Site suitability analysis of indigenous rainwater harvesting systems in arid and data-poor environments: a case study of Sana'a Basin, Yemen

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Abstract

Indigenous rainwater harvesting (RWH) is a promising tool for increasing water availability and conserving groundwater in arid environments. This study aimed to develop a multicriteria analysis (MCA) framework to identify and rank suitable sites for different indigenous RWH systems in data-poor areas taking Sana'a Basin, Yemen, as a case study. Unlike previous research, this study focused only on indigenous RWH systems and, for the first time, considered the site suitability analysis of spate irrigation systems. Five biophysical and six socioeconomic criteria were used to select, prioritize, and map suitable zones for indigenous RWH systems. This study, the first to be conducted in Yemen, found that more than 30% of the case area has a high or very high level of suitability for each of the studied RWH systems. Only 11% to 17% of the area is not suitable for RWH due to socioeconomic activities. Twenty-four percent of the area was considered moderately suitable, and 28% had a low level of suitability for RWH. These results are promising, and the preliminary identification process of suitable areas for indigenous RWH systems is a useful guide for future water resource and land management programs.

Graphical abstract
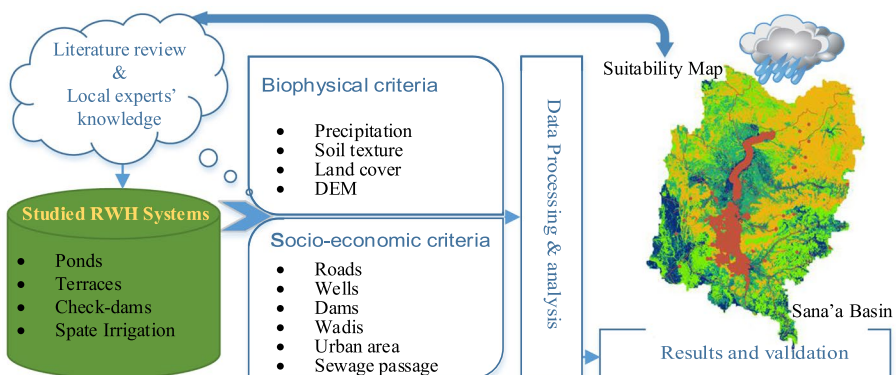
Extended author information available on the last page of the article

Abbreviations

AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency ratio
FAO	Food and Agriculture Organisation
GIS	Geographical Information System
HWSD	Harmonized World Soil Database
KII	Key Informant Interviews
MCA	Multicriteria Analysis
MENA	Middle East and North Africa
NGOs	Nongovernmental Organizations
NWSSIP	National Water Sector Strategy and Investment Program
PWCM	Pairwise Comparison Matrix
RI	Random consistency index
RIW	Relative importance weight
RS	Remote Sensing
RWH	Rainwater Harvesting
SDGs	Sustainable Development Goals
SL	Suitability level
SLI	Suitability level index
WLC	Weighted Linear Combination
λmax	Eigenvalue of the matrix

1 Introduction

Water scarcity problems led previous generations to develop and employ a variety of indigenous rainwater harvesting (RWH) systems in dry regions such as Yemen, Tunisia, Syria, Iran, and India (Beckers et al., 2013; Mbilinyi et al., 2005; Prinz, 1996). RWH was commonly practiced in the past when it was a crucial activity in helping communities achieve water security and promoting their livelihoods (Edmunds & Cardona, 2006; Prinz, 1996). Traditional RWH systems were sustainable for centuries, compatible with local lifestyles and socioeconomic regimes (Gautam et al., 2018; Mbilinyi et al., 2005). Indigenous RWH can positively impact both the economic and health conditions of people, particularly women, as they bear the responsibility for fetching water (Abbas et al., 2021).

A wide range of indigenous RWH systems have been practiced in different countries, including spate irrigation or floodwater diversion systems. Spate irrigation is applied in dry areas where precipitation is low and erratic, often less than 200 mm. Spate irrigation can improve agricultural productivity and livestock production. Spate irrigation, including large systems, can be constructed manually with local materials and experiences (NWP, 2007). Spate irrigation is able to withstand all or a portion of flash floods and gently guides water from wadi courses to adjacent agricultural areas, mitigating drought and flood runoff and slowing the process of erosion (Edmunds & Cardona, 2006). It is believed that spate irrigation started in Yemen 5000 years ago. Today, spate irrigation systems cover around 3.3 million ha worldwide (FAO, 2010).

With the rapid development of modern agriculture, accompanied by the overuse of energy-pumped groundwater, the importance of indigenous irrigation systems declined. Since the 1950s, modern water conservancy projects such as storage reservoirs, diversion systems, and overuse of electrically pumped groundwater increased the amount of available water and began to slowly replace the ancient, labor-intensive systems. However, sustainable water use and management have become increasingly critical issues for further development, particularly in dry environments (Angelakis et al., 2012).

Yemen is one of those arid countries that faced the decline of indigenous RWH systems and related practices (Al-Wadaey & Bamatrf, 2010; Lawrence & Van Steenbergen, 2005). Yemen has already experienced severe depletion of water resources. The country's aridity, limited water resources, and mismanagement and overexploitation of groundwater have contributed to Yemen's water insecurity. The introduction of diesel-operated pumps and tube well-drilling technology during the past century for irrigation has affected the use of traditional rainwater harvesting systems and enabled the extraction of groundwater significantly above recharge levels. This has led to the expansion of agricultural areas and the depletion of aquifers.

Groundwater in Yemen, particularly in Sana'a, has now become the main water source for different uses, including agriculture, which consumes about 90% of groundwater resources (Taher, 2016; WEC, 2004). At the same time, the use of rainwater is steadily decreasing (Taher, 2016). Water resource management in Sana'a Basin is complex due to rapid population growth, increasing aridity, and the complex physiographic environment combined with limited data availability and negligence of traditional knowledge (Alderwish, 2010).

The increase over time of the incidence of drought and the overuse and degradation of natural water resources have renewed interest in indigenous RWH systems (Al-Wadaey & Bamatrf, 2010; Giesecke, 2012). The UN and several nongovernmental organizations (NGOs) are today encouraging and supporting the study and reemployment of traditional technology, which often relies on indigenous knowledge, has little or no dependence on fossil fuels, and utilizes local materials (Akpinar Ferrand & Cecunjanin, 2014; Prinz, 1996). Indigenous RWH may be the most accessible approach to suit site-specific conditions (Grum et al., 2016). RWH is becoming an essential part of sustainable water management and climate adaptation practices around the world. It plays an important role in drought and flood events and enhances water security. It plays an important role in achieving a number of the Sustainable Development Goals (SDGs), increasing the resilience of children and women during wars and periods of drought, and generating many employment opportunities both on and off farms (Aklan et al., 2019; Terêncio et al., 2017).

The identification of appropriate sites and structures for RWH is an important preliminary step for good RWH management (Mbilinyi et al., 2007). Many RWH site suitability analyses have been carried out using different approaches. Forzieri et al. (2008) analyzed sites using cost–benefit ratios, rainfall regime, and the volume of water that can be collected and stored. Terêncio et al. (2018) focused on the balance between sustainability values and storage capacity. Jothiprakash and Sathe (2009) used a water mass balance method and considered a cost–benefit analysis, the reliability of the water supply, and water quality as the parameters for RWH site selection. The present study and others have considered biophysical and socioeconomic criteria (Singhai et al., 2019; Tiwari et al., 2018; Weerasinghe et al., 2011). Supplementary Material A presents a summary review of 36 RWH site suitability studies with different water harvesting systems, approaches, and criteria.

The ignorance of indigenous practices and local socioeconomic factors led to the failure of many modern RWH projects in dry areas (Kahinda et al., 2008; Oweis, 1998; Ziadat

et al., 2012), particularly in the Middle East and North Africa (MENA) region where there is insufficient knowledge of the socioeconomic contexts (Adham et al., 2016). Therefore, integrating socioeconomic and biophysical criteria in the site selection process is a step in the direction toward sustainability in arid rangelands.

An effective approach for site suitability analysis involves combining several methods, including MCA, Remote Sensing (RS) data, and the GIS-integrated approach. Those are the preferred tools for siting RWH systems in data-poor arid regions where RS data can be used or integrated with field data (Ammar et al., 2016; Wu et al., 2018). It is a common GIS-based decision-making method based on different factors and constraints, which can enhance or limit the suitability of an area. With this compound method, criteria are standardized to values or classes, which are then weighted based on their importance to each specific RWH system. This weighted linear combination (WLC) method allows more important criteria to be more influential on the suitability map (Heywood et al., 2011). This approach has been used and validated in many previous studies (e.g., Al-shabeeb, 2016; Isioye et al., 2012; Kahinda et al., 2009; Krois & Schulte, 2014; Singhai et al., 2019).

WLC is one of the most flexible multicriteria evaluation methods. For instance, WLC allows overcoming the limitation of the equal importance of factors by weighting the factors and aggregating them with a calculated weighted linear average. The weights that were assigned govern the degree to which a factor can be compensated by another factor. WLC overcomes the true or false values of other methods by creating different degrees of suitability, which is not the case with Boolean Overlay, for instance.

This paper adopts an indigenous multicriteria decision analysis approach for site suitability analysis of different indigenous rainwater harvesting systems using GIS-based decision analysis while incorporating socioeconomic factors. The novelty of this paper lies in its use of different weights for different indigenous structures. Four indigenous RWH systems for agriculture uses were selected in this study, namely, terraces, check dams, ponds, and spate irrigation systems. The site selection criteria were based on biophysical criteria (precipitation, soil type, and land cover/use, slope, and drainage networks) and socioeconomic criteria (urban area, roads, water wells, dams, wadis, and open sewage passage).

The main outputs of this research are the generated site suitability maps of the studied systems. The contribution of this work is to adapt and further develop the methodology of suitability mapping for indigenous water harvesting systems in limited-data areas and apply it in Yemen. It also considered the site selection analysis of indigenous spate irrigation systems, which have not been considered in previous studies. The results indicated that more than 30% of the area falls in the high and very high suitability category for each of the studied RWH systems. The validation process using experts' knowledge and existing systems supported the developed suitability maps for potential RWH systems.

2 Material and methods

2.1 The study area

Sana'a water basin, with 22 sub-basins, served as the study area for testing and validating the developed framework. It is located in the highlands of Yemen (Fig. 1) at 2200 m.a.s.l with an area of 3200 km^2. It includes the capital city of Sana'a, which, owing to rapid urbanization during the last three decades, has become the largest urban center in the country with a population of approximately two million people (50% of the basin population).
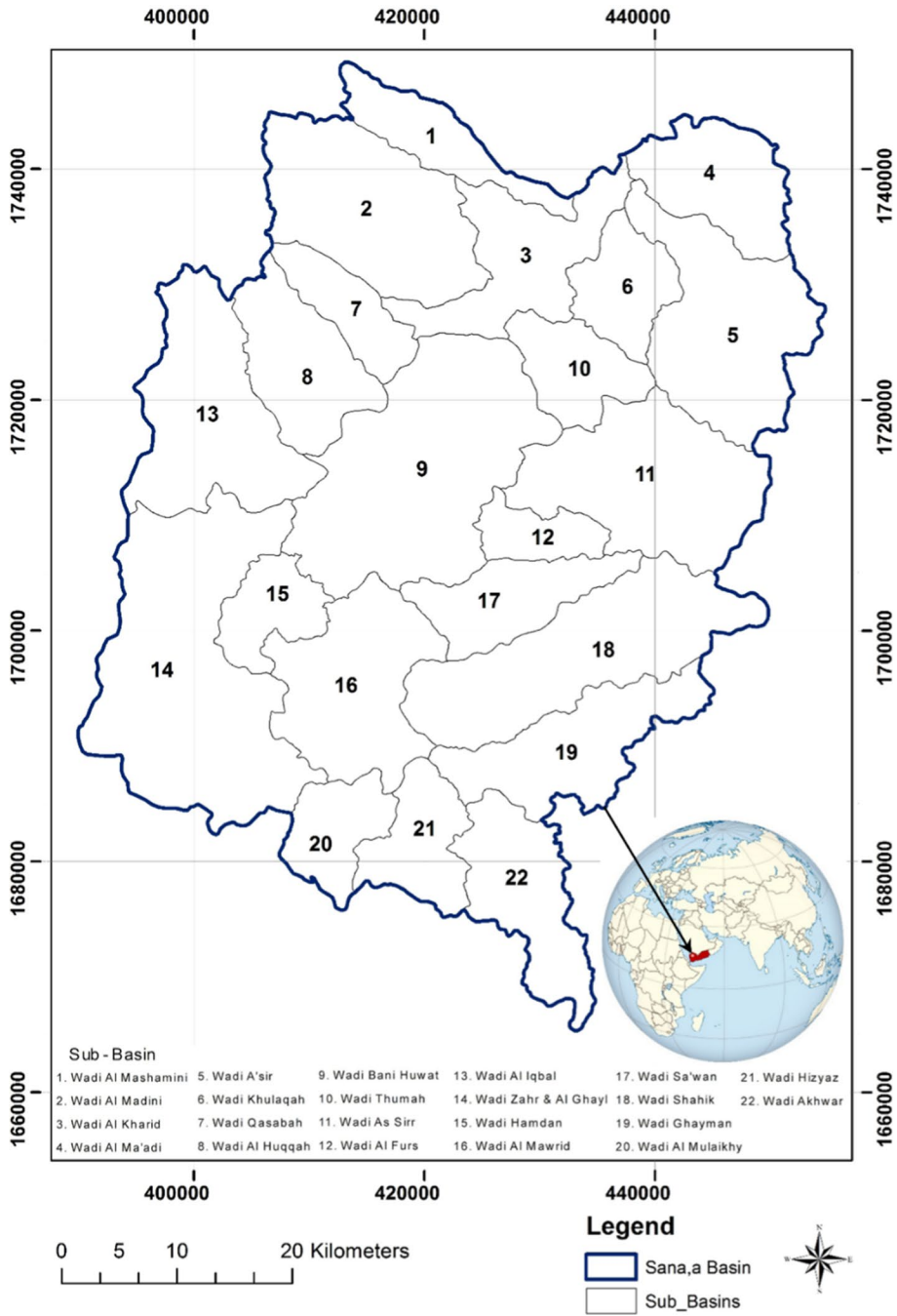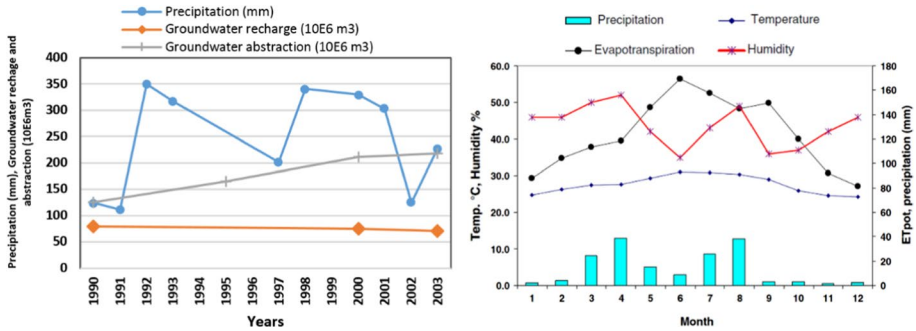
Fig. 1 Sana'a Basin and its sub-basins

Fig. 2 Annual and monthly climate characteristics of Sana'a Basin. **a** Annual average precipitation, groundwater recharge and abstraction 1990–2003. **b** The monthly average climate data

Sana'a Basin is mostly an intermountain plain surrounded to the west, south, and east by highlands (Al-Sakkaf, 2006; JICA, 2007). Diverse landscapes mark the topography of the basin, defined by four major physiographic units, namely plateaus, terraced hillslopes, plains, and wadis. The basin is classified as a semiarid area with low and erratic precipitation. Distinct spatial and temporal variations in precipitation are witnessed in the area (Al-Sakkaf, 2006). The average annual temperature is around 20 °C, and the average annual precipitation and runoff are 240 mm and 40 million m^3, respectively (Al-ameri et al., 2014; Alderwish, 2011; Taher, 2016) (Fig. 2).

Water sources in Sana'a Basin have developed in four stages. (i) Before the 1960s, when indigenous RWH and shallow groundwater (maximum 8 m deep) were the main water resources, and (ii) in the early 1960s when the first pumps were installed and wells were deepened to about 40 m. At that time, shallow groundwater was subject to increasing pressure. (iii) After the 1970s, deep wells or artesian wells were drilled using the new technologies of well drilling machines, and (iv) in the 1990s, the sewage water of Sana'a was used for irrigation downstream of the city (Bani Hawatt wadi) even before the operation of a wastewater treatment plant in 2000 (CES and BRGM, 2010). In Sana'a Basin, a few RWH studies for specific systems in specific areas have been conducted (Alderwish, 2010; INC, 2006; Noman, 2004; WEC, 2016).

2.2 Framework development

In the last 20 years, six groups of applications for combining RWH site selection criteria have been used. Ammar et al. (2016) described the specific requirements and the pros and cons of the four methods: (1) GIS and RS, (2) hydrological modeling combined with GIS and RS, (3) MCA integrated with GIS, and RS (4) multicriteria analysis integrated with hydrological models, GIS and RS. Two other methods used can also be identified: (5) GIS-based multicriteria analysis, where the data are from the field, literature, and/or local organizations (Al-Adamat et al., 2010; Al-shabeeb, 2016; Shadeed et al., 2019), and (6) the participatory research approach including focus group discussions, key informant interviews (KII), and field visits, with (Ziadat et al., 2012) or without GIS (Mbilinyi et al., 2005). Forty-eight percent of the summarized studies (Supplementary Material A) used method 3, GIS-MCA & RS; 17% used method 2, and 10% each used methods 1, 5, and 6. The selection of a suitable method in a particular case is dependent on the objectives and
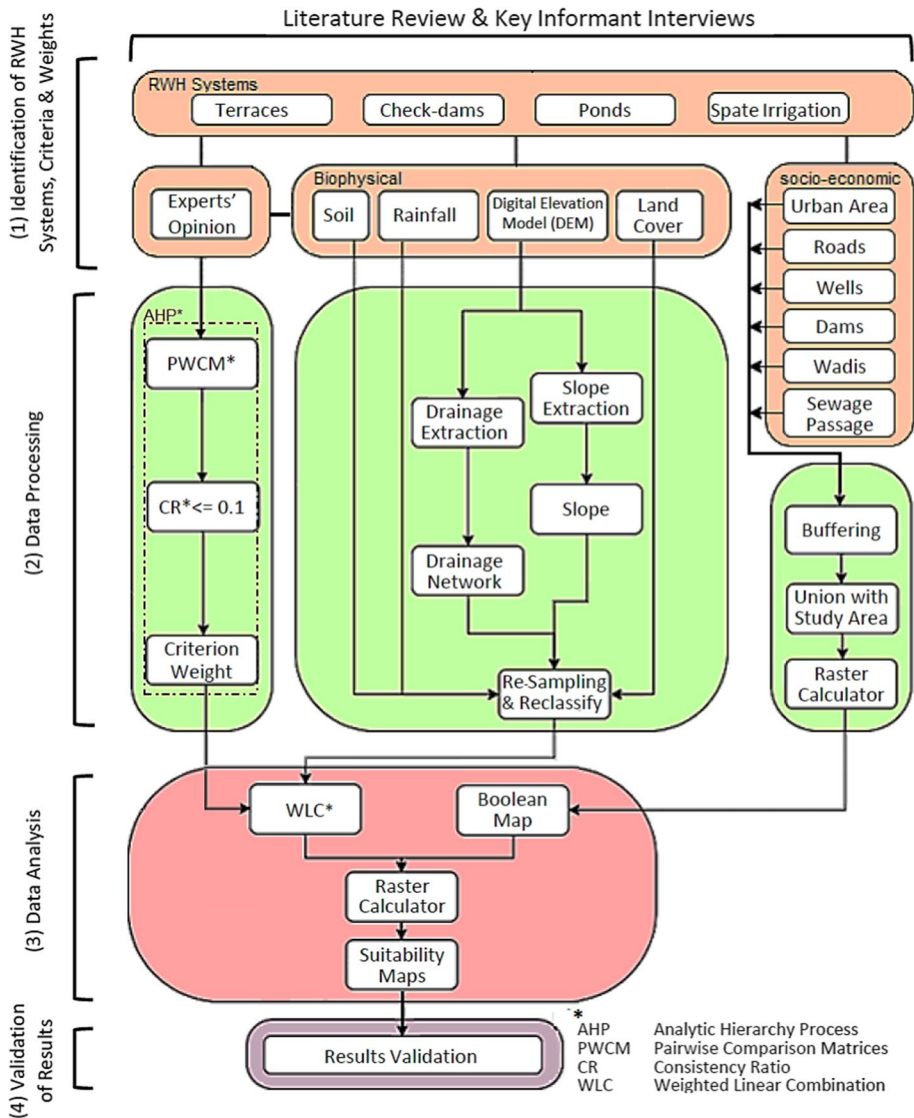
Fig. 3 Multi-criteria analysis (MCA) workflow chart

needs of the project. Data quality and availability also play an important role in the determination (Ammar et al., 2016).

In this study, MCA integrated with GIS and RS data is used for the development of the study's overall conceptual framework (Fig. 3), which consists of four steps: (1) the selection of RWH study systems and site selection criteria and their relative weights, (2) data processing, which consists of reclassifications of biophysical and socioeconomic criteria spatial coverage maps based on suitability level (SL) and the calculation of the final relative importance weight (RIW) of each biophysical criterion for each study system, (3) data

Table 1 Local experts' votes for each RWH system per location characteristics

No	RWH system	Which location in Sana'a basin fits these systems more (number of votes)				
		Upstream	Downstream	Plain areas	Mountain areas	Midstream
1	Terraces	4	1	–	2	–
2	Spate Irrigation	2	3	3	1	–
3	Check dams	2	1	1	3	1
4	Ponds	3	4	1	4	–

analysis by applying WLC and Boolean operators in the GIS environment, resulting in suitability maps for each selected RWH system, and (4) validation of results.

2.2.1 Study systems and site selection criteria

2.2.1.1 RWH systems in this study This study proposed an approach to select the systems to be sited, which was lacking in 94% of the reviewed research studies (Supplementary Material A). In this study, five local experts were purposely selected to (1) prioritize the most promising indigenous RWH techniques, (2) discuss the proposed site selection criteria and determine their relative importance for each study system, and (3) compare the resulting suitability maps with the experts' recommended RWH locations for validation purposes. The local experts are from various water-related institutions and have different backgrounds and experiences related to indigenous RWH, water and agricultural engineering, and socioeconomics. They prioritized four indigenous RWH systems, namely, terraces, spate irrigation, ponds, and check dams, as the most important traditional RWH techniques in Sana'a basin. Table 1 shows the selected systems with the experts' proposed locations, and Supplementary Material B shows the overall analytical key informant questionnaire.

2.2.1.2 Site selection criteria and weights Defining the study criteria for the selection process of RWH sites depends not only on biophysical characteristics but also on the specific local environmental and societal conditions (Dai, 2016). This study uses a combination of biophysical and socioeconomic criteria. The main biophysical criteria used are similar for all types of RWH framework models, including precipitation, soil type, land cover/use, slope, and drainage networks (Supplementary Material C). Based on this, the current study selected and used these six biophysical criteria. However, no similar consensus has been reached on the socioeconomic criteria in site suitability analyses of RWH techniques (Ammar et al., 2016; Terêncio et al., 2018). Based on the specific characteristics of the study area and the recommendation of a number of studies (Al-Adamat et al., 2010; FAO, 2003; Mbilinyi et al., 2005; Oweis, 1998), our research considers six socioeconomic criteria: proximity to urban areas, roads, water wells, dams, wadis, and open sewage passage.

Each criterion uses different classes and carries a different weight for the selection of RWH types and sites (Adham et al., 2016). Different scholars and studies established guidelines, boundary conditions, and preference values (suitability ratings) for different criterion classes according to their suitability level for a specific RWH technique (FAO, 2003; IMSD, 1995; Krois & Schulte, 2014; Mbilinyi et al., 2007; Oweis, 1998; Singh et al., 2017; Terêncio et al., 2018). Many other site suitability studies applied already unified standards

(Kahinda et al., 2009; Singhai et al., 2019). Criterion classes and preference values used in a number of studies are shown in Supplementary Material D. Criterion categories and the related preference values used in this study were classified based on the data range of the study area and a number of studies with similar biophysical characteristics (Al-shabeeb, 2016; Dai, 2016; Krois & Schulte, 2014; Omolabi & Fagbohun, 2019; Terêncio et al., 2017).

Although the spate irrigation systems are among the most important indigenous systems, thus far, there is no comprehensive framework or criteria for their site selection except that of the indigenous knowledge and experiences of local farmers. The farmers were and still are the main actor responsible for the planning, design, rehabilitation, and improvement of spate irrigation systems (FAO, 2010). In all the reviewed studies, not a single study considered site selection criteria for spate irrigation systems. Therefore, the slope criterion of check dams used in this study was considered suitable for spate irrigation. Both check dams and spate irrigation systems are practiced in the same places and are located close to wadis or streams. Also, the land cover/use and soil type criteria of the terraces were considered as suitable for spate irrigation because these two systems are used for agriculture. Although many modern spate irrigation systems are lined with sealing materials, such as concrete, in this study, we considered only the traditional practice of spate irrigation, which relies on natural/local soils.

2.2.2 Data sources

The slope and drainage data of this study were obtained from the third version of the global Digital Elevation Model (DEM) of Shuttle Radar Topography Mission (SRTM), generated in 2015 with a spatial resolution of one arc second (30 m). The 30 m SRTM elevation data present a better absolute vertical accuracy than those of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) version 2 (Elkhrachy, 2018). The drainage network (Stream Network) was delineated and extracted from a DEM raster image using the ArcGIS extension tool of Arc Hydro.

Precipitation is a key factor in choosing RWH systems. Rainfall of 150–750 mm/year is suitable for most RWH systems (FAO, 2003). Sana'a Basin has about 24 rainfall stations, 15 of which were installed within the basin and the rest were installed outside, in close proximity to the basin's boundary. Unfortunately, none of these stations has continuous data and the range of the records in most stations is between two and seven years, including many record gaps. The spatial distribution of the rainfall, however, is not indicated in these data. Therefore, the average monthly precipitation data (1970–2000) derived from the WorldClim-Global Climate Data version 2 that were used for this study. Such data are available with a spatial distribution and with a high spatial resolution of 30 s (~ 1 km).

The soil data were obtained from The Harmonized World Soil Database (HWSD), version 1.2, generated in 2012 with a spatial resolution of 30 s (~ 1 km).[1] The land cover/ land use data used in this study are owned by ESRI and developed by MacDonald, Dettwiler and Associates Ltd. (MDA) (Esri, 2017). These data were created in 2015 with a spatial resolution of 30 m. This dataset was acquired from Online ArcGIS World Land Cover 30 m BaseVue 2013.

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[1] This dataset is acquired from http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

Socioeconomic data were collected from official related authorities. All the socioeconomic criteria in this study were considered as constraints due to the socioeconomic activities of built-up urban areas, roads, wells, dams, and sewage passage. All areas of the aforementioned socioeconomic activities were considered unsuitable locations for RWH, and the Boolean technique in GIS was used to exclude them.

2.2.3 Data processing

Geographical data were converted to one coordinate system, which is used officially in Yemen (WGS_1984_UTM_Zone_38N). Sana'a Basin is covered by two SRTM DEMs. A raster mosaic was implemented to combine them. To facilitate the implementation of the raster calculation in the analysis, all datasets were adjusted into a uniform 30-m spatial resolution DEM.

Within data processing, the following normalization, buffering, and weighting tasks were performed: (i) the reclassification or normalization of biophysical criteria maps based on rating the criteria to a common scale, (ii) the reclassification of socioeconomic criteria by applying buffer zones for each criterion, and (iii) the calculation of relative importance weights (RIW) based on local expert assessments and AHP that resulted in the final eigenvalue of each criterion for each RWH system.

Each biophysical criterion (precipitation, soil type, land cover/use, slope, and density of drainage networks) was reclassified into a common preference scale/class according to its range and suitability level (SL) for a particular RWH system, derived from literature surveys (Table 2). The suitability rating for any particular technique was expressed as a numerical value. This approach scored suitability levels and, thus, standardized boundary conditions (Krois & Schulte, 2014), and created the reclassified maps (Mbilinyi et al., 2007).

Spatial data techniques, including buffering, union, and raster reclassification, were used to process socioeconomic criteria (distance to roads, wells, dams. urban areas, and sewage passage). The buffering zones were applied for each socioeconomic criterion based on the appropriate buffer distance (Al-Adamat et al., 2010; Al-shabeeb, 2016) and based on the specific characteristics of the study area (Table 3). The buffer zones of each socioeconomic criterion were spatially merged with the study area using the union technique followed by raster reclassification for all maps.

The relative importance weights (RIW) method, which is also called comparative importance (Terêncio et al., 2017), is calculated by the Pair-Wise Comparison Matrix (PWCM) method as a tool of the Analytic Hierarchy Process (AHP) (Saaty, 1980, 1990). AHP is an effective and widely used MCA method for handling complex decision-making.

A series of PWCMs was used to compare all the possible pairs of criteria to each other and to define which criterion has a higher priority. A continuous scale ranging from 1 to 9, suggested by Saaty (1980) for PWCM elements, was used. The least value of 1 indicates equal importance of both factors, and a value of 9 indicates the extreme importance of this factor over the others (Krois & Schulte, 2014). Table E.1 in Supplementary Material E shows the scale for the pairwise comparison method with a brief explanation. PWCM resulted in an eigenvalue of each criterion, which represents its RIW (Saaty, 1990). In this study case, judgment on the dominance of one criterion over another was based on the averaged results of the expert assessments that were rounded. The relative importance of each factor with respect to the other factors varied for different RWH systems (Mbilinyi et al., 2007).

Table 2 Classes, preference values for the five biophysical criteria used in this research

Biophysical criteria/ parameters	Criteria classes & preference values used for suitability level analysis								References
	Values/ Classes				Preference value				
	Terraces	Spate irrigation [a]	Check dams	Ponds	Terraces	Spate irrigation [a]	Check dams	Ponds	
Rainfall (mm)	<179 179 – 200 200 – 300 300 – 400 400 – 483				1 2 3 4 5				Terêncio et al., 2017, Dai, 2016
Soil	Loam Loamy Sand Sandy Loam				4 3 5		5 3 4		Omolabi and Fagbohun, 2019, Dai, 2016,
Slope %	0 - 5 5 - 10 10 - 18 18 - 30 >58 30 - 58		0 – 2 2 – 5 5 – 8 8 – 10 >10		1 2 3 4 5		5 4 3 2 1		Krois & Schulte, 2014
Drainage (km2)		0 – 0.5 0.5 – 1 1 – 1.5 1.5 – 2.5 2.5 – 3.7				1 2 3 4 5			Al-Shabeeb, 2016
Land use/ cover	Forest Grassland Shrub/Scrub Barren/ minimal vegetation Agricultural Urban, high to low density				1 3 3 2 4 0		1 1 2 3 4 0		Krois & Schult, 2014

a: Spate irrigation is not used in many site suitability studies and criteria of check dams (slope) and terraces (soil type and land use/cover) are considered as suitable for spate irrigation systems.

The AHP technique has the ability to handle variation in opinions between experts by checking the consistency of the judgments made, thus decreasing the bias in the decision-making process. A consistency check was applied to the PWCM by computing the consistency ratio (CR) to identify the judgment errors, if any:

$$CR = \frac{CI}{RI} = \frac{(\lambda \max - n)/(n-1)}{RI} \tag{1}$$

where CI is the Consistency Index, λmax is the Eigenvalue of the matrix, n is the number of elements compared (five biophysical criteria in our case), and RI is the random consistency index, which depends on the number of comparison criteria as developed by Saaty (1980). In this case study, the compared biophysical criteria were five and the corresponding RI value is 1.12 (Table E.2 in Supplementary Material E). In any case, the maximum value of the CR for an acceptable PWCM is 0.1 (Saaty, 1980).

2.2.4 Data analysis

An aggregation of weighted factors and Boolean constraints was computed (Fig. 3). WLC and Boolean operators were applied in the GIS environment to perform this analysis and obtain a suitability level index (SLI) for each cell in the study area. Final suitability maps for each studied RWH system were then generated.

The WLC technique is flexible in selecting the optimum sites. This technique has been adopted in several studies (Al-Adamat et al., 2010; Al-shabeeb, 2016) and proved its suitability in integrating the RIW and final standardized/reclassified maps to create an overall

Table 3 Types, sources, and buffer zone distances of socioeconomic parameters (based on Al-shabeeb, 2016; Al-Adamat, 2010)

No	Parameters	Source and date of data	Condition (m)	Value	Suitability
1	Urban	Land use/cover map of Sana'a 2007	>250	1	Yes
			≤250	0	No
2	Roads[a]	General Authority of Lands Surveying and Urban Planning 2007	>75	1	Yes
			≤75	0	No
3	Wadis	Wells inventory study, WEC, 2004	>50	1	Yes
			≤50	0	No
4	Wells[a]	National Water Resources Authority (NWRA), 2007	>50	1	Yes
			≤50	0	No
5	Dams	Water and Environment Centre (WEC), 2007	>500	1	Yes
			≤500	0	No
6	Sewage passage[a]	Sana'a Water and Sanitation Local Corporation (SWSLC), 2007	>1000	1	Yes
			≤1000	0	No

[a] Based on the characteristics of the study area

suitability map for each RWH system (Malczewski, 2004). All the thematic maps were combined in ArcGIS using the Raster Algebra tool. The WLC suitability maps were computed using the following equation:

$$\text{SLI}_{xy} = \sum \text{RIW}_{xy} * \text{SL}_{xy} \tag{2}$$

where *SLIxy* is the suitability level index value for each specific RWH system*x* (spate irrigation, terraces, ponds and check dams) for a given cell*y*, RIW*xy* is the relative importance weight of the data input layer*y* (rainfall, slope, land cover/use and soil type) for each corresponding indigenous RWH system*x*. and *SLxy* is the suitability level of the input layer for each corresponding indigenous RWH system*x*. The higher the *SLxy* of a given cell*y*, the better suited it is for the corresponding indigenous RWH system*x*. The *SLI* was rated using five classes: not suitable, low suitability, moderate suitability, high suitability, and very high suitability. These categories of RWH suitable zones are common in the previous studies (Adham et al., 2016; Al-shabeeb, 2016; Mbilinyi et al., 2007). SLI is dimensionless. The final weights of each criterion, preference values of criterion classes, and buffering zones are the main thresholds to identify the site suitability levels for the RWH systems. Boolean criteria were used to eliminate some sites that had been selected by the WLC method (Al-Adamat et al., 2010).

The Boolean technique is based on the variables which have only two possible values: True or False. The Boolean method has already been used in site suitability analysis for RWH systems (Al-Adamat et al., 2010; Al-shabeeb, 2016). In this study, the Boolean technique was limited to the socioeconomic criteria in order to exclude the sites that cannot be used for RWH practices. Six socioeconomic criteria were included for the terrace and pond RWH systems. However, the wadis data were not included for check dams or spate irrigation systems, as wadis are considered to be suitable for both systems as practiced in Yemen.

2.2.5 Results validation and sensitivity analysis

For the validation of the results of this study, three steps were carried out: (i) local experts' perspectives on the proper locations for each RWH system (Table 1), (ii) a literature review and the related studies' suggestions, and (iii) existing indigenous RWH systems.

The sensitivity analysis was also performed to assess how a change in the weights of the criteria can affect the RWH potential site selection. The suitability of a site for a specific RWH system depends on the relative importance of weights and the classes' suitable criteria values. Therefore, sensitivity analysis was an important step to overcome the opacity of the weighting of different study factors (Terêncio et al., 2017). This sensitivity analysis was applied to the criteria used for RWH terrace systems. This analysis was achieved by generating the suitability map of terraces using equal weights for the criteria and then comparing the result with the suitability map that was developed using the relative weights resulting from the pairwise comparison method.

3 Results and discussion

The current case study is an application of the developed framework. RWH can be utilized to meet various demands, including agricultural use, which consumes approximately 90% of the already-depleted groundwater resources in Sana'a Basin, Yemen. The use of harvested rainwater is a more sustainable practice than using scarce groundwater, which requires pumping and wastes energy. Indigenous RWH practices are one of the possible solutions identified and supported by the National Water Sector Strategy and Investment Program (NWSSIP, 2014).

The final suitability maps for each RWH system (terraces, check dams, ponds, and spate irrigation systems) are described below. The degree of suitability is ranked using five categories: not suitable, low suitability, moderate suitability, high suitability, and very high suitability. In this section, suitable locations refer to the high suitability and very high suitability categories.

3.1 Terraces RWH system

It was found that 33% of the study area was suitable for using terraces as a RWH system. The majority of suitable sites were identified in the east and southwest of Sana'a Basin, where sufficient rainfall occurs and there are moderately steep mountainous slopes ($>5°$) with loamy sand soil (Fig. 4a). This soil texture is considered to be one of the best for agricultural purposes. These findings also agree with satellite imagery observations where most of the existing terraces were found on moderately steep slopes. Likewise, according to Krois and Schulte (2014) and Mbilinyi et al. (2007), terrace technologies are usually practiced on sloping areas with unstable soils. Most of the suitable sites for terraces are located in the agricultural land use category, which are the proper locations for this kind of agricultural RWH system. On the other hand, a large portion of the unsuitable and low suitability sites are located in areas with very gentle slopes. The areas unsuitable for terraces represent 17% of the total study area (Fig. 4a).

Most of the experts consulted indicated that terraces can be constructed in the upstream and mountainous areas of the basin (Table 1). Their opinions aligned with the suitability map results, which showed that most of the areas of high suitability and very high suitability lie in the eastern and southern mountainous areas. All areas in the plains are considered to have low suitability for terraces. Yemeni inhabitants have developed huge numbers of terraced fields as an effective method for harvesting rainwater on steep and rugged slopes in the mountainous areas of the country (Bamatraf, 1993). Thirteen locations in the suitable area zone were randomly selected to investigate the accuracy of their suitability ratings compared to areas with existing RWH systems. The suitability map of terraces is displayed above the imagery layer in ArcGIS. The results showed that seven sites are located in areas where indigenous terraces already exist, and four sites are in suitable locations but without any systems. Other similarly suitable areas lack RWH systems. In the predominantly suitable zone, there are some unsuitable areas for terraces, two of which were randomly selected by this investigation method (Fig. 4a).

3.2 Check dams

Areas suitable for check dams (35% of the study area) were found in the gentle to moderate slopes of the center and southwest zones of the study area. The primary soil type

in these areas is loam with high water retention capacity and low seepage and percolation. Check dams can be implemented along streams (1st to 3rd stream order), 0–700 m from cultivated land with slope < 15% (Grum et al., 2016). Check dams are small and sometimes temporary, primarily constructed across wadis or other waterways to counteract erosion and reduce water flow velocity (for flood control). They are effective systems for groundwater recharge as well as for storing and diverting water to nearby land through canals or spate irrigation systems. Most of the unsuitable sites and those of low and moderate suitability for check dams are located in the northeast part of the study area, where there is less rainfall than in other areas (Fig. 4b).

Three out of the five experts indicated that check dams could feasibly be constructed in the mountainous areas of the basin, where this study's results identified several suitable locations for check dams. As a traditional system, check dams are often utilized in upstream areas to prevent erosion and to divert water to nearby fields. Currently, a number of these systems are also being developed in plains areas, not only to prevent erosion
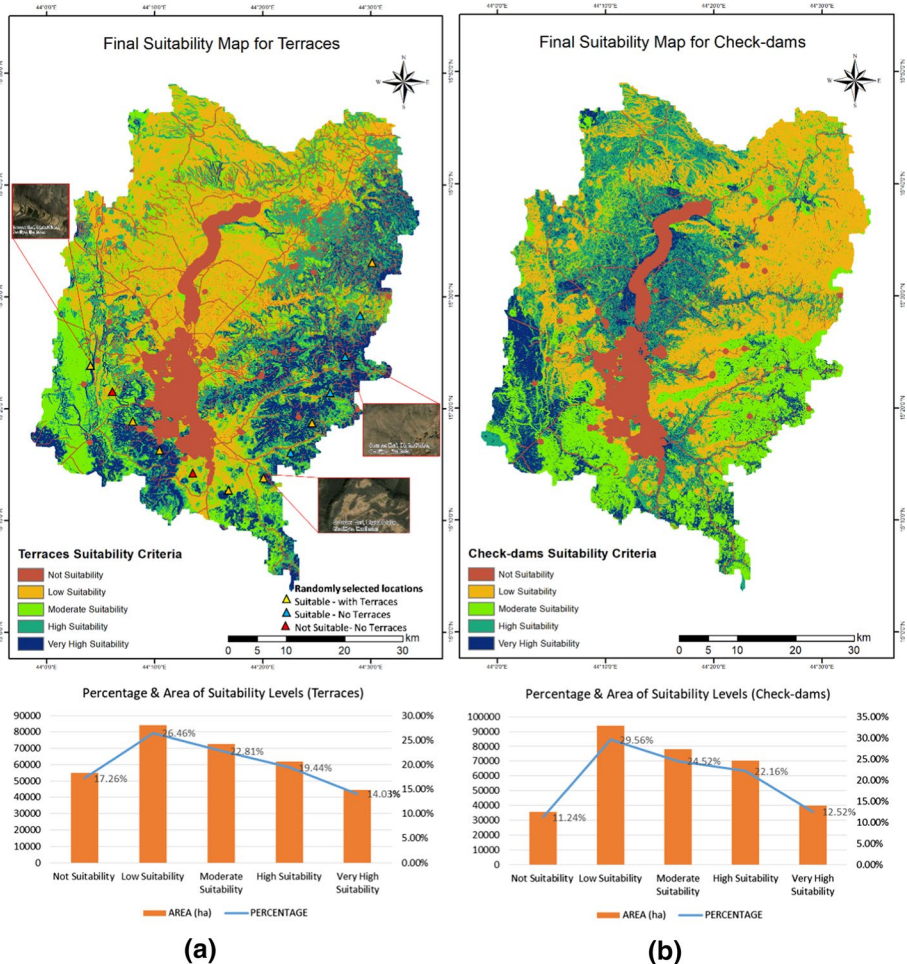

Fig. 4 Final suitability maps & area of each suitability levels for **a** terraces and **b** check dams

and recharge groundwater but also to control flooding. Check dams could also be used to recharge both volcanic and alluvial aquifers in the southern part of the basin, where sub-basins 14, 18, 19, 20, 21, and 22 are located (Ward, 2014). The present study found many highly suitable locations in these sub-basins, especially in the plains areas of the wadis and in sub-basin 14. The existing check dams in the Bani Hoshaish area, which were recently revitalized based on indigenous knowledge of the local inhabitants, are located at sites considered very high suitability by the suitability map.

3.3 Ponds

The center and south of the study area contain the majority of sites suitable for ponds (Fig. 5a). The very highly suitable areas are located on gentle to moderate slopes (0–10%), whereas locations with high suitability have a moderate to a steep slope > 10%; this is in line with Grum et al. (2016). Areas close to the stream network with high drainage density are always preferable for pond construction because water easily enters and exits this RWH system by gravity (Mbilinyi et al., 2005).

The pond suitability map showed that ponds in upstream areas (the southern part of the basin) and the southeastern mountainous area had a high degree of suitability. Only one expert disagreed with this assessment and selected the central plains areas, where the suitability map also showed good potential for ponds. Ponds can be classi- fied into three types based on the topographic conditions of the study area: excavated ponds (for use in a flat topography), embankment ponds (for hilly and rugged slopes), and excavated embankment ponds (Noman, 2004). Approximately 83% of the sites with high suitability for ponds identified in this study have the three aforementioned topogra- phy types. Furthermore, the Sana'a Water and Sanitation Local Corporation has already constructed two large ponds for runoff harvesting. The locations of these ponds were identified by this study as having high and very high suitability (Fig. 5a). Existing ponds within urban areas were not considered or checked due to the exclusion of all urban areas from the study analysis.

3.4 Spate irrigation

The area considered suitable for spate irrigation covers 100,454 hectares, representing 32% of the total study area; only 9% has very high suitability (Fig. 5b). Suitable areas are located primarily in agricultural areas. The northeastern portion consists of barren land with insufficient rainfall and was therefore given a low preference value for spate irrigation systems.

The downstream and plains areas of the basin, as the experts' most preferred areas for spate irrigation systems, were identified in this study as having high to very high suitability for spate irrigation, especially in the southwestern and central parts. The suitability map also identified many sites suitable for spate irrigation in the southern portion (upstream) that were proposed by two experts. Spate irrigation is practiced in Yemen along wadi courses and in the plains (Noman, 2004). Many suitable sites on the suitability map are located in areas where spate irrigation systems are still used, such as in Bani Al-Harith and Bani Hoshaish.
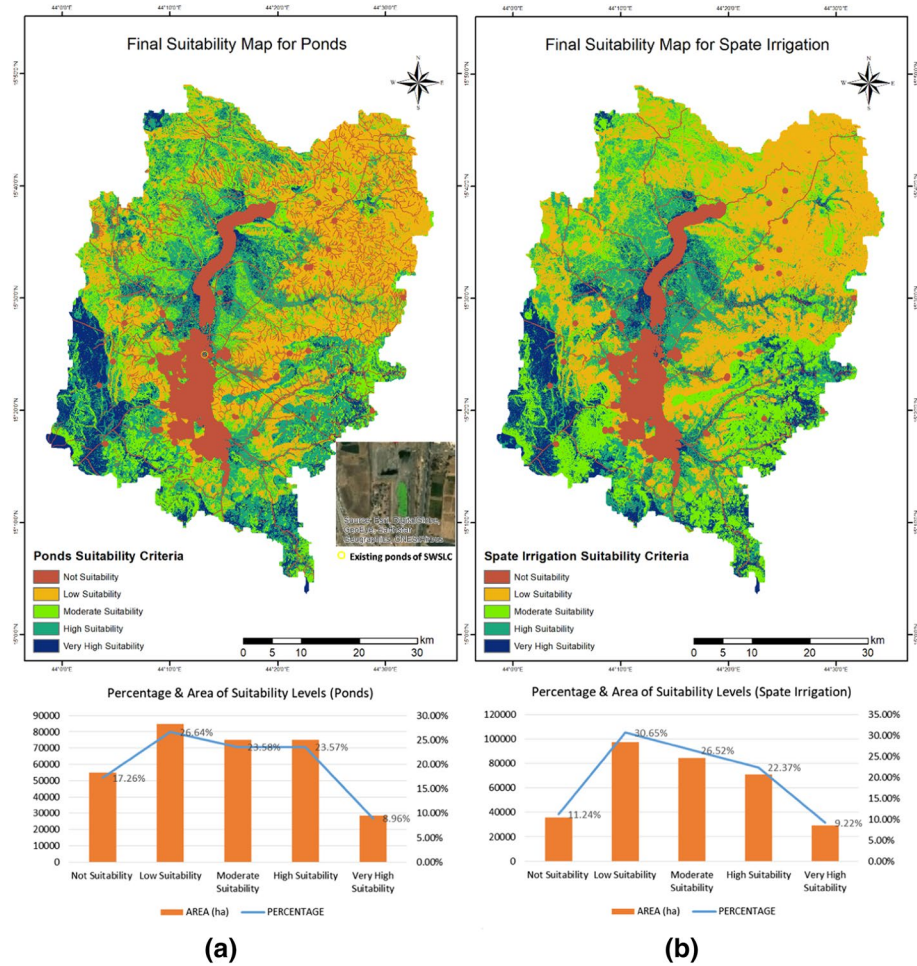
Fig. 5 Final suitability maps & area of each suitability levels for **a** ponds and **b** spate irrigation systems

3.5 Sensitivity analysis

Sensitivity analysis results showed how the relative importance weights of different criteria for a particular RWH system played an important role in the site selection process. Two suitability maps for terrace systems were generated. The suitability map of equal weights (Fig. 6a) identified the plains areas in the center part of the basin as suitable for terraces; however, this is not the case in reality. Although the central part of the basin is suitable for terraces when considering land use, soil, drainage density, and rainfall, this area has a flat and gentle slope and is thus not at all suitable for this type of RWH system, as shown on the suitability map produced using relative weights (Fig. 6b). Results for some locations matched on both maps, especially in the eastern and southern parts of the study area. The suitability map that used equal weights indicated a higher level of suitability than the map using relative weights (41% and 33%, respectively).

The results of this sensitivity analysis revealed that relative weights are more accurate than equal weights for developing suitability maps for potential RWH sites. It was observed that the slope layer is a sensitive layer for terraces and inaccuracies in this layer can lead to errors in the identification of suitable sites. Therefore, the different criteria used to identify potential RWH system sites are not of equal importance. Different classes/weights are assigned to the criteria.

The suitability level analysis of this study was done for each studied system based on input criteria spatial coverage maps (Supplementary Material F), classes, and preference values for different biophysical criteria (Table 2) as well as buffer zone distances of socioeconomic criteria (Table 3). One should note that the rating and SL for the studied systems are almost identical except for the criteria slope and soil (Table 2). Terraces are more appropriate on steep slopes (30–58°) and sandy loam soil, whereas the other systems, including spate irrigation, are optimally suitable on low slopes (< 2°). Sandy loam is preferable for terraces and spate irrigation systems, while loam is the preferred soil type for other systems. The criteria processing was done based on SL and RIW (Sect. 2.2.3). The reclassified maps resulting from data processing and SL analysis can be seen in Supplementary Materials G and H.

Within the Analytical Hierarchy Process (AHP), PWCM scales (Table E.1 in Supplementary Material E) were used to collect the relative importance weights of criteria by KII, from which the RIWs were calculated. The rainfall factor was the most important criterion for decision-making and, thus, given the highest relative weight followed by the slope factor (Table 4). To assess the consistency between the experts' opinions, the consistency ratio (CR) was calculated. The CRs for all the experts' weights for RWH systems ranged between 0.03 and 0.07, which are less than the maximum CR value for an acceptable pairwise comparison (0.1). This indicates that the acquired experts' opinions are consistent and, thus, suitable for MCA analysis. The results of the PWCM, including the final RIW for each criterion, λmax, RI, and CR, are shown in Table 4, while the detailed calculations for the RIW can be found in Supplementary Material I.

Final WLC suitability maps for the selected RWH systems are shown in Supplementary Material J. Boolean criteria maps, where all socioeconomic maps were integrated to generate two Boolean suitability maps, are shown in Supplementary Material K. Of the two Boolean maps, RWH-unsuitable areas of 11% and 17%, respectively, were illustrated.

The data analysis results of the WLC and the Boolean techniques (Sect. 2.2.4) were integrated to generate a final suitability map including the five categories of suitability levels used for each study system: terraces, check dams, ponds, and spate irrigation systems (Figs.4 and 5). Terraces and ponds have the same percentage of areas of very high and high suitability (33%). Out of the four study systems, check dams have the largest (35%), and spate irrigation systems have the lowest areas considered of high and very high suitability.

The different relevant weights of criteria ensure that site selection attributes are given different importance depending on the proposed application. Although the results showed that the rainfall factor is the most important criteria in this analysis, and thus given the highest relative weight for all the study systems (Table 4), the study highlighted the importance of other local features and socioeconomic factors. The best rainfall collection catchments were not always the most suited to the installation of the RWH systems (Terêncio et al., 2017). A comprehensive assessment depends on the type of system and related weights and Booleans of other study parameters.

Overall, this study's planning and siting framework allowed the selection of suitable sites for different indigenous RWH systems in dry and data-poor areas to be used as water resource techniques for agriculture. This GIS-based MCA and the defined hierarchic
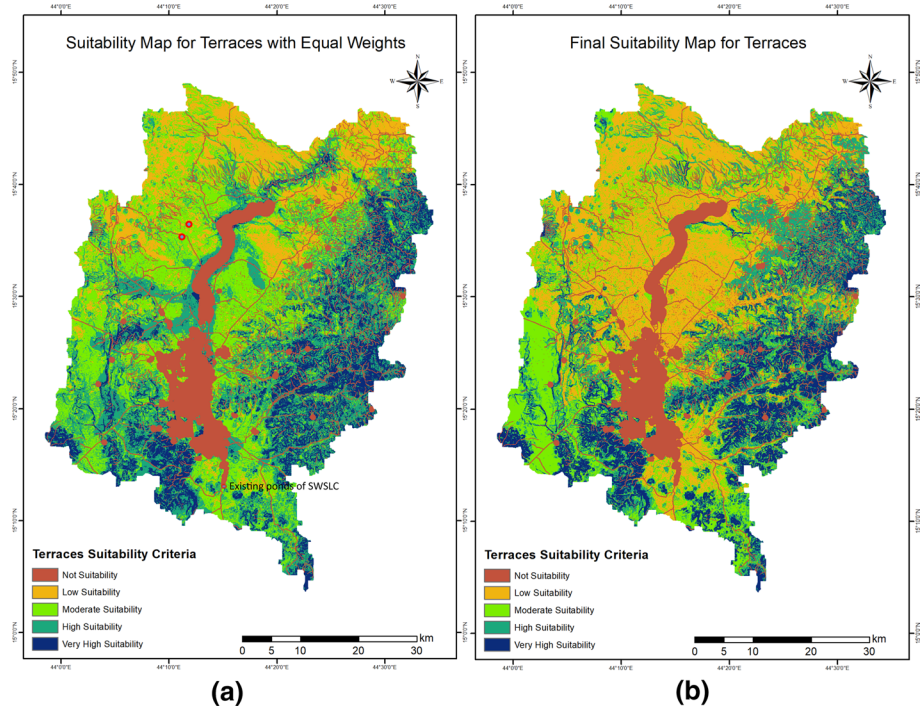
Fig. 6 Suitability map of terraces using **a** equal weights and **b** relative weights

structure of decision criteria reduce the conflicting positions among stakeholders involved in the decision-making process. Although similar approaches have been applied in other areas (Al-shabeeb, 2016; Krois & Schulte, 2014; Singhai et al., 2019; Tiwari et al., 2018), this is a new approach for Yemen and Sana'a Basin. Nevertheless, this approach is a highly flexible tool that can be adapted and applied under different local and environmental settings. It enables the adjustment of RWH site locations to local features and socioeconomic conditions, such as distance from urban areas, roads, water wells, and open sewage passage.

One should note that the studied spate irrigation systems in this research were not considered in previous approaches and technical studies. Spate irrigation systems are largely controlled and judged by local farmers, who are the most experienced in identifying the opportunities and challenges for improving and expanding spate irrigation techniques. The role of engineers in assisting farmers in terms of runoff and water need calculations is still limited. Sediment load, soil type, intake location, and management roles of locals are common features for spate irrigation practices (FAO, 2010). In this study, all areas suitable for spate irrigation systems were identified based on biophysical and socioeconomic criteria. However, the experiences and opinions of locals and farmers are still important in determining the intakes and final locations of the spate irrigation systems.

The present site assessment study has yielded significant results that may be followed up on. High spatial resolution field data and in-depth field investigations are key to complement the useful and reliable findings from scientific studies. Because it is not always possible to obtain field data, however, this proposed method could be a useful tool in regions with limited data. Nevertheless, the lack of field data and investigation in this study have

Table 4 The calculated relative importance weights for the five biophysical criteria used in this research

Biophysical criteria	Result of Relative importance weights %			
	Terraces	Spate irrigation	Check dams	Ponds
Rainfall (mm)	37	47	45	54
Soil	14	14	6	6
Slope	35	22	31	20
Drainage (km2)	7	9	11	12
Land use/ cover	7	8	7	8
λmax	5.3	5.12	5.12	5.2
RI	1.12	1.12	1.12	1.12
CR	0.07	0.03	0.03	0.04

generated some uncertainty regarding the results. Therefore, this study is to be considered a first step; the actual adoption and implementation of these traditional RWH measures require further studies that consider a cost–benefit analysis, locals' and landowners' involvement, and more site investigations. It is highly recommended that local habits and practices, available construction materials, and related socioeconomic and environmental effects also be taken into account. Political factors in Yemen are still the basis for most projects, and a political orientation toward sustainable projects that depend on renewable resources is required. This study provides scientific guidelines for politicians, decision-makers, and water- and land use managers for the effective future planning, management, and revitalization of traditional RWH at a large scale.

The framework developed in this study can be applied elsewhere to consider the suitable types and sites of indigenous water harvesting systems, particularly in arid and data-poor areas. The study deepens the understanding of traditional knowledge and socioeconomic criteria through the operationalization of their definitions into specific key indicators. The framework provides a set of site selection criteria for the important spate irrigation systems, which can be highly effective, especially in MENA regions, Pakistan, and Kazakhstan, where there are large areas of spate irrigation systems.

4 Conclusions

This research assessed the suitability of indigenous RWH sites in Sana'a Basin and adapted existing methodologies to suit data-poor environments. This study lies within the use of different weights for different indigenous structures and is the first to be conducted in the country.

This study revealed that Sana'a Basin is suited to traditional RWH with 55–60% of its area having very high, high, or moderate suitability for the implementation of the studied indigenous RWH systems. Only 11% of the study area was found to be unsuitable for any RWH system, primarily due to socioeconomic conditions. Although rainfall received the highest relative weight in the analysis, it was not always the primary factor for determining the optimal type and location of RWH systems. The inclusion of other socioeconomic and biophysical criteria rendered some areas with sufficient rainfall unsuitable for RWH. Local experts' indigenous knowledge was critical for prioritizing RWH systems, weighing study criteria for each relevant RWH system, facilitating MCA analysis, and validating the final results of the suitability maps.

While Yemen is facing droughts and desertification, the dense and short-lived heavy rains are being lost as they are not well harvested and managed to grow crops, irrigate rangeland, replenish diminished groundwater and reduce flash flood hazards. The revitalization of indigenous RWH systems will increase resilience and water availability and mitigate drought and flash flood risks and damages. To adopt such revitalization, one-size-fits-all strategies must be avoided. Rainfall density, land use, and socioeconomic conditions vary widely throughout the country. Therefore, each district requires a specific approach that must be determined according to its particular criteria. This study helps develop RWH strategies and related policies for revitalizing indigenous RWH systems as local water savings and stormwater management tools. The framework presented in this study can be replicated in other parts of the country and elsewhere in dry and limited-data regions.

Declarations

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

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