International Journal of
Geo-Information

MDPI

Article

Potential Water Harvesting Sites Identification Using Spatial Multi-Criteria Evaluation in Maysan Province, Iraq

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Received: 1 March 2020; Accepted: 8 April 2020; Published: 10 April 2020

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Abstract: Rainwater harvesting is a promising tool for supplementing surface water and groundwater to overcome the imbalance between water supply and demand under changing climate conditions. Multi-Criteria Evaluation is one of the well-known methods of decision-making. In this study, the geographical information system (GIS)-based Multi-Criteria Evaluation is used to select the optimum rainwater harvesting sites in Maysan province, Iraq. Fuzzy membership is used for standardization of the criteria, and Fuzzy Gamma overlay for a combination of multi-layers using ArcGIS 10.5. Seven criteria layers, including slope, stream order, soil type, precipitation, evaporation, roads, and the Normalized Difference Vegetation Index (NDVI) are derived to identify rainwater-harvesting catchment. The results determined the optimum sites for water storage within the study area. The resultant potential rainwater harvesting catchment map can be used as a reference to enhance the effectiveness of water management, especially in drought-stricken areas that offer significant potential for sustainable agricultural production in the semi-arid region.

Keywords: fuzzy model; GIS; MCE; spatial analysis; water-harvesting catchment

1. Introduction

Water is one of the most important natural resources, if not the most valuable of all. The earth has an abundance of water, but unfortunately, only a small percentage (less than 1 percent) is even usable by humans [1], and more than 99 percent is unusable in the oceans, soils, icecaps, and floating in the atmosphere. Climate change, population growth, and rapid industrialization are regarded as the three main global drivers increasing stresses on safe water supply worldwide [2]. Stress on freshwater resources due to rising demand is already leading to water scarcity in many places, especially in arid and semi-arid areas that face a water scarcity problem in terms of domestic use and agriculture. Moreover, there is a global uneven distribution of both population density and water resources. Areas that are occupied by people are not necessarily areas with abundant water resources.

Water scarcity is the lack of freshwater resources to meet water demand; it is a major threat to livelihood globally, and one of the main limitations on socio-economic development. It is a worldwide problem that was classified as one of the largest global risks in terms of potential impact over the next decade by the World Economic Forum in 2019 [3]. Water scarcity may be either physical or economic. Physical scarcity is the situation when and where there is naturally limited accessibility to water in a country or a region [4], as in arid and semi-arid areas. Whereas economic water scarcity is caused by poor investment in water or a shortage of human capacity to meet the needs for water, even in water-abundant places.

Studying water resource scarcity is essential in framing policies at global and national levels. The Eighth Phase of the International Hydrological Programme (IHP-VIII), which focuses on water security, includes "Addressing water scarcity and water quality" as one of its six themes [5]. Water security has been defined as "the reliable availability of an acceptable quantity and quality of water for health, livelihoods, and production, coupled with an acceptable level of water-related risks" [6].

Generally, many issues exacerbate water scarcity in Iraq. Much water is wasted either directly to the Arabian Gulf, or through evaporation due to a lack of irrigation planning and water harvesting [7]. The study area, Maysan province, is located 300 km south-east of Baghdad in the arid zone with dry climate conditions [8]. The Tigris River is now the main water supply of the Maysan governorate, which has lost most of its agricultural lands after the environmental disaster of marshes drainage in the 1990s. The water supply of Maysan is of poor quality with low discharge, as it is located at the last part of the route of the Tigris before meeting the Euphrates river in Al Qurna, 100 km southward [9]. In January 2019, 100 locations were identified by the International Organization for Migration (IOM) as facing drought and/or water scarcity in the southern part of Iraq, and 58 of these locations were in Maysan Governorate, 22 in Muthanna, 11 in Basra, and 9 in Thi-Qar [10].

Iraq has recorded the highest rainfall in last winter compared to the previous ten years, which resulted in floods and torrents, especially the provinces of Maysan and Wasit [11]. This flood led to the sinking of a number of villages and the collapse of dozens of homes, which forced the families to displace. Maysan province had frequently experienced heavy rainfall that causes floods, which come after significant periods of drought. The Emergency Response Coordination Centre (ECHO) reported that the study area experienced a flood in 2019 along the Tigris river, which led to the displacement of 545 families, with a further 2000 families at risk, following damage to a number of internally displaced persons camps [12].

Rainwater harvesting (RWH) is "the collection and management of rainwater runoff to increase water availability for domestic and agricultural use, as well as ecosystem sustenance" [13]. It is an old water supply technique used in water scarcity cases to meet ever-increasing water demand, address climate changes and variability, and to combat desertification [14,15]. Potential site selection for RWH is vital in semi-arid areas for increasing water availability and maximizing the productivity of the land [16]. Water harvesting on the land or in cisterns also controls erosion and flooding, and reduces water pollution. The use of the RWH technique has various advantages: it captures the water to ensure a part of the water demand for irrigation, and extenuates the periods of water scarcity due to droughts by using the storage water. Peoples living in arid and semi-arid areas with highly variable rainfall rates are subjected to periods of droughts or floods that affect water availability. Rainwater harvesting and artificial groundwater recharge induction by dam construction is one of the effective methods to overcome water shortage and to avoid the risk of floods. The success of RWH systems mainly depends on selecting a suitable site. Sustainable water resources management systems could increase water availability by identification of the optimum RWH sites.

Many previous studies mentioned the use of RWH successfully as an effective alternative water supply solution, or as a mean of reduction of flood risk in urban areas [17,18]. Gupta et al. [19] developed a water harvesting strategy in the semi-arid area of India using a geographical information system (GIS). Topographic and soil information were digitized as a GIS database. Land cover information was derived as Normalized Difference Vegetation Index (NDVI) from satellite images (IRS-1A), and the results showed the importance of GIS in the planning of water harvesting. Jabr and El-Awar [20] introduced a site selection methodology for water harvesting reservoirs in Lebanon to improve agriculture. Mbilinyi et al. [21] identified potential RWH sites using a GIS-based decision support systems and remote sensing data. Sayl et al. [22] used remote sensing and GIS-based multi-criteria decision-making techniques for data-scarce areas to locate suitable RWH sites.

In the past decades, Maysan province witnessed very few researches in RWH, as it was mainly dependent on the surface water of marshes and the Tigris River. However, the increasing danger of drought and water shortage, especially following marshes drainage in the 1990s, suggests RWH as an effective alternative solution. In this context, Al-Abadi et al. [23] conducted a study to identify potential sites for water harvesting in the Northeastern Maysan Governorate using GIS-based fuzzy logic and analytic hierarchy process (AHP). Five criteria were used: soil, land cover, runoff, slope, and distance to the river. RWH suitability levels were classified into five classes: unsuitable, poor, moderate, good, and excellent.

In the last decade, massive interest has been witnessed in the application of remote sensing and geographical information system (GIS) in hydrology and water resources. Digital image processing techniques provide access to Spatio-temporal data on watershed from regional to global scales. New sensors and imaging technology have increased the remote sensing capability in hydrological applications [17]. Previous studies have integrated remote sensing and GIS with good results e.g., [24–28]. GIS-based Multi-Criteria Evaluation (MCE) is one of the effective approaches to analyze the site suitability [29]. Generally, the multi-criteria decision problems include a set of a potential decision alternative that is evaluated based on specific criteria [30]. Over the last decade, many studies have used the MCE in the GIS environment for different purposes e.g., [31–37].

The aim of this study is the selection of the potential RWH locations in Maysan province, south-eastern Iraq, using remote sensing and GIS-based MCE. Fuzzy membership is used for standardization of the criteria and Fuzzy Gamma overlay for criteria combination using ArcGIS 10.5.

2. Materials and Methods

2.1. Study Area

The study area, Maysan province, is located in the south-east of Iraq between longitudes 46°00′–48°00′ E, and latitudes 31°00′–32°40′ N, as shown in Figure 1. It covers a total area of about 16,072 km^2. Tertiary rocks and Quaternary deposits are the primary geological features; Quaternary deposits cover 72% of the area, whereas Tertiary rocks extend over the remaining 28% [38]. More particularly, the Tertiary rocks comprise up to 2000 m of fining upward cycles of gravely sandstone, sandstone, and red mudstone, that become replaced almost entirely by conglomeratic facies in the high-folded zone of the north-east [38]. In contrast, the Quaternary sediments are unconsolidated and usually finer-grained than the underlying Tertiary rocks [39]. The climate in the study area is characterized by hot, dry summers and cold, wet winters. The fall and spring seasons last predominantly few weeks only. The average annual temperature varies between 23.74 °C and 26.43 °C, with very little variation across the area [40]. The study area is an important economic area, where most people work in agriculture, especially crops of grain production and vegetables, mainly tomatoes and potatoes.

2.2. Dataset

The important step in most GIS projects is building the spatial database. In this study, various datasets are used such as Digital Elevation Model (DEM) soil data, Landsat 8 images, and satellite-based climatic data. ArcGIS 10.5 is utilized to process, analyze and interpret these datasets. The Universal Transverse Mercator system, WGS 84 and zone 38 N is used to geo-reference all the criteria layers.

2.2.1. DEM

Elevation data were obtained by the NASA Space Shuttle Radar Topography Mission (SRTM) using InSAR with a spatial resolution 30 m (1 Arc Sec) [41]. DEM provides essential data for the topographical features of a basin, such as a slope, flow direction, flow accumulation, stream order, and catchment area. The D8 algorithm is a very useful method to interpret the elevation data and extract the above-mentioned features. The study area STRM DEM is shown in Figure 2. The topographical elevation for Maysan province ranges between 10 m to 264 m. DEM is employed to derive the stream orders using ArcGIS/hydrology tools based on the Strahler method [42]. The main steps include filling the DEM sink, identify the flow direction using the D8 algorithm by defining the slope direction for each cell, create the flow accumulation raster, and finally derive the stream order. The stream order map is created based on DEM using ArcGIS 10.5 software as illustrated in Figure 3. Additionally, DEM data are used to derive the slope map. The average slope is an independent variable that offers information about the topography. The average slope radically influences the value of the time of concentration and, directly, the runoff generated by rainfall. The slope percent rise map based on DEM data is shown in Figure 4.

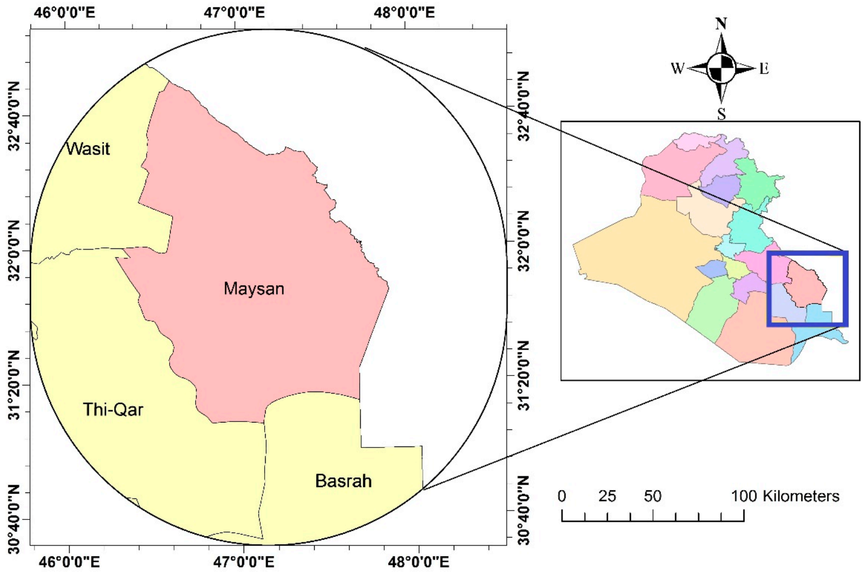

Figure 1. The study area location (Maysan province).

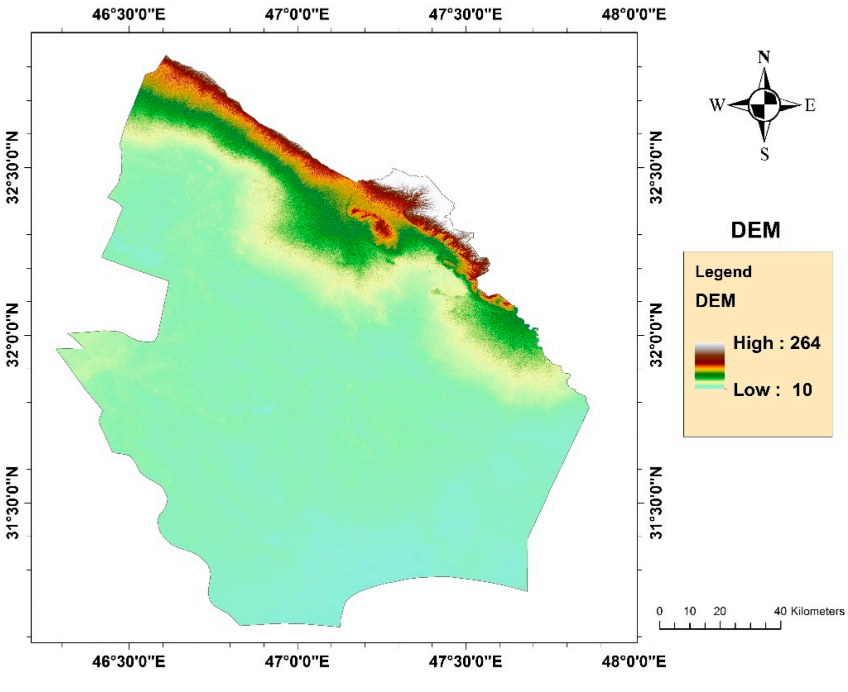

Figure 2. The Digital Elevation Model (DEM) for the area of study.

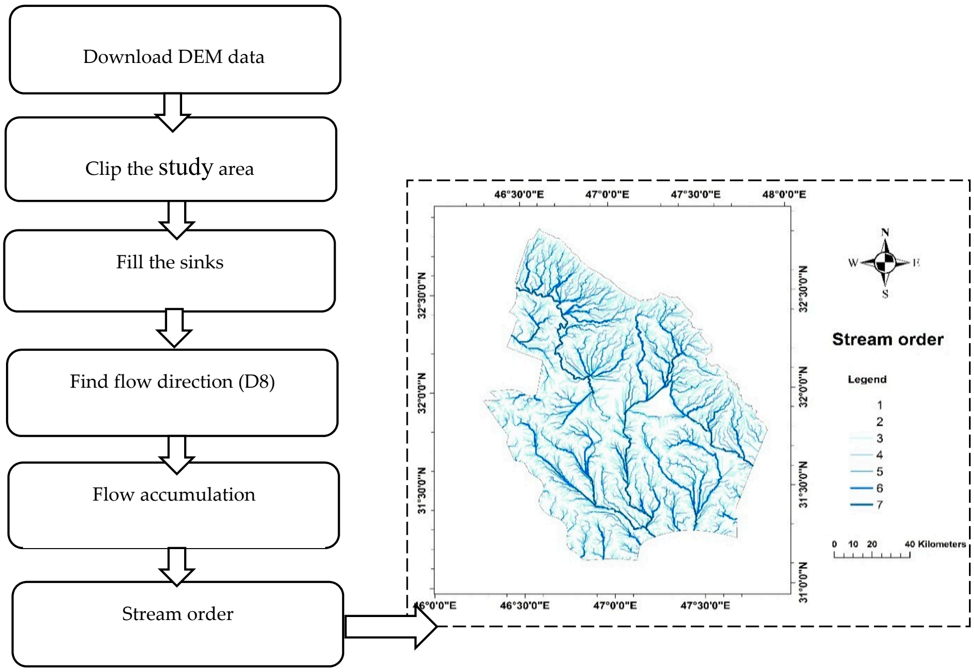

Figure 3. Main steps to derive the stream order based on DEM.

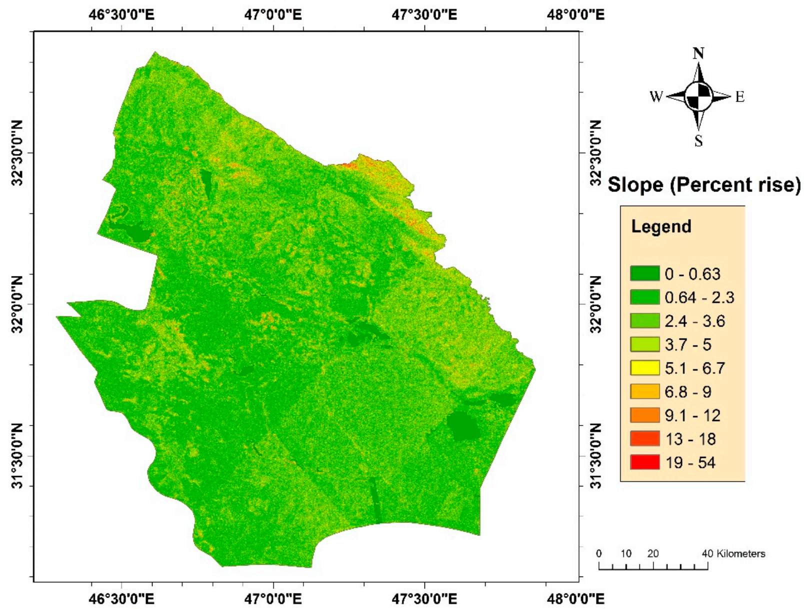

Figure 4. Slope percent rise map.

2.2.2. Satellite-Based Climate Data

Remote sensing rainfall estimation from the Tropical Rainfall Measuring Mission (TRMM) is considered as a potential alternative to supply the rain gauge data with a good spatial distribution [43,44]. The TRMM is a joint U.S.-Japan satellite mission to monitor tropical and subtropical precipitation and to estimate its associated latent heating. Precipitation data for the period January 2000–January 2019, based on TRMM, was downloaded and processed with spatial resolution of 0.25 degrees. Data downloaded in NetCDF form are then converted to shapefile and interpolated using Kriging ordinary/spherical model. Figure 5 illustrates the time-averaged map of the monthly precipitation rate.

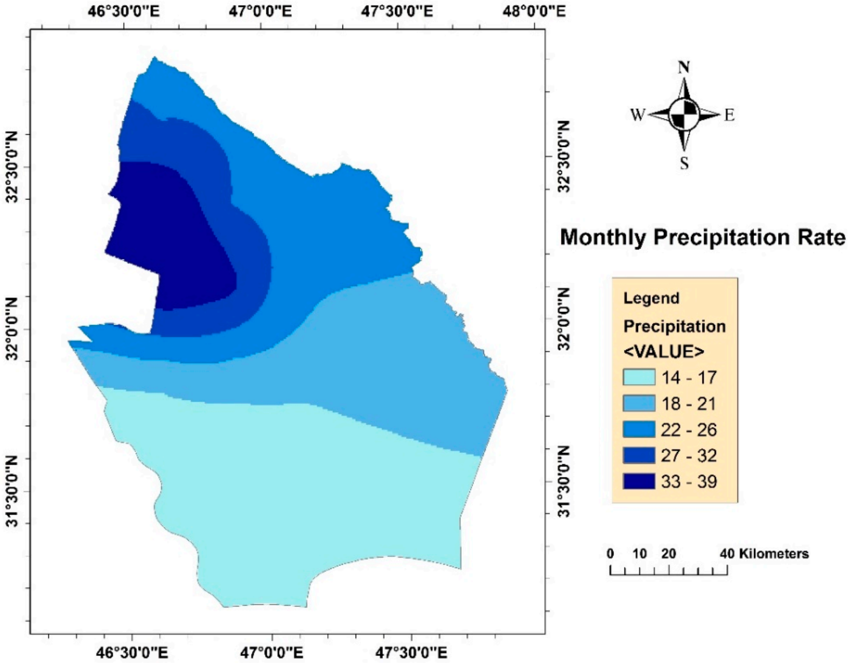

Figure 5. Interpolated map for the monthly precipitation rate based on Tropical Rainfall Measuring Mission (TRMM) data (mm/month).

The monthly potential evaporation rate was downloaded from the Global Land Data Assimilation System (GLDAS) Model _NOAH025-M-2 [45] in W/m^{2}unit for the period January 2000–January 2019, with a spatial resolution of 0.25 degrees. Data downloaded in NetCDF form are then converted to shapefile and interpolated using Kriging ordinary method/spherical model as shown in Figure 6. The goal of the GLDAS is to ingest satellite and ground-based observational data products, using advanced land surface modeling and data assimilation techniques in order to generate optimal fields of land surface states and fluxes [46].

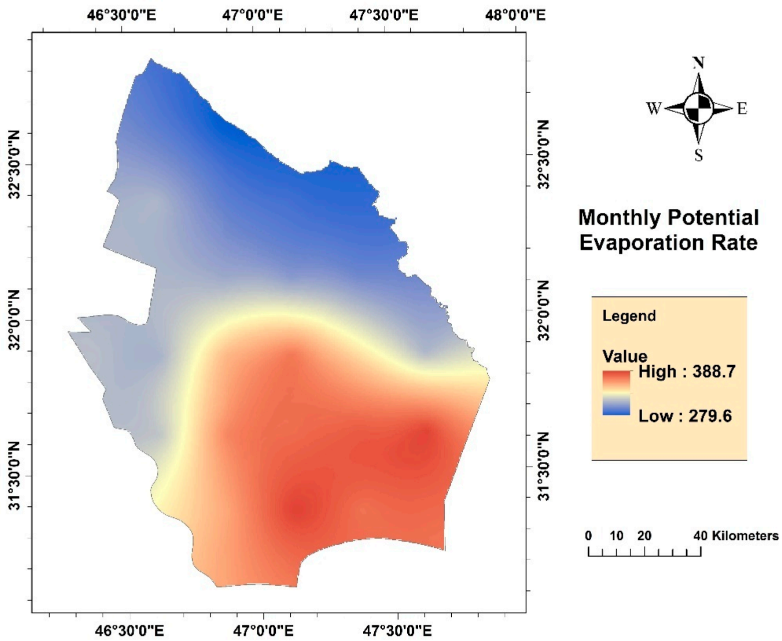

Figure 6. Interpolated map for the monthly potential evaporation rate based on Global Land Data Assimilation System (GLDAS) data.

2.2.3. Land Cover Data

In this study, the Normalized Difference Vegetation Index (NDVI) is used to target agricultural areas and avoid urban areas. It was calculated from a red band and near-infrared (NIR) band of Landsat 8 images. The NDVI is a commonly used vegetation index derived from remotely sensed measurements of electromagnetic energy in the red and near-infrared spectral regions. NDVI is calculated using the Equation [47]:

$$\mathrm{NDVI} = \frac{NIR - VIR}{NIR + VIR} \tag{1}$$

where the typical NDVI values range from −1 to 1, where positive values represent the vegetated areas, while the negative values represent water bodies, snow, clouds, and non-vegetated surfaces [48]. Three Landsat 8 images for March/2019 are used to obtain the NDVI layer using Equation (1). As shown in Figure 7, the NDVI values vary between −3 to 0.6.

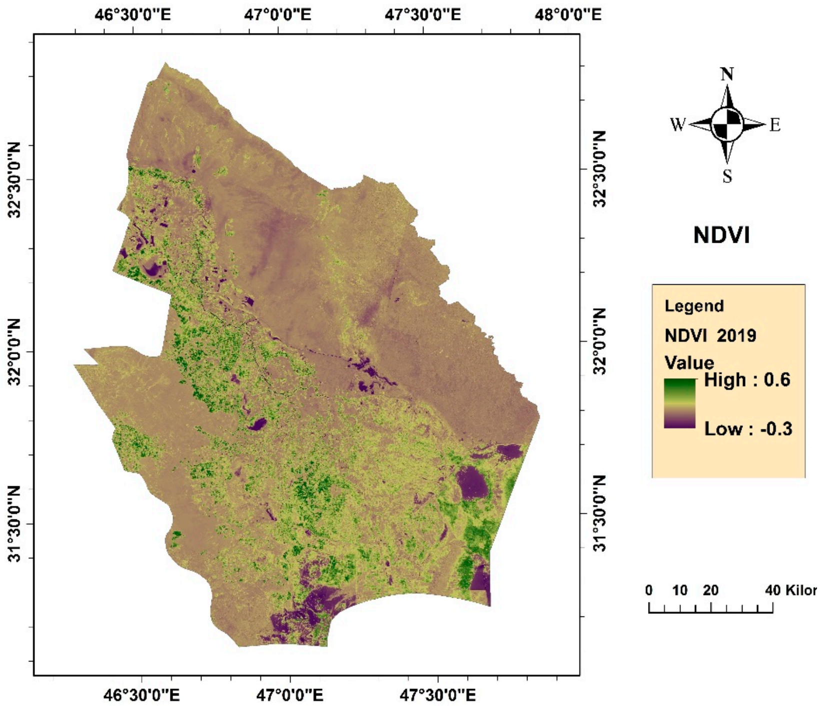

Figure 7. Normalized Difference Vegetation Index (NDVI) layer, based on Landsat 8 images.

The Euclidean Distance function is used to determine the distance to roads. The Euclidean distance is the straight-line distance between two points on a plane. As shown in Figure 8, the Euclidean distance values vary from 0 to 25,000 m.

Soil type map was acquired from the Food and Agriculture Organization (FAO). Four soil classes are noted in the study area; namely young soils in alluvial deposits, saline soils, soil with very limited soil development, and sand dunes, as shown in Figure 9.

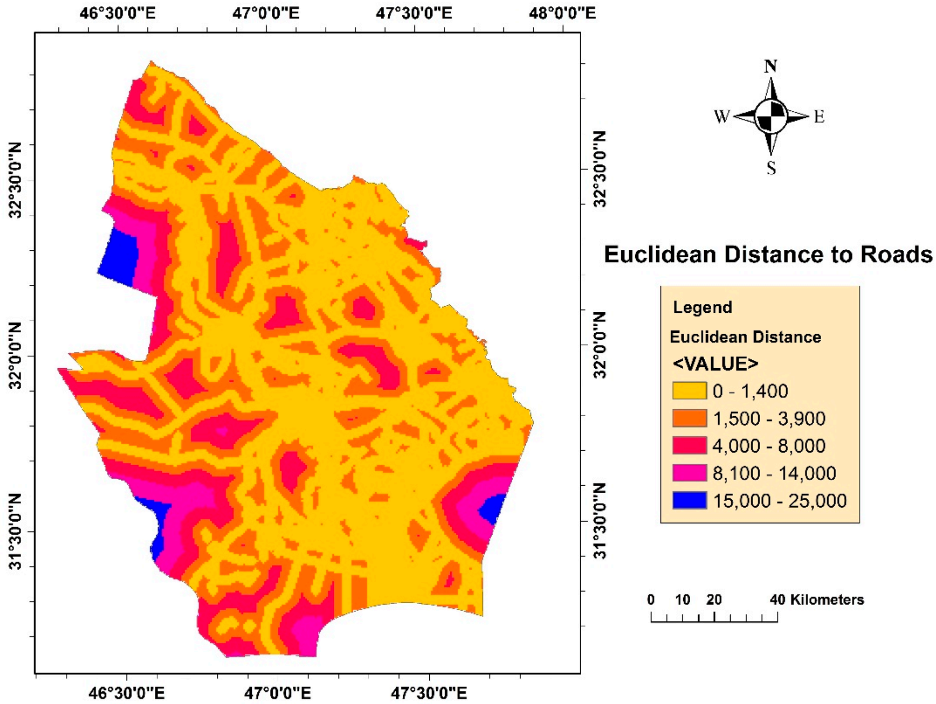

Figure 8. The roads raster using Euclidean distance function.

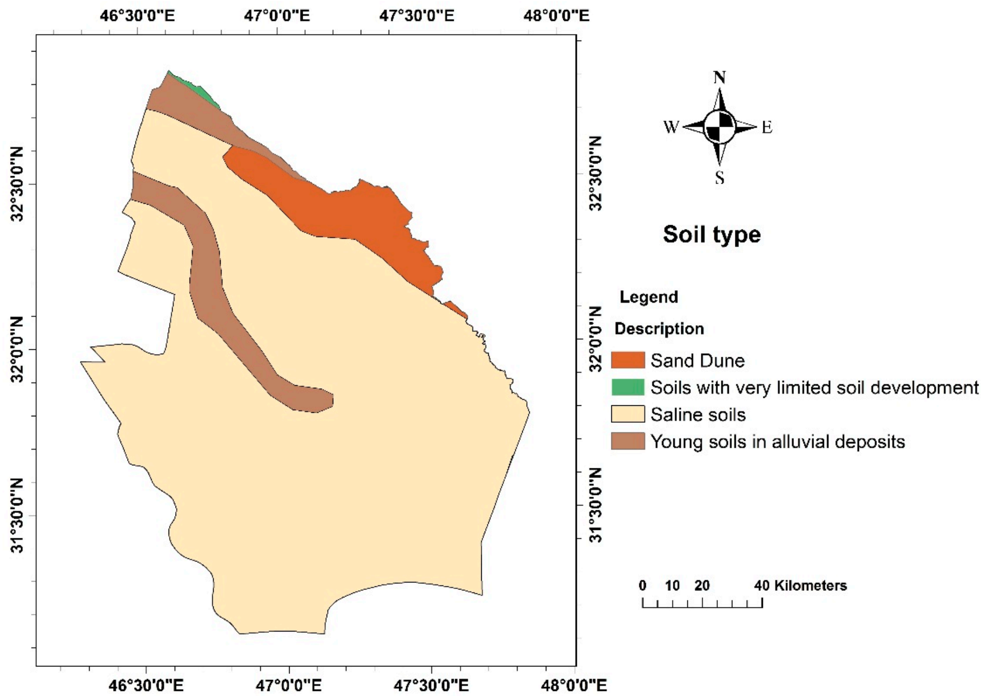

Figure 9. Food and Agriculture Organization (FAO) soil map.

2.3. Multi-Criteria Evaluation

GIS-based MCE analyzes the suitability to fit a specific objective based on various criteria in selected areas [49]. The criteria are called factors and reflect a different degree of suitability for the decision under consideration. The standardization process involves converting the data to a uniform numerical scale [50]. In this study, MCE is performed to identify the potential RWH site, based on a number of criteria and constraints. Seven criteria are chosen, namely, slope, roads, NDVI, stream order, precipitation, evaporation, and soil. These criteria are standardized using Fuzzy membership to convert the criteria layers to a uniform numerical scale range between 0 and 1. Then the Fuzzy Gamma overlay method was applied to produce the final suitability map.

2.4. Fuzzy Logic

2.4.1. Fuzzy Membership

The Fuzzy Logic method is generally used to solve complex topics, and it was first proposed by Zadeh in 1965 [51]. Fuzzy membership enables the operator to decide the suitability of a site. It reclassifies the input data into a range between 0 and 1, depending on the possibility of being a member on a specified set. A zero value is assigned to the locations that are definitely not a member, while one value is assigned to the locations that are definitely a member of a specified set. The entire range of possibilities between 0 and 1 are assigned to some level of possible membership. Fuzzy membership types are Fuzzy Gaussian, Fuzzy Large, Fuzzy Linear, Fuzzy MS Large, Fuzzy MS Small, and Fuzzy near. In this study, Fuzzy Linear membership (FLM) is used to standardize all the criteria layers.

2.4.2. Fuzzy Overlay

The final stage to apply the Fuzzy logic to the criteria layers is the Fuzzy overlay. There are five types of Fuzzy operators, namely, Fuzzy OR, Fuzzy AND, Fuzzy algebraic sum, Fuzzy algebraic product, and Fuzzy Gamma operator. Fuzzy Gamma is used in this study to combine the criteria layers. Fuzzy Gamma establishes the relationships between the multiple input criteria and does not simply return the value of a single membership set, as does Fuzzy OR and Fuzzy AND [52]. The output value is always larger than (or equal) to the largest contributing Fuzzy membership value. The methodology flowchart using the Fuzzy Gamma overlay is illustrated in Figure 10.

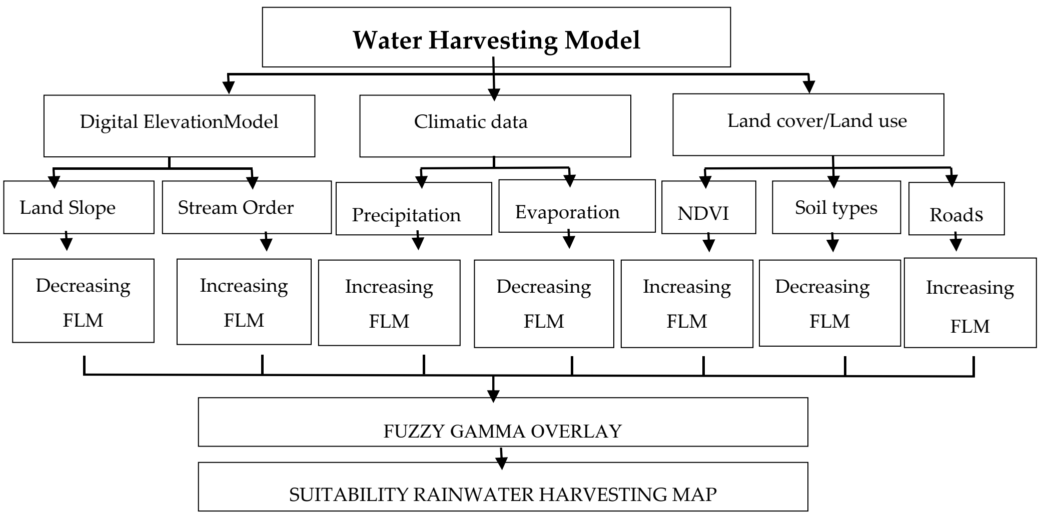

Figure 10. Rainwater harvesting model using Fuzzy Gamma overlay.

2.5. Criteria Identification

The selected criteria describe the factors which define the best site for harvesting rainwater. In this study, seven criteria layers, including slope, stream order, soil type, precipitation, evaporation, roads, and NDVI are selected from the literature reviews and the researches of different scientists, taking into account the generality in the references and the data available in the studied area. Table 1 illustrates the criteria specification used to identify the potential RWH site for this study. The criteria constrain details are as follows:

Table 1. Criteria specification for the rainwater harvesting (RWH) model.

No.	Criteria	Source	Criteria	FLM
1	Slope	DEM	<5%	Min = 5% Max = 0%
2	Stream order	DEM	>3rd Order	Min = 3rd Max = 7th
3	Precipitation	TRMM	Maximize	Min = 14 Max = 39
4	Evaporation	GLDAS	Minimize	Min = 388 Max = 279
5	NDVI	Landsat 8	> 0	Min = 0 Max = 0.6
6	Soil	FAO	Minimize	Min = 2 Max = 1
7	Roads	shapefile	>100 m	Min = 100 Max = 25,000

The slope is an essential criterion in RWH structure site selection; it determines the size of the harvesting structure and the water storage quantity. High slope areas are unsuitable for storage structures, as a large structure (in terms of height) is needed for the storage of a significant amount of water. Medium or low slope areas are more convenient, as a large storage capacity can easily be contained in smaller structures. According to Critchley et al. [53], areas with a slope more than 5% are not recommended for RWH, due to irregular runoff distribution and economical loss resulting from excessive earthwork required.

Stream order is dependent on tributaries connection. Its analysis is important to select a potential RWH site, and a lower stream order means higher permeability and infiltration [54]. In this study, the spatial analysis tools are used to derive and produce the stream order map based on DEM data. According to AL-Ardeeni [55], the stream order must be higher than the third order.

Precipitation is the major component in any water harvesting systems. More precipitation in any particular area means higher possibilities of harvesting part of it [56]. The availability of precipitation data collected over many years is crucial for the determination of the rainfall-runoff potential of a given region. This is particularly true in arid and semi-arid regions, where precipitation varies considerably from year to year. However, average precipitation can still be used in areas with insufficient precipitation data [57]. Additionally, evaporation from the ground is one of the essential sources of water loss that affect the RWH process, low evaporation rate is a good indication of the area's suitability for water harvesting [57].

Roads network expansion should be considered in the planning of RWH projects. Inhabitants use these roads to move with their livestock searching for grass and water. The distance between RWH structure and roads is to prevent any future conflict between the constructed ponds and roads development [56]. According to AL-Ardeeni [55], the minimum acceptable distance to roads is 100 m.

Vegetation strongly affects surface runoff. The density of vegetation in a given area can be determined in a variety of ways; remote sensing is particularly useful if the project area is large. Remote sensing uses the different reflectance of soil and vegetation as an indicator of the density of the vegetation [58]. Vegetation cover affects the water harvesting land suitability. Harvesting in inhabited cropped areas is more practical than relocating the inhabitants to a suitable potential area. [57].

Soil type is an important factor in selecting RWH site for providing water for human, livestock and agricultural purposes [56]. According to Critchley et al. [53], a serious limitation for the application of water harvesting is soil with a sandy texture.

3. Results and Discussion

3.1. Criteria Standardization

For the application of the Fuzzy overlay, the criteria layers must be on the same scale and units [59]. Additionally, the vector layers (like soil and roads) must be converted to raster format. Figure 11 shows layers standardizations using Fuzzy Linear membership (FLM).

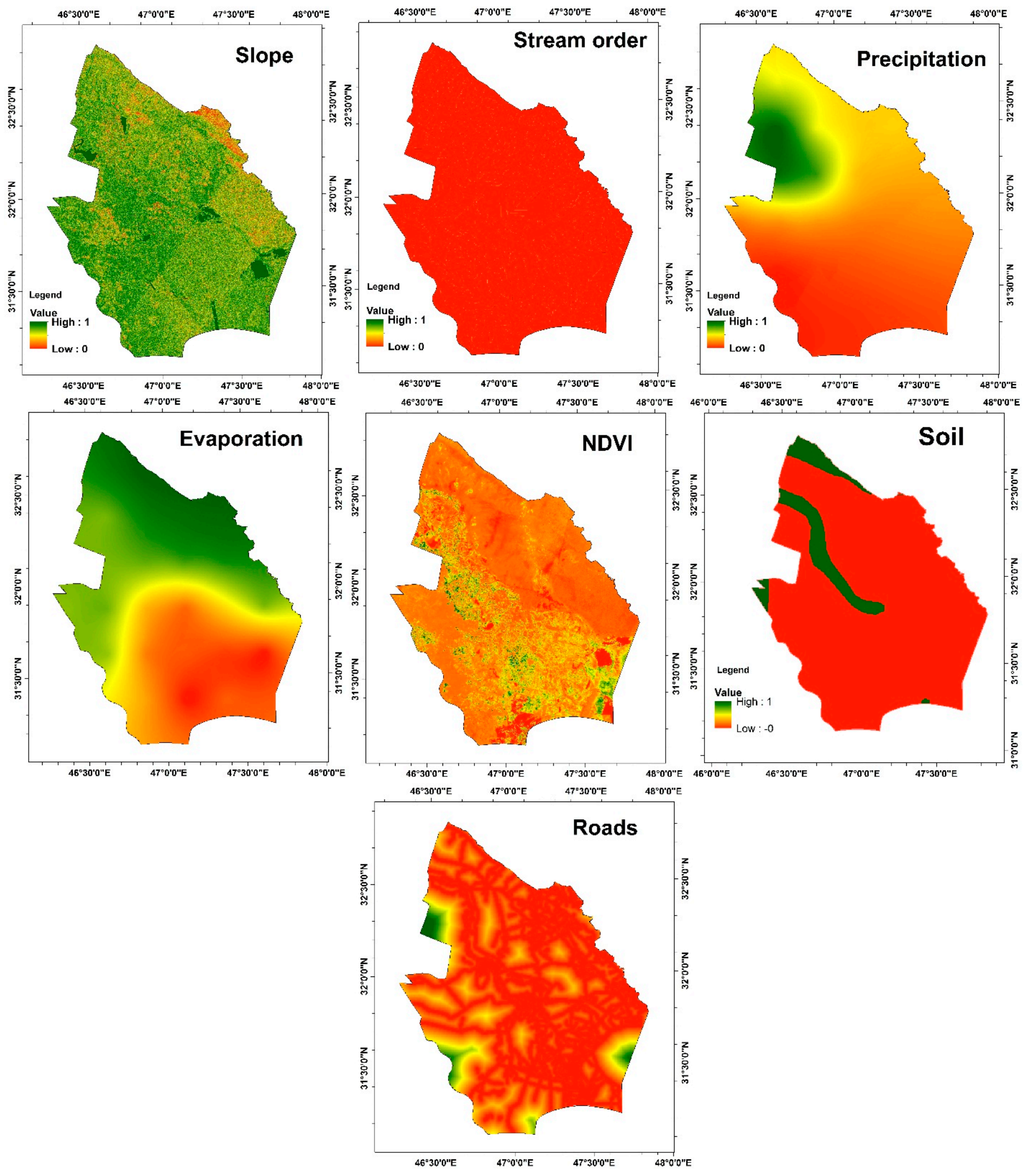

Figure 11. Criteria layers standardization using Fuzzy Linear Membership (FLM).

The slope is the surface gradient and is generally expressed as a percentage, it is vital for the formation of soil, as it affects the runoff and drainage. In this study, the slope values varied between 0-100. The slope layer was standardized using the decreasing FLM; the maximum value was set as zero, while the minimum value as 5%. The standardization slope layer values range between one and zero, the suitable area was indicated by one value, whereas zero indicates an unsuitable area. Additionally, DEM is used to derive stream order. The stream orders varied from first to seventh order. The stream orders constraint is the value higher than the third order. The increasing FLM was applied for standardization of the stream order layer; only higher orders were taken into consideration to select the suitable RWH sites. The maximum value was set as seventh order while the minimum value as third order.

The TRMM data are used to produce the monthly precipitation rate map. The precipitation values ranged from 14 to 39 mm/month. The increasing FLM was used to standardize the precipitation layer. The maximum value was set as 39, while the minimum value as 14. Moreover, the monthly potential evaporation rate was downloaded from GLDAS, the evaporation values ranged between 279–388 W/m^2. The decreasing FLM was used to standardize the evaporation layer. The maximum value was set as 279, while the minimum value as 388.

NDVI layer was obtained based on Landsat 8 images, the NDVI values varied from −0.3 to 0.6. According to the NDVI typical values, in order to target the vegetation areas, only the positive value must be considered. The increasing FLM was used to standardize the NDVI. The maximum value was set as 0.6, while the minimum was zero.

Soil layer was downloaded from FAO maps, in a vector form, then converted to raster. Decreasing FLM was used to standardize the soil layer. The young soils in alluvial deposits was set as one, while Saline soils as zero. Soil with very limited development and sand dunes were excluded.

The distance to the roads layer was generated using the Euclidian distance. Its value varied between 0 to 25,000 m. The road layer was standardized using the increasing FLM, the maximum distance was set as 100 m, while the minimum as 25,000 m.

3.2. Sites Selection

The final step after standardization of the seven criteria layers is collecting them together. These layers were combined, and the probable RWH sites in the south-east part of Iraq (Maysan Governorate) were selected using the Fuzzy Gamma overlay/0.9 operation. This study revealed that the north-western part of the studied area is a suitable area for RWH, whereas other parts are classified as unsuitable zones for RWH. The RWH suitability map displays a varied range of suitability of 0% to 56%; this range is classified into five classes, as shown in Figure 12. To limit the potential sites in the study area, only the higher values (represented in the fifth class) were considered, resulting in eleven sites. These sites were digitized and presented in Figure 13. The proposed potential RWH sites coordinates are shown in Table 2. The suggested type of RWH is retention ponds by topographical terrain and soil permeability, presumably used for watering livestock, groundwater recharge, irrigation, or any other purpose other than potable uses.

Table 2. Proposed RWH sites coordinates.

Point	Latitude	Longitude
1	653,779	3,618,370
2	648,232	3,622,110
3	647,583	3,627,010
4	647,029	3,595,310
5	651,959	3,589,110
6	652,033	3,585,900
7	656,365	3,584,250
8	657,933	3,579,920
9	664,084	3,561,660
10	669,681	3,554,780
11	667,204	3,548,170

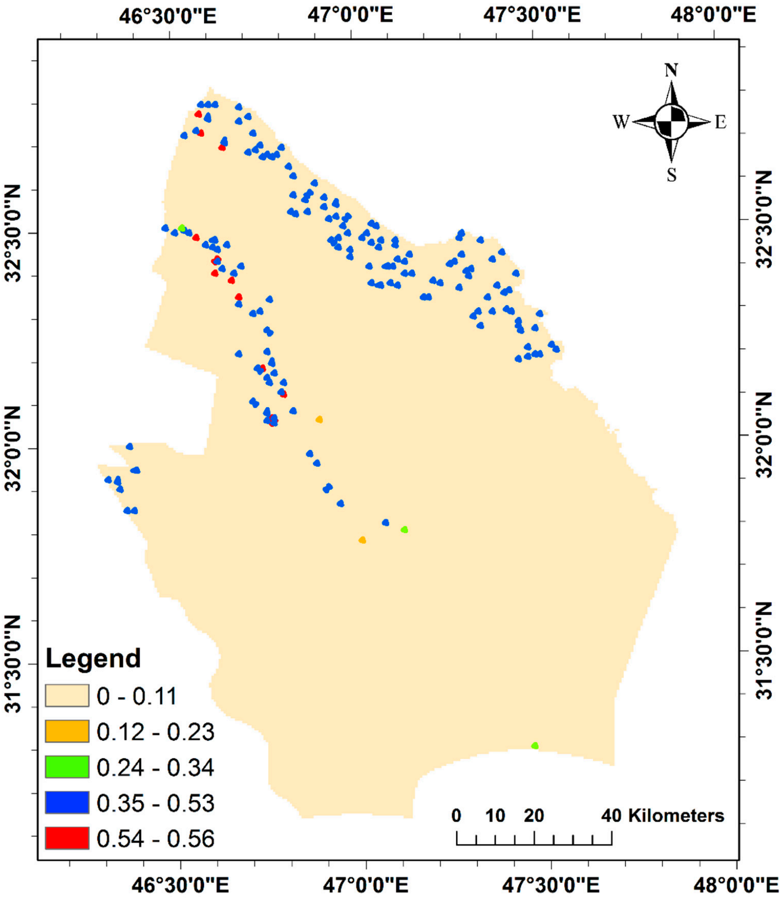

Figure 12. RWH map using Fuzzy Gamma overlay.

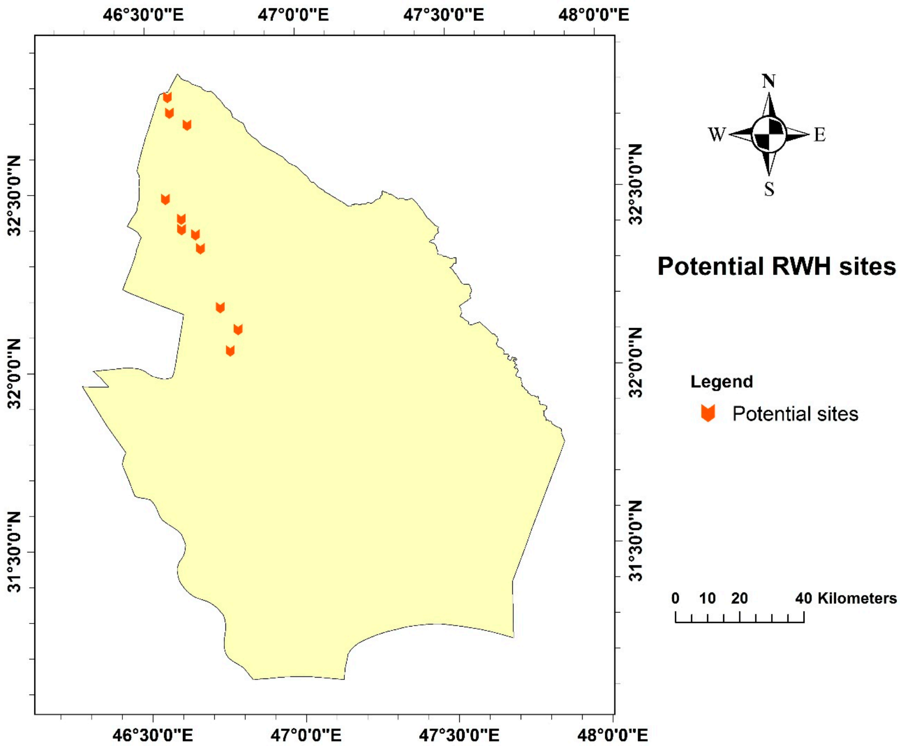

Figure 13. Potential rainwater harvesting sites.

4. Conclusions

Rainwater harvesting is a promising technique for the effective management of water scarcity problems by enhancing water supplies in the long-term. In this context, the present study shown a methodology for RWH potential site selection using GIS-based MCE and fuzzy model in the south-east part of Iraq (Maysan Governorate). The suggested RWH type is retention ponds by topographical terrain and soil permeability. Seven criteria layers, including slope, stream order, soil type, precipitation, evaporation, roads, and NDVI were used for this purpose. Fuzzy Linear membership is used for standardization of these layers, and Fuzzy Gamma overlay to combine them. Based on the results of this study, the north-western part of the study area is suitable for rainwater harvesting. Eleven potential sites, expected to have a high potential for RWH, were selected according to the purpose criteria. Iraq is in urgent need for scientific tools that help the plan-makers at various levels of government to combat water shortage, and to save the money and time needed to select the best RWH sites. The final map could be of help to decision-makers, investors, and other stakeholders to enhance water resource management by choosing suitable locations for RWH, and to conserve water spatially in arid and semi-arid regions.

Author Contributions: Methodology Imzahim A. Alwan; Nadia A. Aziz; Software Nadia A. Aziz; Formal Analysis Mustafa N. Hamoodi.; Writing-Original Draft Preparation, Nadia A. Aziz; Writing-Review & Editing, Imzahim A. Alwan; Mustafa N. Hamoodi. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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