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ORIGINAL ARTICLE

Assessment of water harvesting potential sites using GIS-based MCA and a hydrological model: case of Werie catchment, northern Ethiopia

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Abstract

Due to erratic and unpredictable rainfall pattern in northern Ethiopia, water availability for various purposes is becoming uncertain. As a result, harvesting potential surface runoff during the wet season is indispensable for satisfying demands in the dry period. The objective of this study was, therefore, to develop site suitability index for the implementation of water harvesting techniques (WHTs) such as check dams and farm ponds. A GIS-based multi-criteria analysis (MCA) integrated with the Soil Conservation Service-Curve number model was used to process and generate the suitability index. Results of the WHTs suitability index showed that from a total of 885 km stream length, 52.3% was highly suitable and 40.6% was moderately suitable for check dams. Similarly, 18% of the total study area was highly suitable and 51.2% was moderately suitable for farm ponds. The developed suitability indexes were validated and results showed that 88% of existing functional check dams were located in a moderately to very highly suitable streams. The remaining 12% of the check dams were located in unsuitable streams. Similarly, 74% of existing functional farm ponds were located in a moderately to highly suitable areas and the remaining 10% were located in unsuitable areas. Validation of GIS-based MCA integrated with hydrological model indicates that a similar method can be used to assess suitability of other areas to WHTs. Moreover, practitioners and decision makers can also use these findings for planning and development of water resources.

Keywords Analytical hierarchy process · Multi criteria analysis · SCS curve number · Surface runoff · Water harvesting techniques · Werie catchment

Introduction

The complex nature of land use land cover dynamics along with climate change aggravated the negative impacts of human interventions on freshwater availability in many parts of the world (El-Khoury et al. 2015; Liu et al. 2017; Hyandye et al. 2018; Dibaba et al. 2020; Arantes et al. 2021). Hence, securing fair fresh water distribution among all competing sectors for current and future demands are a challenge for many developing countries (Zehnder et al. 2003; Rockström et al. 2009). On the other side, high population growth, migration and internal instability coupled with climate change and poor natural resources management in the sub-Saharan countries imposed heavy pressure on availability and quality of fresh water resources because of increasing water demand and pollution (OCHA 2010; Okello et al. 2015; Jägerskog and Swain 2016; Woldearegay et al. 2017UNESCO 2020).

According to FAO (2014), the eastern African region is highly vulnerable to climate variability. Ethiopia being the most populous country in the region is subjected to high environmental degradation due to anthropogenic effects exacerbating the already poor agricultural productivity and access to potable water (Feoli et al. 2002; Ayenew 2007; Woldearegay et al. 2017; Wassie 2020). Irrespective of these constraints, World Bank (2006) and Makombe et al. (2007)

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argue that water resources have played a key role on the overall socio-economic development of the country.

Ethiopia has abundant surface water resources potential with 12 major river basins. The estimated total annual surface runoff generated from the basins is about 124.4 billion cubic meters, out of which 97% drains out of Ethiopia through seven transboundary rivers (MoWR 2002; Berhanu et al. 2014). Despite its enormous potential, Ethiopia has developed only a very small part of its water resources for agricultural production, energy generation, domestic and industry water supply. This is due to the uneven spatial and temporal distribution of its water resources, financial constraints, poor technical skills along with lack of comprehensive planning and poor management (Nedaw 2010; Berhanu et al. 2014).

Nowadays, the government of Ethiopia is planning a huge investment in water resource exploration and development for various purposes by constructing medium- to large-scale dams. This could help to improve the traditional irrigation system by increasing the efficiency of water use and developing multipurpose reservoirs for water supply and hydroelectric power (Nata 2006). It is however a challenge to address the uneven distribution of water resources by developing large water projects because of difficult topographic and variable climatic conditions (Berhanu et al. 2014). Particularly, the arid and semi-arid part of the country receive undependable rainfall (Few et al. 2015; Kiros et al. 2017). Thus, there is a need to store water in the wet season in view of meeting demands in the dry season with storage facilities such as dams and small-scale water harvesting systems (Ajibade et al. 2020).

Implementation of water harvesting techniques (WHTs) is essential for conservation of natural resources, effective water use and improving availability of water for local communities (Awulachew et al. 2010). Furthermore, Wondumagegnehu et al. (2007) emphasized that implementation of WHTs is supposed to bring an overall welfare for the local community by alleviating food insecurity. Amha (2006), for example, confirmed that implementation of farm pond in Alaba, southern Ethiopia, had a positive impact on household living standard. Recent policy of Ethiopia also promotes water harvesting and considers it as a main strategy for securing water resources for small-scale irrigation and domestic water supply (Binyam and Desale 2015; Andualem et al. 2020). Water harvesting also helps in replenishing ground water recharge in arid and semi-arid regions (Nedaw and Walraevens 2009; Tiwari et al. 2018; Andualem et al. 2020).

Worldwide, there are historical evidences of water harvesting practices. For example, Al-Adamat (2008) has found an ancient evidence of water harvesting practices in the Middle East region. Beckers et al. (2013) also documented experiences of water harvesting for water supply system in the drylands of ancient settlements in Mediterranean and Western Asia. Similarly, water harvesting systems were practiced in northern part of Ethiopia during the Axumite Kingdom (Fattovich 1990). In spite of a long history of water harvesting practices in different parts of the world, identification of suitable sites for a given biophysical, socioeconomic circumstances is still a challenge (Gowing et al. 2003). In Ethiopia, Alamerew (2006) and Woldearegay et al. (2017) identified that the poor performance of WHTs was mainly due to lack of combining scientific and traditional knowledge and applying top-down governance approach during implementation. Consequently, excessive seepage, high evaporation losses, early siltation, insufficient runoff, and poor water withdrawal mechanisms were attributed to poor site selection for WHTs (Amha 2006; Segers et al. 2008). Furthermore, Rämi (2003) argued that the poor performance of WHTs emanates from lack of skilled personnel during construction and targeting beneficiaries regardless of technical criteria with a quota system, often imposed by the government.

Many scholars tried to identify suitable sites for the development of WHTs with different approaches to improve water harvesting efficiency in arid and semi-arid regions (e.g., Grum et al. 2016; Adham et al. 2018; Ibrahim et al. 2019; Mugo and Odera 2019; Aghaloo and Chiu 2020; Al-Khuzaie et al. 2020; Ejegu and Yegizaw 2020; Al-Ghobari and Dewidar 2021). For example, Adham et al. (2016) summarized and categorized the methods and tools used for identifying situatable sites for WHTs in to four groups, i.e., (1) geographic information system (GIS)/remote sensing (RS), (2) hydrological modelling with GIS/RS, (3) multi-criteria analysis (MCA) integrated with hydrological modeling and GIS/RS and (4) MCA integrated with GIS. Among these methods, MCA integrated with GIS/RS and hydrological modeling is getting much attention as a result of the method's high flexibility in dealing with both qualitative and quantitative factors (Malczewski 2004, 2006). As result, this method has been used commonly by several researchers to map suitable sites for WHTs (e.g., Ramakrishnan et al. 2009; Krois and Schulte 2014; Prasad et al. 2014; Al-Ghobari and Dewidar 2021).

Implementation of WHTs on large watersheds necessitates the use of hydrological models for understanding hydrological processes such as flow directions, runoff concentration and collection areas and ultimately areas of high impoundments (Nagarajan et al. 2015; Kumar and Jhariya 2016). Despite the use of several methods to identify suitable sites for WHTs, these methods rarely apply a validation procedure that confirms if these methods are working correctly or not. Many WHTs fail during implementation because of insufficient runoff collected in the selected sites. Hence, runoff response of the catchment upstream of the water harvesting site should be well understood so that adequate water is stored in the site. This can be achieved by combining a GIS-based MCA with hydrological models such as the Soil Conservation Service Curve Number (SCS-CN) methods for identifying suitable sites for WHTs.

The main objective of this study was, therefore, to identify suitable sites for WHTs using a GIS-based MCA integrated with a hydrological model (SCS-CN) and applying a validation procedure to ascertain the proposed suitable area with location of existing techniques. This method was implemented in a semi-arid Werie catchment, northern Ethiopia.

Materials and methods

Description of the study area

The study was conducted in Werie catchment located in the Tekeze river basin in Tigray region, northern Ethiopia (Fig. 1). The Werie catchment lies between 13°50′48″–14°15′50″ N and 39°00′10″–39°13′35″ E. It has a total area of 1797 km^2. It is a major tributary of the Tekeze-Atbara river basin. The topography of the catchment is characterized by undulating terrain and steep slopes with altitudes ranging from 1378 to 3027 m above sea level.

Due to anthropogenic effects, the catchment is highly degraded and has a fragile environmental condition (Hagos et al. 1999; Nyssen et al. 2004a). The Werie catchment has a semi-arid climatic condition with long dry season (October to May) and wet season (June to September). More than 77% of the total annual rainfall of the catchment occurs during wet season and only 23% of rainfall occurs during the dry season. Annual rainfall for the study area ranges from 610 to 1070 mm and shows a decreasing trend from western to eastern direction. Besides, the rainfall depicts high spatial and temporal variability causing recurrent drought and repeated failure of crops (Awulachew et al. 2005; Araya and Stroosnijder 2011; Binyam and Desale 2015).

The dominant land use/cover for the Werie catchment was cultivated land (27.2%), bushland (26.7%) and grass land (25.3%). Based on FAO (1998) the major soil texture in the catchment is silt clay loam (49.8%), sandy loam (26.4%), silty loam (21.1%) and clay (2.7%). In general, subsistence agriculture is the main source of living for the people in the study area. A mixed agricultural system (rain-fed crop production and livestock) is practiced in the lowland part of the catchment.

Methodological framework and data

FAO (2003) identified six key factors for identifying potential suitable sites for WHTs. These factors include slope, land use/cover, rainfall and rainfall-runoff relationship, soil

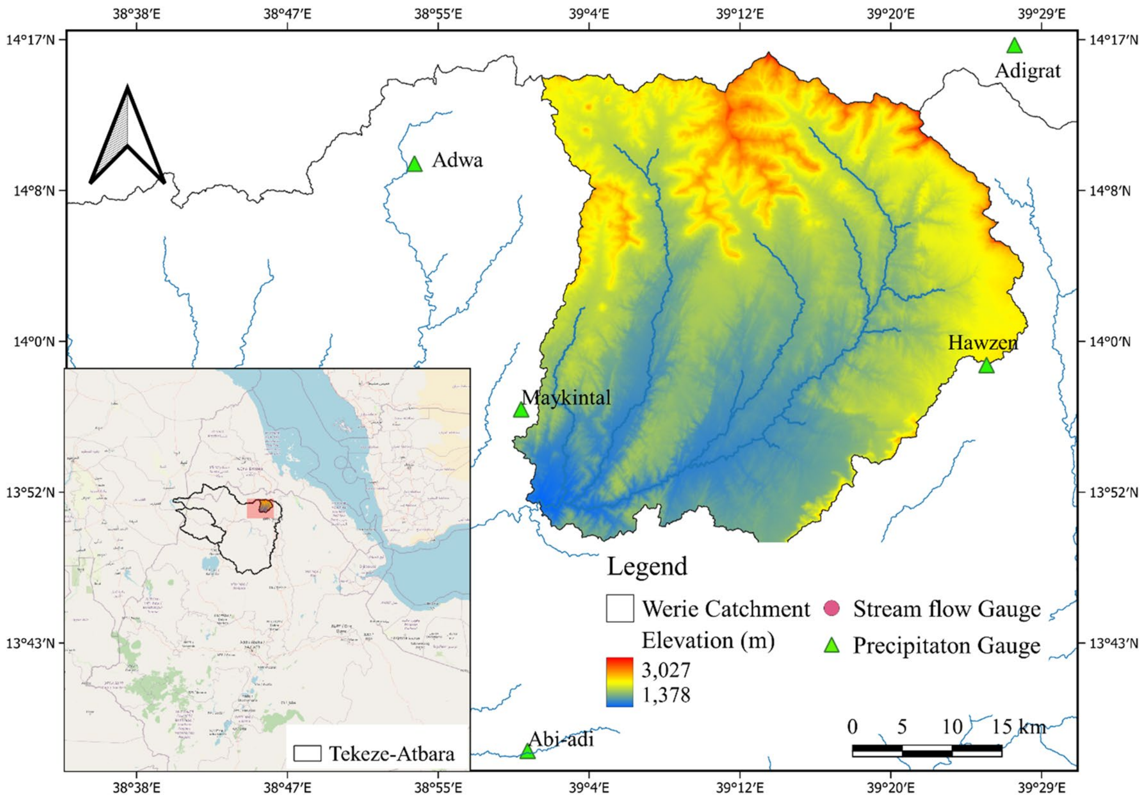


Fig. 1 Location and topography of the study area

texture and socio-economic issues. The socio-economic factors include accessibility, project implementation costs, workforce water laws and people's priority of the area under consideration. In this study, five biophysical and one socio-economic factor were selected. These factors or criteria were stream order, slope, land use/cover, soil texture, runoff depth and distance to cultivated land.

Spatial data were collected from different sources and organized in ArcGIS environment. Landsat 8 and digital elevation models (DEM) with 30 m spatial resolution were retrieved from the United States Geological Survey (USGS) website. Daily observed rainfall for five meteorological stations (Adigrat, Adwa, Abi-Adi, Hawzen, and Maykinetal) were collected from the Ethiopian Meteorological Agency. The rainfall data spans from 2000 to 2018. The soil data was obtained from the soil and terrain database for northeastern Africa (FAO 1998).

The overall framework for identifying suitable sites for WHTs is demonstrated in Fig. 2. The main methods in this framework include preparation of spatial datasets, weighing suitability criteria, reclassification of thematic maps into common scale of suitability, weighted overlay to develop suitability maps for WHTs and validation of the developed suitability map.

Data processing and preparation thematic map

Rainfall

Rainfall distribution over the study area was important in identifying suitable sites for WHTs. Rainfall is the main factor which affects runoff generation in hydrological process. Hence, to know the amount of runoff to be harvested in the study area, a spatial raster map of rainfall was generated using average annual rainfall of seven rainfall stations located in and around the study area. The spatial rainfall raster map was interpolated using the inverse distance weighting (IDW) method. The performance of the spatial interpolation was evaluated using the cross-validation procedure in GIS interface. Result of the cross-validation for the seven rainfall gauging stations is shown in Fig. 3. The percent bias of the cross validation ranged from − 12.9 to 23.9% with mean value of 4.6%. Overall, the cross-validation result is good considering the small number of gauging stations used for rainfall interpolation. Figure 3 also shows good agreement (R^2 = 0.92) between predicted and observed mean annual rainfalls of the stations.

Annual rainfall shows high spatial variation across the study area (Fig. 4). For example, the eastern part of the

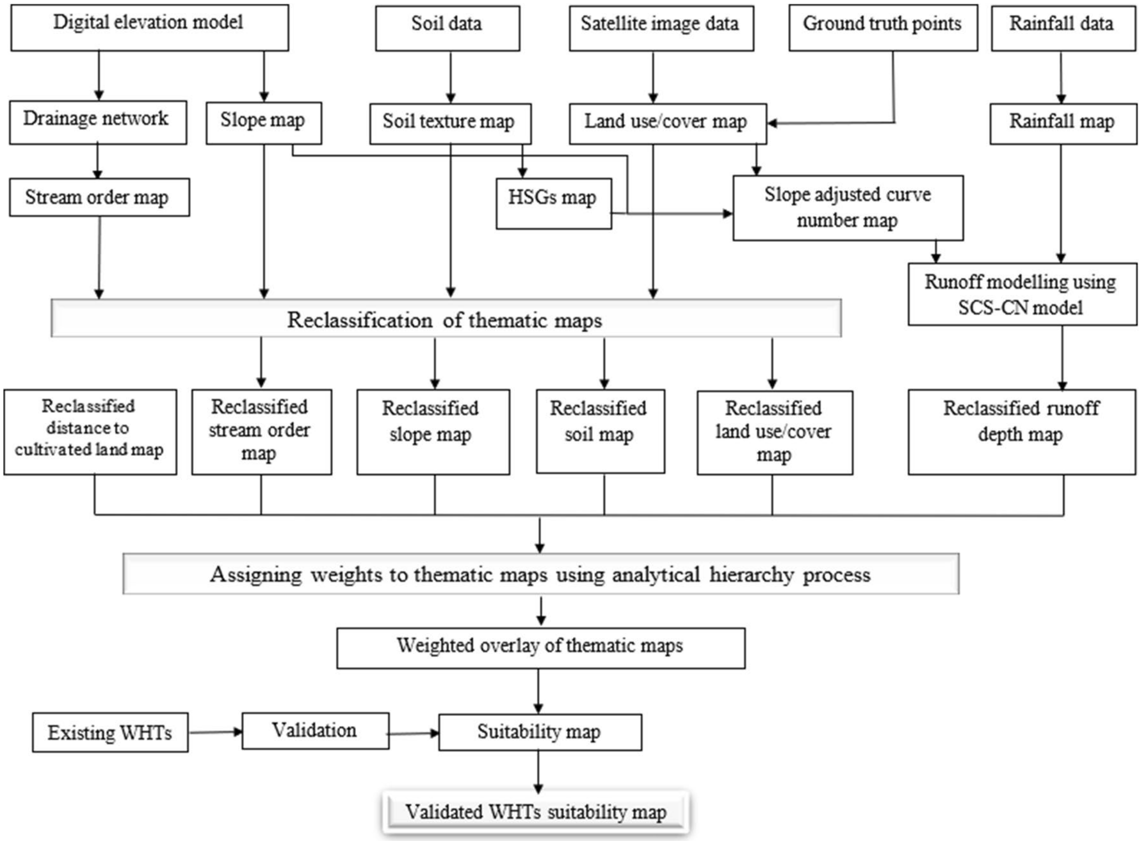
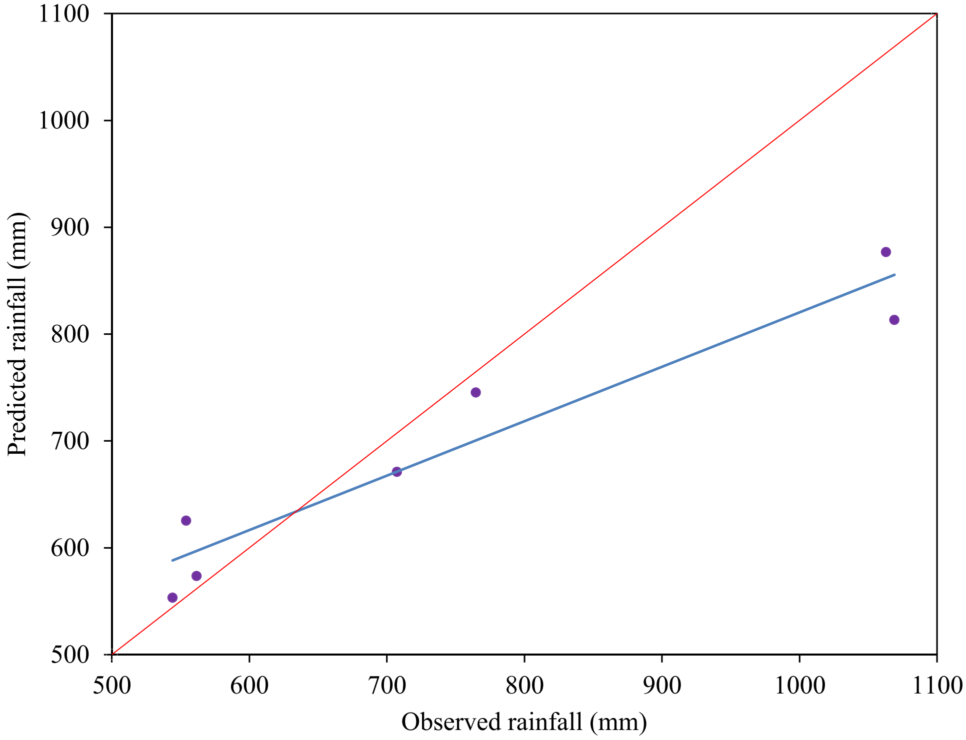


Fig. 2 Conceptual framework for identifying suitable sites for water harvesting techniques (WHTS)

Fig. 3 Cross validation mean annual rainfall prediction in Werie catchment



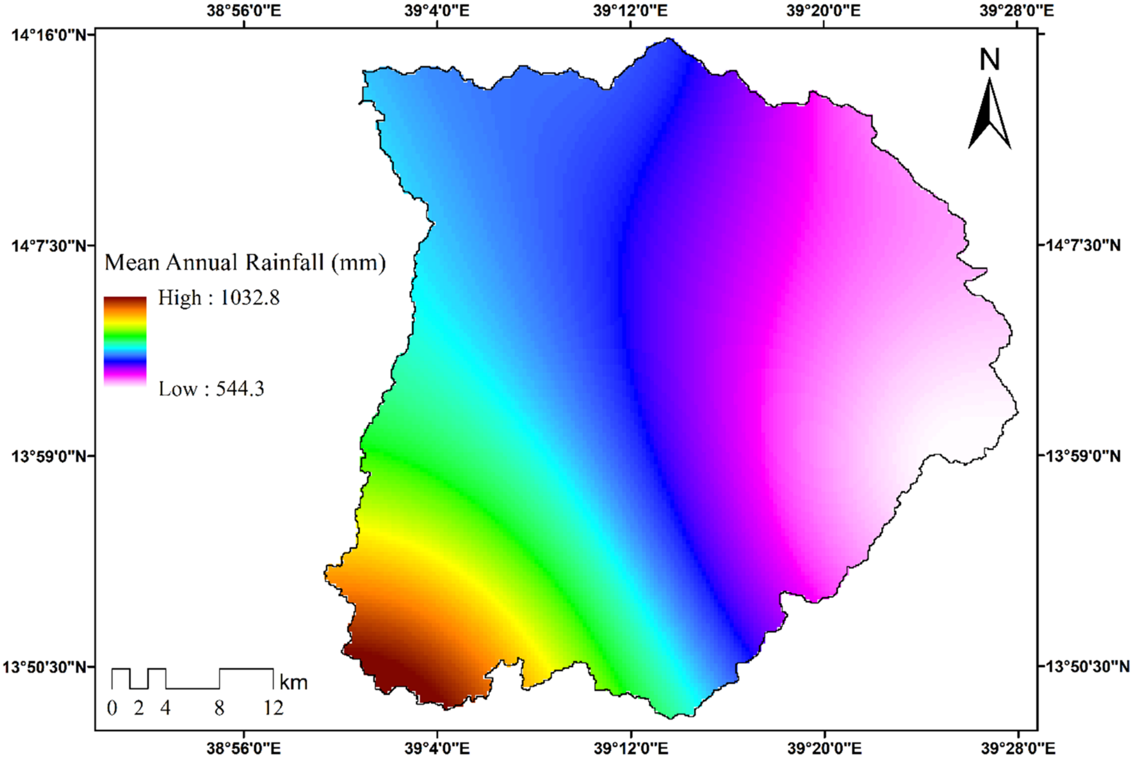


Fig. 4 Annual rainfall distribution of Werie catchment

catchment receives less than 670 mm annual rainfall. However, the southwestern part receives more than 870 mm annual rainfall.

Land use/cover

Land use/cover was considered as a main criterion for identifying suitable sites for WHTs. It was derived from Landsat 8 RS images and classified through supervised classification using earth resources data analysis system (ERDAS) imagine 2015 software. Google Earth and 1500 ground control points were used for validation (Fig. 5). Analysis of land use/land cover map showed that the major portion of the Werie catchment was covered by cultivated land (27.1%), bush land (26.7%) and grass land (25.3%). Remaining land uses are bare land (13%), open forest (6.4%), built-up area (1.3%) and water body (0.3%).

Soil map

The suitability of an area for WHTs depends strongly on the soil's characteristics. In general, soils with high water holding capacity are suitable for WHTs (Kadam et al. 2012; Krois and Schulte 2014). As a result, loamy soils are considered the most suitable soil texture for WHTs. Sandy soils are considered the least suitable soil texture because of their high infiltration capacity. Clay soils are less suitable because of their low infiltration capacity and high risk of waterlogging (Tumbo et al. 2014). Therefore, soil property has great influence on hydrological processes of a catchment and is considered an essential factor in generations of runoff. As indicated in Fig. 6a, silt clay loam, sandy loam and silty loam are the dominant soil textures which account 49.8%, 26.4% and 21.1% of the catchment area, respectively. Clay (2.7%) is insignificantly found in the eastern tip of the catchment.

For the purpose of SCS-CN model input, the soil data was further classified based on hydrological soil groups (HSGs) designated by A, B, C and D (NRCS, 2009). Table 1 summarizes the four categories of HSGs. The soil groups A, B, C and D are recognized as having low, moderately low, moderately high and high runoff potential, respectively (NRCS 2009). Based on the United States Department of Agriculture (USDA) soil classification system, the catchment soil texture is categorized in to three HSGs namely A, B and D (Fig. 6b). The catchment HSGs coverage is therefore 41.1% of A, 7.5% of B and 51.5% of D.

Slope gradient

Slope gradient is one of the major criteria in the generation of suitability map for WHTs. The significance of slope in

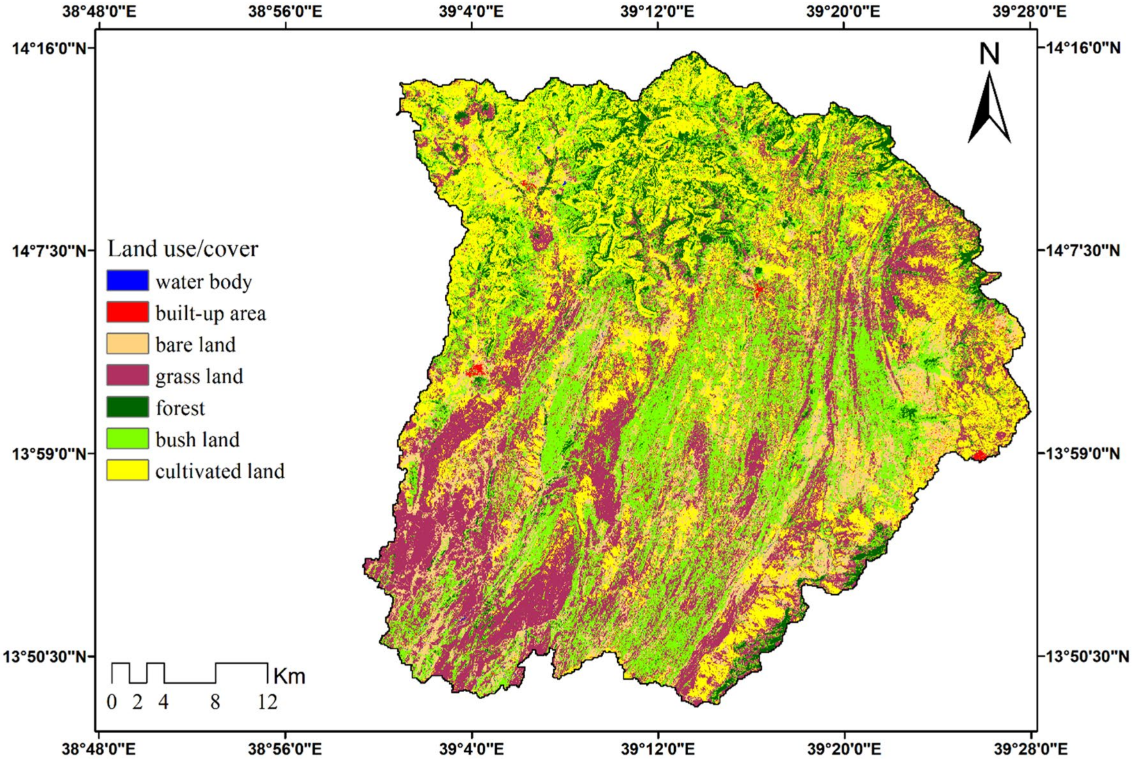


Fig. 5 Land use/cover of Werie catchment

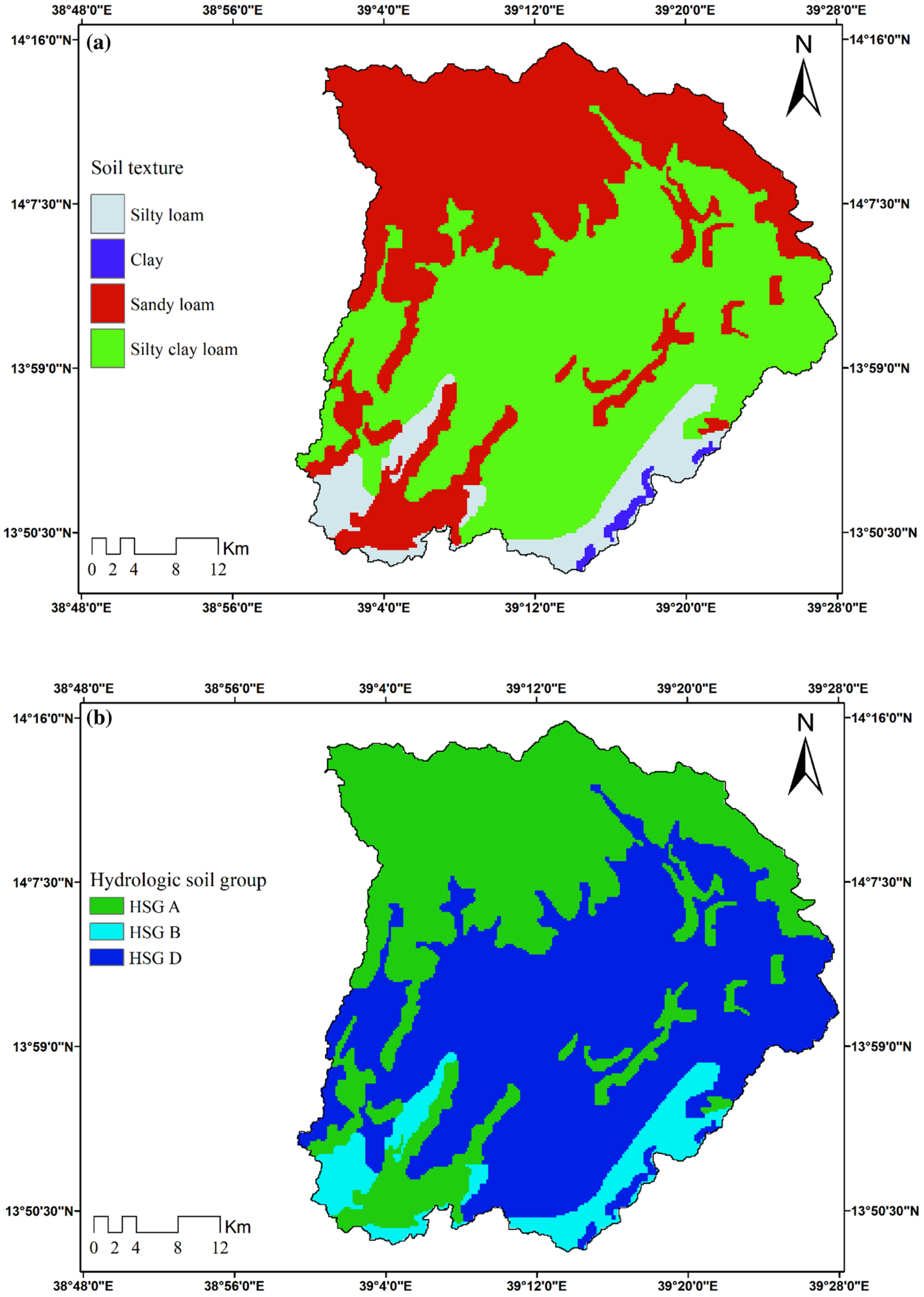


Fig. 6 Thematic maps **a** Soil texture, **b** Hydrologic soil group of Werie catchment

Table 1 United States Department of Agriculture-Natural Recourses Conservation Services (USDA-NRCS) hydrological soil groups (NRCS 2009)

HSG	Infiltration rate (mm/h)		Soil texture
A	High	> 25	Sand, loamy sand, or sandy loam
B	Moderate	12.5–25	silt loam or loam
C	Low	2.5–2.5	Sandy clay loam
D	Very Low	< 2.5	Clay loam, silty clay loam, sandy clay, silty clay or clay

identifying suitable sites for WHTs relies on the fact that slope of a given catchment affects the amount of runoff and movement of surface water. DEM is used to generate slope gradient in a GIS environment. Slope gradient helps to locate the area of maximum water storage or collection areas. According to De Winnaar et al. (2007) slope is classified into five classes, namely (i) flat (< 3%), (ii) gentle (3–8%), (iii) sloping (8–15%), (iv) hilly (15–30%), and (vi) mountainous (> 30%). Slope gradient of the study area is shown in Fig. 7.

Stream order

Stream order was produced using the spatial analysis tool of ArcGIS 10.3 which derived the hydrological parameters based on DEM of the study area (Fig. 8). Stream order is defined as the hierarchical networking between the flow sections and allows the drainage basins to be classified according to their size (Strahler 1957). Since stream order greatly governs time of concentration of water flow, lower stream orders are considered suitable for water harvesting. As stream order increases, the suitability of stream for water harvesting decreases (Kumar and Jhariya 2016).

Rainfall-runoff modeling

SCS-CN model developed by the United States of Soil Conservation Service (SCS 1972) was used for estimation of runoff volume and depth. The SCS-CN estimates runoff depth based on slope, soil characteristics, land use/cover and antecedent moisture condition of a catchment. The SCS-CN model is suitable for estimating runoff because it combines almost all physical factors that influence runoff generation (De Winnaar et al. 2007; Zheng et al. 2018). CN is used as an input parameter that controls runoff generation using the SCS-CN model. In this study, CN helps to determine runoff considering AMC II, and based on combined land use/cover and HSGs maps as input in ArcGIS environment (Ibrahim et al. 2019). Thus, based on the HSGs and land use/cover output maps CN values were assigned to each combination following the procedure illustrated by SCS (1972).

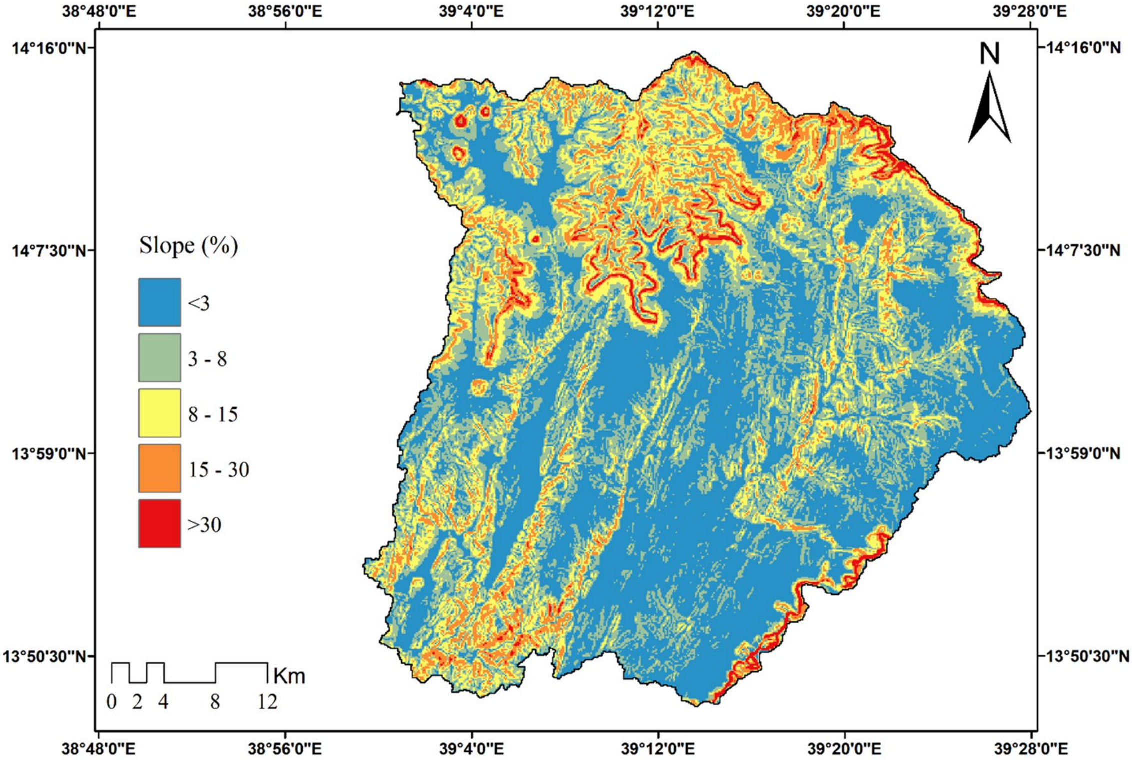


Fig. 7 Slope gradient of Werie catchment

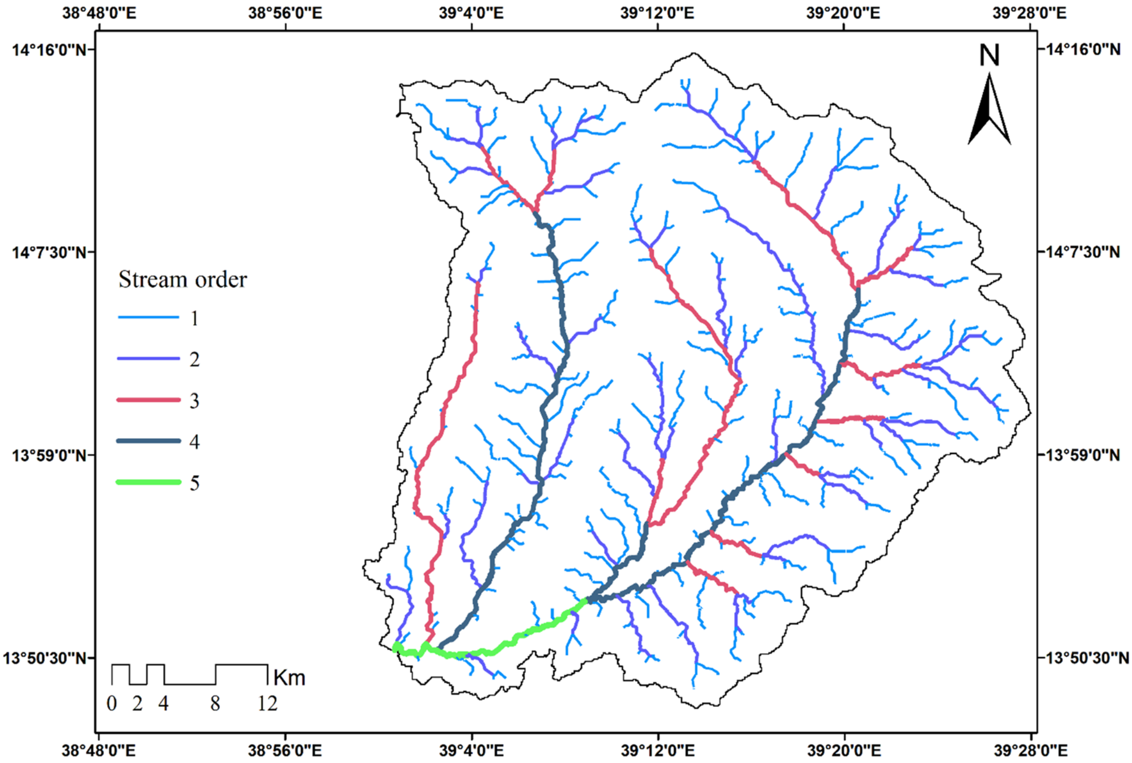


Fig. 8 Stream order of Werie catchment

Theoretically, CN values range between 0 and 100, with higher CN values related to higher runoff potential. However, slope is a crucial factor in determining water movement within a catchment in steep slope areas. Slope affects surface runoff determination using SCS-CN model in three aspects including reduction of initial abstraction, decrease in infiltration and reduction of the recession time of overland flow (Ebrahimian et al. 2012). Hence, in this study Eq. 1 developed by Huang et al. (2006) was used to estimate a slope adjusted CN (Fig. 9a). Ebrahimian et al. (2012) had used the expression of Huang et al. (2006) for slope adjustment in rainfall-runoff events in the Kardeh catchment of Iran and found a positive correlation between observed and estimated runoff depths.

$$\mathrm{CNII}\alpha = \mathrm{CNII}\frac{322.79 + 15.6\alpha}{\alpha + 323.52}, \tag{1}$$

where CNIIα is adjusted CN for a given slope and α is slope gradient (m/m).

All required parameters were fed into the SCS-CN model in ArcGIS10.3 environment and the catchment surface runoff was computed. The SCS-CN model has been used to calculate the runoff depth at cell level required to identify a suitable site for water harvesting using Eqs. 2 and 3. Results of runoff depth estimation using SCN-CN model is found in Fig. 9b.

$$\begin{aligned} Q &= \frac{(P-0.2S)^2}{P+0.8S} \quad \text{for} \quad P > 0.2S \\ Q &= 0 \quad \text{for} \quad P \le 0.2S, \end{aligned} \tag{2}$$

$$S = \frac{25400}{\mathrm{CN}} - 254, \tag{3}$$

where Q is runoff depth (mm), P is precipitation (mm), S is maximum retention and CN is curve number.

MCA to identify suitable sites for WHTs

Determination of potential suitable sites for WHTs needs a basic understanding of rainfall distribution, soil properties, topography characteristics and land use of a particular area (Ibrahim et al. 2019). Therefore, the process of identifying suitable sites for WHTs is a multi-criteria decision process relying on both biophysical and socioeconomic factors of a specific location. To apply the adopted methodology for identification of suitable sites for WHTs, different spatial scales of selected factors map should be converted into the same comparable units (Mahmoud et al. 2015).

Therefore, the factor maps were reclassified into five comparable units, i.e., suitability classes namely; 5 (very highly suitable), 4 (highly suitable), 3 (moderately suitable), 2 (marginally suitable) and 1 (not suitable). This scale of

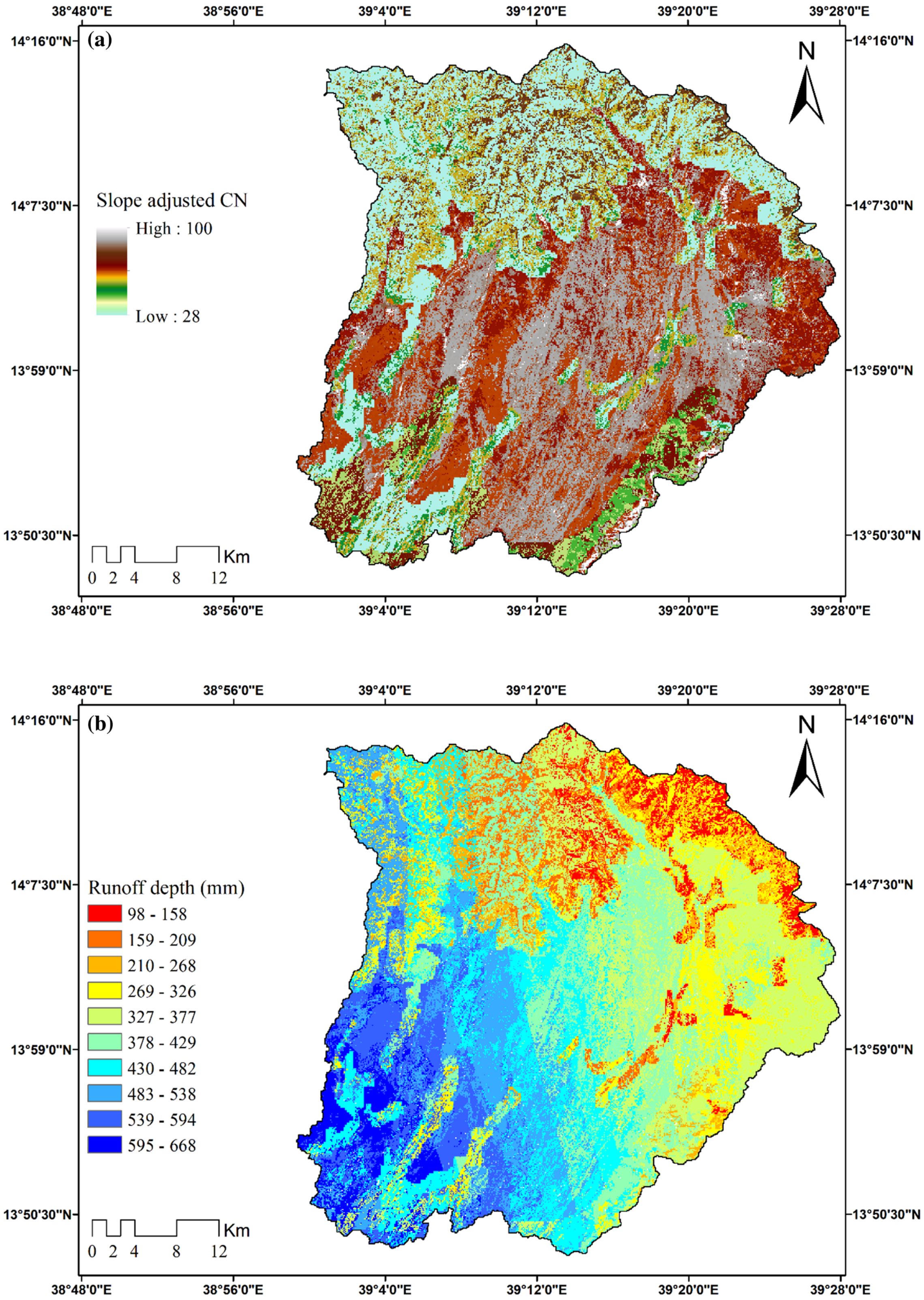


Fig. 9 Thematic maps **a** adjusted curve number, **b** runoff depth map of Werie catchment

suitability was selected based on similar previous studies on different part of the world (Oweis et al. 2001; Mbilinyi et al. 2007; Kahinda et al. 2008). It has been found to be a vigorous and a reliable method (Mahmoud and Alazba 2014).

Assignment of weights to the criteria

Weighting the factors is an important step in the MCA decision process in determining relative contribution towards achieving the general objective of the study. Weights were assigned to the factors by applying the pair-wise ranking known as analytical hierarchical process (AHP) and rank-sum methods developed by Saaty (1977, 2005, 2008). It involves evaluation of a criterion against another criteria. This was done in pairs to decide which criterion is more significant than the other for a given objective (Saaty 2008). The consistency of the judgment about weights of the criteria was checked by consistency ratio (CR) computed using Eq. 4. A pair-wise comparison for assigning relative weight is judged consistent if CR value is less than 0.1.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RCI}}, \tag{4}$$

where RCI is random consistency index, and CI is consistency index given by Eq. 5

$$\mathrm{CR} = \frac{\lambda_{\max} - n}{n - 1}, \tag{5}$$

where $\lambda_{\max}$ is the principal eigenvalue computed by the eigenvector technique, and n is the total number of criteria.

A GIS model for generating WHTs suitability map

Model builder of ArcGIS 10.3 was used to generate suitability map of different criteria thematic maps. The model produces WHTs suitability maps by incorporating various factor map layers using MCA. Several tools of ArcGIS were built-in the model to solve various spatial challenges that included reclassifying values, re-projecting and overlaying. The weighted linear combination is a widely used MCA process for suitability site analysis (Grum et al. 2017; Saha et al. 2018). This model includes the standardization of suitability maps, the weighting of the comparative significance of suitability maps and merging of weights and criteria maps to achieve a suitability value (Ibrahim et al. 2019).

All vector type format maps were converted into raster datasets to enable the ArcGIS weighted overlay (Malczewski 2004). All factors were combined by using a weight to each factor followed by a summation of the results to generate a suitability map calculated using Eq. 6.

$$S = \sum W_i \times X_i, \tag{6}$$

where S is suitability output level per pixel i, W_i is weight of factor i, X_i is criteria score of factor i.

Therefore, the higher the suitability value, S of a given size (pixel) i, the more suitable the pixel is for WHTs. S is based on the established suitability ranking of 1–5. Table 2 shows the suitability criteria for the WHTs developed based on a critical review of previous studies and indigenous knowledge.

Results and discussion

Suitability results of thematic maps

Figure 10 indicates the specific suitability level of individual factors such as soil texture, slope, runoff depth, land use/cover, distance to cultivated land and stream order.

Table 2 Suitability criteria used for identifying sites for WHTs (Kumar et al. 2008; Ramakrishnan et al. 2009; Kadam et al. 2012; Krois and Schulte 2014; Saha et al. 2018)

Criteria	Level of suitability				
	5	4	3	2	1
(a) Check dam					
Runoff depth (mm)	> 850	700–850	500–700	350–500	200–350
Stream order	1	2	3	4	> 4
Slope (%)	8–15	3–8	< 3	15–30	> 30
Soil texture	Clay	Silty clay loam	Silty loam	Loam	Sandy loam
Distance to cultivated land (m)	20–100	100–300	300–500	500 –700	> 700
(b) Farm pond					
Runoff depth (mm)	> 850	700–850	500–700	350–500	200–350
Slope (%)	3–8	8–15	< 3	15–30	> 30
Soil texture	Clay	Silty clay loam	Silty loam	Loam	Sandy loam
Land use/cover	Cultivated land	Bush /bare land	Grass land	Open forest	Built-up / water body
Distance to cultivated land (m)	0–50	50–150	150–250	250–350	> 350

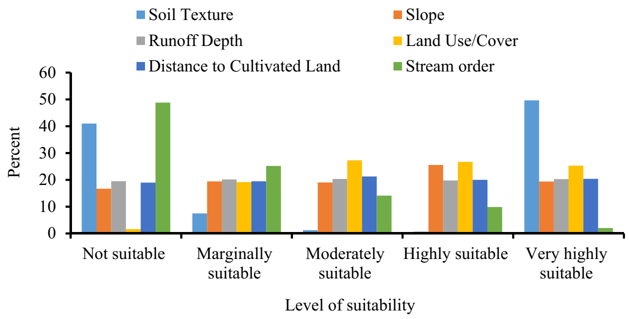


Fig. 10 Suitability level of individual factors for Werie catchment

Table 3 Weight of factor for each thematic layer of Werie catchment

Thematic layers	Relative weight factor of criteria	
	Check dam	Farm pond
Stream order	0.43	NA
Runoff depth	0.27	0.41
Slope	0.15	0.28
Soil texture	0.09	0.17
Land use/cover	NA	0.09
Distance to cultivated land	0.06	0.05
CR	0.004	0.003

NA-Not applicable

The relative weights of the criteria for suitability analysis are also shown in Table 3. In terms of suitability level for individual factors, soil texture (51.6%), slope (63.9%), runoff depth (60.4%), land use/cover (79.3%) and distance to cultivated land (61.6%) of the total area were moderately to very highly suitable for farm ponds. Moreover, 26% of the total stream length of Werie catchment was found to be moderately to very highly suitable for check dams.

The computed result of CR for check dams and farm ponds WHTs revealed that the pair-wise comparison was within the acceptable ranges (Table 3). The CR for check dams and farm ponds were 0.004 and 0.003 respectively which is less than 0.1 (Saaty 1977). The suitability analysis result revealed that stream order (43%) and runoff depth (41%) were the most influential assessment criteria for check dams and farm ponds respectively. Other previous studies (e.g., Adham et al. 2018; Ibrahim et al. 2019; Mugo and Odera 2019; Aghaloo and Chiu 2020; Al-Khuzaie et al. 2020; Ejegu and Yegizaw 2020) also indicated that runoff depth is the most influential criteria for identifying suitable sites for farm ponds. The most probable reason for runoff depth to have high weight for identifying suitable sites for farm ponds is because runoff is derived from soil texture, land use/cover and slope (Al-Khuzaie et al. 2020). For check dams, studies by Shalamzari et al. (2019) and Ajibade et al. (2020) have also found stream order to be the top ranking criteria in the suitability analysis. Other studies (Ramakrishnan et al. 2008; Rahmati et al. 2019; Harka et al. 2020; Rana and Suryanarayana 2020), however, found slope to be the top important criteria for locating suitability for check dams. The main reason for stream order to be more influential in this study and a study by Shalamzari et al. (2019) than other similar studies could be due to the dendritic characteristic of the drainage networks.

WHTs potential suitability map

Check dams suitability map

The suitability map analysis indicated that 49.9% and 40.6% of the total length of streams were found to be highly suitable and moderately suitable for construction of check dam, respectively, (Fig. 11). In addition, 2.4% and 7.1% of the total length of streams were found to be is very highly suitable and not suitable, respectively. Stream order 1 to 3 were most suitable for check dams.

The results also agree with findings by Mbilinyi et al. (2005) who stated that check dams are constructed on the river courses with low to moderate slopes. In general, check dams are usually suggested for lower-order streams (up to third order), the slope of the area should be between flat to gentle slope in order to collect a maximum possible quantity of water. However, suitable sites should have minimum slope gradient where water can easily flow by mere action of gravity (Mbilinyi et al. 2005). Furthermore, Nyssen et al. (2004b) also indicated that slope gradient and catchment size are the main factors controlling check dam stability. Ibrahim et al. (2019) further elaborate a slope gradient has influence on runoff generation and surface velocity that affects site condition of check dams. Thus, the very highly suitable sites are identified in areas of slope less than 3% and generate high runoff depth.

Farm pond suitability map

Farm ponds were constructed on the lower elevation of agricultural fields to store surface runoff (Weerasinghe et al. 2011). The water storage could be used in times of water scarcity. Farm ponds are WHTs that play an important role for storing of water in wet season which is used for various purposes such as irrigation, cattle feed, domestic water supply, etc. during the dry season.

The farm pond suitability map (Fig. 12) depicted that 17.7% and 0.3% of the study area is classified under highly suitable and very highly suitable, respectively. These cover a total area of about 322.6 Km^2. Majority of these areas are found in locations that have relatively high annual runoff potential of about 700–850 mm and in silty clay loam soil

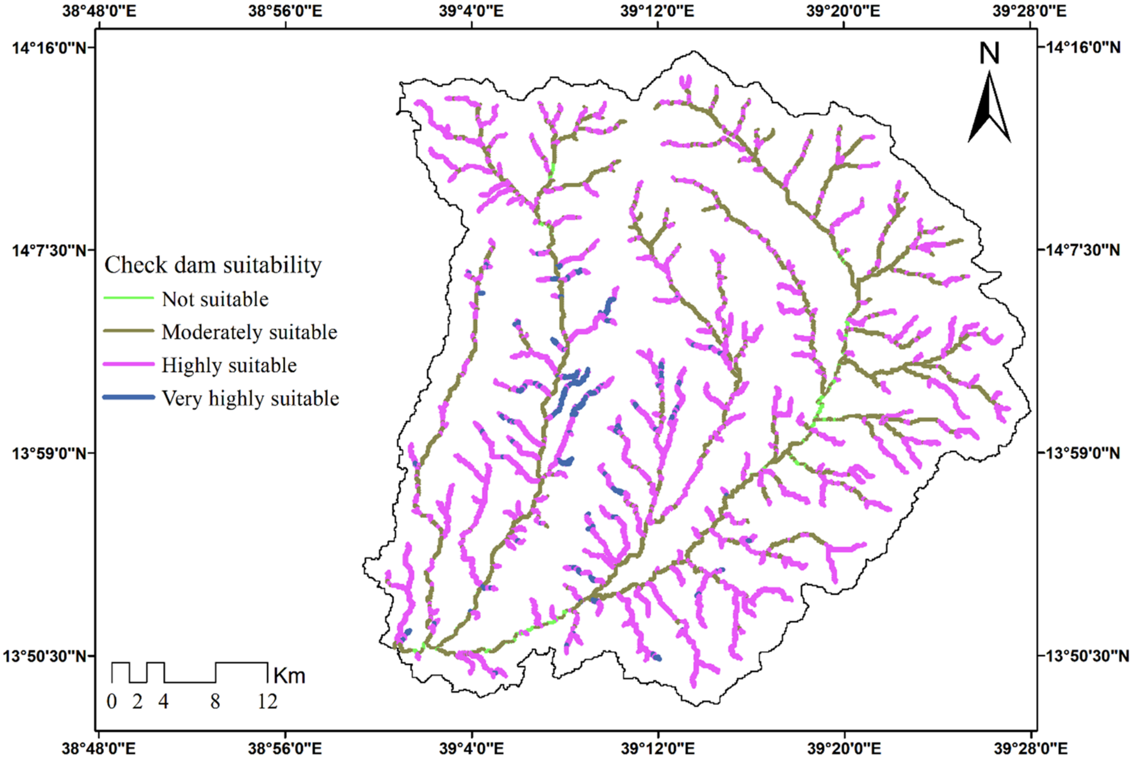


Fig. 11 Suitability map for check dams in Werie catchment

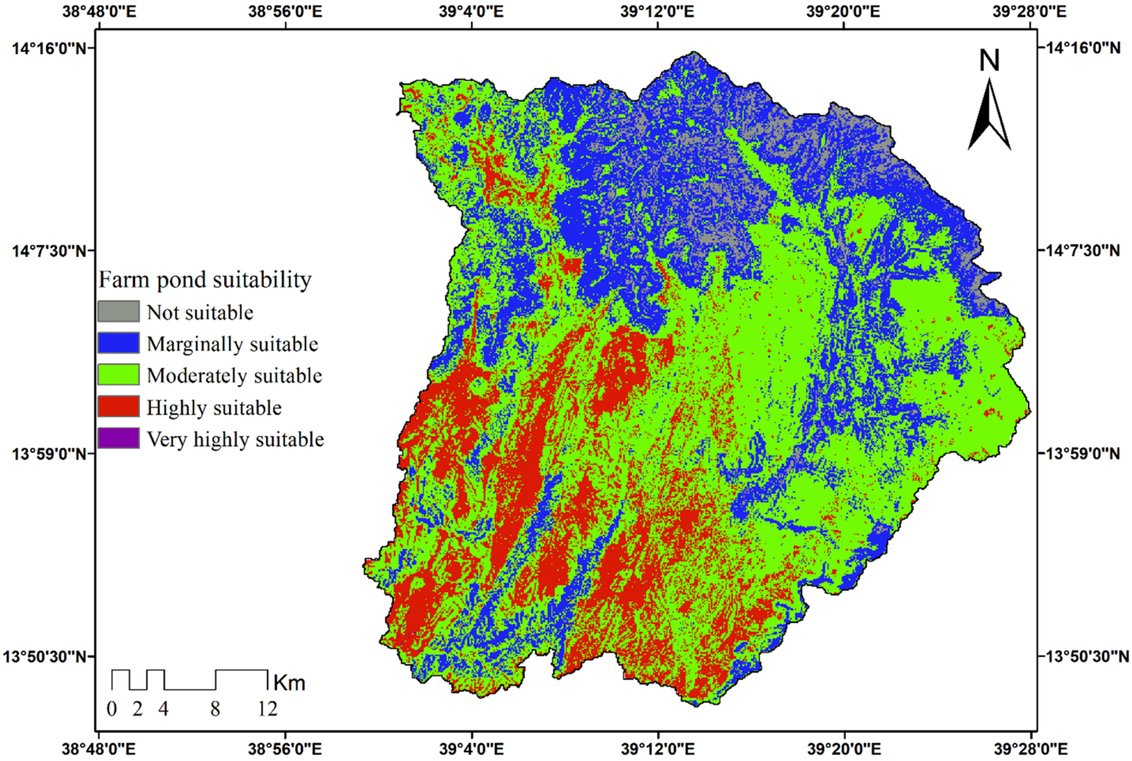


Fig. 12 Suitability map for farm ponds in Werie catchment

texture. These types of soils are suitable for most WHTs systems due to their high water holding capacity and low seepage and percolation (Al-Adamat 2008). Most of these suitable sites are located on flat to gentle landscape with a slope ranging between 3 to 8%.

From the total area, 51.2% is moderately suitable for farm ponds. Majority of the potential sites with moderately suitable class are located in the middle part of the study area in which the soil types are majorly sandy loam and silty clay loam. The dominant land use/cover are cultivated land and bush land. The unsuitable areas were found in areas that have low annual average runoff depth of 200–500 mm and a slope greater than 30%. The underlying soil texture in these sites are mostly sandy loams and described by excessive to moderate percolation rate. As a result, this textural class is not suitable for the location of farm ponds as it loses the harvested water through seepage and percolation.

Validation of the suitability analysis results

The validation of the suitability map for WHTs was analyzed by percentage of overlap of existing WHTs in the developed suitability map. For validation purpose, 65 and 79 locations of functional existing WHTs for both check dams and farm ponds were collected. Respectively. Through field survey. In addition, location of 18 non-functional existing WHTs were collected for farm ponds. Hence, the validity of each developed suitability map was checked by superimposing existing WHTs with the developed map for each WHT. The location of existing WHTs in Werie catchment were overlaid over the developed suitability maps.

Suitability level of individual factors was also tested against the existing WHTs. Figure 13a shows the suitability region of individual factors for check dam. Out of 65 existing check dams more than 74% were located in moderately to very highly suitable area considering stream order, runoff depth, slope and distance from cultivated land. Considering soil texture, only 52.3% were placed in very highly suitable and remaining 47.7% were placed in marginally suitable to unsuitable areas. Similarly, Fig. 13b indicates the suitability region of individual factors for farm ponds. From 79 existing farm ponds, 66% (soil texture), 75% (runoff depth) and 82% (slope) were located from moderately to very highly suitable area. In addition, 58% and 59% of existing farm ponds were located in moderately to very highly suitable area for distance from cultivated land and land use/cover factors respectively.

The results shown in Fig. 14a indicate that 55% of functional check dams were located in areas of high suitability, 29% were located in areas of moderately suitable. Moreover, 12% were located in areas of not suitable and only 4% were located in areas of very highly suitable. For farm ponds (Fig. 14b) 10% were found within an area of not suitable, 16% in marginally suitable, 23% in moderately suitable and 51% in highly suitable areas. The non-functional existing farm ponds' validation result revealed that 56% were located in area of not suitable, 28% in area of marginally suitable, 11% in moderately suitable and 5% in highly suitable areas.

Most site suitability analysis for WHTs are rarely validated with existing locations of WHTs. There are, however, some attempts (Kadam et al. 2012; Grum et al. 2016; Singhai et al. 2017) to validate GIS-based site suitability analysis with existing site conditions of WHTs. The validation process in these studies showed a good agreement between the GIS-based suitability analysis and existing locations of the WHTs.

The results give an indication of the reliability of the developed WHTs suitability maps, the relevance of selected biophysical and socio-economic factors. Thus, the created maps have given a reliable map of the spatial distribution of suitable areas for check dams and farm ponds. The maps can provide a quick reference for governmental and non-governmental agencies during planning and implementation of WHTs.

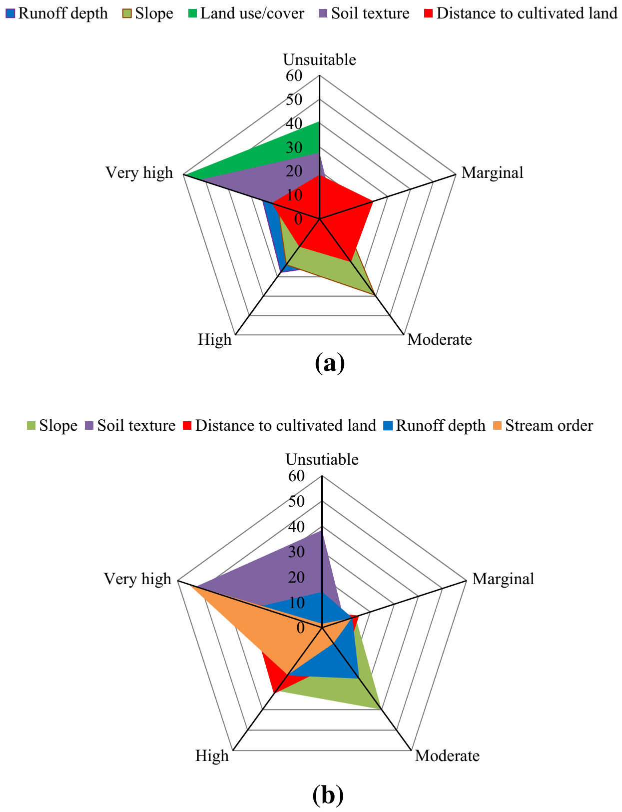


Fig. 13 Suitability level of individual factors to existing **a** check dams, **b** farm ponds in Werie catchment

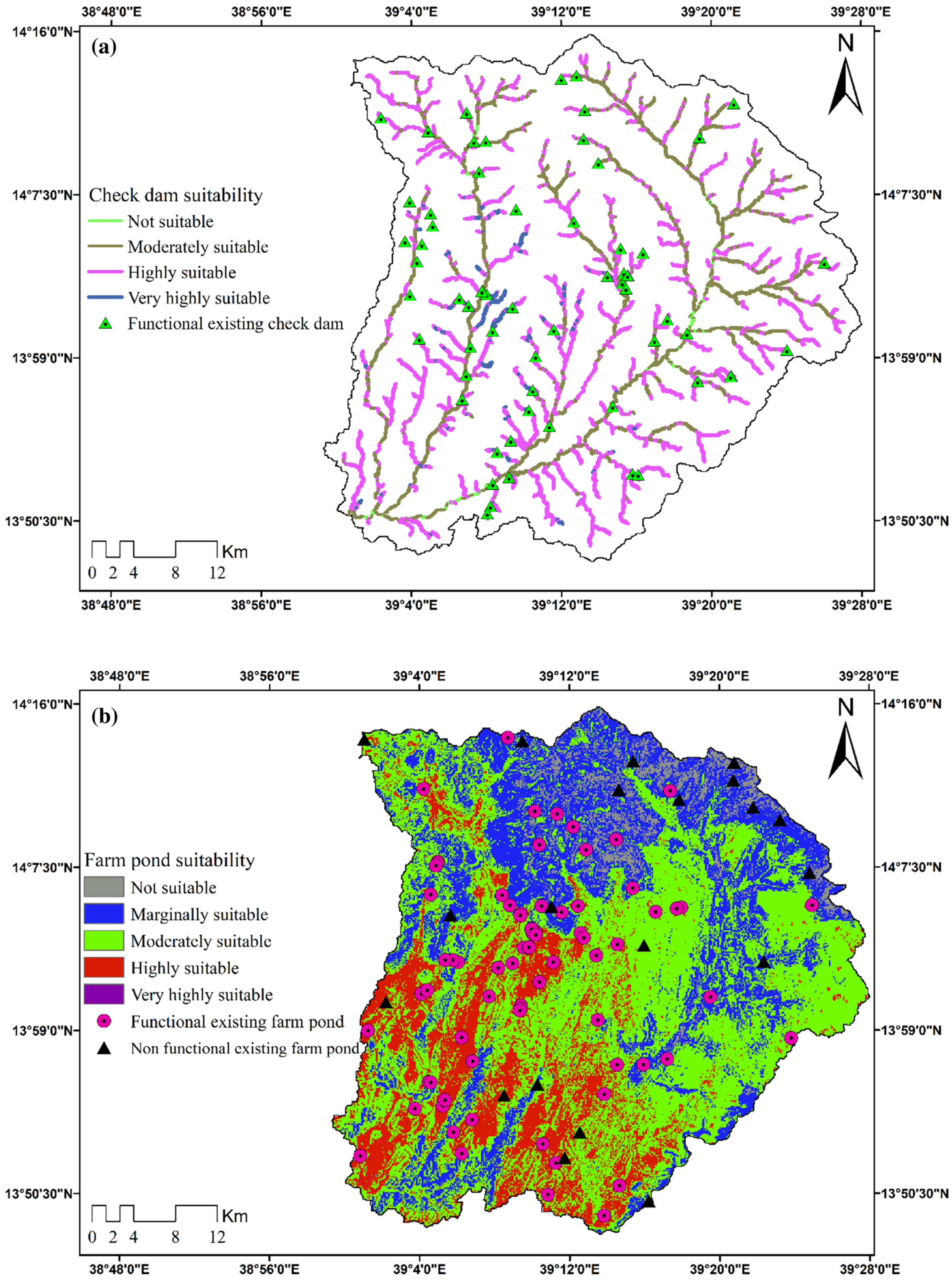


Fig. 14 Validation of suitability map, **a** check dams, **b** farm ponds of Werie catchment

Conclusion

This study has presented a detailed analysis of the selected biophysical factors to assess the suitability of the Werie catchment for developing water harvesting techniques (WHTs). Based on the findings of this study, the following conclusions were drawn:

- Relative comparison of factors indicated that stream order and runoff depth are the most influential criteria for developing check dams. Similarly, runoff depth and slope are important factors for developing farm ponds.
- The site suitability analysis result indicates that check dams should be constructed in lower order streams and areas of high runoff potential.
- The developed suitability maps validation for both check dams and farm ponds revealed an excellent performance for both existing functional and nonfunctional farm ponds and existing functional check dams.
- The good performance of the suitability analysis indicate that a GIS-based multi-criteria analysis can be integrated with a hydrological model for identifying suitable sites for WHTs.
- The validated suitability maps provide useful information about check dams and farm ponds that could help practitioners and decision makers for planning and development of water resources.

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Author contributions FA contributed to the conceptualization, data collection, data analysis, preparing of the original draft manuscript. BAA contributed to formulating the objectives, methods, project administration, supervision, review, and editing. Ahmed Mohammed Degu assisted with the objective, methods, review, and editing. HG provided guidance during the project and edit the manuscript. BG contributed to the conceptualization, formulating of the overall project, supervision, structuring of the manuscript.

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Data availability The recorded daily rainfall data of the currently existing rain gauge stations were obtained from Ethiopian National Meteorological Agency, Landsat 8 image and digital elevation models (DEM) from USGS website, and Soil data was obtained from the soil and terrain database for northeastern Africa (FAO 1998).

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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