




Article

Rainwater Harvesting Site Selection for Drought-Prone Areas in Somali and Borena Zones, Oromia Regional State, Ethiopia: A Geospatial and Multi-Criteria Decision Analysis

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Abstract: Rainwater collection systems play a crucial role in enhancing water availability in regions with low precipitation. This study focused on identifying potential rainwater harvesting (RWH) locations in drought-prone areas, specifically the Borena zone of Oromia and the regional states of Somali. This research leveraged geospatial techniques and a multi-criteria decision analysis (MCDA) to assess feasible RWH sites. The dataset comprises essential factors such as rainfall, drainage density, slope, soil texture type, and land use/land cover. These thematic layers serve as inputs for analysis, with each factor being weighted using the Analytical Hierarchy Process (AHP) method based on its significance. Reclassifying factors into subclasses facilitates suitability analysis. The weighted linear combination (WLC) technique is applied to identify and prioritize potential rainwater harvesting (PRWH) locations based on four suitability classes: highly suitable, moderately suitable, low suitability, and unsuitable. Our findings reveal that 1% of the study area, covering approximately 3288 km², is highly suitable for RWH. Areas with moderate suitability constitute approximately 12% (37,498 km²), while regions with low suitability, representing the majority, encompass about 75% (242,170 km²). Additionally, 13% (41,000 km²) of the study area is deemed unsuitable for RWH. The proposed technique for identifying suitable RWH sites is adaptable to other low-precipitation regions. However, before implementing RWH structures, further research is imperative. This study proposed the exploration of socioeconomic variables in future research and urged for an in-depth examination of various aspects of environmental sustainability. Our research paves the way for adapting rainwater harvesting systems to align with community needs and life cycles while also exploring the socio-economic and environmental dimensions of sustainability for future study. The insights offer promising solutions to address the urgent issues associated with water scarcity. This should include comprehensive site depictions, an exploration of social and economic activities, and the meticulous preparation of a cost-benefit analysis.



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Keywords: rainwater harvesting; site selection; multi-criteria decision making; weighted linear combination; Analytical Hierarchy Process; Borena zone and Somali region

1. Introduction

Rainwater harvesting involves collecting and maintaining rainwater before it is dispersed as surface runoff and is a key water intervention system. Effective water management, especially in arid and semi-arid regions, is a critical concern for human existence [1,2].

Addressing this global challenge requires the development of innovative solutions to ensure sustainable water management. Out of the total amount of water in the world, only 1% of freshwater is available for human consumption, and resources are also threatened by a multiplicity of problems, including climate change, overdevelopment, and water pollution, despite their significance to natural existence [3–5]. The challenge of water scarcity has been intensified by climate change, global warming, and population expansion, leading to critical shortages of water resources worldwide [6,7]. In response to this, rainwater harvesting (RWH), an age-old practice involving the collection, storage, and reuse of rainwater, has regained prominence as a viable solution for water supply in various regions across the globe [8]. Water is the most significant component of all food availability and nutrition determinants, such as agricultural production, energy, poverty reduction, economic growth, and survival [9,10]. Water resources and rainwater, in particular, are renewable sources and are some of the most important resources for the development and livelihood of societies with limited water capital in low precipitation areas. Rainwater also increases groundwater potential if properly harvested [11,12].

Ethiopia has a variety of topographies, with climatic differences between regions, unequal temperatures, and precipitation. High rainfall and humidity are prevalent in the south and southwest of the country, whereas the northeast, eastern, and southern lowlands are characterized by arid and semi-arid climates with very little rainfall. The Bale Mountain in the south of the country is characterized by Afro-alpine vegetation. The central and northern highlands of the country experience cooler climates [13]. Despite there being several major perennial rivers and lakes in Ethiopia, uneven distribution and inconsistencies in rainfall have affected the country on several occasions, particularly in areas below 1500 m [14]. There is substantial interannual variability in rainfall across the country [15,16]. Low precipitation has affected rural communities in Ethiopia's lower land area for a decade. Despite persistent low precipitation, water remains vital for communities in this region, which depend heavily on livestock for their livelihoods. These communities not only depend on cattle and other farm animals for income through sales, but also for essential resources such as milk and meat for their dietary needs.

From 1980 to the present, rainfall data for southeast Ethiopia show an overall decline in rainfall between March and September. Across the country, this decrease has led to intense and frequent droughts [17]. In the study region, recurrent drought events, both historical and recent, have inflicted considerable damage, leading to livestock fatalities and crop losses. As a result, drought-prone areas of eastern Somali and the Borena zone of the Oromia region have been severely affected by droughts since 2020, and a low rainfall record for the third consecutive year has resulted in a high number of livestock depletions and food insecurity, particularly in the Somali and Borena zones. Droughts have serious implications for the lives and livelihoods of approximately 1.8 million people [18]. Areas with an average altitude of less than 1500 m have a warm, hot climate where rainfall is deficient (almost all of the Somali and Borena zones of the Oromia region). In these areas, situated on the peripheries, most of the land is arid and semi-arid, and most people living in the region are either pastoralists or semi-pastoralists. These areas constitute 10 and 12% of the country's population [19]. RWH techniques are increasingly being recognized as valuable strategies to mitigate water scarcity in drought-prone regions [20,21]. This is particularly relevant for arid and semi-arid areas like Ethiopia's Borena zone and Somali region, where rainfall variability and limited water resources pose significant challenges [22]. Insufficient rainfall during the growing season has resulted in crop failure across numerous agricultural lands. The scarcity of water has posed challenges for local villagers, particularly during the summer of 2022, when water shortages significantly affected animal husbandry.

RWH presents a compelling approach to managing agricultural water resources in regions prone to drought [23]. It enables farmers to capture and store rainwater during periods of high precipitation, making it available during critical dry spells [24,25]. Dams can hold water for later use, and their auxiliary reservoirs can protect against extreme weather events that may be detrimental to livestock, irrigation, fodder, or domestic

consumption [26]. The best solutions to ensure improved access to and availability of water from rainfall for communities' livelihoods and to improve the quality of life within regions are selecting rainwater harvesting sites and building structures [27]. RWH encompasses all techniques for collecting rainwater from rooftops or ground surfaces. This collected water can then be used for various purposes, including agriculture, domestic needs, or even drinking. However, identifying suitable locations for RWH structures presents a complex challenge [28]. The selection of suitable sites for rainwater collection necessitates the consideration of specific criteria that account for the geoenvironmental characteristics of the area [29]. The integrated RWH technique and storage facilities within landscapes in a planned and systematic manner are crucial. Therefore, suitable areas should be established for harvesting water and constructing structures to reduce vulnerability to droughts and seasonal fluctuations in rainfall [30]. Rainwater harvesting is crucial for reducing runoff, protecting soil erosion, and increasing groundwater resources through infiltration into the ground, ensuring a continuous supply throughout the year [31].

Rainwater harvesting holds immense significance, particularly in drought-prone areas of Ethiopia, where water scarcity poses substantial challenges. The implementation of rainwater harvesting techniques serves as a sustainable solution to augmenting water resources, addressing the pressing issue of water availability during extended dry periods. In Ethiopia, characterized by erratic rainfall patterns and recurring droughts, rainwater harvesting emerges as a critical strategy to enhance water resilience and alleviate the impacts of water scarcity on agriculture, livelihoods, and ecosystems. Studies, such as those conducted in [32], emphasize the positive impact of rainwater harvesting on water security, crop production, and community well-being in drought-prone regions of Ethiopia. The adoption of these techniques not only contributes to local water self-sufficiency but also aligns with broader water management strategies, fostering sustainable development in the face of climatic uncertainties [33].

There is a need to introduce an innovative and cost-efficient water-saving alternative to mitigate the problem of drought caused by low precipitation and the uneven distribution of rainfall. The assessment of RWH potential and the identification of suitable sites is a demanding and time-consuming task for water resource managers and planners, especially when dealing with large-scale applications. The selection of a potential site for water harvesting structures requires a multi-factor disciplinary approach, in which the use of remote sensing data with geospatial technique applications has become common practice in recent times [34,35]. However, advancements in geographic information system (GIS) and remote sensing (RS) technologies have streamlined and expedited the site selection process for RWH structures. These technologies have not only reduced the number of recommended sites but have also facilitated the identification of the most optimal locations. Different methodologies have been developed to select appropriate RWH sites. Hydrological modeling techniques enable the assessment of water availability and flow patterns, while field surveys provide on-the-ground insights into local conditions and community needs [36]. Also, MCDA methods, such as the AHP or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), can be employed to prioritize potential rainwater harvesting sites based on multiple criteria, including water availability, land suitability, and socioeconomic factors [37]. Currently, remote sensing (RS) and geographic information systems (GISs) stand out as highly valuable tools for the management of ecosystems and natural resources [38]. Also, participatory approaches involving stakeholder engagement and community consultations contribute to the identification of culturally appropriate and socially acceptable RWH sites [39].

Furthermore, the application of MCDA plays a pivotal role in the determination of appropriate zones for RWH [40]. The fusion of MCDA with GIS involving the integration of spatial data layers has been extensively employed in the RWH process [41]. The preferred method for choosing suitable sites for RWH in small geographical areas is field surveys, while another method also plays a role in determining which locations are appropriate. Such a method may include the main elements that play essential roles in finding suitable

areas for RWH: rainfall, land use/land cover (LULC), a Digital Elevation Model (DEM), topography, soil texture, and environmental factors [42]. RWH projects can be significantly enhanced by employing a multi-criteria analysis (MCA) approach for site selection [43,44]. This technique involves systematically evaluating potential sites based on a defined set of criteria that influence the success and sustainability of the RWH system.

Below-average and uneven rainfall distributions have repeatedly affected the study area, resulting in drought and floods. However, the RWH site selection technique as a foundation for building structures must be considered by analyzing factors that have never been applied. This research aims to develop a robust methodology for creating a suitability zone map for rainwater harvesting (RWH) in drought-prone regions, specifically focusing on the Borena zone and Somali region. The proposed approach will be customized to align with the prevailing environmental, economic, and social conditions of the target region. Moreover, this study aims to identify optimal locations for installing various RWH systems. These systems encompass a variety of water management structures, such as waterholes, potential rainwater harvesting zones, and ponds designated for agricultural and livestock utilization. To achieve this, this study will leverage advanced technologies, including RS, GIS, and MCDA techniques. These tools will be employed to systematically identify potential RWH sites in the study area. Finally, this research aims to employ geospatial techniques and a multi-criteria decision analysis to discern viable water harvesting sites in drought-prone areas of the Borena zone in Oromia and Somali regional states.

2. Materials and Methods

2.1. Study Area

The Somali and Borena zones in the Oromia region are situated in the southern and southeastern parts of the country (Figure 1). They lie between latitude 3.40° to 9.11° N and longitude 36.64° to 47.94° E. The study area is approximately $323,955 \text{ km}^2$, accounting for nearly $1/3$ of the country's total area. Dry and partly arid climatic conditions dominate it; most of the population's livelihoods are nomadic and based on livestock production. The Somali regional state alone is the second-largest region, following the Oromia region of Ethiopia. The Wabe-Shebelle and Juba rivers are the only perennial rivers in the region. 90% of their flow originates within the study area and flows to Somalia in East Africa. The altitudes of the area extend from 163 to 2459 m above sea level, with the highest altitude being recorded in the northern parts of Somalia and the areas of Borena in the Oromia region. Most areas (approximately 77%) are below 1000 m in altitude.

According to [45], Ethiopia is mainly divided into five traditional agroecological zones, of which three are located in the area based on the altitude range: "Bereha" (hot-arid lowlands), which is situated at less than a 500 m altitude, characterized by very limited crop production or not at all; "Kolla" (hot lowlands), which is located between 500 and 1500 m in altitude and experiences crop production such as sorghum; And "Woina dega" (midlands), which is situated between 1500 and 2300 m in altitude above sea level. The altitude range is good for crop production, such as teff, wheat, and barley, but a very small proportion of the study area participates in growing such crops [46]. When looking into the soil textural properties of loam, loamy sand is the dominant coverage, followed by sandy loam and sand, and a small proportion of clay and clay loam exists.

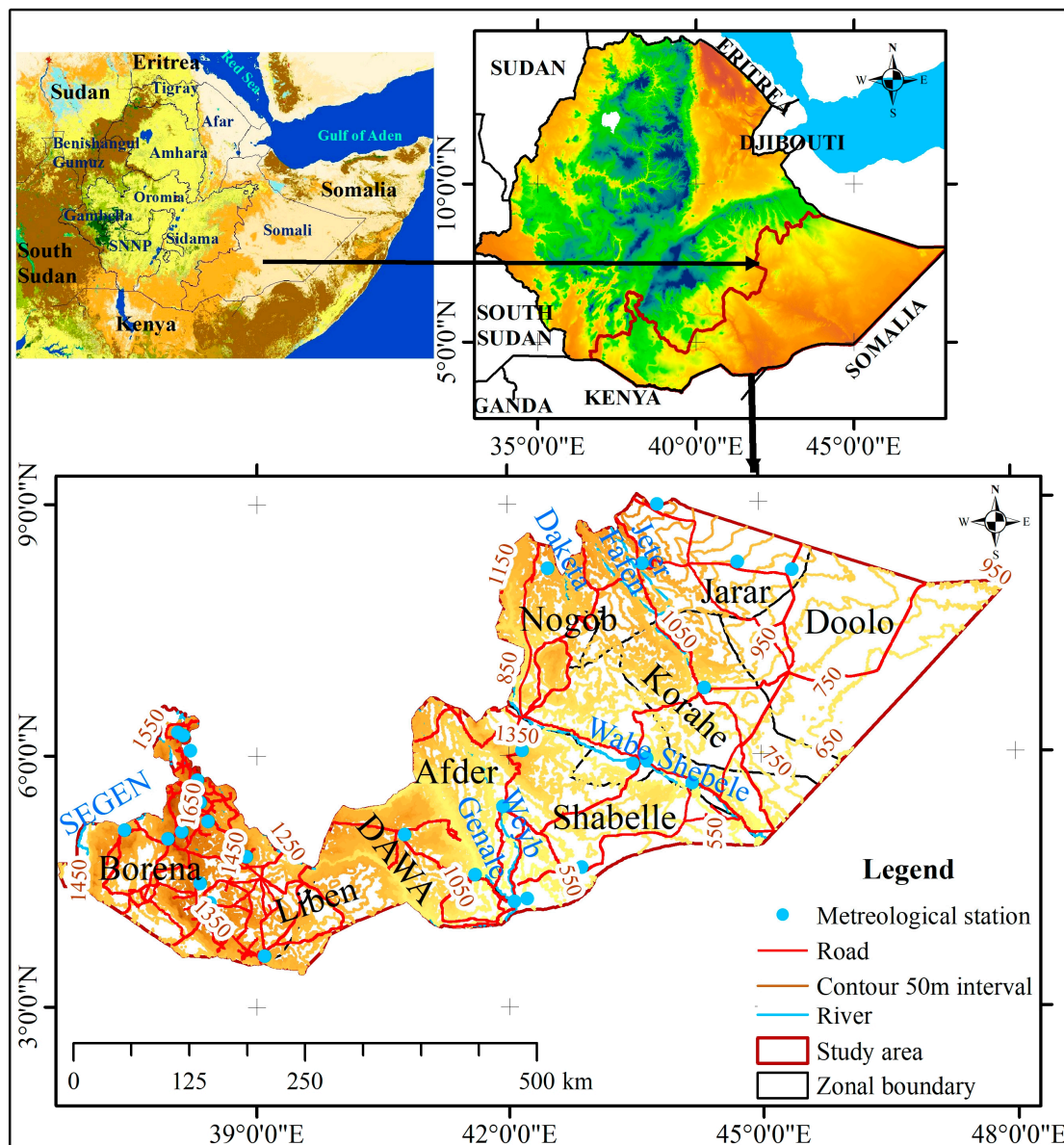


Figure 1. Location map of the study area.

2.2. Data Source

The central data sources for this study are satellite images, meteorological data, and soil characteristics. Satellite images were used to produce slope and drainage density data using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM and Shuttle Radar Topographic Mission (SRTM) [47,48] at a 30 m resolution. The data were downloaded from an open-source geo-database of the United States Geological Survey (www.usgs.gov). Rainfall records that were converted to an annual average precipitation of ten years from 2012 to 2021 were collected from the Ethiopian meteorological service based on 15 meteorological stations. LULC data were downloaded from the open-source dataset “Ethiopian Sentinel 2: LULC 2016” [49] and trimmed for the research area. Soil characteristic data for the study were adopted from [50,51].

2.3. Methodology

Identifying suitable areas for PRWH involves multiple criteria for a multi-factor problem. This study adopted a GIS-based MCDA model. Thematic input databases, such as rainfall, drainage density, slope, land use, cover, and soil texture, were prepared for

suitability analysis. The ArcGIS 10.8 platform is ideal for locating the appropriate areas and suitable levels for potential RWH site selection. This study employed a multi-step approach for RWH site suitability mapping in the study area. First, relevant factors influencing RWH site selection were identified. Suitability levels were then assigned to each factor based on established criteria. Then, thematic layers were generated using spatial data for these factors. Weights were assigned to each factor based on its relative importance for RWH, followed by a weighted overlay analysis. Finally, the integrated weighted thematic layers were synthesized to create an RWH suitability map, delineating the most favorable locations for implementing RWH systems (Figure 2).

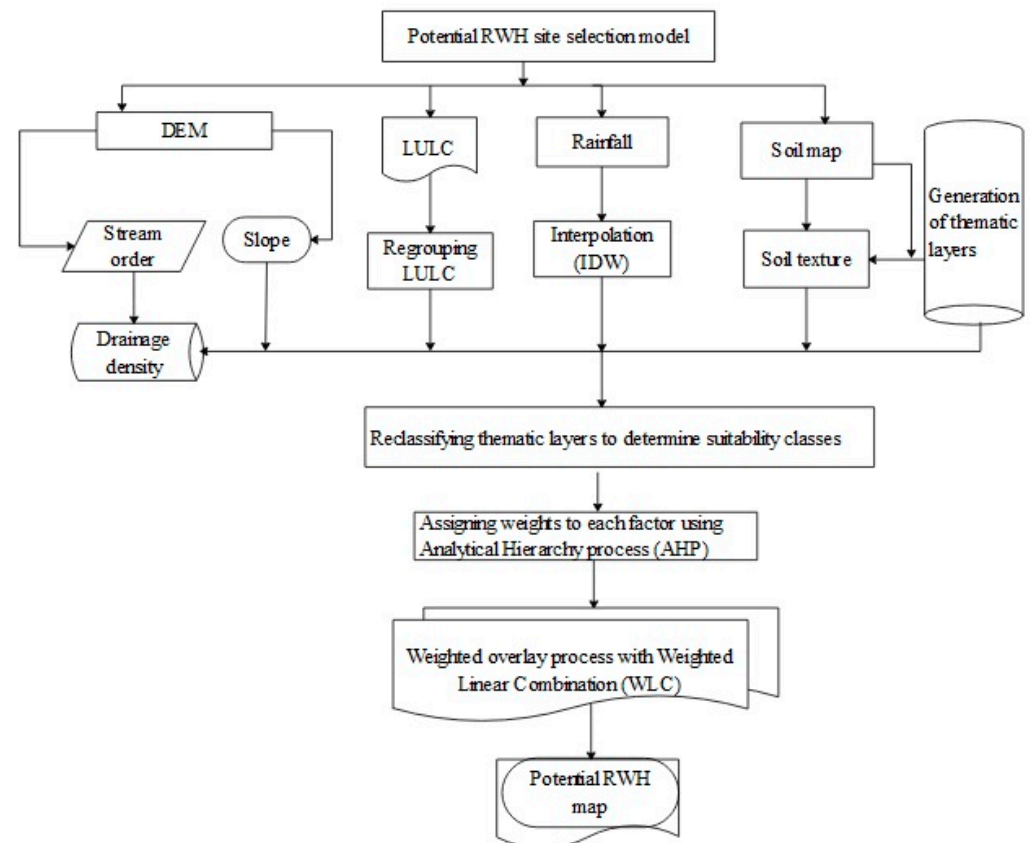


Figure 2. A conceptual model for the selection of potential rainwater harvesting (PRWH) sites.

Parameter Selection

The identification of thematic layers for RWH site selection is determined by several factors: a literature review of earlier studies on RWH, climatic conditions, physical characteristics, the socioeconomic state of the area, and the availability of data [52]. In previous related studies, a large percentage of the parameters were identified, and most of the studies focused on climate and topographic characteristics, such as rainfall, slope, soil type, and LULC [53,54]. Hameed [55] reviewed 48 studies; in most of them, the parameters indicated were the factors that are frequently utilized to identify probable RWH sites.

This study utilizes geospatial MCDA methods to select optimal RWH sites. Environmental criteria that are crucial to RWH suitability, such as rainfall patterns, soil texture, slope, LULC, and drainage density, are identified and assessed. Thematic layers depicting the spatial distribution of each criterion are developed using geospatial data and RS techniques. Additionally, weights are allocated to these criteria according to their significance in RWH site selection. Through a weighted overlay analysis, the thematic layers are integrated to produce a comprehensive RWH suitability map. This method identifies areas with the greatest potential for successful RWH implementation by collectively evaluating the influence of these environmental factors. This method facilitates the identification of

optimal locations for RWH implementation, promoting efficient water resource utilization and mitigating drought impacts.

2.4. Data Processing

2.4.1. Rainfall

Rainfall is the key parameter that affects RWH storage and receives the maximum weighting factor when deciding where to store it [56,57]. RWH site selection largely depends on rainfall variability and the volume of water collected in a suitable space. Annual rainfall data for ten years (2012–2021) were provided by Ethiopian Metrology Services for 14 meteorological stations inside and outside the study location. The average annual rainfall was again averaged based on the location of the meteorological stations, as shown in Figure 3, and latitude and longitude points were created using ArcGIS 10.8, ArcPro 2.9, and the QGIS 3.4 environment to assign the average rainfall data to a rainfall distribution map (Figure 3). This process aimed to assess and quantify the amount of rainfall in the study area, as this information constitutes a critical meteorological parameter. Annual rainfall data collected from the Ethiopian Meteorological Institute (EMI) were processed in Microsoft Excel for cleaning and analysis. Subsequently, the data were loaded into ArcMap 10.8 to generate a rainfall map, aiding in understanding spatial variability and informing RWH site selection with sufficient precipitation. The geostatistical method known as Inverse Distance Weighted (IDW), a widely accepted approach for interpolating rainfall variables, was employed to estimate the spatial distribution of rainfall across the region. This method relies on the geographical direction and distance of existing data points to approximate rainfall values for unobserved locations [58]. The careful utilization of these tools and methods enhances the accuracy and reliability of the rainfall data analysis, contributing valuable insights to the study's findings. Spatial variability in rainfall is a key factor in the selection of RWH sites. Conducting an analysis of meteorological station data allows us to visualize this variability through rainfall distribution maps. These maps are crucial for identifying areas with consistent precipitation, a prerequisite for successful RWH implementation (Figure 3).

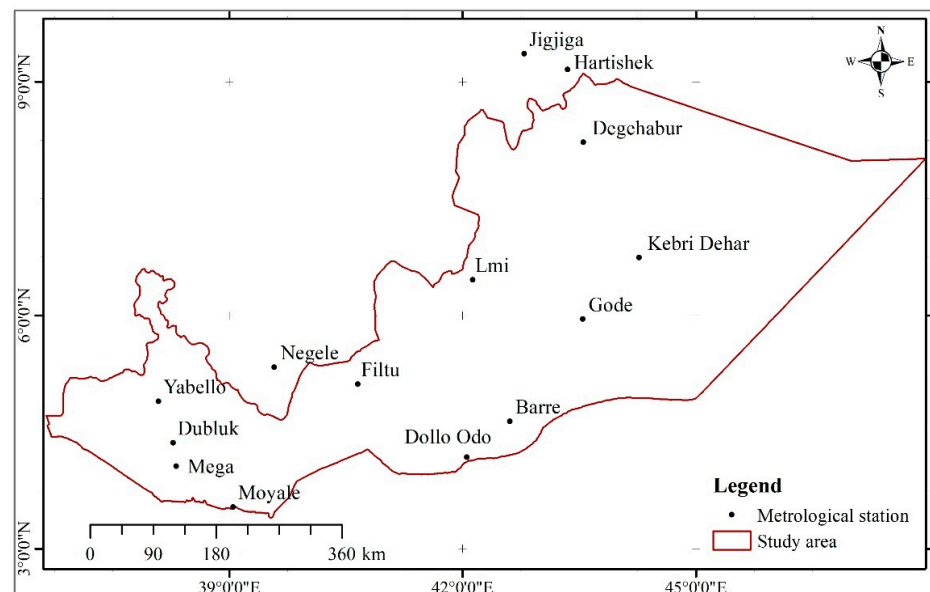


Figure 3. A map of meteorological stations in the study area.

2.4.2. Slope

The slope has an essential influence on runoff generation, water infiltration, the modulation of sedimentation, and the velocity of water flow. This is a valuable parameter for the selection of RWH sites. A slope greater than 8% may not be suitable for RWH,

whereas areas with low slopes are suitable for RWH site identification [59,60]. ArcGIS was used as a spatial tool for the processing of DEMs at a 30 m resolution. A DEM map of the study area is shown in Figure 4. The slope tool in ArcGIS 10.8 was used to create the slope map. To determine the suitability level for RWH site identification, the slopes derived in the study area were subdivided into percentage categories.

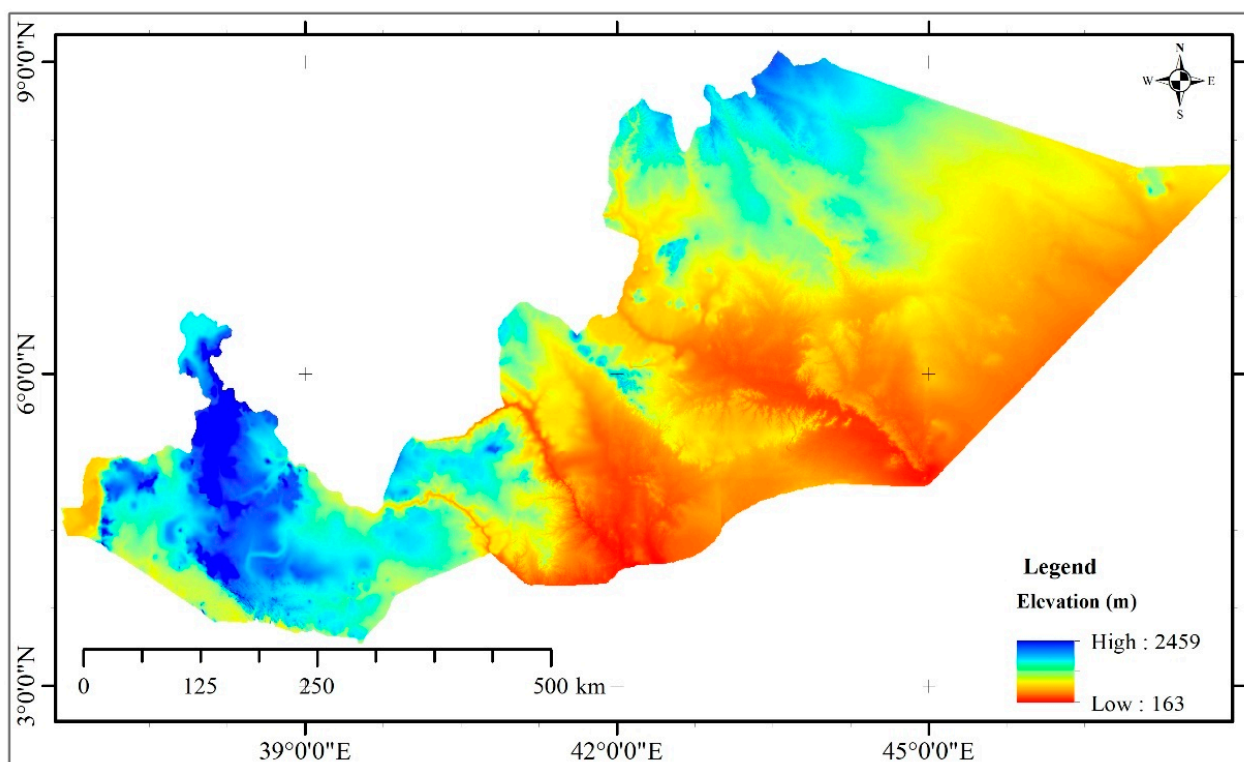


Figure 4. A DEM map of the study area.

2.4.3. Soil Texture

Soil texture plays a critical role in RWH site selection effectiveness due to its influence on the infiltration rate and water-holding capacity. This characteristic is determined by the relative proportions of mineral particles (sand, silt, and clay) within the soil. Finer-textured soils with higher clay content exhibit greater water-holding capacity, making them more suitable for RWH site selection [61,62]. Conversely, coarser-textured soils with higher sand content may allow for faster infiltration but have a lower capacity to retain water, potentially limiting their suitability for RWH applications. When the ratio of clays is increased, the pore space is reduced, and thus, there are also reductions in infiltration. This limits water movement through the soil, improves drainage, and is useful for RWH [63,64].

The soil map utilized in this study was sourced from the Food and Agriculture Organization (FAO), and the global soil gridded information is available at <https://www.isric.org/explore/soilgrids> accessed on 20 April 2024 [65]. The country-level soil texture map was georeferenced and converted to the GCS_WGS_1984 Coordinate Reference System (CRS), which was also clipped to the study area and digitized on-screen using the GIS platform for spatial analysis (Table 1). According to [66,67], the soil texture types were reclassified into four soil texture categories based on similar properties. This reclassification was also in line with the classification of the hydrologic soil category of soil conservation services [68]. The SCS was also separated into one of the four HSGs, as shown in Table 1. Soil groups can be used to estimate rain overflow precipitation generation and identify rainwater storage sites [69].

Table 1. Hydrologic soil group (HSG).

Soil Group	Description	Texture Class
A	Lowest overflow possibilities because of high penetration rate	Sand and loamy sand
B	Moderately low overflow possibilities and moderate penetration rate	Sandy loam and loam
C	Moderately high overflow possibilities due to slow infiltration rate	Silt loam, silt, and sandy clay loam
D	Highest overflow possibilities with very low infiltration rate	Clay loam, silt clay, sandy clay, and clay

2.4.4. LULC

Land use types and coverage influence the generation of overflow, volume, and velocity of water that streams to the lesser slope zones [70]. Areas with higher plant coverage tended to have a higher penetration rate owing to obstruction by dense vegetation coverage. However, areas with thin vegetation cover increased the overflow volume [71]. The Ethiopian Sentinel-2 LULC 2016 dataset initially consisted of six land use classes. These classes were then reclassified into four groups based on their suitability for rainwater harvesting RWH. The reclassified groups include shrubland, bare land, grassland, woodland, cropland, forest, and water bodies. The LULC analysis in the study area involved cross-referencing data through the use of Google Earth maps, randomly selected points, and on-site ground observations. This approach was employed to precisely define the different land use classes within the satellite imagery that had been classified. This reclassification was performed using spatial analysis tools, considering the suitability of land use/cover for RWH.

2.4.5. Drainage Density

Drainage density is defined as the total stream length per unit catchment [72]. Regions characterized by an elevated drainage density typically exhibit increased runoff suitable for harvesting [73]. Sites with high drainage density, characterized by lower-order streams, are particularly suitable due to their high infiltration and permeability rates [74]. This is because lower-order streams often have less channelization, allowing water to infiltrate the ground more effectively. Groundwater availability, the capacity of overflow loss due to penetration, and most hydrological processes are mainly influenced by drainage density; the lower the drainage density, the lesser the possibilities for RWH, while a higher drainage density has a higher probability of RWH [75,76]. RWH proves to be more effective in regions characterized by higher drainage densities, as it establishes a framework that facilitates the swift capture and retention of runoff [77]. The drainage density was derived from the DEM using ArcGIS 10.8 environment hydrological tools. Drainage density layers were generated through a series of steps involving DEM processing. These steps included filling depressions in the DEM, determining flow direction, delineating streams, and calculating line density.

2.5. AHP and Weight for Different Factors

AHP procedures were used to calculate the weight of each factor and identify an appropriate RWH location, followed by a GIS-based multi-criteria decision-making (MCDM) procedure. The primary objective of the AHP is to quantify the influence level of each criterion and show their relationship. An AHP analysis was conducted for each parameter and subsequent ranking, and the determined percentage of influence was then incorporated as input for the weighted overlay analysis within the ArcGIS software [78]. AHP prioritizes options based on biophysical (rainfall, topography, and soil), socio-economic (water needs and land ownership), and technical (technology type and storage capacity) factors. Pairwise comparisons conducted by experts help to determine criterion weights, ensuring that water

needs, infrastructure, and sustainability are considered for optimal RWH site selection. The AHP technique is a structured system for forming and examining multifaceted decision making to govern suitable areas [79]. Thomas L. Saaty developed this technique from 1971 to 1975 [80,81]. For the location of proper RWH site selection, this method was employed to determine the significance of each factor in percentages. The AHP procedure was used to compare the factors identified using inverse matrices. Gradings from 1 to 9 were assigned to the criteria based on their importance for rainwater harvesting suitability. Pairwise comparisons ascertain the comparative significance of two factors and aid in assessing their appropriateness for a specific purpose. The evaluation involves a continuous 9-point scale, wherein the two factors are compared and assigned values (Table 2).

Table 2. Foundational scale used for assessing relative significance of criteria in Analytic Hierarchy Process (AHP).

Relative Importance	Intensities	Description
1	Equally important	Both activities contribute equally to the objective.
3	Moderately important	One activity is slightly preferred over another.
5	Strongly important	One activity is significantly preferred over another.
7	Very strongly important	One activity is exceptionally preferred, dominating in practice.
9	Extremely important	The evidence supporting one activity surpasses all others with the highest level of confirmation.
2, 4, 6, 8	Values between adjacent judgments	Additional subdivision or compromise when required.

The lowest rank is equally important, whereas the highest rank is excellent for rainwater harvesting site selection. To assess the reliability of weights assigned to different factors in the matrix, the Random Index (RI) is determined based on the size of the comparison matrix (n), and its values are derived from simulations involving random matrices of the same size. The Consistency Ratio (CR) is calculated to assess the level of consistency in the expert judgments [82]. The CR is derived from the following formula:

$$CR = \frac{CI}{RI} \quad (1)$$

where CI is the Consistency Index and RI is the Random Index.

The Consistency Index (CI) is calculated using the following formula:

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

where λ_{\max} is the largest eigenvalue of the comparison matrix and n is the size of the comparison matrix. Once the pairwise comparison matrix is constructed, eigenvalues are calculated. An eigenvalue (λ) of a matrix is a special scalar value associated with a non-zero eigenvector (v) of the matrix. An eigenvalue represents a scaling factor that stretches or shrinks the eigenvector when multiplied by the matrix [82]. The equation for calculating eigenvalues can be written as follows:

$$Av = \lambda v \quad (3)$$

where A represents the pairwise comparison matrix, v represents the eigenvector, and λ represents the eigenvalue. Solving this equation for λ requires specialized mathematical methods, often handled by software packages designed for AHP analysis. The RI serves as a standardized metric established by [83]. The RI is a benchmark for comparing the Consistency Index (CI) against random matrices. The RI value depends on the size of the matrix (n). It is derived from a large number of randomly generated pairwise comparison matrices and is given in a tabulated form for matrices of different sizes. This involves

summing up all of the CIs and dividing by the number of matrices generated. The formula used to calculate RI is

$$RI_n = \frac{\sum CI \text{ random}}{N} \quad (4)$$

where RI_n is the Random Index for a matrix of order n , $\sum CI$ random represents the sum of the consistency indices obtained from randomly generated pairwise comparison matrices of order n , and N is the number of randomly generated matrices used to compute the average.

The RI serves as a benchmark for evaluating the consistency of pairwise comparisons made by experts or stakeholders. It provides a standardized measure of consistency across different pairwise comparison matrices. In the calculation of the Consistency Index (CI), the RI is used as the denominator, serving to assess the reliability of the comparisons. The formula for both the RI and CI involves the term $(n - 1)$, where n represents the size of the comparison matrix. This standardization ensures that the consistency of comparisons can be objectively assessed regardless of the matrix size. The variability of RI values is contingent upon the number of parameters delineated in Table 3. The importance of these criteria in identifying appropriate locations may vary according to their respective weights, and the decision-making process heavily relies on these criterion weights. In this study, the Analytical Hierarchy Process Consistency Ratio (AHP-CR) was employed to evaluate the consistency of the assigned weights across various layers. The Random Index (RI) value, a reference point for calculating the CR, can be found in Table 3 based on the number of compared parameters. By rigorously applying the AHP-CR, this study ensured that the assigned weights across various criteria were consistent and reliable. This methodological rigor strengthens the validity of the multi-criteria decision analysis, ultimately leading to more accurate and credible site selection for rainwater harvesting in the drought-prone Somali and Borena zones. Consequently, this approach supports better-informed and more effective interventions for water security in these regions.

Table 3. Random Index values.

Order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

The AHP is a decision-making framework used to simplify complex problems by organizing them into hierarchical structures comprising criteria, sub-criteria, and alternatives. It prioritizes these elements through pairwise comparisons. However, due to the potential for inconsistencies in such comparisons, the AHP incorporates a consistency ratio to verify the reliability of judgments. AHP pairwise comparisons assigned weights to RWH suitability factors. A ratio lower than a predefined threshold, typically 0.1, signifies acceptable consistency. According to Saaty [83], the value of CR should be less than 0.1 or less than 10%; otherwise, the weights should be re-evaluated to maintain uniformity. In our study, we identified 5 parameters, and according to Saaty's CR threshold, comparisons are deemed sufficiently consistent when CR is less than 0.1. We proceeded to calculate the RI based on these 5 parameters. Specifically, for order 5, the calculation yielded $CI = 1.11 - 5/5 - 1 = -3.89/4 = -0.9725$. In this study, the AHP pairwise matrix for the factors indicated in Table 4 was calculated according to the importance of the factor assigned. The process involves systematically comparing each factor against every other factor to determine their pairwise importance. Participants in the decision-making process assign numerical values, typically on a scale of 1 to 7, to express the relative importance or preference of one factor over another. These judgments are then organized into a pairwise matrix, quantifying the importance ratio between each factor pair. This structured approach facilitates decision making by revealing the hierarchical relationships among factors.

Table 4. AHP pair-wise matrix for factors.

	Drainage Density	Land Use/Land Cover	Soil Texture	Slope	MAAR
Drainage density	1	7	5	3	1
Land use/land cover	1/7	1	1/3	1/5	1/7
Soil texture	1/5	3	1	1/2	1/5
Slope	1/3	5	3	1	1/3
Monthly average annual rainfall (MAAR)	1	7	5	3	1

Rankings from 1 to 7 were assigned to the criteria for the study, and for each criterion, the percentage influence was calculated, as shown in Table 5. Several factors were considered when ranking criteria for the RWH site selection in this study. Firstly, criteria directly impacting rainwater harvesting, such as the average annual rainfall or drainage density, were given higher rankings due to their direct influence on the amount of rainwater collected. Secondly, criteria affecting water storage and usability, like soil texture or slope, were ranked based on their ability to retain and make harvested rainwater accessible. Lastly, criteria influencing long-term sustainability, such as LULC, were ranked with a focus on minimizing issues like land degradation or competition for water resources, ensuring the viability of the site selection over the long term. Finally, weights were assigned to each criterion using CR, RI, and CI calculations, ensuring a systematic and comprehensive evaluation process. In addition, fractional values in the table may arise due to various reasons. Participants may detect slight variations in factor importance, resulting in fractional assignments. Equally important factors might receive numerical values reflecting their shared significance. Factors such as soil texture and slope play crucial roles in rainwater harvesting, each with a unique level of importance. Employing fractional assignments in the pairwise comparison matrix allows participants to precisely articulate these distinctions. In our study, we found that drainage density holds a moderate level of importance compared to LULC but exhibits greater significance than soil texture, and they were assigned values of 3 (moderate importance) and 5 (strong importance), respectively, reflecting these differences. To quantify the weight and influence of each factor and to standardize the comparison matrix, each column's elements are divided by the sum of that column. This normalization process ensures that the values are appropriately scaled, facilitating fair comparisons across factors. For instance, consider the drainage density column in Table 5: the sum of its values is $1 + 1/7 + 1/5 + 1/3 + 1 = 1.796$. Normalizing involves dividing each value in the drainage density column by 1.796. Following normalization, a consistency check is conducted to ensure the internal reliability of the pairwise comparisons. This check entails computing the CI and the CR. The CI is determined from the largest eigenvalue (λ_{max}) of the comparison matrix, while the CR is computed by dividing the CI by the RI. A CR below 0.1 indicates that the matrix is internally consistent and reliable. Finally, to normalize the weights, we summed the average weights and adjusted them to ensure they add up to 1. The sum of the drainage density column is calculated as follows: $1 + 1/7 + 1/5 + 1/3 + 1 = 1 + 0.1429 + 0.2 + 0.3333 + 1 = 2.6762$. We normalized the values by dividing each element of the column by the value of 2.6762. Drainage density: $1/2.6762 = 0.37371/2.6762 = 0.3737$. Land use/land cover: $1/7/2.6762 = 0.00541/7/2.6762 = 0.0054$. Soil texture: $1/5/2.6762 = 0.07471/5/2.6762 = 0.0747$. Slope: $1/3/2.6762 = 0.12461/3/2.6762 = 0.1246$. MAAR: $1/2.6762 = 0.37371/2.6762 = 0.3737$.

Table 5. Weights of each criterion for RWH calculated by AHP model.

Criteria	Drainage Density	Land Use/Land Cover	Soil Texture	Slope	MAAR	Average (Weight)
Drainage Density	0.3737	0.7778	0.625	0.6429	0.3737	0.5586
Land Use/Land Cover	0.0054	0.1111	0.0417	0.1071	0.0054	0.0541
Soil Texture	0.0747	0.3333	0.125	0.2143	0.0747	0.1644
Slope	0.1246	0.5556	0.375	0.4286	0.1246	0.3217
MAAR	0.3737	0.7778	0.625	0.6429	0.3737	0.5586

The eigenvalue (λ) used in the calculation of the CR is derived from the CI and the RI. The RI is a reference value based on the order of the pairwise comparison matrix, which, in this case, is 5, as there are 5 criteria (drainage density, land use/land cover, soil texture, slope, and MAAR). The RI value for a matrix of order 5 is empirically determined to be 1.12. Considering a CI of 0.024 and an RI of 1.12, the pairwise comparison matrix is deemed consistent if the CR falls below 0.1. Since the calculated CR of 0.024 indicates a consistent matrix, this allows us to proceed with calculating the eigenvalue (λ) using the following formula:

$CR = CI/RI$. Given that $CR = 0.0216$, we rearrange the formula to solve for CI: $CI = CR \times RI$, $CI = 0.0216 \times 1.12$ and $CI = 0.024192$. Now that we have the CI value, we can use it to find the eigenvalue (λ) using the formula $CI = \lambda - 1/n - 1$, where λ is the eigenvalue and n is the order of the matrix (number of criteria). Given that $n = 5$ (since there are 5 criteria) and $CI = 0.024192$, we rearrange the formula to solve for λ :

$\lambda = CI \times (n - 1) + n$, $\lambda = 0.024192 \times (5 - 1) + 5$, $\lambda = 0.024192 \times 4 + 5$, $\lambda = 0.096768 + 5$ and $\lambda = 5.096768$. So, the eigenvalue (λ) derived from the given data is approximately 5.097.

The AHP model employs the pairwise comparison matrix from Table 4 to compute the weights for each criterion in Table 5. Each entry in Table 4 signifies the relative significance of the criterion in its respective row compared to the criterion in its corresponding column. For instance, to determine the weight for drainage density, we sum the values within its column in Table 4, resulting in a total of 1.796. Subsequently, we normalize the matrix by dividing each entry in the drainage density row by this sum, generating the values presented in Table 5. Then, to ascertain the weighted average for drainage density, we multiply each normalized value by its corresponding weight in Table 5 and sum the products. For example, the calculation proceeds as follows: weighted average for drainage density = $(0.3737 \times 0.3442) + (0.0054 \times 0.3442) + (0.0747 \times 0.3442) + (0.1246 \times 0.3442) + (0.3737 \times 0.3442) = 0.127 + 0.00186 + 0.02567 + 0.04273 + 0.127 = 0.32496$. This procedure is replicated for each criterion to establish its weighted average, subsequently recorded in the "Average (Weight)" column of Table 5. Moving on to Table 6, the percent influences for each criterion are determined by dividing the weight of each criterion by the sum of all weights and then multiplying by 100 to express the result as a percentage. For instance, to compute the percentage of influence for drainage density, we perform the following calculation: percent influence for drainage density = $(0.3442/1) \times 100 = 34.42\%$. This process is iterated for each criterion, culminating in the values showcased in the "% of Influences" column. Rankings were assigned based on the relative priority of each factor Table 6. To calculate the weight for each factor, we can use the drainage density as an example: the sum of the drainage density row was 17, and the total column sum of all factors was 49.37. Therefore, the weight for drainage density was calculated as $17/49.37 = 0.3442$. The value of $CR = 0.0216$, which is less than 10%; therefore, the assignment of weight above was consistent and acceptable (Table 6). After the weight of the criteria was determined, the potential RWH site was acquired using the weighted overlay process (WOP), intersecting all of the weighted criteria using the weighted linear combination (WLC) technique using the ArcGIS tools. This technique applies to suitability analysis and has been used in many previous studies [83,84]. A weighted linear combination is an analysis technique used

when working on multi-criteria decision making (MCDM) or when considering more than one criterion [85,86]. A WLC suitability map was generated using the following equation:

$$S = \sum Wi * SLi \quad (5)$$

where S is the suitability location and Wi is the relative importance weight of the criteria (rainfall, slope, soil texture, land use, land cover, and drainage density) for the RWH site selection procedure and SLi suitability levels for input factors.

Table 6. Percentage of influences CI, RI, and CR for each criterion.

No.	Criteria	Weight	% of Influences
1	Drainage density	0.3442	34.42
2	Land use/land cover	0.0368	3.68
3	Soil texture	0.0992	9.92
4	Slope	0.1755	17.55
5	MAAR	0.3442	34.42
	SUM	1	100

Note: Eigenvalue (λ) = 5.09797, CI = 0.024, RI = 1.11, CR = CI/RI, CR = 0.0216.

2.6. Addressing Subjectivity in AHP for RWH Site Selection

This study addresses the inherent subjectivity of the AHP when used for rainwater harvesting site selection in drought-prone areas. Firstly, we advocate for a multi-stakeholder approach involving experts in hydrology, environmental science, community development, and local communities [84–89]. This diverse team can contribute specialized knowledge and potentially reduce bias by including various perspectives. Secondly, experts not involved in the AHP process can evaluate the final decision model and its outcomes, objectively assessing its validity and ensuring credibility [90]. Thirdly, we emphasize the importance of comprehensive transparency and documentation. This includes clear justifications for criteria selection, assigned weights, and final site selection results [91]. Finally, to reduce bias and ensure transparency, we propose establishing pre-agreed criteria weighting. This can be achieved through stakeholder consensus or expert judgment at the project's outset [92]. Furthermore, we support the concept employing diverse criteria and sub-criteria to enhance the robustness of the AHP results. As [93] suggests, analyzing how changes in criteria weights affect the final decision strengthens the overall credibility and reliability of the process. Similarly, a sensitivity analysis, where weights and pairwise comparisons are slightly altered to observe the impact on site selection, can identify potential biases in the AHP judgments [94].

2.7. Validation

The validation process is a crucial step in ensuring the accuracy of the suitability map generated for diverse RWH site selection. This evaluation assesses the effectiveness of the methods and techniques employed. The determination of RWH suitability in arid and semi-arid regions, specifically within the Borena zone and Somali region, primarily relies on a combination of field studies, existing data, high-resolution satellite imagery from Google Earth, and ground truth information collection using optical satellite maps. Validation was conducted using ground truth data obtained through visits to selected RWH sites identified geospatially by MCDA. This validation process encompassed various aspects, including measuring actual rainfall, assessing soil characteristics, and evaluating slope conditions in comparison to the data utilized in the analysis. Furthermore, the presence of suitable locations for water storage and accessibility for the local population was examined on-site.

Additionally, potential limitations not accounted for in the geospatial data, such as land ownership issues or social factors, were assessed during field validation. This approach, as outlined by [95], involves leveraging geospatial technology. Moreover, ancillary data from

various institutions are incorporated to validate and compare the study results against a classified and analyzed map of potential RWH suitability. The RWH suitability zone map is meticulously compared to the functional RWH structures within the study area. To achieve this, existing RWH structure points are sourced from reputable entities such as the Ministry of Water and Energy, the National Disaster Risk Management Commission, and the central statistical agency. By analyzing the spatial distribution of existing RWH structures relative to the suitability classes, this study evaluated the level of agreement between the model's predictions and the on-ground reality. A high degree of overlap between existing RWH structures and the highly suitable zones on the map strengthens the model's credibility and the potential effectiveness of the proposed RWH sites.

3. Results

Each parameter was subdivided into different importance levels for the RWH to produce the final potential suitability map. The importance level (suitability level) was divided into four categories: unsuitable, low suitability, medium suitability, and high suitability. In the results of this study, the basis for assigning limits to each category is primarily derived from a combination of expert knowledge, relevant studies in the literature, and an empirical data analysis. Existing research findings were carefully reviewed for each parameter, and consultation with domain experts was undertaken. Statistical analyses were conducted to establish thresholds that differentiate between various suitability levels. These thresholds are determined based on specific criteria relevant to each parameter and aim to capture meaningful distinctions in the suitability of the study area to carry out RWH. Furthermore, a systematic approach was employed to ensure consistency and objectivity in the categorization process. While the exact limits for each category may vary depending on the parameter and the specific characteristics of the study area, the aim is to provide a clear and scientifically justified framework for assessing suitability.

3.1. Rainfall

This study assesses rainfall levels in the area using Ethiopia's agroclimatic zone classification system, focusing on the drought-prone Somali and Borena zones. The regional states of the Somali and Borena zones of the Oromia regional states of Ethiopia are more often characterized by semi-arid and arid climatic conditions. Prioritizing rainfall data is essential for RWH site selection in these regions. Annual rainfall in the area ranges from 294 to 601 mm. However, some areas in the north and southwest of the study area are characterized as sub-moist areas, where the annual RF is between 350 and 566. The annual average rainfall for the given stations for 10 years was produced using the Inverse Distance Weight (IDW) spatial interpolation method and clipped to the study area. The RWH site identification was determined based on the relative availability of rainfall. High-response areas showed the highest opportunities for RWH. Rainfall variability in the area ranged from 294 to 619 mm. A relatively high rainfall variability was observed in the north, southwest, and some points in the center of the study area, whereas the eastern and most of the central parts scored lower rainfall amounts.

A mean annual average rainfall > 500 mm was considered highly suitable for RWH, offering the potential for larger storage capacities and more frequent harvests (referred to as dry kolla). Sites with medium suitability, receiving 500–600 mm of rainfall annually (labeled as Bereha), can still benefit from RWH, albeit with potentially lower storage capacities and harvest frequencies [96,97]. Conversely, regions with less suitability, receiving 400–500 mm of rainfall annually, may face challenges due to limited water availability (Figure 5). However, a further analysis, such as an analysis examining the drainage density, could identify micro-locations suitable for RWH implementation within these zones. Regions receiving less than 400 mm annually are unsuitable for RWH due to insufficient rainfall and being highly prone to drought. The reclassification of rainfall showed that a 79,284 km² (24.47%) area was classified as being unsuitable, a 73,110 km² (22.57%) area was classified as having

low suitability, a 104,666 km² (32.31%) area was classified as having medium suitability, and a 66,896 km² (20.65%) area was classified as having high suitability for RWH site selection.

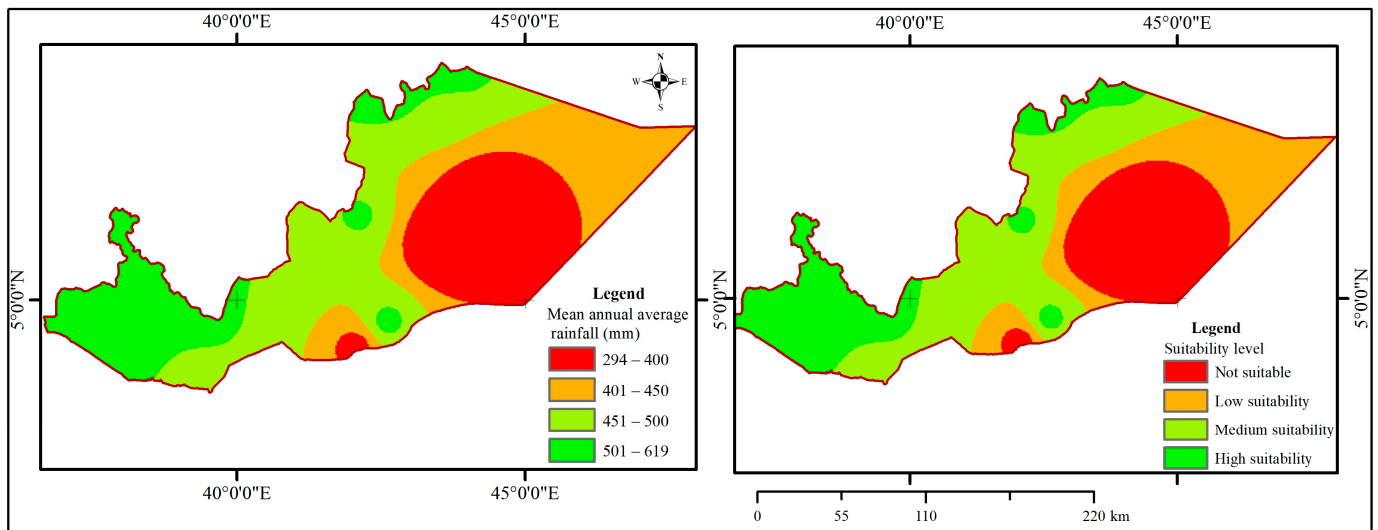


Figure 5. Average annual rainfall (2012–2021) distribution and reclassified rainfall map.

3.2. Slope

A slope map was derived from a DEM with a 30 m resolution for the entire area. The GIS environment in ArcGIS was used to calculate the slope percentage or degree of slope. For this study, the percentage of slope (the percentage ratio of elevation change with horizontal distance) was calculated and used for the suitability analysis. Table 7 shows the percentage range of the slope calculated and the suitability levels of the slope for the RWH site selection procedure.

Table 7. Slope percentage categories, suitability level, and area coverage.

Factor	Slope Range	Suitability Level	Coverage (%)	Area (Km ²)
Slope	>15	Not suitable	0.41	1328.22
	10–15	Low suitability	1.06	3433.92
	5–10	Medium suitability	4.75	15,387.86
	<5	High suitability	93.78	303,805
Total			100	323,955

Figure 6 shows the distribution of the slopes and topography of the study area. The consensus among researchers worldwide underscores the significance of slope factors in determining suitable sites for RWH, a notion affirmed by our study’s classification system. Moderate slopes, typically falling within the 5–10% range, emerge as optimal locations for RWH because they facilitate runoff while mitigating soil erosion risks [98]. Gentle slopes, spanning 0–5%, are highly suitable for RWH, offering advantages such as efficient water collection, reduced erosion risks, enhanced groundwater recharge, and simplified construction processes. Conversely, steeper slopes, ranging from 10 to 15%, pose challenges, including heightened erosion risks and construction complexities. Such slopes are prone to soil erosion, potentially leading to sedimentation in RWH storage structures and diminishing their efficacy. Extremely steep slopes exceeding 15% are deemed unsuitable for RWH sites due to substantial erosion hazards and construction difficulties. Most of the study area, which is predominantly flat and gentle, covered approximately 98% of the entire area, and has medium and high appropriateness for RWH site identification,

and less than 2% of the area has steep slopes. A smaller slope and flat area will slow down water movement and increase the chance of it staying on the soil’s surface. Most of the area is suitable for rainwater storage, but the porosity of the soil governs the duration of water holding in the area. Incorporating slope considerations into MCDA for RWH site selection in the Somali and Borena zones is imperative for supporting the effectiveness and sustainability of RWH interventions in alleviating drought impacts.

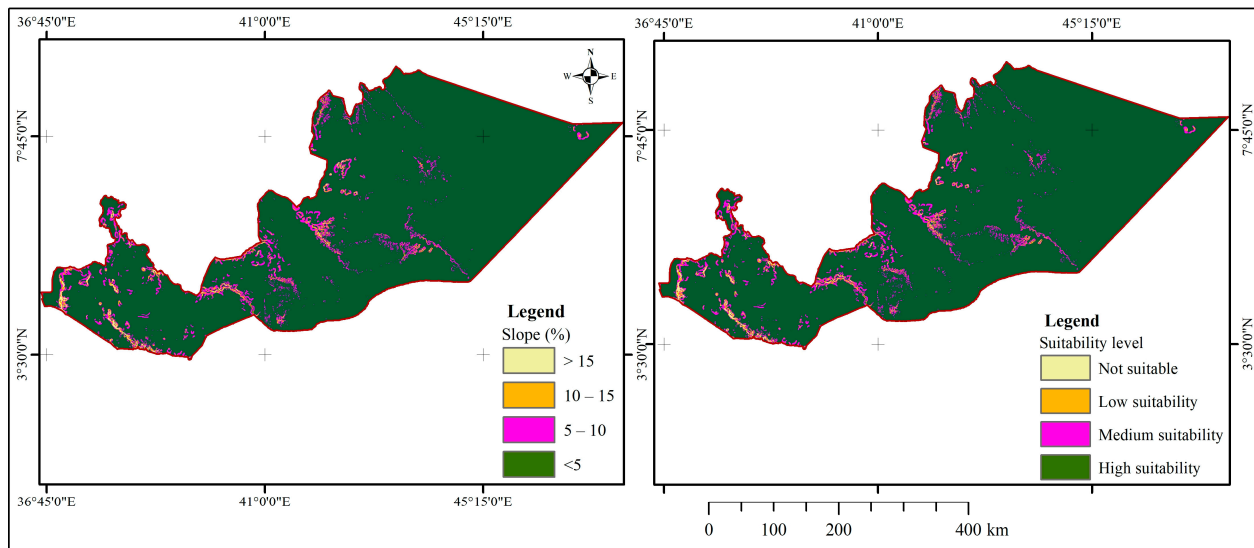


Figure 6. Slope distribution and suitability class map.

3.3. Soil Texture

Our study aligns with global research highlighting the importance of soil characteristics in RWH site selection through a soil data analysis. The soil texture within the study area was reclassified into four categories: clay, clay loam, loam, and loamy sand. Soil data are commonly utilized in site selection studies, with soils possessing good infiltration rates, such as sandy loam or sandy clay loam, generally considered more suitable due to their capacity to facilitate water percolation and groundwater recharge capabilities. Our findings present a unique case. Clay soil emerged as the most suitable type in this specific area due to its ideal balance between infiltration and water-holding capacity, aligning with previous studies [99]. However, clay loam, while moderately suitable, may require additional measures for optimal water capture due to its lower infiltration rates. Conversely, loam and loamy sand soils exhibit lower suitability due to very low infiltration rates, potentially causing surface runoff and limiting water storage within the soil profile. Sandy loam and sand are entirely unsuitable for RWH due to their rapid drainage and minimal water retention despite having high infiltration rates. Figure 7 depicts the spatial distribution of soil textures, with sandy loam and sand covering the majority of the study area (59%). Loam and loamy sand are less prevalent, followed by the most suitable clay soil type, which accounts for approximately 11% of the total area. Table 8 summarizes the soil types, their corresponding suitability classes, and their respective area coverage.

Table 8. Soil type suitability level and coverage.

Factor	Type	Suitability Class	Coverage (%)	Coverage (Km ²)
Soil type	Clay	High suitability	10.8	34,987
	Clay loam	Medium suitability	0.97	3142
	Loam and loamy sand	Low suitability	29.65	96,053
	Sandy loam and sand	Not suitable	58.58	189,773
Total			100	323,955

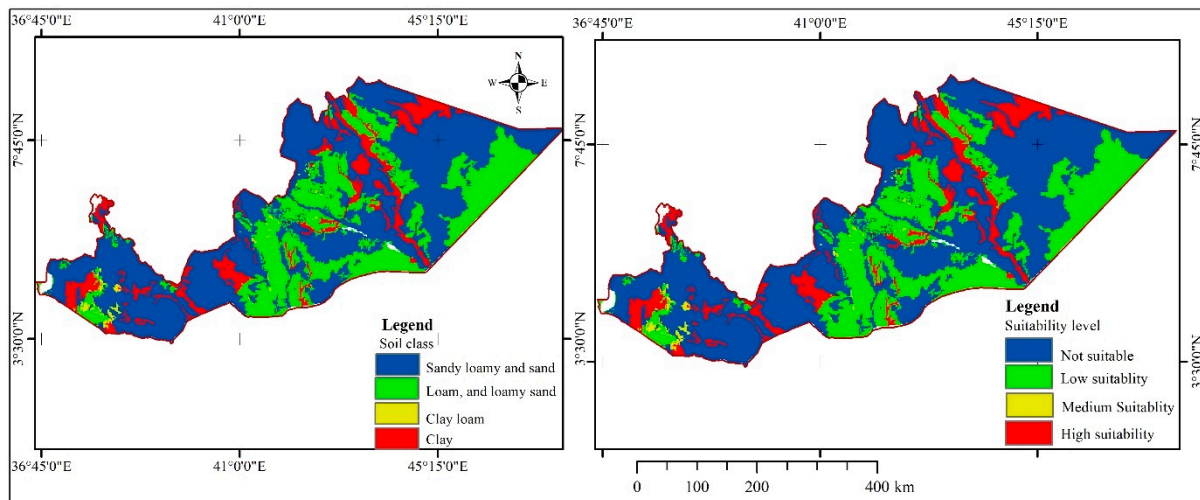


Figure 7. Soil texture class and reclassification suitability map.

3.4. LULC

Ethiopian Sentinel-2 land use/land cover 2016 was the major input to drive LULC data, and reclassification was performed while considering the type of LULC potential for RWH. This study revealed that areas with minimal human intervention, such as shrublands or open woodlands, are well suited for RWH due to their sparse vegetation cover, which reduces interference, erosion, and contamination risks. Bare land, which is commonly found in drought-prone regions, was classified as moderately suitable for RWH due to its flat, non-vegetated nature, facilitating potential water collection, albeit with attention regarding erosion risks. Conversely, areas characterized by dense settlements, industrial zones, closed woodlands, or dense grasslands were considered less suitable for RWH due to their high interception, potential contamination, and increased runoff, limiting water availability [100]. Furthermore, croplands, forests, and water bodies were considered unsuitable due to concerns regarding agrochemical pollution and dense vegetation, which can interrupt rainfall. A comprehensive understanding of LULC dynamics is crucial for accurate RWH site suitability assessments in drought-prone areas. The integration of information on vegetation cover, impervious surfaces, agricultural practices, and land degradation into MCDA frameworks can greatly enhance the effectiveness of RWH site selection strategies, contributing to sustainable water resource management in the Somali and Borena zones of Ethiopia’s Oromia regional state. As shown in Table 9, shrubland constitutes the largest spatial coverage at about 44% (142,929 km²), followed by grassland and woodland with about 37% (121,030 km²); cropland, forest, and water bodies with 16% (53,193 km²); and bare land with the least spatial coverage, constituting only 2% (6803 km²) of the entire area.

Table 9. LULC, suitability class, and area coverage.

Factor	Type	Suitability Class	Coverage (%)	Coverage (Km ²)
Land use/cover	Shrubland	High suitability	44.12	142,929
	Bare land	Medium suitability	2.1	6803
	Grassland and woodland	Low suitability	37.36	121,030
	Cropland, forest, and water body	Not suitable	16.42	53,193
Total			100	323,955

In terms of suitability for RWH site selection, 44% of the entire coverage in the study area was determined to be highly appropriate because the area was covered by shrubland. Approximately 2% of the area covered by bare land was determined to have medium suitability. Grassland and woodland covered 37% of the area and was determined to have

low suitability, and cropland, forest, and water bodies contributed 16% of the area and were determined to be unsuitable for RWH site selection (Figure 8).

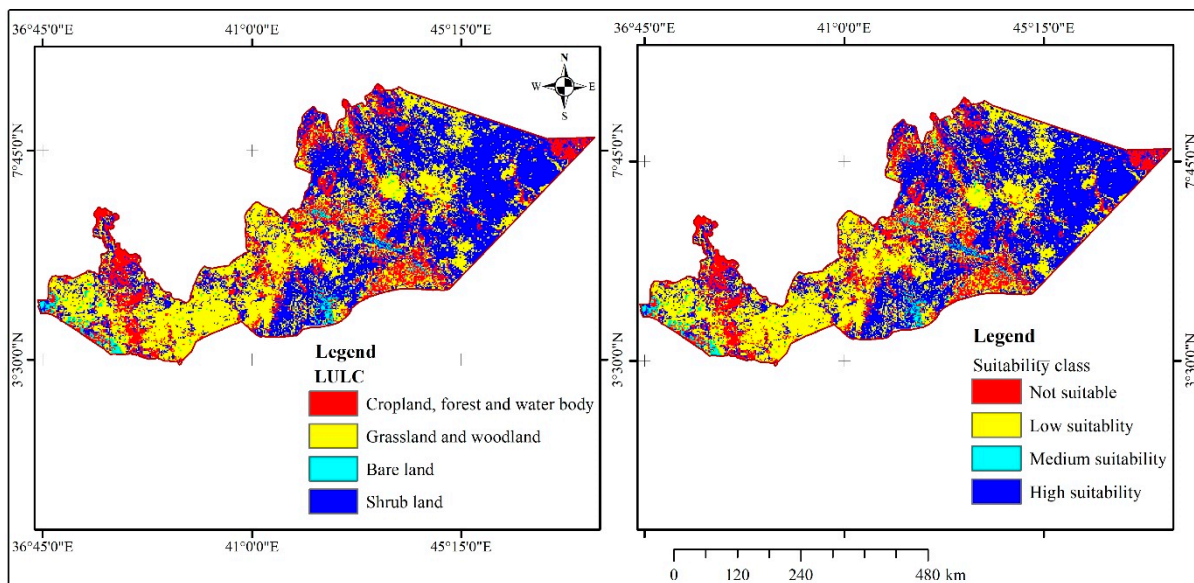


Figure 8. LULC distribution and suitability map.

3.5. Drainage Density

The drainage density of the area extended from 0 to 13. Table 10 lists the deranged density intervals and suitability classes assigned. The higher the drainage density, the more likely the RWH site is to be located, which means that when the area is dominated by rainwater accumulation in several streams, it is more likely to occur in an area with high drainage density and vice versa. The analysis of drainage density revealed its importance in RWH site selection for drought-prone regions. Areas with high drainage density (8–13 km/km²) were classified as highly suitable due to their potentially higher infiltration rates and higher surface runoff, leading to greater water storage within the soil profile and increased capture by RWH structures [101]. Conversely, areas with less drainage density (3–4 km/km²) were classified as being less suitable due to rapid surface water runoff and limited infiltration. Moderate drainage density (5–7 km/km²) areas might still be suitable with additional measures to improve infiltration, while very low drainage density (below 2 km/km²) areas were deemed unsuitable for RWH.

Table 10. Drainage density intervals, suitability class, and coverage.

Factor	Interval	Suitability Class	Coverage (%)	Coverage (km ²)
Drainage density	0–2	Not suitable	46.21	149,700
	3–5	Low suitability	39	126,342
	5–7	Medium suitability	12.97	42,017
	8–13	High suitability	1.81	5864
Total			100	323,923

Figure 9 shows the drainage density and the reclassification map for suitability. Less than 2% of the area had the highest stream concentration, indicating higher suitability. The RWH covered 5864 km² of the study area. Approximately 13% (42,017 km²) of the area was determined to have medium suitability, 39% (126,342 km²) was determined to have low suitability, and the remaining 46% (149,700 km²) was unsuitable for RWH site selection.

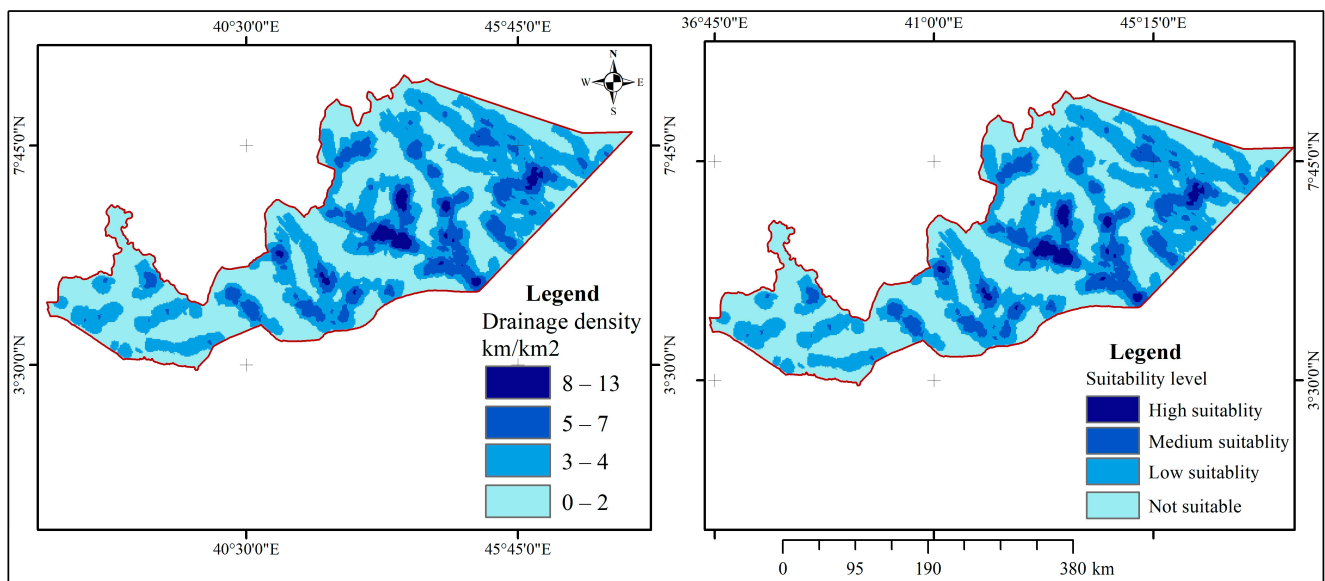


Figure 9. Drainage density distribution and drainage suitability class map.

3.6. Final Potential RWH Suitability

The final RWH suitability map was produced using the weighted linear combination (WLC) method and weighted overlay process in ArcGIS. Weight and suitability rankings were assigned using a scale of 1 to 9, capturing the relative importance of factors in RWH site selection. These weights were derived from a comprehensive consideration of previous research, expert perceptions from hydrologists, environmental scientists, and community development specialists, as well as local knowledge facilitated through a multi-stakeholder approach. Further enhancement of the weightings was achieved through a pairwise comparison matrix and the AHP, with the CR ensuring their reliability. The thematic layers’ suitability levels were also determined on a scale of 1 to 9 using a weighted linear combination tool in ArcGIS. The suitability levels were determined using a weighted linear combination equation, assigning values 1, 3, 5, and 7 based on the importance scale. A suitability level of 1 indicated areas that were considered unsuitable for RWH site identification due to their lack of significance, and they were considered restricted zones. On the other hand, a suitability level of 7 represented areas that were highly suitable for RWH implementation. The importance scale delineated two distinct categories: areas considered practically unsuitable (rated 1 and 3) and areas deemed suitable (rated 5 and 7). This classification ensured clear differentiation between zones considered viable for RWH and those deemed unsuitable. Each factor was then rated based on the calculated weight, and the factor sub-levels were prioritized, as shown in Table 11.

Table 11. Importance scale for suitability classes by factor.

Importance Scale	7	5	3	1
Rainfall	501–619	451–500	401–450	294–400
Slope	<5	5–10	10–15	>15
Soil texture	Clay	Clay loam	Loam and loamy sand	Sandy loamy and sand
Land use/cover	Shrub land	Bare land	Grassland and woodland	Cropland, forest, and water body
Drainage density	8–13	5–7	3–4	0–2

The suitability scale denoted by 1 considers a restricted area for suitability analysis because of its insignificance for RWH site identification; a suitability scale of 7 denotes the

most appropriate area for RWH. Before the suitability analysis, all thematic layers were converted to a similar spatial reference system, and a final suitability map for PRWH with four suitability categories was generated based on multi-criteria decision (MCD): high suitability, medium suitability, low suitability, and unsuitable categories. Figure 10 depicts the distribution of suitability for PRWH.

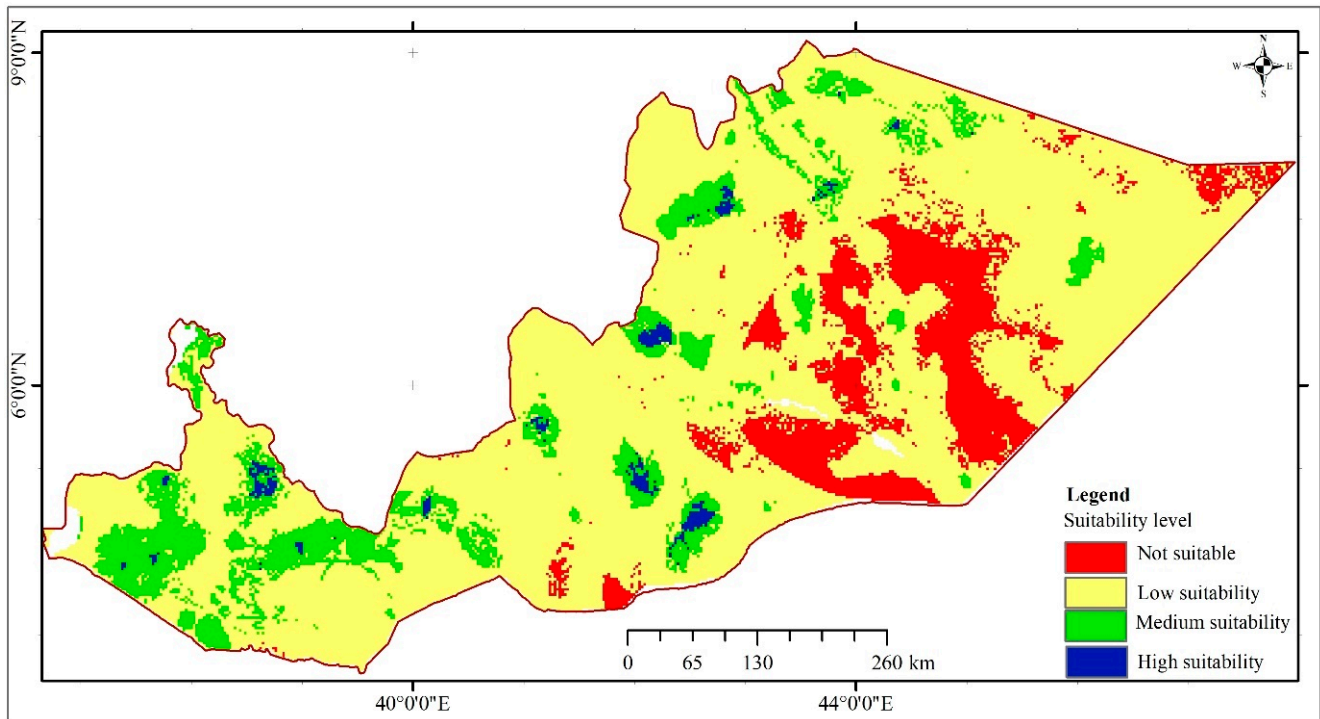


Figure 10. Potential rainwater harvesting (PRWH) suitability map.

This study employed the AHP with a pairwise comparison matrix to establish weights for the factors influencing RWH suitability. These factors included rainfall, slope, soil texture, LULC, and drainage density. For each potential RWH location, specific criteria were evaluated for each factor. The rainfall amount, slope angle, soil texture type, LULC category, and drainage density values were identified. A score was assigned to each factor value based on predefined importance scales. For instance, rainfall between 501 and 619 mm received a score of 7 (highly suitable), while areas with rainfall between 294 and 400 mm received a score of 1 (unsuitable). Similar importance scales were established for other factors to determine suitability classes. The suitability score (S) for a location is calculated by multiplying the weight of each factor by its corresponding score and summing these values across all factors. Suitability classes were determined using two common approaches: Quantile Classification, which divides the range of S values into equal intervals (quartiles), and Natural Breaks Classification, which identifies significant changes in the S value distribution. Suitability classes are then assigned based on these breaks. Following this classification, suitability limits were established for each class (unsuitable, low suitability, medium suitability, and highly suitable), and a tabulated distribution of suitability values along with a statistical analysis was provided. The analysis results in Table 12 show that among the entire study area, 1% of the area was highly appropriate for RWH, covering approximately 3288 km². Approximately 13% (37498 km²) of the area had medium suitability; most of the study area was represented by regions with low suitability, constituting 75% or 242,170 km² of the area. A region with 13%, or 41,000 km², was regarded as unsuitable for RWH. Finally, adopting sustainable water management strategies, such as integrated water resource management that considers groundwater and other resources, is essential to combat water scarcity.

Table 12. Suitability levels and coverage area for PRWH site.

Suitability Level	Coverage (%)	Coverage (km ²)
Not suitable	12.66	41,000
Low suitability	74.75	242,170
Medium suitability	11.58	37,498
High suitability	1%	3288

4. Discussion

This study aimed to identify an appropriate site for harvesting rainwater for communities lacking rainfall, especially in semi-arid and arid areas. Several studies have confirmed the effectiveness of RWH systems in providing water for diverse purposes in drought-prone regions [102–107]. In the study area, low rainfall patterns are characterized by infrequent yet intense precipitation events, resulting in significant surface runoff and flooding. To mitigate water scarcity during extended dry seasons, the implementation of large-scale RWH structures is imperative. Despite the irregular nature of rainfall, data spanning from 1997 to 2015 indicate an adequate number of rainy days annually (up to 49), supporting the feasibility of RWH through strategic site selection for large-scale structures [108]. Identifying appropriateness using a suitability analysis for any plan often requires several possible options that can be assessed based on multiple criteria. Creating suitability index maps through GIS and MCDA models can be challenging due to the influence of numerous factors [109]. This study employed the WLC method to assign weights to various thematic layers within the model. This approach offers significant flexibility in weight allocation, allowing for a more nuanced consideration of these factors [110]. This study established the factors used to locate suitable areas for RWH based on their appropriateness and applicability to potentially suitable sites. Based on the leveling assignment, the weighted factors and their subgroup (internally ranked factor) intersections produced the PRWH site. The areas identified were technically in line with similar studies, and the results depict how the importance of weight determines the selection of suitable areas. Most sites identified as highly suitable for PRWH are situated in areas with clay soil, high rainfall, gentle slopes, shrublands, bare land, and high drainage density.

According to [111], clay soil has the highest runoff potential with a very low infiltration rate and is highly suitable for water harvesting, whereas sandy loam and sandy soils have the least potential for water storage because they have the lowest water-holding capacity due to their high infiltration rate. The same is true for sparsely vegetated land, such as bare land and shrubland, which are types of land cover that are more often recommended for water harvesting site selection [112]. The flat and gentle regions in the study area also had the highest share of the PRWH site. This aligns with findings from another study [113], steep slopes are unsuitable for rainwater storage; however, they significantly contribute to overflow generation and the speed of water flow to the harvesting area on flat and gentle slopes.

A total of 13% of the area was an excellent and reasonably proper zone for RWH; therefore, attention should be given to this area for the construction of RWH structures. These areas are best suited for rainfall, slope, land use, land cover, soil texture, and drainage density. However, in most of the areas studied, approximately 87% were unsuitable for RWH. By naming the suitability location by administrative unit, the following districts (smaller administrative units) and zones (higher administrative units) in the study area were identified. These were the Dugda Dawa, Yabelo, and Melka Soda districts and some areas in the Borena zone of Oromia. The Hudet District in the Liben zone; the Bare, Chereti, and West Imi districts in the Afder zone; and East Imi in the Shebelle zone in the Somali regional state were identified as suitable for RWH. The exact locations can be determined by extracting the geographic coordinates (X and Y) from the potential water harvesting (PRWH) suitability map.

The final PRWH suitability map, shown in Figure 9, reflects the suitability levels of the RWH site. For instance, the most suitable sites for RWH are located in areas with higher rainfall (>450 mm), with slopes extending from 0 to 10, and in large drainage density areas (8–13) because rainfall and drainage density had the highest weight factors, followed by slope. These results agree with the assumption of factor suitability level allocation. The results also reveal that areas of high and medium suitability for RWH were mostly located in areas where shrubland, bare land, clay, and clay loam were predominant. These LULC and soil types are appropriate for rainwater storage, as has been explained in several similar studies [114,115].

Generally, the analysis results show that significant conclusions were asserted from factors and methods used to develop a suitability result, including criteria levels of suitability and relative importance weights. All factors were combined in a weighted overlay analysis using the weighted linear combination technique to produce suitable rainwater collection sites. According to a study by [116], RWH requires a significantly flat topography to harvest overflow water and easily construct the structure. When considering the study area, predominantly flat topography accounts for approximately 94% of the area (<5% slope), which makes it easy to harvest overflow water and reduces earthwork costs; however, rainfall variability and drainage density were the most important factors given the greater weights out of all factors, which were governed for the identification of a highly suitable location. Since the area has often experienced very low rainfall amounts, resulting in continued drought and the depletion of livestock in recent years, the implementation of RWH projects in the Borena zone in the Oromia and Somali regional states will be very important for crop production, water for livestock fodder, and even water for human consumption.

5. Conclusions

This study identified a suitable site for RWH using geospatial techniques and an MCDA approach for the Borena zone of the Oromia and Somali regional states. ArcGIS tools were the main instruments used to combine different thematic layers, and it was convenient to analyze the data using a weighted overlay process with weighted linear combination (WLC) to identify suitable locations. The criteria/factor importance weights were extracted using the AHP method. The area is more often affected by drought due to low precipitation over a longer period and is usually called a drought-prone area. This area is more dominantly characterized by arid and semi-arid climatic conditions that attract attention to RWH options to mitigate drought problems as a result of low precipitation.

RWH is an important method for overcoming water deficiency during longer drought periods. This study highlights the potential of RWH for drought mitigation in drought-prone areas of the Somali and Borena zones. However, for long-term water security, an integrated approach is crucial. Combining RWH with existing groundwater resources and other water management strategies can maximize water availability. The result of this study leveraged multiple factors influencing RWH suitability, including elevation, slope, precipitation, land use, soil type, and drainage density. The AHP was employed to assess the relative importance of these factors. Through pairwise comparisons and weight assignment, we established a robust method for evaluating potential RWH sites. This approach yielded a suitability map with clearly defined criteria levels and weightings, providing valuable insights for informed RWH site selection. Drainage density and rainfall factors are given higher weights than other factors to increase their usefulness for RWH. The suitability model generated four suitability classes: high suitability, medium suitability, low suitability, and unsuitable. Eighteen suitable sites were identified in the study area, of which thirteen were highly suitable, and five were considered moderately suitable. Almost all highly suitable areas were surrounded by moderately suitable areas, meaning that these two suitable areas were adjacent to each other. This adjacency provides flexible opportunities for constructing RWH structures.

The findings of this study will guide regional state authorities, concerned federal state bodies, and decision makers in planning future development approaches for handling water

insufficiency within the selected study area. Additionally, this study guides the design of cost-effective interventions aimed at maximizing rainwater utilization and alleviating water scarcity in the Ethiopian regions under study. The technique used to identify appropriate RWH sites can also be adapted for other low-precipitation areas. However, lack of site visits, ground validation, and complete socio-economic data were some of the limitations in this study, so additional investigation is needed to execute the RWH system, such as comprehensive site depictions, social and economic viability characterization, in-depth assessments of environmental sustainability, and detailed cost–benefit analyses.

6. Future Work

Further studies should be conducted focusing on refining the decision-making framework by incorporating additional criteria or datasets to improve the accuracy of RWH site selection. This could involve integrating socioeconomic factors, such as population density or land tenure arrangements, to better capture the sociocultural context of the study area. Additionally, exploring the integration of climate change scenarios into the MCDA framework may improve the robustness of RWH interventions. Moreover, exploring advanced modeling techniques, such as machine learning algorithms or spatial optimization methods, could enhance the predictive capabilities of the RWH suitability analysis and facilitate more informed decision making. Additionally, longitudinal studies tracking the performance of selected RWH sites over time could provide valuable insights into their effectiveness and inform adaptive management strategies for sustainable water resource management in drought-prone regions.

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