



# Remote sensing and multi-criterion analysis for identifying suitable rainwater harvesting areas

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## Abstract

Water scarcity and soil erosion are the main constraints small holder farmers are facing in Tigray, the northern most part of Ethiopia. Both very high and very low precipitation can cause a damage to agriculture which is the case in semi-arid regions like Tigray. While too little rainfall cannot support the growth of crops resulting in crop failure, the short but intense rainfall also causes a runoff thereby washing away essential soil nutrients. Installation of different micro/macro-catchment rainwater harvesting can address both water scarcity and soil erosion if they are properly designed prior to construction. This research was intended to develop a methodology for identifying suitable rainwater harvesting (rwh) sites by using weighted overlay analysis. It also utilizes Ahp (analytical hierarchy process) as effective multi-criterion decision-making tool in eastern Tigray at Kilde Awlaelo district on an area of 1001 km<sup>2</sup>. This method was chosen because it is simple to use, cost effective, flexible and widely adopted. Physical, hydrological, climate and socio-economic aspects were taken into account during criteria selection. The result indicated four suitability classes with 8.74% highly suitable areas (85.25 km<sup>2</sup>), 56% suitable areas (550.75 km<sup>2</sup>), 30.8% moderately suitable areas (303.2 km<sup>2</sup>) and 4.46% less suitable areas (43.87 km<sup>2</sup>). The produced rwh suitability map was also validated by both ground truth on google earth pro and a field trip to the study site. In situ and ex situ rwh including bench terraces, wells, and enclosure areas were identified during the field visit that verified the suitability model. Finally, depending on weight and scale of criteria and sub-criteria that matched to each identified suitable areas, different micro-catchment and macro-catchment techniques of water harvesting are recommended. This methodology can be utilized as decision-making tool for rwh practitioners, local and foreign organizations working on soil water conservation programmes and policy-makers during their early planning stages.

**Keywords** Water scarcity · Rainwater harvesting · Geographic information system · Site suitability · Analytical hierarchy process · Weighted overlay

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## Introduction

Tigray, a region in the northern most part in Ethiopia, is among the highly degraded semi-arid areas with subsequent records of drought and famine. Annually, around 42 Mg/ha soil is eroded. Nutrient loss is also a threat with about 4 kg/ha phosphorus and 25 kg/ha nitrogen being lost via runoff (Hengsdijk et al. 2005). The main reason for deteriorating soil quality in Tigray is hilly and mountainous topography, cultivation of more marginal land, climate change, increased human population, deforestation, overgrazing, erratic nature of rainfall, etc. (Descheemaeker et al. 2009; Grum et al. 2017). The loss of vegetation in the area reduced the formation of humus which is produced by decomposing litter (Descheemaeker et al. 2009). Frequent wars that has existed in the region for centuries and till date are also another

causes of land degradation. This phenomenon brought about water scarcity, soil erosion, and decline in agricultural productivity (Behailu and Haile 2003).

Some soil water conservation techniques such as bench terraces, deep trenches, reforestation, water harvesting ponds, percolation pits (Tadesse et al. 2016), stone bunds (Vancampenhout et al. 2006), tied ridges (Gebreegziabher et al. 2009), and mulching (Nyssen et al. 2000) were constructed in parts of the region in order to combat land degradation and frequent drought since 1980s (Haregeweyn et al. 2012; Nyssen et al. 2010). However, these measures are very limited to certain areas and could not be easily reproduced and adopted on other areas of the region. Reproducing such experiences to other areas requires the study of suitability site assessment for rainwater harvesting. Moreover, 85% of the people in Tigray live in rural areas, where small holder agriculture is mainly exercised to sustain their life. Farmers in the region experience water scarcity quite often that leads to frequent crop failure. This prevents farmers from achieving food security making them depend on external food aid their whole life. However, adoption and extension of rwh techniques can address this problem. The primary step during rwh adoption is to carry out suitability assessment in order to select suitable areas. Therefore, this research is essential and timely in areas with scarce water resources.

Even though rwh (rainwater harvesting) as an alternative water resource has been in place for thousands of years around the globe (Prinz and A. Singh 2000a; b), it is still not fully utilized in those areas due to various reasons including low or no participation of farmers, lack of detail site selection approach, lack of access to local markets, lack of land ownership, etc. (Merrey et al. 2005; Nji and Fonteh 2002; Tabor 1995). Poor selection of suitable areas and mismatching of the practice with both technical and socio-economic requirements is a setback to effective rainwater harvesting and has been reported by (Ketsela 2009; Ziadat et al. 2012). Most of the conducted rwh structures in the region either stopped functioning or are serving much below their intended service life mainly because they were implemented with no or very little information on location-specific conditions (Ketsela 2009).

Introducing appropriate method for identifying suitable rwh areas can improve their performance and rate of adoption. Suitable site assessment in this case means assessing the extent to which an area is conducive for rainwater harvesting. In smaller areas, rainwater harvesting suitability assessment can be conducted by field survey. Larger areas, however, need extensive quantitative information and thus require the use of GIS (geographic information system) and remote sensing (RS) tools. Identifying optimal rwh areas depends on many factors including biophysical and socio-economic conditions. Tumbo et al. (2013) mentioned the most important parameters affecting suitable rwh

site selection as rainfall, soil texture and depth, topography, drainage conditions, and land use or vegetation cover (Ibrahim et al. 2019; Mwenge Kahinda et al. 2009; Oweis 1998). Most of the authors have focussed on biophysical and environmental factors (Ammar et al. 2016; Ibrahim et al. 2019; Mahmoud and Alazba 2015; Oweis 1998; Wu et al. 2018; Zheng et al. 2018; Ziadat et al. 2012). Socio-economic factors nevertheless have been given a very little attention (Chen 2015). Only few tried to include socio-economic factors such as distance to road, distance to settlement, distance to river. This indicates the socio-economic aspects have not been adequately covered in the past and thus require scientific attention. With this in mind, this research included climate, bio-physical and socio-economic factors as criteria for suitable rwh site selection. Rainfall, aspect, slope, soil texture, soil moisture, land cover (Lc), stream order (hydrology), distance to road and distance to rivers are selected criteria for this research.

The role GIS plays in determining rwh suitability analysis is quite significant. It is very helpful tool for collecting, storing and analysing of preferred datasets, especially in areas with limited information (Mahmoud and Alazba 2015; Mati and Bock 2006; Raj et al. 2017; de Winnaar et al. 2007). They are cost-effective and time-saving methods of rainwater harvesting site selection. Ammar et al. (2016) reviewed the different methods of choosing optimal rwh areas. These methods were grouped in to four. Geographic information system (GIS), GIS & remote sensing, hydrological modeling and remote sensing with multi-criterion analysis (MCA). After detailed evaluation of each method, combining GIS with MCA was regarded as the most convenient method of suitability selection. The pros of using this method is that it is flexible, effective; updating criteria is easy and can be applied in differently sized areas. (Ammar et al. 2016; Wu et al. 2018).

Using AhP (analytical hierarchy process) as multi-criterion decision-making approach has also a lot of merits such as simplicity, flexibility, and structuring complexity (Zahedi 2019). This research is therefore aimed at developing a methodology for rainwater harvesting site suitability assessment by combining GIS and multi-criterion analysis in northern Ethiopia at Kilte Awlaleo district.

## Study area description

The study area (Fig. 1) is called kilte awlaleo situated in eastern zone -Tigray region, northern Ethiopia. There are cool humid to sub-humid agro climatic zones with altitude between 1500 and 2500 masl. Annual rainfall lies from 500 to 1200 mm. The weather is characterized by a short summer and long winter receiving very intense but short rainfall during summer leaving the rest of the months dry. The average temperature is 25 °C. It contains a total of 18 tibias

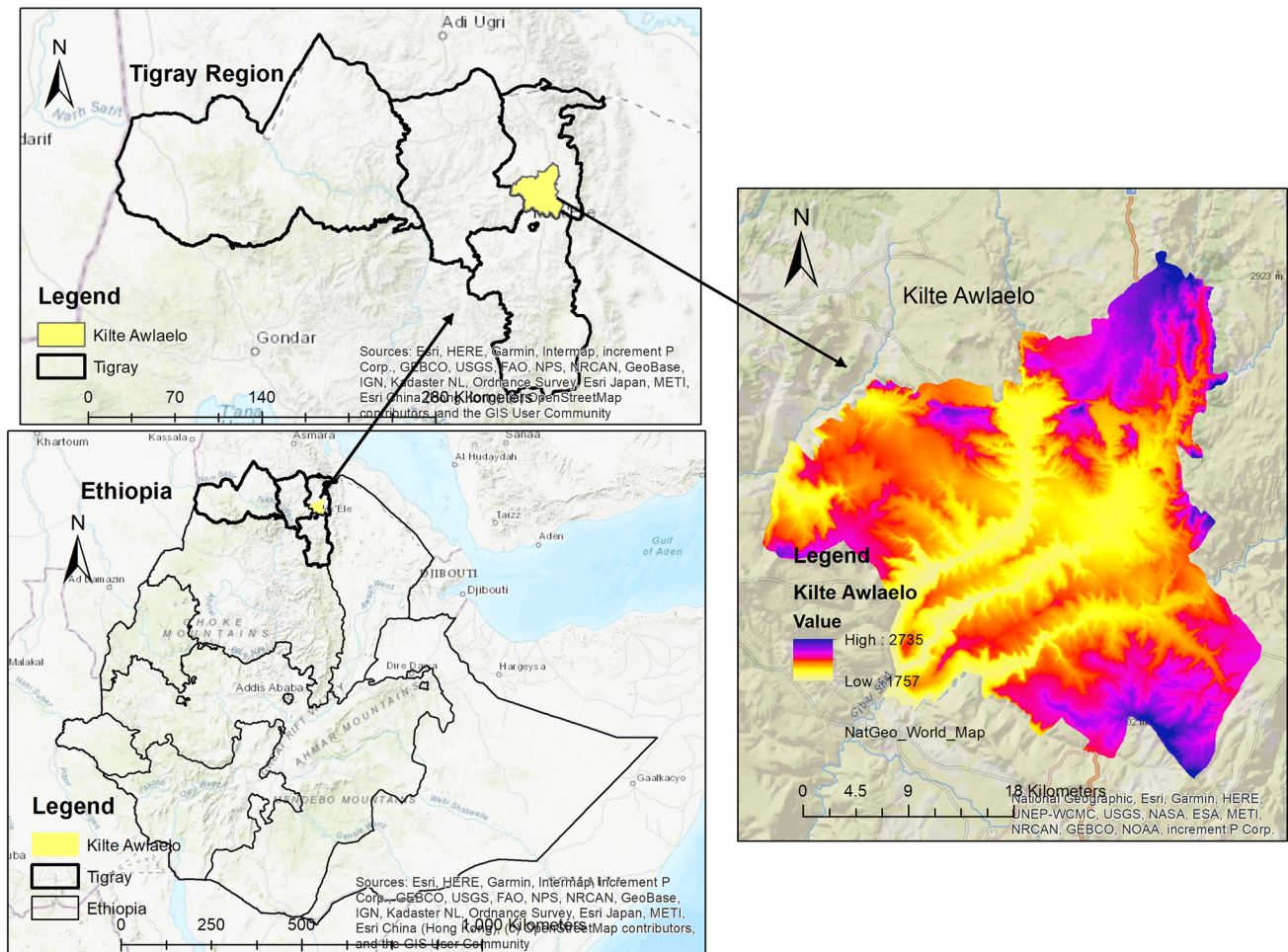


Fig. 1 Study area map

(the smallest administration unit) of which Abraha Atsbeha is one of these Tabias. Area of the study site is 1001 km<sup>2</sup> and a total population of 114,001 with 51% female and 49% male. Agriculture and livestock are the main stay economy (Temesgen 2011; Woldu 2019; Zerssa et al. 2021). The area is covered by magmatic rocks followed by Mesozoic sedimentary rocks. It is bounded by heterogeneous meta-volcanic hills on the northwest and complex rugged hills on north east (Rabia et al. 2013). Soil types such as clay, clay loam, and sandy loam are typical in the area.

## Material and methods

In this research, a combination of Gis and multi-criterion analysis was applied to develop suitability model for optimum rainwater harvesting areas using a set of criteria selected depending on their relevance to rwh site selection. It uses various remotely sensed data as criteria and AhP as a multi-criterion analysis in order to calculate their

respective relative weights. The AhP works in such a way that the objective is specified first which is identifying optimum rwh areas. Then, relative weights for each criterion were calculated through pairwise comparison (Saaty et al. 1980). Both primary and secondary data were used in this method. The methodology (Fig. 2) consisted of a multi-step process that includes spatial data collection, data processing, criteria selection, suitability analysis, analytical hierarchy process, sensitivity analysis, suitability analysis and model validation.

## Data collection

Data used for developing a methodology for suitable rwh site identification were mainly spatial datasets. Primary data such as Landsat 8 images and digital elevation model for 2020 were acquired from United States geological survey (<https://earthexplorer.usgs.gov>) from which slope map, aspect map, Lulc map soil moisture map and stream order map were derived. Administrative maps, road and river

networks were extracted from diva gis (<https://www.diva-gis.org/>). Digital soil dataset was derived from global food and agriculture organization (FAO) soil data base (<https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/>) from which soil texture map for the area of interest was derived. Rainfall data for a period of 10 years (2011–2020) were extracted from climate research unit (<https://crudata.uea.ac.uk/cru/data/hrg/>).

### Criteria selection

All criteria were selected after intensive literature review and based on FAO (food and agriculture organization) guidelines and expert judgments. Both biophysical and socio-economic aspects were considered during criteria selection. Various criteria including climate, soil, hydrology, socioeconomic,

topography and agronomy have been reported by FAO guideline for optimum rwh areas (Kahinda et al. 2008; Wu et al. 2018). Wu et al (2018) selected slope, soil texture, distance from road, distance from farmland, and land cover for their research on rwh site suitability. According to Adham et al. (2016), mostly used bio-physical factors in the literature were slope, land use/cover, precipitation, and soil type. Same authors reported socio-economic factors as distance from road, distance from settlement, distance from river and cost in their review. Some of the bio-physical and socio-economic criteria frequently used in the literature are presented in Table 1. For the present study, precipitation, slope, aspect, land use/land cover, soil texture, soil moisture, stream order were selected as bio-physical factors, whereas distance to road and distance to river were selected as socio-economic factors. Higher number of criteria was used in this research

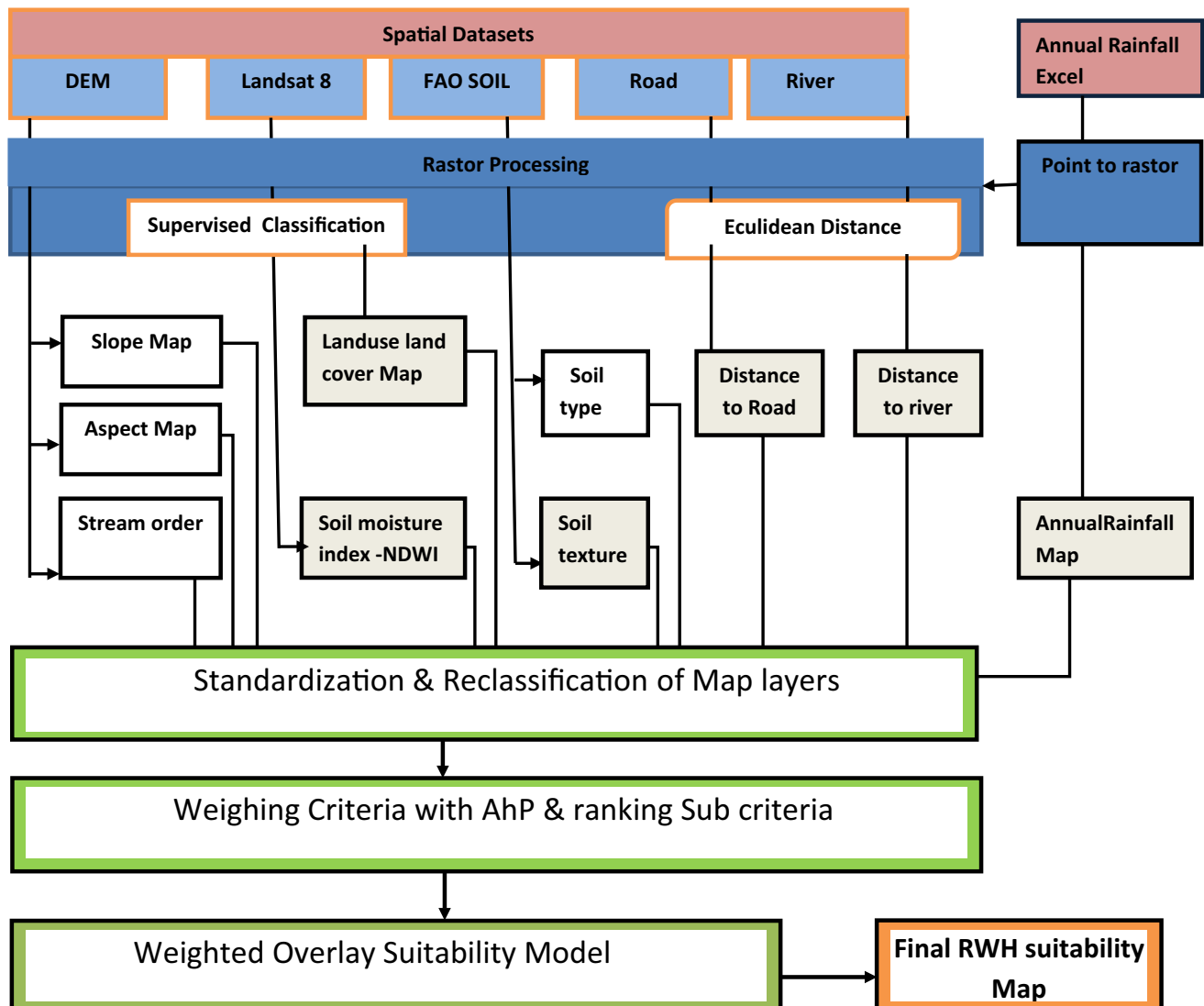
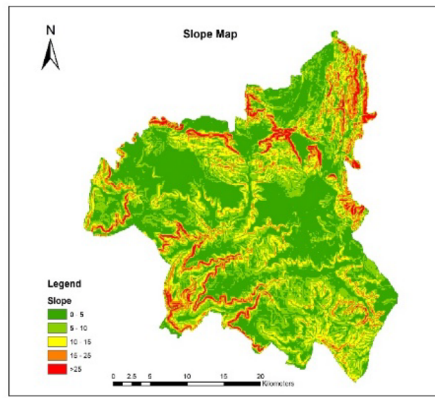
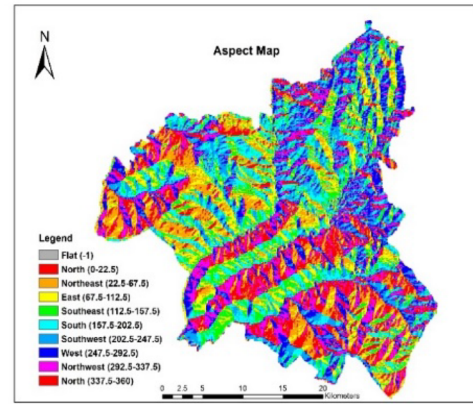


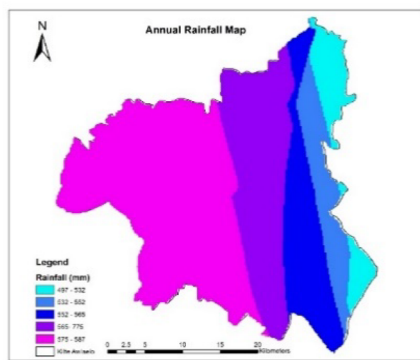
Fig. 2 Methodology for suitable rwh site identification using weighted overlay and analytical hierarchy process



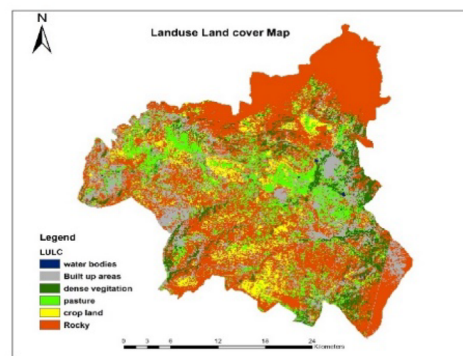
(a) Slope map



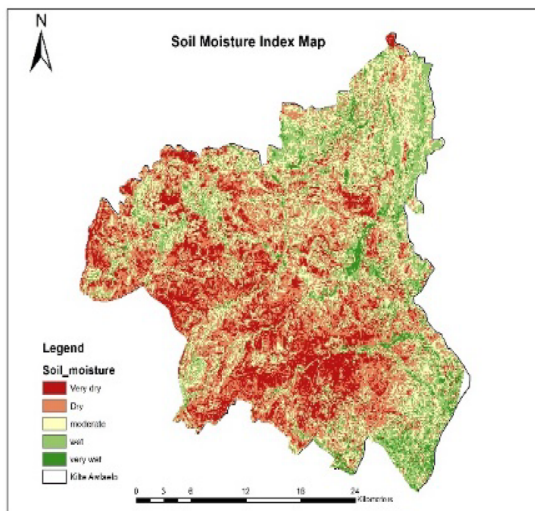
(b) Aspect map



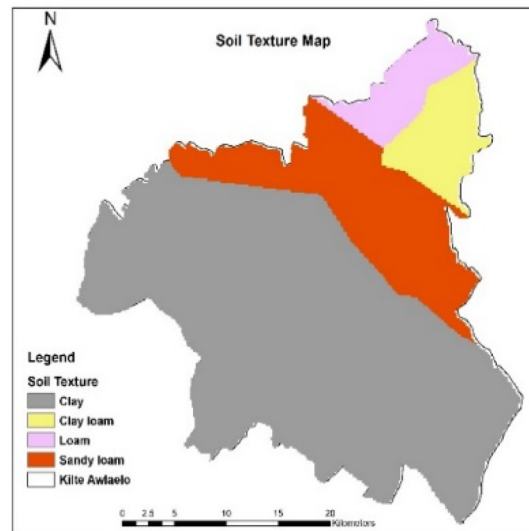
(c) Annual rainfall map



(d) Landuse/land cover map



(e) Soil moisture map



(f) Soil texture map

Fig. 2 (continued)

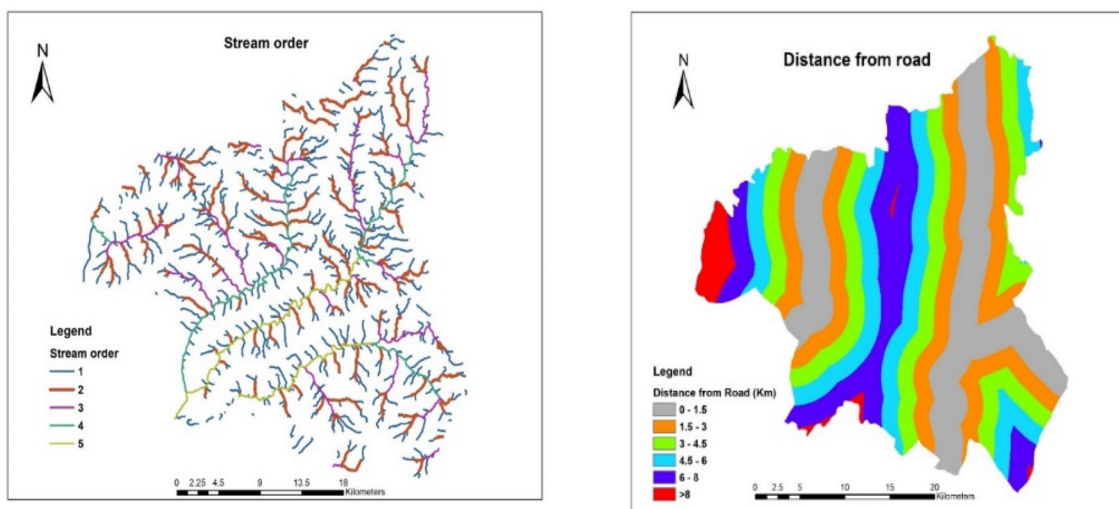
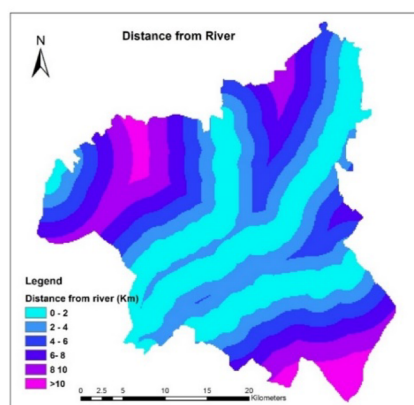
(g) *Stream order map*(h) *Distance from road map*(i) *Distance from river map*

Fig. 2 (continued)

relatively to other studies in the literature (Table 1) in order to assist accuracy of the model. The above-mentioned bio-physical factors directly influence the amount of harvested rainwater. Runoff, a portion of rainfall to be harvested, is primarily affected by the amount, extent and intensity of precipitation (Buda et al. 2009). Land cover of the area mainly vegetation cover reduces runoff by intercepting the precipitation thus allowing sufficient time for infiltration (Zhan and Huang 2004). Soil texture and soil moisture are also key parameters which determine the amount of water stored on the soil profile (Ziadat et al. 2012). Course-textured soils favour infiltration, while fine-textured soils favour runoff (Usda 1986; Woyessa and Bennie 2004). Similarly, the moisture status of the soil prior precipitation also impacts the rate of runoff. Dry soils infiltrate more rainfall than wet soils until the soil pores reach a point of saturation (Woyessa

and Bennie 2004). Slope of a catchment is another important criteria contributing to more runoff volume. Steep slopes generate more runoff rates than gentle slopes (Adham et al. 2016; Prinz and A. Singh 2000a, b; Rana and Suryanarayana 2020). Aspect is a bio-physical factor showing the direction where a slope faces. It is linked with receiving solar radiation and soil moisture retention (Singh 2020). North-facing slopes receive less solar radiation enabling them to retain more moisture. Mountainous areas facing to the equator also receive high amount of solar radiation for a longer time span (Singh 2020). Stream order is a hydrological parameter which refers to the availability of river channels in an area. The higher the stream order, the more branched the river streams (Pradhan 2017). The order of streams is inter-connected with relative catchment dimensions, channel size and stream discharge (Strahler 1957). Socio-economic factors

**Table 1** Some bio-physical and socio-economic criteria's applied for determining optimal rwh areas

Name of authors	Selected criteria
(Mugo and Odera 2019)	Slope and drainage, LuLc, lineaments, soil texture
(Adham et al. 2018)	Runoff depth, slope, soil texture, LuLc, stream order
(Rana and Suryanarayana 2020)	Slope, LuLc, soil texture, curve number, stream order, drainage
(Ibrahim et al. 2019)	Slope map, stream order, LuLc, soil types,
(Suryabhagavan 2019)	Soil texture, LuLc, lineaments, elevation, slope, drainage density, geology, fault, distance to settlement, distance to road
(Alwan et al. 2020)	Stream order, slope, rainfall, evaporation, land cover, soil type, dist. to road
(Saha et al. 2018)	Rainfall, soil type, LuLc, slope, runoff potential, drainage density, lithology and design peak discharge
(Mahmood et al. 2020)	Soil group, rainfall, slope, drainage density, land cover
(Mugo and Odera 2019)	Texture, runoff depth, drainage density, LuLc, lineament density
(Wu et al. 2018)	Soil texture, land cover, slope, distance from agricultural land, distance from road, runoff
(Rajasekhar et al. 2020)	Slope, contour, LuLc, soil type, geology, drainage density
(Mahmoud and Alazba 2015)	Soil texture, rainfall surplus, slope, runoff coefficient, vegetation cover
(Tumbo et al. 2013)	Soil texture/depth, topography, rivers, rainfall, LuLc
(Tiwari et al. 2018)	Drainage network, depth of depression, soil map, rainfall, runoff
(Adham et al. 2016)	Rainfall, drainage length, storage capacity, storage dimensions, soil texture/depth, slope, distance to settlements
(Aghaloo and Chiu 2020)	Slope, rainfall, soil texture, drainage network, river, constraints (road and railway)

affect rwh indirectly. As most rwh structures are installed on rural areas where farmers have very limited income and lack of access to road and alternative water resource, both road proximity and river proximity become more crucial factors for the success of installed rwh structures (Prinz and A. K. Singh 2000a, b; Rockström and Falkenmark 2015). Other similar researches also indicated distance to road and distance to river as the main socio-economic criteria during suitable rwh site selection (Abeyou 2013; Aghaloo and Chiu 2020; Suryabhagavan 2019).

### Generating criteria maps

Collected spatial datasets were processed in Arc Map 10.4.1 using geospatial techniques in order to generate thematic map layers. Slope and aspect maps were derived from a DEM with 90 m spatial resolution using spatial analyst tool in Arc GIS tool box (de Winnaar et al. 2007). Landsat 8 satellite imagery was used for land use/cover map and soil moisture index (Pramanik 2016). A supervised classification based on maximum likelihood classification was applied to prepare land use/cover map (Fig. 2d) by preparing training sample (Thakkar et al. 2015). Accuracy assessment of the produced supervised classification was made to check the accuracy based on the method in Rwanga and Ndambuki (2017). Soil moisture index map (Fig. 2e) was computed as the normalized difference moisture index by dividing the summation of land sat 8 bands (Eq. 1) which represent refracted radiations between the near-infrared (band 5) and short wave infrared bands (band 6) to their difference as in Thakkar et al (2015). Knowledge of soil moisture

helps us understand variations of surface temperature, drought and flood (Robock et al. 1994) by regulating the eco hydrological process of storm events (Western et al. 2006) thus useful especially for the case of in situ rainwater harvesting. Stream order map (Fig. 2g) that shows the availability of more branched river streams according to the order of tributaries (Pradhan 2017; Strahler 1957) was derived from DEM using the hydrology tool in Arc Map (Rana and Suryanarayana 2020). Lower stream order is meant the catchment has more infiltration rate, whereas higher stream order indicates more runoff thus is essential criteria for rwh (Adham et al. 2018). Soil texture map (Fig. 2f) for the catchment was extracted from FAO digital soil dataset using extraction by mask in Arc Map (Suryabhagavan 2019). Average annual rainfall map (Fig. 2c) for ten years (2010–2020) was produced by converting point data (vector dataset) in to raster data in Arc GIS environment. Inverse distance weighted- IDW was used for spatial interpolation of rainfall map (Zahedi 2019). Both distance to river (Fig. 2h) and distance to road maps (Fig. 2i) were computed by using the Euclidean distance function in the spatial analyst tool of Arc Map as described by (Zahedi 2019). All the generated criteria were classified into sub-criteria using the guideline for agricultural rwh in arid/semi-arid areas (Oweis et al. 2012). Table 5 shows all classified criteria and sub-criteria along with their areal percentile.

$$\text{NDMI} = \frac{\text{Band5} - \text{Band6}}{\text{Band5} + \text{Band6}} \quad (1)$$

## Standardization of criteria maps

All produced thematic map layers were converted into raster format, same cell size and same coordinate system (UTM Anadian 37 N) in Arc GIS 10.4.1 before imported to weighted overlay model. Besides, all attribute classes/sub-criteria for each criterion map (table) were reclassified with an integer 1–9 using the reclassify tool in the spatial analyst tool box in order to have uniform measurement units (Effat and Hassan 2013).

## Calculating relative weights using AhP

The analytical hierarchy process (AhP) was carried out in order to determine weight (% influence) of the parameters involved in the weighted overlay (WOA) suitability model by using expert judgements from various fields of geology, water resource engineering, agriculture, environmental engineering and geography. AhP, a commonly applied multi-criterion decision-making technique, is used in order to hierarchically rank a group of elements based on their significance and priority with respect to a stated objective. AhP makes it easier for quantifying comparisons made among criteria's through a pairwise technique (Table 2) that minimizes the complex nature of decision-making (Saaty et al. 1980). It determines the weight of importance based

on pair-wise comparisons of various parameters according to their relative significance (Miller et al. 1998). Three steps were involved for determining weight of the selected criteria. First, pairwise comparison was made among all the criteria by assigning a continuous scale value of 1 to 9 using (Table 3). Secondly, a  $9 \times 9$  normalized matrix was constructed (Table 4) and  $\lambda$ , a maximum eigen vector were calculated by Saaty et al. (1980). The final step was calculating the consistency ratio  $CR$ , using (Eqs. 2 and 3) where  $CI$  indicates consistency index,  $RI$  stands for random index, and  $n$  is number of criteria. The consistency judgement is acceptable for  $CR < 0.1$  indicating factors are evaluated with no bias (Feizizadeh and Blaschke 2013) (Table 4).

$$CI = \frac{\lambda - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

## Site suitability analysis

The suitability analysis was conducted in Arc GIS 10.4.1 with weighted overlay analysis model (WOA) method (Fig. 3). WOA is a common technique of site suitability modelling applied in various fields and works as a

**Table 2** AhP relative importance ranking scale and their meaning (Saaty et al. 1980)

Imp. rank	Definition	Explanation
1	Equal importance	Two criteria enhance similarly the stated goal
3	Slightly significance	Judgements slightly favour one criteria over another
5	Strong or essential importance	Judgements highly affect one against the other
7	Established importance	A criteria established a dominance
9	Absolute or high importance	The evidence favouring one criteria is very likely
2,4,6,8	Intermediate values	
Reciprocals	If criteria i are assigned a number relative to j, criteria j will then be assigned the reciprocal	

**Table 3** Pair-wise comparison matrix

Criteria	Rainfall	Soil texture	Soil moisture	Slope	Aspect	Stream order	LULC	Dis_road	Dis_river
Rainfall	1	3	3	5	4	5	5	7	7
Soil texture	1/3	1	3	3	4	7	3	3	3
Moisture	1/3	1/3	1	2	3	5	3	3	5
Slope	1/5	1/3	1/2	1	2	2	2	3	3
Aspect	1/4	1/4	1/3	1/2	1	3	2	3	3
Stre.ordr	1/5	1/7	1/3	1/2	1/3	1	1	3	1
LULC	1/5	1/3	1/3	1/2	1/3	1	1	5	5
Dist. road	1/7	1/3	1/3	1/2	1/3	1/5	1/5	1	1
Dist. river	1/7	1/3	1/3	1/3	1/3	1/5	1/5	1	1

**Table 4** Normalized matrix for weighing criteria

Criteria	Rainfall	Texture	Moisture	Slope	Aspect	St.order	LULC	Dis_road	Dis_river	Weight (%)
Rainfall	0.357	0.496	0.334	0.379	0.261	0.204	0.287	0.241	0.241	31
Soil texture	0.118	0.165	0.334	0.227	0.261	0.286	0.172	0.103	0.103	20
moisture	0.118	0.054	0.1115	0.151	0.195	0.204	0.172	0.103	0.172	14
Slope	0.071	0.054	0.057	0.075	0.130	0.081	0.114	0.103	0.103	9
Aspect	0.089	0.041	0.036	0.037	0.065	0.122	0.114	0.103	0.103	8
Str. order	0.071	0.023	0.036	0.037	0.021	0.041	0.057	0.103	0.034	5
LULC	0.071	0.054	0.036	0.037	0.021	0.041	0.057	0.172	0.172	7
Dist. road	0.051	0.054	0.036	0.025	0.021	0.008	0.011	0.034	0.034	3
Dist. river	0.051	0.054	0.015	0.025	0.021	0.008	0.011	0.034	0.034	3

$$\lambda = 9.87, CI = 0.108, RI = 1.45, CR = 0.074$$

linear combination of all the cell value of criteria and its sub-criteria- as in Eq. 4 (Ibrahim et al. 2019; Mahmoud and Alazba 2015). All the standardized criteria maps were imported in to WOA along with their relative weights obtained from AhP. In addition to the weights from AhP, the sub-criteria or the attribute classes in each criterion map were given a score value ranging from (1 to 9) depending on their importance for rwh (Table 5). Three types of rwh were considered for our case. First emphasis was given to micro-catchment (in situ) rwh followed by macro-catchment rwh and large-scale rwh. Ranking of all the sub-criteria was conducted using a guideline for agricultural water harvesting by Oweis et al (2012) and after in-depth literature review. For instance, slope map was classified in to five classes (0–5, 5–10, 10–15, 15–25, > 25)°. High suitability rank was given to gentle slope (0–5)° because in situ rwh is easily installed on flat areas than on steep slopes. After ranking all the sub-criteria accordingly (Table 5), the model was run and a single rwh suitability map was generated.

$$S = \sum_i^n W_i X_i, \quad (4)$$

where  $S$  = suitability,  $W_i$  = weight of each criterion,  $X_i$  = weight of sub-criterion,  $n$  = number of criteria.

### Sensitivity analysis

Sensitivity analysis was conducted by the method described in Wu et al. (2018) in order to evaluate % influence for the weights of the criteria on the suitability analysis. This was done by varying the relative weights of the criteria. For our study, two cases were considered. In Case 1), relative weights calculated from expert judgement (Table 3) were used. Here, more weights were given to bio-physical criteria where as socio-economic factors were given 3%. In case 2) equal weights (11%) were

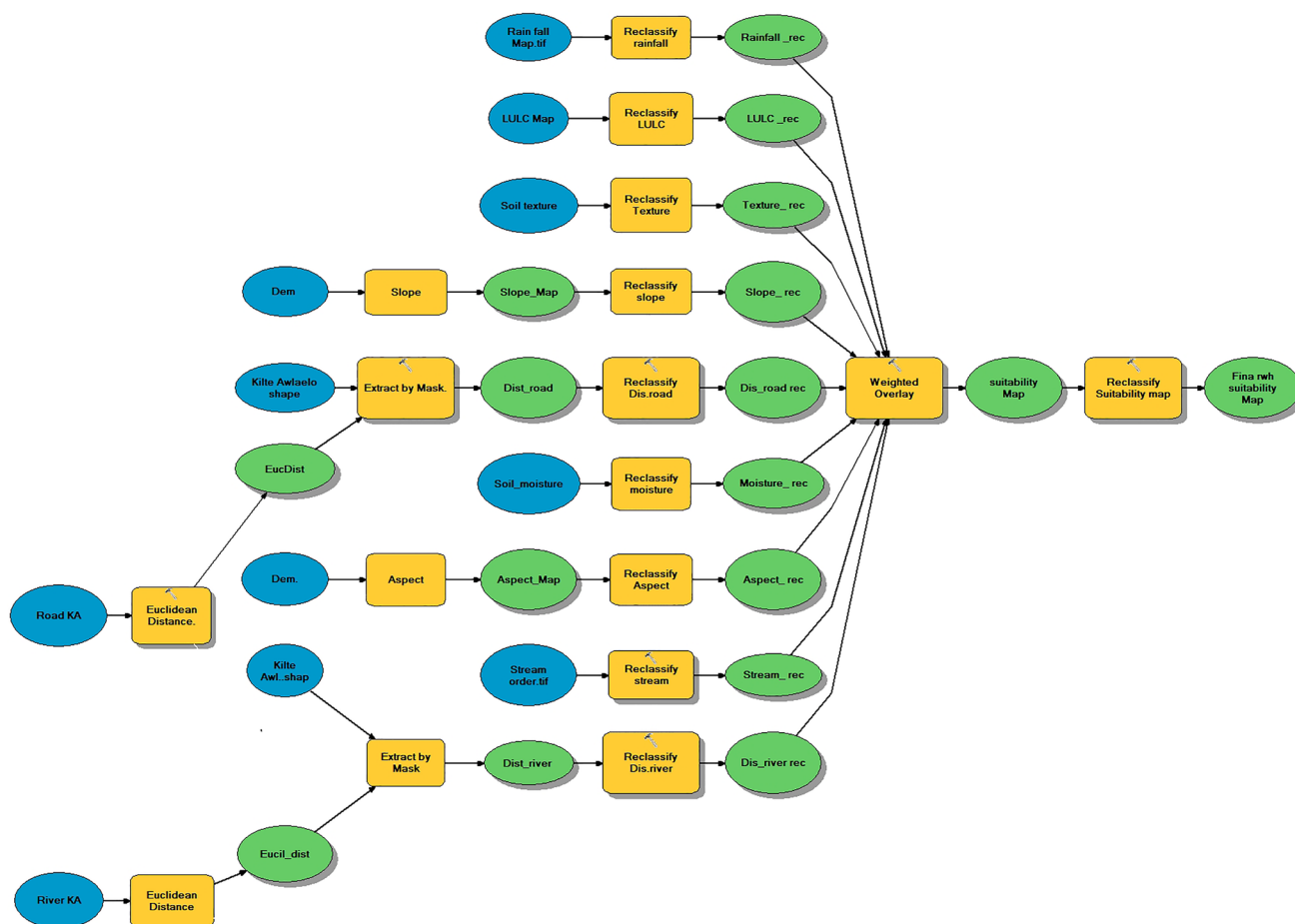
generated automatically for all the nine criteria in the weighted overlay model assuming all criteria have equal % influence. Produced suitability classes for the two cases were compared to evaluate effect of weight variation on rwh suitability analysis.

### Model validation

The developed rainwater harvesting suitability model was validated by field visit and ground truth with high-resolution imagery and topographic maps using google earth pro & Arc Map 10.4.1. A visual field trip was made to the study area on the year 2020 and 2021. A GPS was used to record the xy coordinates of identified rainwater harvesting techniques. Being the area is large (1000 km<sup>2</sup>), a sample village (Abraha Atsbeha) was selected for further verification of the suitability model. Abraha Atsbeha "tabia" (a lowest administration unit in villages) was selected because different reforestation, watershed management programmes and soil water conservation practices were undertaken on the area (Alemu and Kidane 2014; Balehegn et al. 2019).

### Result

In this research, various bio-physical and socio-economic criteria were applied for determining suitable rwh sites. Based on weights from AhP, precipitation was given the highest weight (31%) followed by soil texture (20%) soil moisture (14%), slope (9%), aspect (8%), stream order (5%), lulc (7%). Distance to road and distance to river were assigned lowest weight (3%). Calculated consistency ratio, (CR), was 0.074 (< 0.1) showing the weights assigned to all criteria are made with no bias (Saaty et al. 1980). Six land cover types were identified in kilte awlaelo via supervised classification, namely Dense vegetation (7.8%), Pasture (14.7%), crop land (7.4%), mountainous area (52.2%) and water body (1.6%). Similar results were reported on a study



**Fig. 3** Developed weighted overlay model for identifying optimal rwh areas

by (Tadesse et al. 2017). Accuracy assessment conducted by using Kappa coefficient method as in Thakkar et al. (2015) yielded 72% of accuracy.

Dominant soil texture was a clay soil (68%) followed by sandy loam (19%), clay loam (7%) and loam (6%). Majority of the area is rocky and rugged topography with 3.23% flat to gentle slopes (0–5)° whereas 43.23% (431.23 km<sup>2</sup>) steep slopes > 28°. The steepness of the area is also reported by Tadesse et al (2016). The aspect map showed that most of the gentle slopes were directed south to south west direction. The slopes get steeper towards northeast to East direction. The stream order map showed decrement as we go down from first order covering the highest area (55%) to fifth order stream (5%) indicating the area has less branched streams. Annual rainfall ranged from 581 mm (46%) maximum to 497 mm (7%). The moisture index map showed 50% of overall area dry, 27% moderate and 23% wet. Distance from road map indicated 35% of the district can be accessible to road with 0–2 km, 29% (2–4) km, 23% (4–6) km, whereas 12.6% is accessible with more than 6 km making it less suitable for rwh. Most rivers in the district are within range of [0–4.5]

km, while 20% of rivers are accessible at more than 4.5 km (Table 6).

The WOA suitability model (Table 7) yielded four suitability classes: highly suitable, suitable, moderately suitable, and less suitable sites for the two cases. In case I, the weight (%) influence for the selected criteria was calculated from AhP with the help of expert judgement where bio-physical factors were assigned much more weight than socio-economic factors assigned only 3%. Final suitability maps for case I & case II are shown in Figs. 4 and 5. For case I, the suitability class showed 56% (550.75 km<sup>2</sup>) suitable area, 8.6% (85.27 km<sup>2</sup>) highly suitable areas and 303.23 km<sup>2</sup> (30.8%) moderately suitable area for implementing rwh, whereas only 4.46% of the area was classified as less suitable/poorly suitable area. Those areas include rocky surface and some built up areas. For case II, the weight (%) influence was assigned equal value to all the criteria (11%) by setting the equal % influence in the WOA model. Suitability class for case 2 indicated 22.42 km<sup>2</sup> (2.2%) highly suitable area, 372.5 km<sup>2</sup> (37.6%) suitable area, 504.7 km<sup>2</sup> (50.5%) moderately suitable, and 85.95 km<sup>2</sup> (8.6%) less suitable areas.

**Table 5** weighted overlay method

Criteria	Weight (% influence)	Sub-criteria	Score [1–10]
Slope-0°	9	0–5	9
		5–10	8
		10–15	7
		15–25	6
		> 25	5
Aspect- 0°	8	Flat, North	9
		East	8
		SE,SW	6
		West	5
		N.West	5
Annual rainfall(mm)	31	497–532	7
		532–552	7
		552–565	8
		565–775	9
		575–587	9
LULC	7	built-up area	1
		Dense Vegetation	2
		Pasture	7
		Crop land	8
		Mountainous	6
		Water bodies	9
Soil texture	20	Loam	7
		Sandy loam	6
		Clay loam	8
		Clay	9
		Very dry	3
Moisture index	14	Dry	4
		Moderate	5
		Wet	7
		Very wet	7
		1st	3
Stream order	5	2nd	3
		3rd	5
		4th	6
		5th	7
		0–2	9
Dist to road (Km)	3	2–4	8
		4–6	6
		6–8	3
		> 8	2
		0–1.5	7
Dist to river (Km)	3	1.5–3	5
		3–4.5	5
		4.5–6	3
		> 6	3

Result from sensitivity analysis for the two cases indicated that the weights assigned to the criteria brought about significant changes to the suitability classes. Conducted suitability analysis for case I, where weights were assigned through AhP increased highly suitable areas by 73.7% and suitable areas by 32.4%. In contrary, less suitable areas and moderately suitable areas increased by 48.9% and 39.9%, respectively.

The model validation was conducted at Abraha Atsbeha village (Fig. 6) in a sample study site. Results from model validation identified seventeen bench terraces, six shallow and hand-dug wells and three enclosure areas (areas protected from grazing and used as biological soil and water conservation measure). Their geographical locations were cross-checked with the suitability map to determine which suitability classes they belong to. Eight of the bench terraces were observed on moderate areas, six on suitable areas where as the rest three were observed on less suitable areas. Two shallow wells were identified on moderate areas, while the other four were observed on suitable areas. All enclosure areas were identified under suitable class. These were installed mainly by community-based water harvesting and through watershed management programmes conducted in various forms (Tadesse et al. 2016). Validated rwh suitability map is shown in Fig. 7.

## Discussion

By looking at the attribute classes of each criteria maps or the sub-criteria, the area can be classified as typical semi-arid climate, mountainous region with scarce arable land and limited water resource. These characteristics are similar to a research by (Haile and Merga 2002; Rabia 2012; Segers et al. 2008). Majority of the soil texture being clay soil also supports in situ rwh (water stored on soil profile). Similar soil texture results were reported by (Ahmed Harb Rabia 2012). Both bio-physical and socio-economic factors played important role during conducting rwh suitability analysis for kilte Awlaelo wereda. Assigned weights from AhP (expert judgements) in decreasing order were precipitation, soil texture, soil moisture, slope, aspect, LuLc, stream order, distance to road and distance river. Consistency ratio indicated the weights assigned by expert judgements (Ahp) were consistent. The weights are an indication that all the selected criteria had different levels of significance. It can be seen, however, that selected bio-physical factors were more significant than socio-economic factors. This is obvious since bio-physical factors have direct influence on rwh suitability. Similar cases were observed on study by (Pramanik 2016; Wu et al. 2018). Besides to weighing the criteria, giving score values to sub-criteria (attribute classes) was equally important for the suitability analysis. Score values were

**Table 6** Areal coverage of criteria and sub-criteria for input to weighted overlay suitability model

Criteria	Sub-criteria	Area _km <sup>2</sup>	Area (%)
Slope-0°	0–5	432.1	43
	5–10	288.5	29
	10–15	163.68	16
	15–25	81.92	8
	>25	3.21	3
Aspect-0°	Flat, North	206	21
	East	194	19
	SE,SW	204	20
	West	187	18
	N.West	210	21
Annual rainfall(mm)	497–532	460.2	46
	532–552	233.9	23
	552–565	147.9	15
	565–775	89	9
	575–587	70.15	7
LULC	built-up area	178	18
	Dense vegetation	78.16	8
	Pasture	146.95	15
	Crop land	74.23	7
	Mountainous	521.7	52
Soil texture	Loam	55.6	5.5
	Sandy loam	189.51	19
	Clay loam	66.4	6.6
	Clay	690	69
Moisture index	Very dry	193.66	19
	Dry	317.84	32
	Moderate	267.93	27
	Wet	174.36	17
Stream order	Very wet	45.59	6
	1 <sup>st</sup>	338	33
	2 <sup>nd</sup>	142	14
	3 <sup>rd</sup>	63.5	6.3
	4 <sup>th</sup>	439	43.3
Dist to road (km)	5 <sup>th</sup>	30.5	5
	0–2	354.2	35
	2–4	291.3	29
	4–6	228.2	23
	6–8	110.9	11
Dist to river (km)	>8	16.16	1.6
	0–1.5	331	33
	1.5–3	265	27
	3–4.5	196	19
	4.5–6	147	15
>6	61	6	

**Table 7** Identified suitable rwh sites for case I and case II with their area coverage

RWH site suitability	Area (km <sup>2</sup> ) case (I)	% Case (I)	Area (km <sup>2</sup> ) Case (II)	% Case (II)
Highly suitable	85.27	8.6	22.4	2.27
Suitable	550.75	56	372.5	37.6
Moderately suitable	303.23	30.8	504.7	50.5
Less suitable	43.87	4.46	85.9	8.6

assigned for sub-criteria in the WOA model (Table 5) where each of the values in the attribute classes was ranked for their suitability for in situ rwh, ex situ rwh and large-scale rwh, respectively. The following factors: runoff volume, catchment area, labour and cost of rwh were considered during suitability ranking for sub-criteria (Ziadat et al. 2012).

According to sensitivity analysis, Case I- rwh suitability combined with AhP showed significant changes on the suitability classes than case II- rwh suitability without AhP. This is in fact expected because Case II considers equal weights to all criteria regardless of their level of importance, while weights for case I were assigned with the help of expert judgement and detailed review. Other similar studies also reported more effect of bio-physical features compared with socio-economic factors (Wu et al. 2018).

Final suitability maps for the two cases (Figs. 4 and 5) showed highly suitable and suitable areas for case I were located on the downstream, while most of the moderate to less suitable areas were located on the upstream. This is in agreement with a similar study on rwh suitability by Adham et al. (2018) where suitable areas were located downstream areas of the watershed.

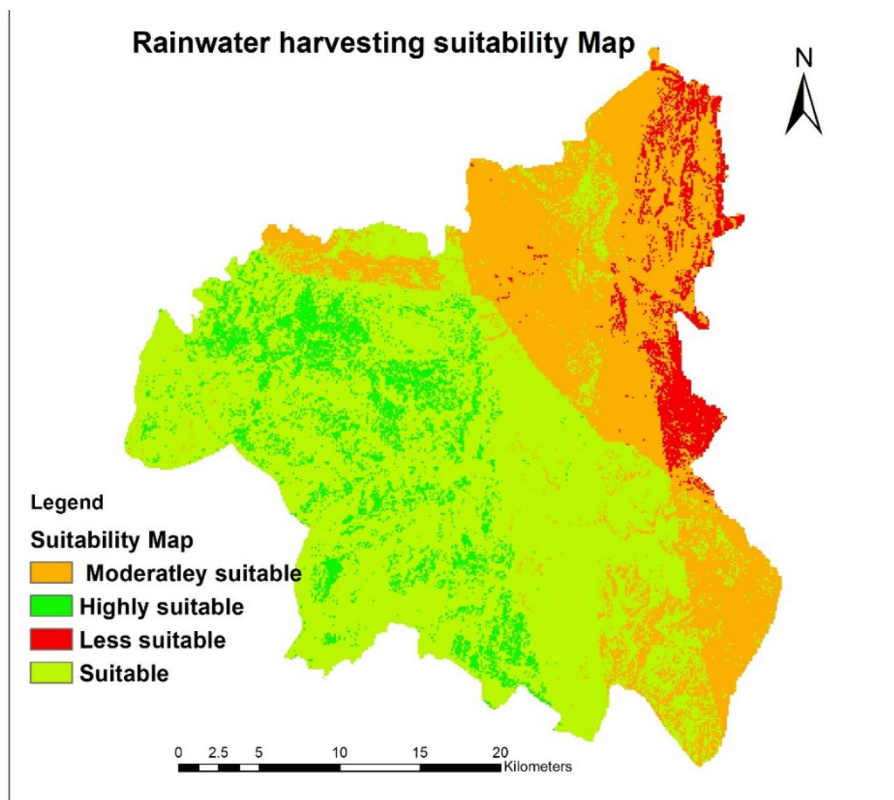
Depending on the runoff source, water storage mechanism, end use requirements, catchment size and type of rwh structure, different rwh types that could match to the suitability classes have been discussed. Rwh pond and shallow wells are ideal rwh types for highly suitable areas because those areas are situated at the downstream concentrating adequate water amount during the short rainy seasons of the year. It is evident that pond construction in those areas would be beneficiary to both domestic use and farming. It helps bridge the dry spells which are serious problems on the semiarid regions. The presence of flat to gentle slopes in such areas makes it preferable for in situ rwh (Oweis et al. 2012). Wet moisture condition in those areas might be associated with adequate water amount at the sub-surface which favours the construction of shallow wells (Grum et al. 2017). This reduces time, resources and avoids unaffordable costs for boreholes or deep percolation. Other rwh ideal for highly suitable areas is rwh pond. Ponds are dug-out enlargements of natural depressions in order to store runoff water from hillslope, grasslands, and natural water courses

in areas where no alternative water source exists. They are applied mostly by individual households in villages at a storage capacity from 200 to 500 m<sup>3</sup> (Mati 2020). Ponds are also used to irrigate fields, livestock and for domestic uses. The runoff flow from the catchment to the storage takes place by gravitational force and hence does not need a conveyance system (Mati 2020). Ponds are, however, not without limitation. Being an open system, ponds may be subjected to losses into subsurface soil due to seepage and evaporation. Seepage losses in rwh ponds can be prevented by lining the bottom surface with either plastic sheets or concrete; similarly covering rwh ponds (especially for the case of small scale rwh pond) can prevent water losses up to 50% (Forward 2020). They can be constructed on areas with catchment size up to 200 ha and predominant turbulent type of flow. The catchment to cropping area ratio lies between 10:1 and 100:1 (Oweis et al. 2012). The runoff area or the catchment can be treated with various materials such as concrete, plastic sheeting, and metal foils for more runoff harvest (Mati 2020). Other rwh structures including small-scale subsurface dams, check dams, underground storage can be installed depending the available farm size of the individual households.

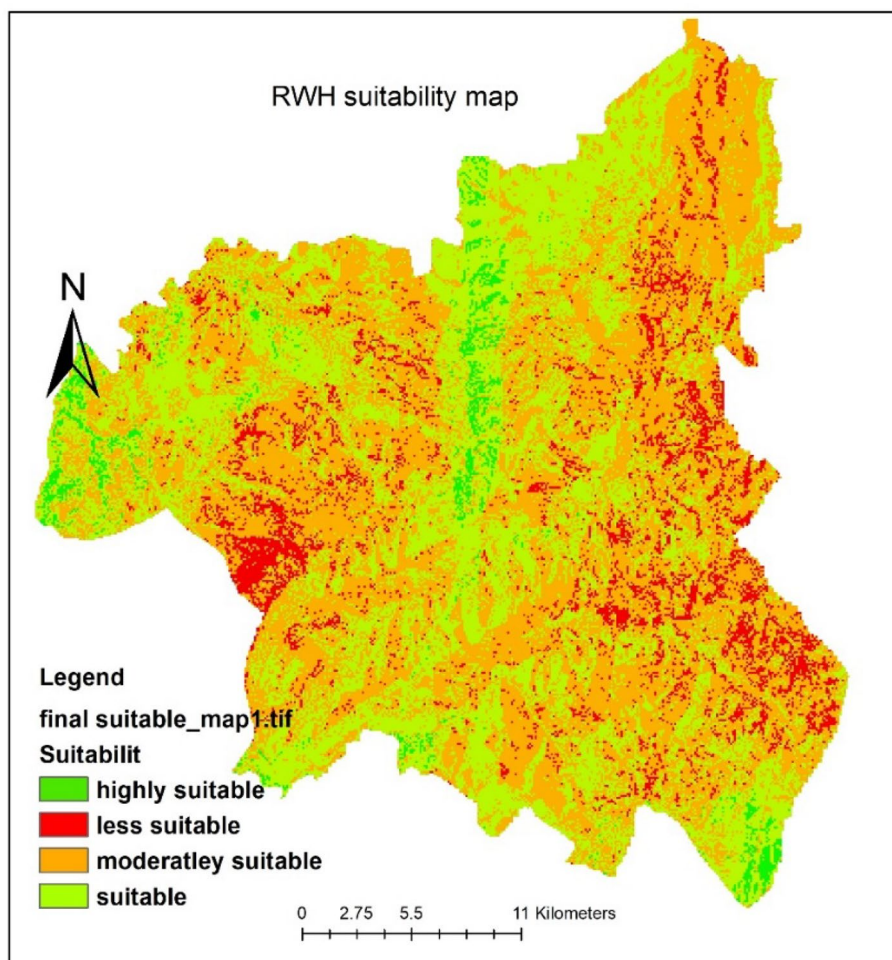
Suitable areas covered more than half of the study area and are characterized by lower elevation and high stream order. Majority of the land use types here were crop lands, pastures and hilly mountainous. Because of steepness of

the area, installing rwh pond or well might not be viable option in such a case, in situ rain water harvesting could be installed easily with less cost (Prinz 1996; Prinz and A. K. Singh 2000a; b). In such micro-catchment rwh (MiRWH) techniques, it is the soil profile that serves as the storage and run off is stored in the root zone to be utilized directly by plants. The catchment area that produces runoff under MiRWH can be either natural surface, treated surfaces, compacted or covered with plastics to induce more runoff (Oweis et al. 2012). Examples are rwh pits, circular/semi-circular bunds, and soil/stone bunds, terracing, deep trenches, etc. (Tadesse et al. 2017, 2016; Vohland and Barry 2009). MiRWH has a lot of merits as they are simple to use, require less cost, can be replicated easily. Since MiRWH is installed with in farm fields, farmers have full control of installed systems and this helps to properly monitor and maintain installed structures. Due to the availability of resources such as stones, the construction and expansion of stone bunding among others bring a meaningful change in landscape restoration by preventing both runoff erosion. Terracing is also another in situ rainwater harvesting practised in semi-arid lands. Terraced fields prevent runoff and slowly infiltrate runoff water coming down the hillslopes. Each terraced wall retains certain amount of water that raises the volume of capillary water ready for crop growth by eventually infiltrating in to the soils (Article 2014). Conventional rwh techniques such as terracing are showing a

**Fig. 4** Final rainwater harvesting suitability map for case I



**Fig. 5** Final rainwater harvesting suitability map for Case II



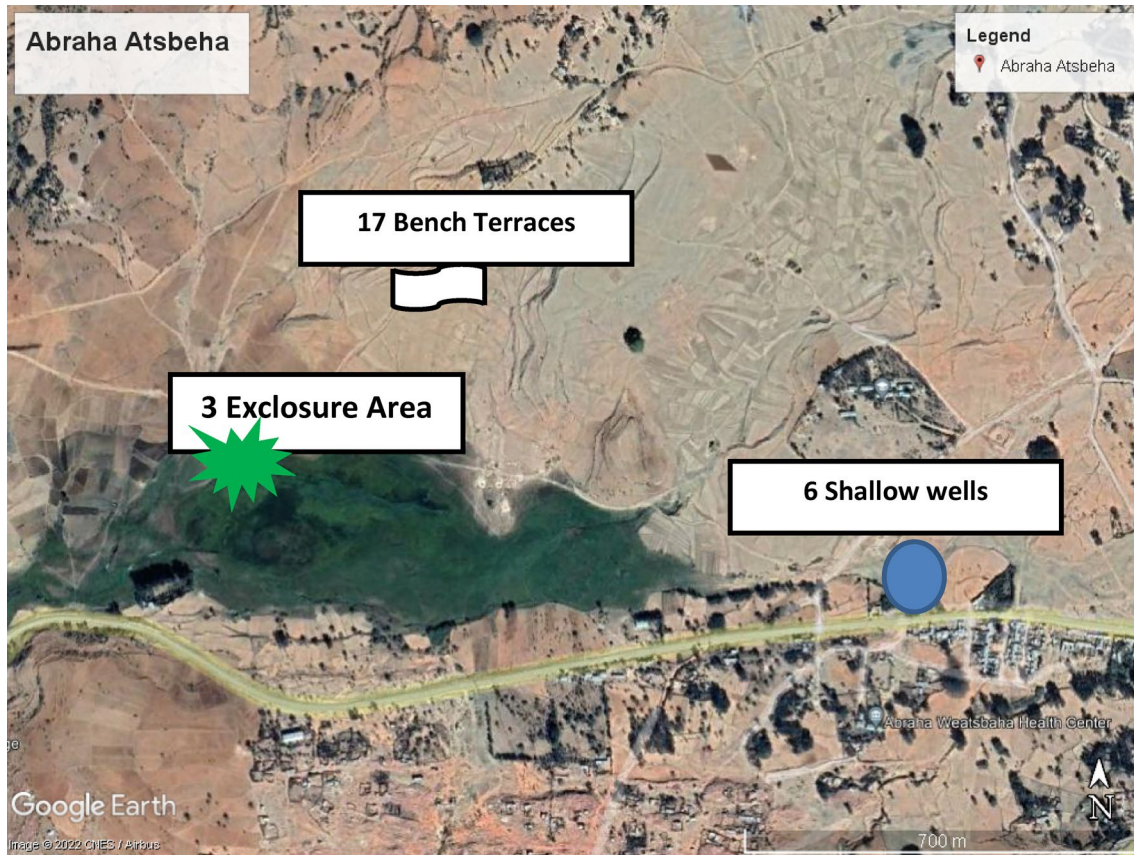
revival especially in areas where irrigation is not possible (Rockström and Falkenmark 2015).

Moderate rwh suitability contained major densely vegetated areas (shrubs) and slightly contained build-up areas. All soil textural classes were present among which sandy loam was dominant soil type. This might be attributed to the weathering of parent material rocks. Such soils favour infiltration rate due to their high permeability. Similar soil types were found by Haregeweyn et al. (2012). Those areas were located from undulating to rolling slope upstream and Siluh River downstream (Tadesse et al. 2017). Excess runoff produced from the steep slopes flow down to flat areas. Macro-catchment rwh like above-ground storage (Check dams), underground storage, subsurface dams, and sand dams not only alleviate problems of water scarcity but also prevent soil erosion (Mati and Bock 2006). However, building such structures is both labour and resource intensive which might limit construction at household level (Prinz 1996). Initiating community-based rwh could bring farmers of the area together and eventually get benefited from the communal works. Check dam is building of walls made

of concrete and stones across streams and shallow rivers and serves as a barrier (Djuma et al. 2017). This barrier decreases the water flow thereby enhancing groundwater recharge, stores water behind the dam and prevents further soil erosion. Check dams are designed with spillway that enable them controlled release of excess water ones the reservoir gets full (Djuma et al. 2017). Sand dams are also another alternative for underground water storage. These are reinforced concrete walls built across a sand river bed with aim to infiltrate and store water underground during a seasonal flow of water. The stored water is then abstracted by construction of shallow wells, boreholes or a collector drain along the dam (Mati 2020).

## Conclusion

Water scarcity in arid/semi-arid climate is nowadays affecting people's day to day life, especially on poor rural areas, where farming is completely rainfed. Employing rwh



**Fig. 6** Visualization of the suitability model using high-resolution Google Earth images at Abraha Atsbeha sample site

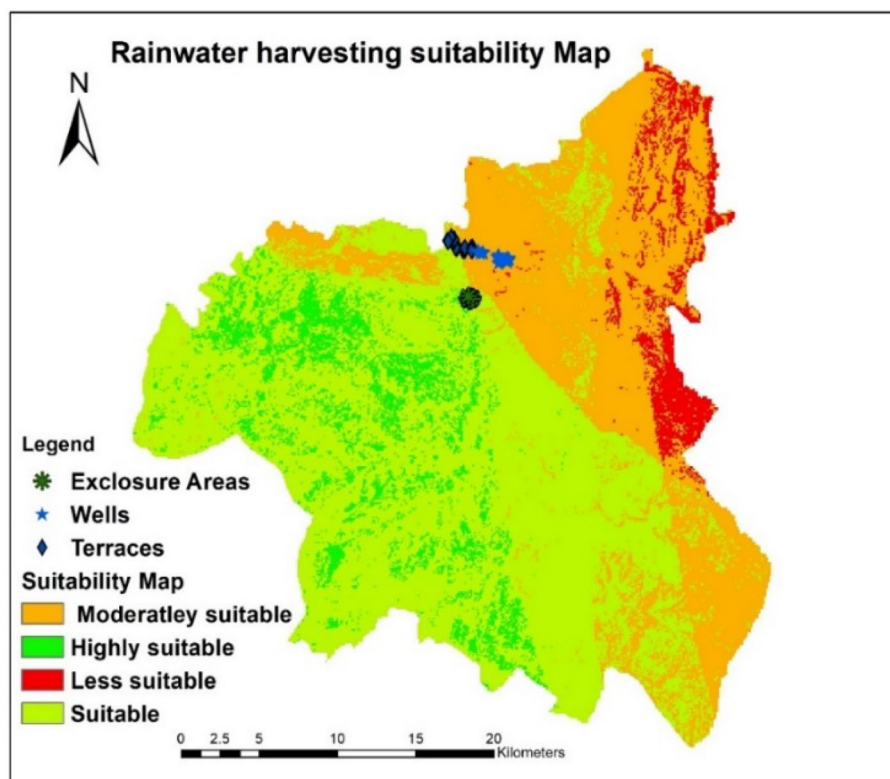
techniques can either partially or fully alleviate water scarcity in those areas. Thus, the main purpose of this study was to develop a methodology for identifying suitable rwh sites by integrating GIS/RS data and multi-criterion analysis. The method used various bio-physical and socio-economic parameters as criteria, each processed in the Arc GIS environment, classified in to sub-criteria and used a WOA (weighted overlay analysis) model & Ahp for conducting the suitability analysis.

The final suitability map produced four suitability classes, namely highly suitable, suitable, moderately suitable and less /poorly suitable classes. 56% suitable area, 8.6% highly suitable areas and 30.8% moderately suitable area were obtained for implementing rwh, whereas only 4.46% of the area was less suitable /poorly suitable area of the total area, respectively. The conducted sensitivity analysis proved incorporating Ahp during rwh suitability analysis brought about significant changes. Results were validated with the help of field surveys and ground truth using Google Earth imagery and topographic maps in Arc GIS where rwh

structures such as bench terraces, shallow wells and exclosure areas were located on the suitable areas.

The contribution made in this study is that it tried to cover as many bio-physical and socio-economic criteria as possible when compared with the literature. It also utilized Ahp (analytical hierarchy process) from expert judgement to weigh the criteria which is missing in almost all the literature review we covered in this study. The limitation of the paper was that it used only one sample village for model validation due to security issue. The research showed the importance of geographic information system and remote sensing data for suitability analysis. It can be used as alternative decision-making tool during rwh suitability analysis for large areas. This will enable to further expand existing/innovative rwh structure both inside and ex situ to other areas of the region. Future rwh works should focus to include more socio-economic factors and to compare different rwh suitability models in terms of cost, data availability and model accuracy.

Fig. 7 Validated suitability map



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## Declarations

**Conflict of interest** The authors declare no conflicts of interest.

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