [44]. To create a thematic map of HSG in the study area, Al-Abadi [28] gathered 20 soil samples, each of which was assigned a soil texture name using the online version of the US Department of Agriculture triangle. The soil texture of each sample was converted into a measure of soil permeability based on soil taxonomy and assigned a range of infiltration rate in mm/h. Stochastic kriging interpolation was then used to interpolate the typical infiltration rate over the study area to generate the map of HSGs (Fig. 4a). Figure 4a shows that the study area is predominantly covered by soil pertaining to A and B (more permeable) groups (less permeable soils). The soil groups A and B are found to cover 22% (470 km^2) and 47% (983 km^2) of the study area, respectively. The C and D groups of soil (less permeable) are found to cover 21% (216 km^2) and 10% (428 km^2) of the study area, respectively. Groups C and D concentrate primarily in the southeastern part of the study area, as well as in a small central area, whereas groups A and B are distributed irregularly throughout the rest of the area. Since runoff increases with decreased soil permeability, the large fuzzification algorithm was also used to create membership functions of the HSG layer (Fig. 4b).

The land cover map was prepared from Landsat 8 imagery. The raw satellite image of the study area was acquired on February 6, 2015, and downloaded using the platform Earth Explorer (http://earthexplorer.usgs.gov/). Seven bands of the image were combined to create a mosaic raster of the study area and enhanced using radiometric algorithm. Supervised maximum likelihood classification was used to produce the land cover map of the study area (Fig. 5a), for which training samples were collected using field surveys to create a spectral signature file. Four land cover classes were identified: bare exposed rocks, shrub land, barren land, and rangeland. Bare exposed rock encompasses 14% (304 km^2), shrub land 30% (607 km^2), barren land 38% (797 km^2), and rangeland 19% (390 km^2). The large fuzzification method was also used for the fuzzification of pixel data of the land cover map (Fig. 5b), because barren and shrub lands extend over a large area and are more suitable for WH structures such as surface ponds.

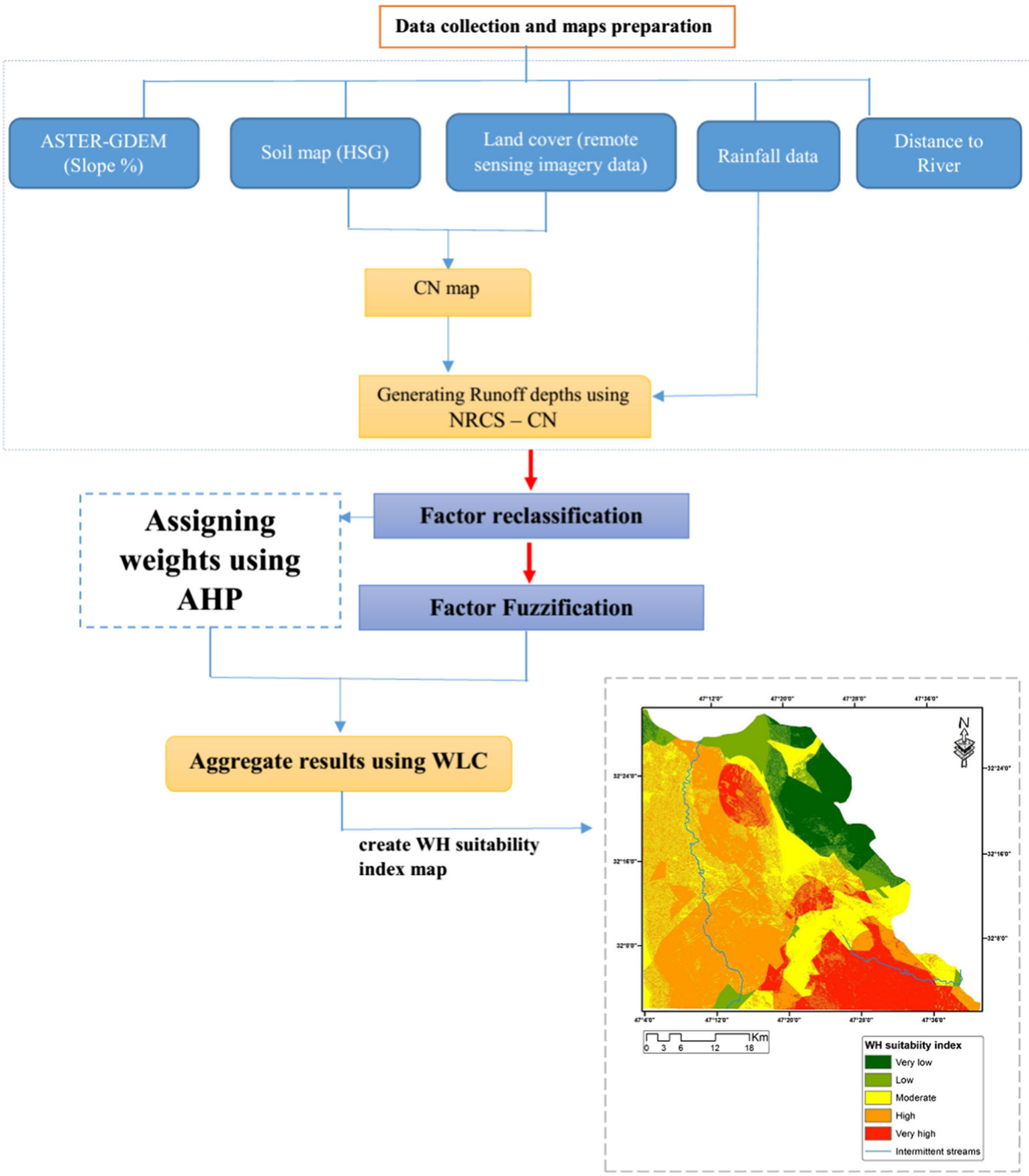

Fig. 2 Flowchart for the delineation of WH in the study area

Surface runoff is an important hydrological variable used in developing hydraulic structures. Since accurate information of runoff in an arid region such as Iraq is scarce and accessible only in a few sites, runoff estimation techniques suitable for ungauged watershed were used. Among the different techniques for estimating the runoff of ungauged basins, the Resource Conservation Services Curve Number (NRCS-CN) is the most widely used method worldwide and computes direct surface runoff using an empirical equation that requires the rainfall and a single watershed coefficient as input [45]. The single watershed coefficient is termed the *curve number* (CN), a dimensionless number ranging from 1 to 100 determined according to four factors: HSG, land use-land cover (LULC), hydrological conditions, and antecedent moisture conditions (AMC). High CN values reveal high surface runoff, whereas low ones imply low runoff [23]. The NRCS-CN method is developed depending on the water balance equation and two fundamental hypotheses [45]. The water balance equation is written as:

$$P = I + F + Q \tag{7}$$

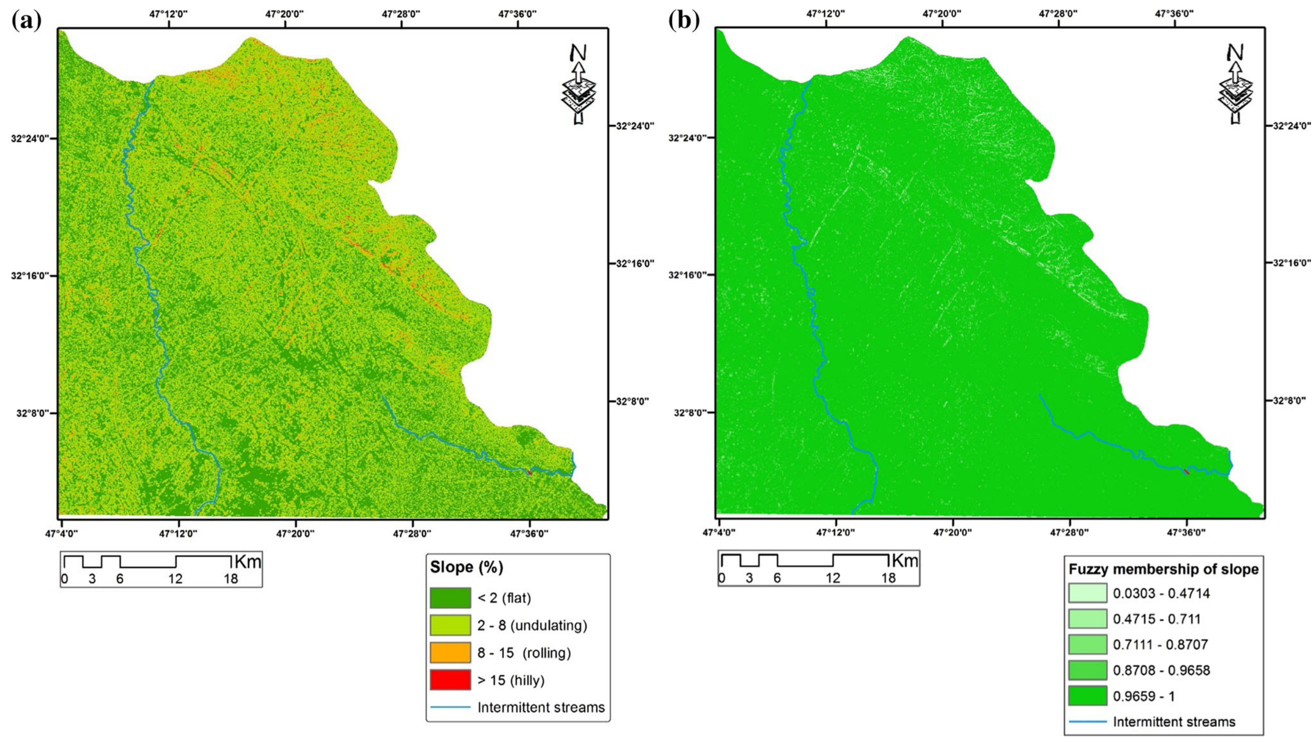

Fig. 3 **a** Map of slope (%); **b** fuzzy membership map of the reclassified slope layer

Table 3 SCS Hydrologic soil group (after USDA [44])

Soil group	Description	Final infiltration rate (mm)
A	*Lowest runoff potential*. Includes deep sands with very little silt and clay, also deep, rapidly permeable loess	8–12
B	*Moderately low runoff potential*. Mostly sandy soils less deep than A, and less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting	4–8
C	*Moderately high runoff potential*. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D. The group has below—average infiltration after pre-saturation	1–4
D	*Highest runoff potential*. Includes mostly clays of high selling percent, but the group also includes some shallow soils with nearly impermeable sub-horizons near the surface	0–1

in which P is the total rainfall (mm), I the initial abstraction (mm), F the amount of potential maximum retention (mm), and Q the actual direct runoff (mm).

The first hypothesis states that the ratio of the infiltrated water (F) to watershed storage (S) equals the ratio of actual direct runoff (Q) to total rainfall (P), minus initial abstraction, written as [46]:

$$\frac{F}{S} = \frac{Q}{P - I} \tag{8}$$

in which S is watershed storage (mm). The amount of rainfall infiltrated after runoff begins is calculated as:

$$F = (P - I) - Q \tag{9}$$

By substituting Eq. (7) into Eq. (5) and solving for Q in terms of P, I, and S, Eq. (6) becomes:

$$Q = \frac{(P - I)^2}{(P - I + S)} \tag{10}$$

Regarding the second hypothesis, initial water abstraction I is related to the potential maximum retention through the following formula:

$$I = 0.2S \tag{11}$$

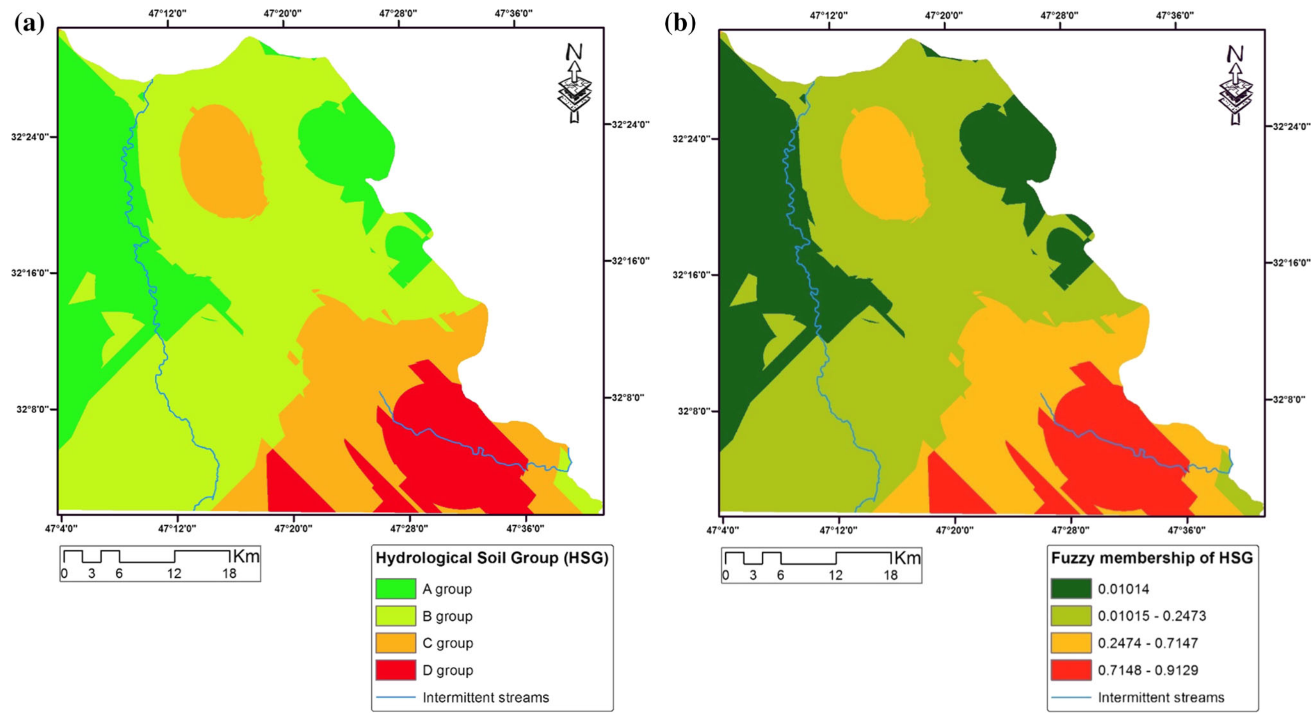

Fig. 4 **a** Hydrological Soil Group (HSG) layer; **b** fuzzy membership of reclassified HSG layer

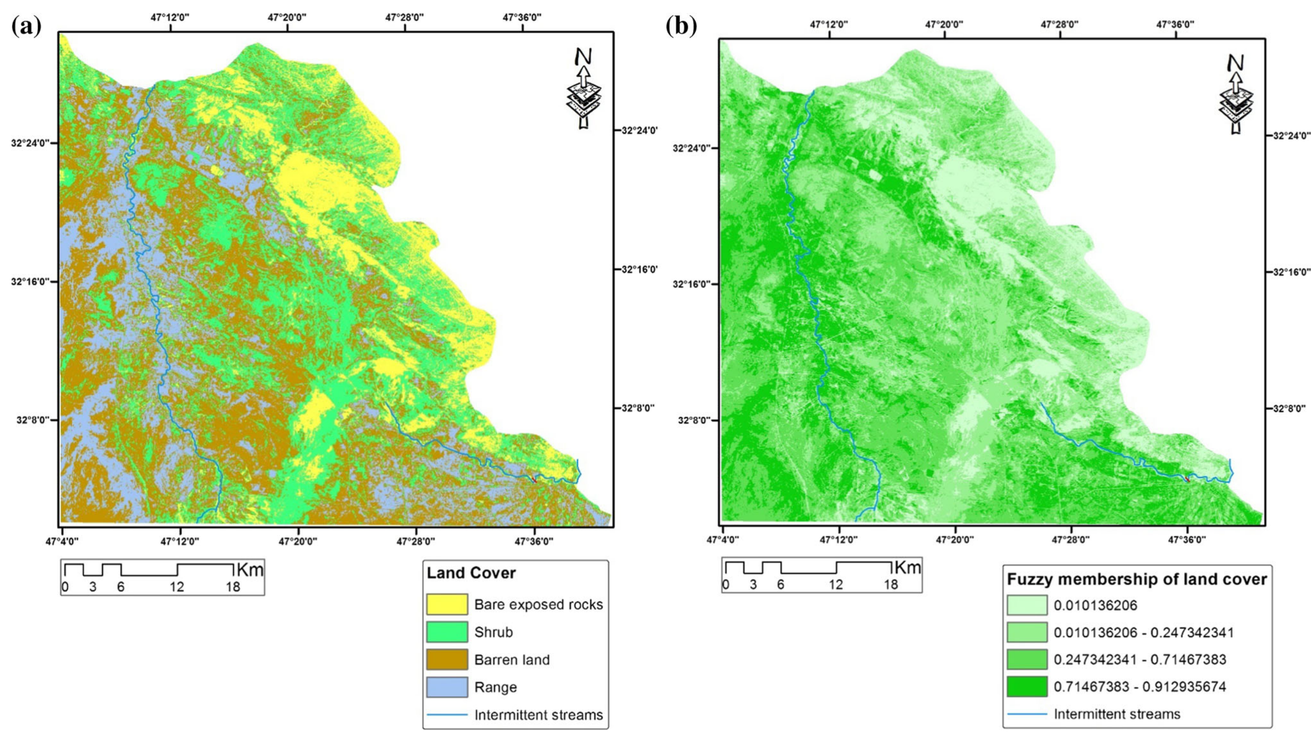

Fig. 5 **a** Land cover layer; **b** fuzzy membership of reclassified land cover layer

Substituting Eq. (9) into Eq. (8) yields

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{12}$$

which is the rainfall–runoff equation used by the NRCS-CN for estimating the depth of direct runoff from a storm event on the daily basis [47]. The potential maximum retention storage, S, of the watershed is related to a CN through the following equation:

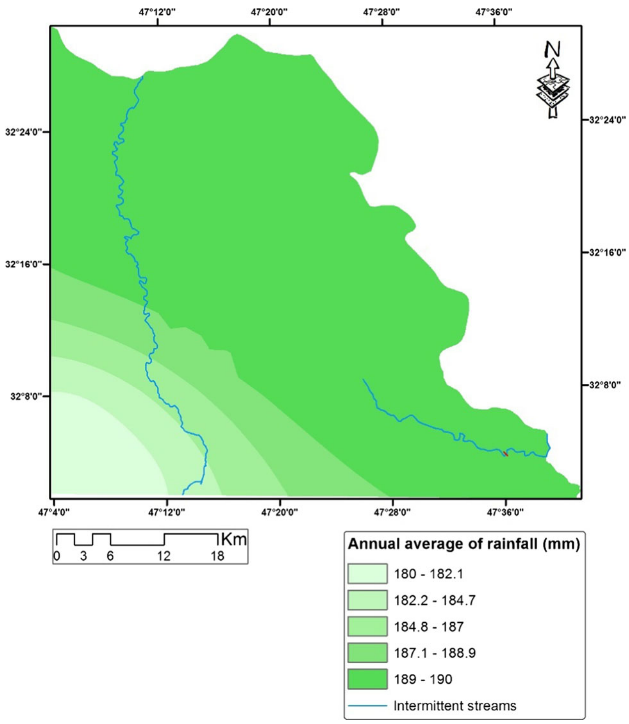

Fig. 6 Spatial distribution of annual average of rainfall for the period 1980–2013

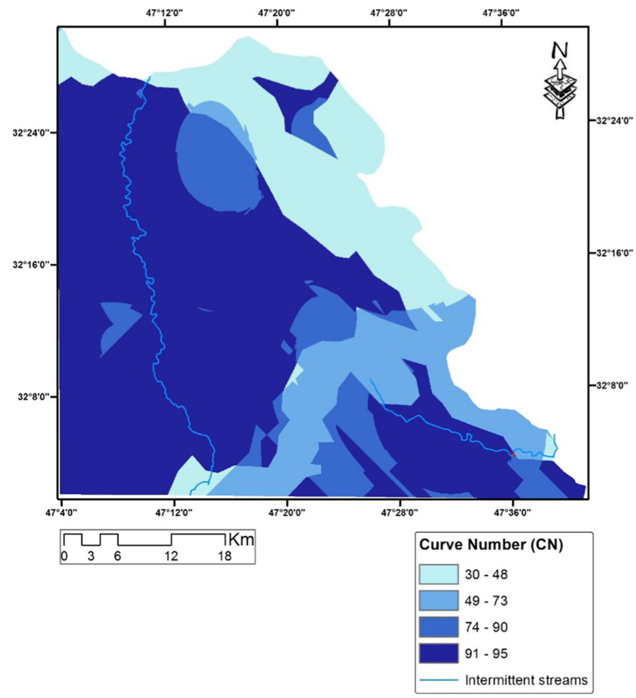

Fig. 7 Curve number (CN) layer (After Al-Abadi and Shahid [24])

$$S = \frac{25400}{\text{CN}} - 254 \quad (13)$$

The spatial distribution of the annual average rainfall over the study area [48] for southern Iraq was used (Fig. 6). Those authors used historical monthly rainfall records from meteorological stations for 1980–2013 and the stochastic ordinary kriging technique to spatially estimate annual rainfall over the study area. The map clearly shows that the average rainfall increases from southwest to northeast. The minimum, maximum, and average annual rainfall in the study area are 180, 190, and 188.64 mm, respectively. At the same time, the raster map of CN over the study area provided by Al-Abadi and Shahid [49] was also used (Fig. 7). The map clearly shows that the area has a high hydrological ability to generate runoff, since most of the area (about 72%) has a high CN (>60). The maximum potential retention S for each pixel is computed using Eq. (11), after which the runoff depth over the study area was estimated using Eq. (10), with the aid of traditional algebra, in the Raster Calculator of ArcGIS 10.2. Figure 8a shows the generated raster map of runoff depth, for which the minimum, maximum, and average depths (mm) in the area were found to be 7.57, 175.20, and 133 mm, respectively. Runoff depths were found to be high in the southeast and central parts of the area and to gradually decrease in both northeast and southwest directions. Standardized pixel values of the runoff depth map (Fig. 8a) were fuzzified using the large fuzzification method (Fig. 8b), since a location with high runoff depth is more suitable for WH.

The map of the distance to the intermittent stream was produced using approximate analysis with the Euclidean Distance module in the Spatial Analysis extension of ArcGIS 10.2. The continuous values of distance to intermittent streams were manually classified into five categories to prepare the raster map (Fig. 9a). Since flash floods triggered by rainfall occasionally occur near to the intermittent river and it is thus possible to harvest floodwater by locating WH near the river, the small fuzzification method was used to fuzzify the pixels of that raster map (Fig. 9b).

4.2 Integration of the Thematic Map

The Expert Choice 11 software, a commercial software primarily used in decision making, was used to derive the weights of the factors (i.e., slope, HSG, land cover, runoff depth, and distance from an intermittent river), presented in Table 4. The importance of each factor with respect to the others was determined in reference to expert opinion and literature reviews. The CR value was found to be 0.02, and thus the decision can be considered consistent.

4.3 Generation of Suitable Zones on the WH Structures Map

The suitability levels for WH were estimated by integrating the raster maps of the factors using the WLC technique with

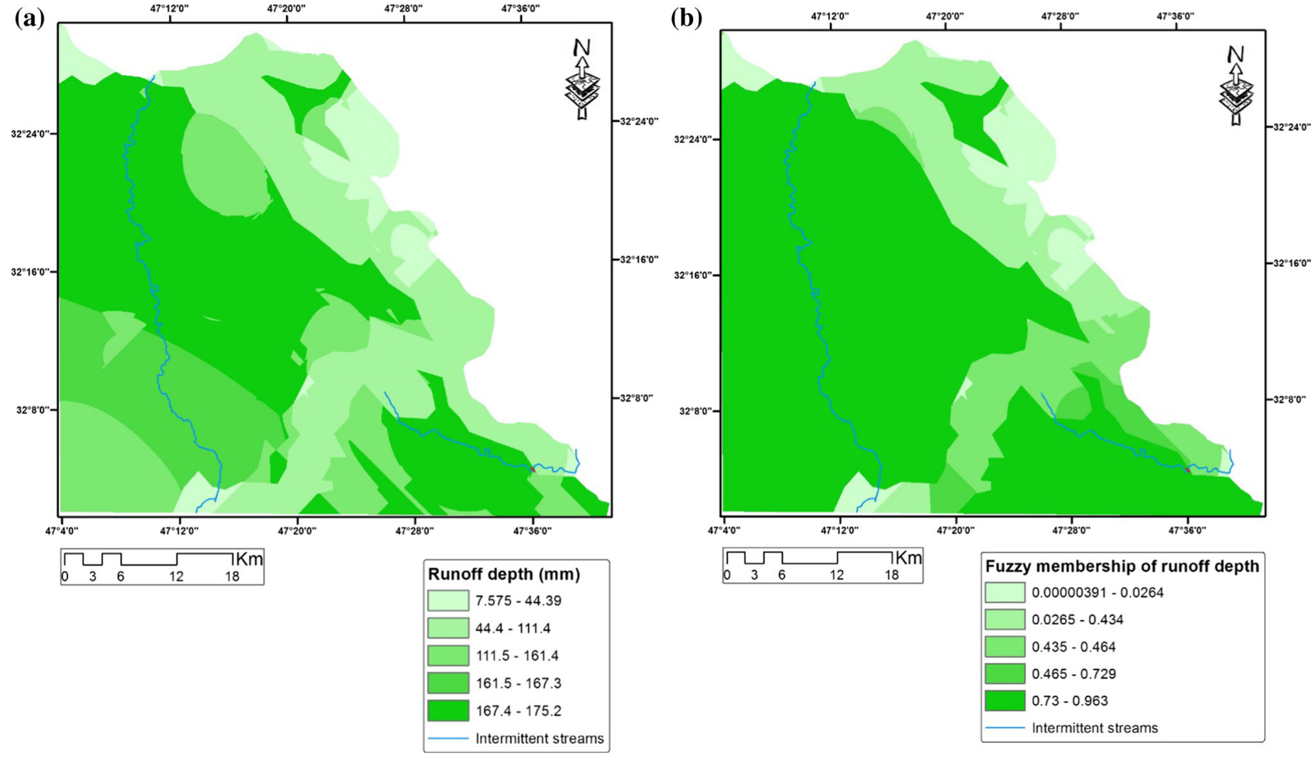

Fig. 8 **a** Runoff depth (mm); **b** fuzzy membership of reclassified runoff depth layer

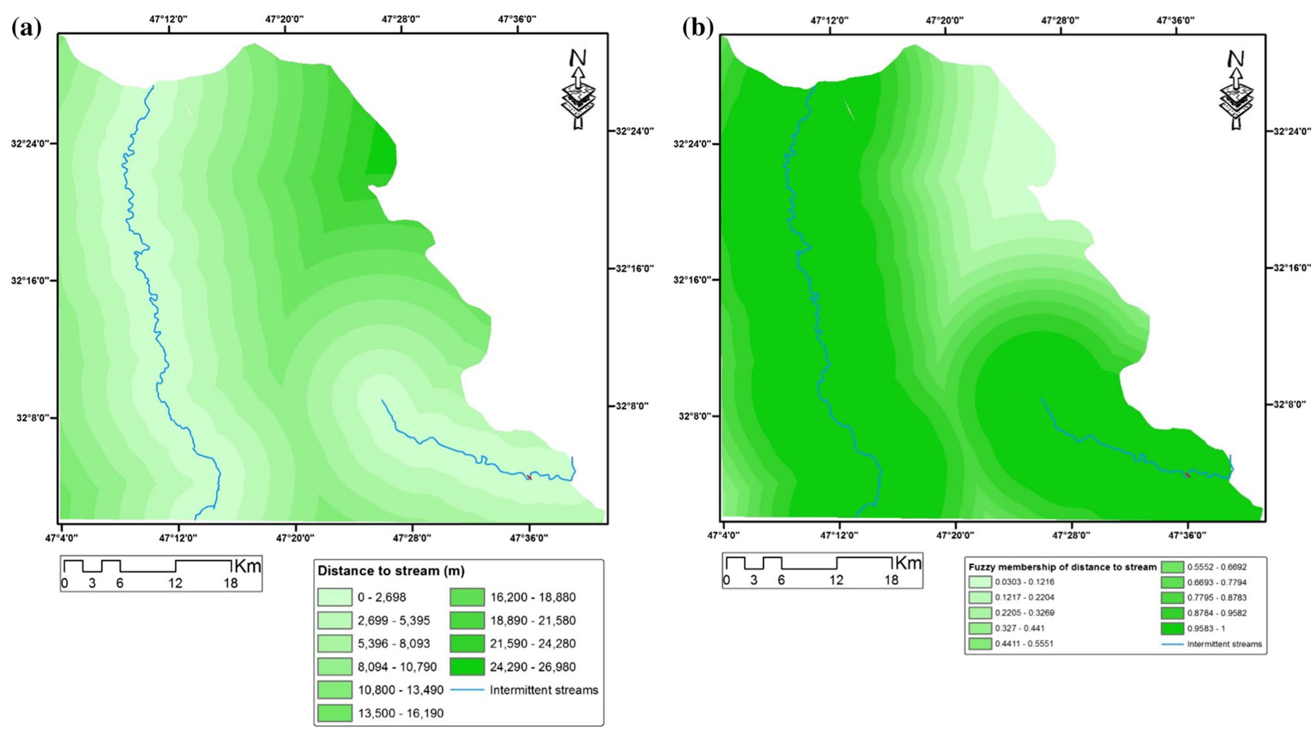

Fig. 9 **a** Distance to intermittent streams (m); **b** fuzzy membership of reclassified distance to intermittent streams layer

Table 4 Factor weights by using AHP

Factor	Runoff depth (mm)	HSG	Land cover	Slope (%)	Distance to streams
Weight	0.368	0.248	0.117	0.069	0.198
				Consistency ratio	0.02

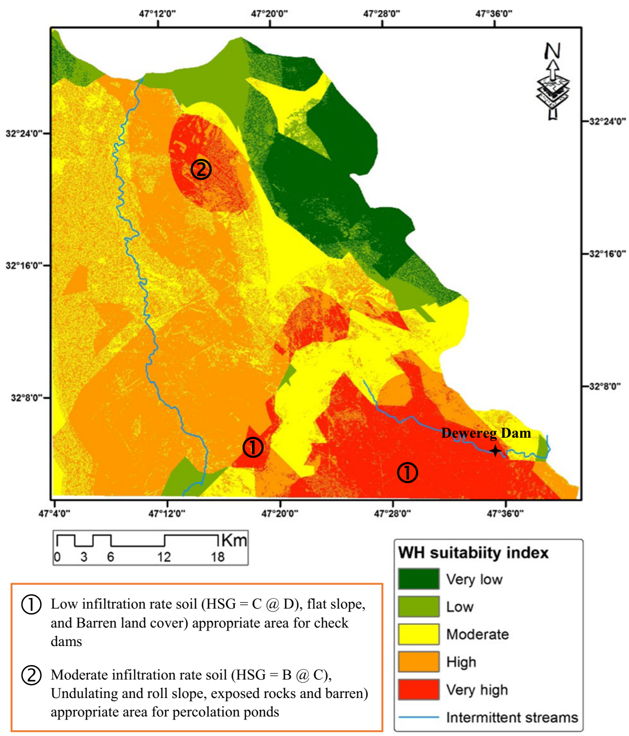

Fig. 10 Water-harvesting suitability index map

ArcGIS 10.2. Thematic maps weighted by AHP were combined using WLC to yield the WH suitability map shown in Fig. 10. The resulting pixel values, found to range from 0.22 to 0.94, were classified by suitability into five different zones: unsuitable, poor, moderate, good, and excellent [41]. About 218 km^2 (10%) of the study area was found to be unsuitable, 174 (8%) poor, 538 km^2 (26%) moderately suitable, 888 km^2 (42%) good, and 280 km^2 (13%) excellent for WH. Good and excellent zones are primarily located in the southeastern part of the area, near the Dewereg stream, as well as a small central part, whereas the unsuitable and poor zones for WH were found primarily in the elevated region in the northeast of the area, near the Iraq–Iran border. The moderate zone is distributed between the low and good zones, which are mostly located in the east of the area. Areas with good and excellent potential zones for WH have flat, undulating slopes (2–8%) and soil types of groups C and D, with low infiltration rates and a high capability to generate surface runoff.

The WH-suitable zone map was validated by comparing the location of existing WH structures. A field survey confirmed that the study area contains only one dam, which was recently constructed to control flooding during rainy seasons on the Dewereg stream by the Ministry of Water Resources of Iraq. The location of the existing WH is shown in Fig. 10. A comparison of the WH suitability map and the location of the Dewereg stream dam show that the dam is located in the excellent zone demarcated by the study, which indicates that the methodology adopted has a good capability to identify locations suitable for WH.

5 Conclusion

Despite the abundance of surface water flows through the Euphrates and Tigris Rivers, as well as their tributaries in Iraq compared with its neighboring countries, increasing water crises due to decades of war and improper water resource management are major concerns in Iraq. Lack of water due to unprecedented droughts in recent years has prompted thousands of people to move from marshland regions in southern Iraq (Maysan, Nasiriya, and Basra) into the nearest cities. There is thus an urgent need to take necessary action toward mitigating water scarcity in Iraq. To that end, WH, which ranks among the most viable solutions to water scarcity, is an efficient technique to harness excess runoff that is often lost and use it later during water deficits. A methodology to map areas suitable for WH by integrating fuzzy logic with AHP using WLC in a GIS environment was proposed to develop a suitability map using five factors: slope (%), HSG, land cover, runoff depths, and distance from an intermittent river. Results revealed that 280 km^2 (13%) of the study area, located mostly in the southeastern part, near the Dewereg River, in a small central part, and around intermittent rivers, is excellent for developing WH projects. The suitable zone map was validated with existing WH information. Results indicated the efficacy of the proposed GIS model based on fuzzy logic and AHP to demarcate suitable zones for WH.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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