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SELECTION OF RAINWATER HARVESTING SITES BY USING REMOTE SENSING AND GIS TECHNIQUES: A CASE STUDY OF KIRKUK, IRAQ

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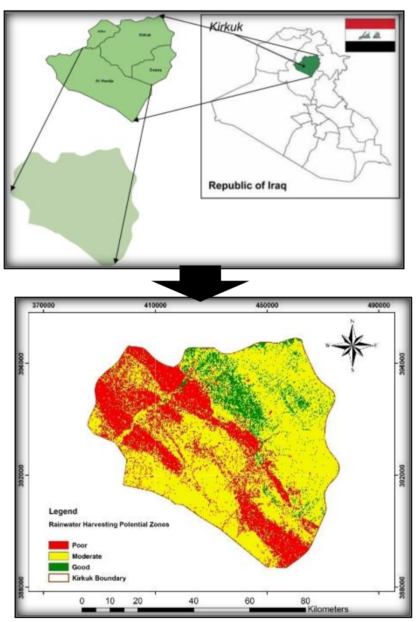
Graphical abstract



Abstract

Arid and semi-arid areas such as Iraq suffer not only from limited precipitation but also from poor management of rainwater for agricultural use. One technique for rainwater harvesting (RWH) is to collect excess runoff water during the rainy season and store it for agricultural purposes during dry spells. Remote sensing (RS) and geographic information systems (GIS) are widely used to identify suitable RWH sites. In this study, an integrated approach was adopted to determine suitable RWH sites in Kirkuk City, Iraq. The methods were integrated with the multi-criteria decision analysis (MCDA) method to evaluate the parameters that significantly contribute to RWH site selection. Thematic layers, such as runoff depth, slope, drainage, and land use/land cover, as well as their features were assigned suitable weights and then integrated in a GIS to generate a RWH potential map of the study area. Suitable sites for different RWH structures, such as farm ponds and check dams, were also identified. The study area can be classified into three potential RWH zones: high suitability zone (8.2% or 399.75 km^2), moderate suitability zone (63.4% or 3,090.75 km^2), and low suitability zone (28.4% or 1,384.5 km^2). Around 3.7% of the study area (181.6 km^2) is suitable for farm ponds while 4% (197 km^2) is suitable for check dams. The integrated RS, GIS, and MCDA techniques were found to be a cost-effective and environmentally friendly way to recover rainwater and select suitable RWH sites.

Keywords: Rainwater harvesting, remote sensing and geographic information system, multi-criteria decision analysis

1.0 INTRODUCTION

Rainwater harvesting (RWH) has become an increasingly important practice because of global warming and the depletion of fresh water sources. The scarcity of fresh water has resulted in the need to identify and utilize other fresh water sources that could satisfy the growing water demand. Another issue is the drainage and contamination of groundwater, which has given rise to the requirement of recharging groundwater [1] [2]. RWH is the process of gathering and storing rainwater for later beneficial utilization. Collected rainwater is stored in tanks, ponds, and underground storages of groundwater. Many academicians, specialists, and non-specialists have promoted the use of RWH techniques because of their low cost and simple implementation in addressing the water crisis and other water-related emergencies [3], [4]. RWH is one of the artificial recharge techniques used in water resource management around the world. In general, RWH involves storing runoff to recharge shallow groundwater aquifers by using RWH techniques [5], [2]. RWH has several advantages [6], [7], [8]. For instance, rainwater is a clean and free source of water. Its harvest and use in crop planting is beneficial because it is not chlorinated. Moreover, rainwater can supplement existing water supply, such as groundwater and metropolitan water. It also reduces water supply costs, satisfies basic water needs, and supports environment protection efforts. As cited in [9], RWH is adjusted in arid and semi-arid areas where the amount of rainfall is inadequate to maintain decent yields and field growth. In inclined areas, RWH can fundamentally increase plant growth during dry seasons by directing rainwater/runoff in the total area. In Kirkuk City, Iraq, residents do not have access to a permanent source of water supply and thus depend on rainwater and groundwater for their daily activities. The groundwater table in Kirkuk has gradually dropped because of climate change and the indiscriminate digging of wells by farmers. This situation highlights the need to establish a system for storing water from precipitation, which can then be utilized as a supplemental water source during dry seasons.

Several factors influence the selection of suitable RWH sites. One critical factor is the land slope [2], [10], [11], [12]; other factors include land use [4], [11], [12], [13], [14] and soil type [4], [12], [13], [15]. Runoff potential and proximity to utility points (e.g., irrigation and drinking water supply schemes), geology, and drainage beside the land slope, land use, and soil type are also considered as criteria to identify suitable RWH sites [13]. In [4], rainfall, soil depth, and other ecological and socio-economic factors, in addition to the abovementioned factors, were used in the selection of RWH sites. In [10], porosity and permeability, runoff potential, stream order, and catchment area were adopted as criteria to select suitable sites for various RWH/recharging structures. In the UK [16], suitable RWH zones were identified using a geographic information system (GIS)-based decision support system (DSS) and remote sensing (RS). Specifically, the authors used combinations of thematic layers, including rainfall surplus, slope, curve number (CN), land use/land cover (LULC), and soil texture, in the DSS. Another work adopted a GIS-based DSS [8], together with remotely sensed data, and limited field survey to delineate the best suitable locations for RWH. In a study on Iraq, specifically Erbil [17], suitable RWH zones were identified by using GIS and multi-criteria evaluation (MCE). An analytic hierarchy process (AHP) method was employed to estimate the weight of each factor.

MCE has also been used by other researchers. For instance, the authors in [12] adopted MCE to determine the optimum locations for RWH structures in the Pisangan watershed of the Ajmer District. In this research, different layers were investigated to assess the weights of the criteria, which included soil texture, slope, rainfall data, LULC, geomorphology, lithology, lineaments, and drainage streams. In [18], the researcher identified potential RWH sites in the "Eight Communities of the Chianti" area.

A procedure that considers continuous runoff potential has been integrated into GIS frameworks to estimate the runoff potential of an area. In [19], the Soil Conservation Service Curve Number (SCS-CN) was used as an efficient method to identify the potential runoff zones in a semi-arid area, and potential RWH zones were found.

In the present work, we aim to identify suitable RWH sites in Kirkuk City using RS and GIS techniques. The results of this study can benefit decision makers as they establish water management plans for Kirkuk with the aid of multi-criteria decision analysis (MCDA) and ultimately resolve the water scarcity in the city. The optimum locations of RWH construction sites are determined in this study.

2.0 STUDY AREA

Kirkuk is located in the northern part of Iraq, specifically between the Zagros Mountains in the northeast, the Lower Zab and Tigris Rivers in the west, the Hamreen Mountains in the south, and the Dyala River in the southwest. The average elevation is 331 m, the latitude is 35 28N, and the longitude is 44 24E. Kirkuk is also approximately 250 km (155 m) away from Baghdad. The governorate is relatively small, as it covers a land area of only 9,679 km^2, which represents 2.2% of the total land area of Iraq. Iraq's northeastern highlands begin in southern Kirkuk and extend toward the Iraqi borders with Iran and Turkey. The other three districts of Kirkuk are Daquq, Al-Hawiga, and Dibis. In 2007, the Iraqi government estimated the population of Kirkuk at 902,019, or about 3% of Iraq's total population. Kirkuk features a hot semi-arid climate with extremely hot and dry summers and cool, rainy winters. The study area lies in the central and northern parts of Kirkuk with an area of 4,875 km^2 (Figure 1).

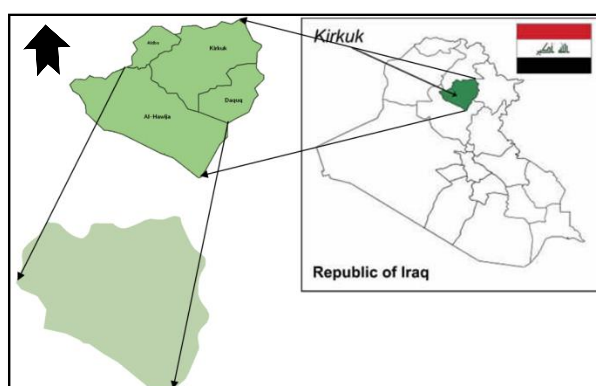


Figure 1 Study area (Kirkuk, Iraq)

3.0 METHODOLOGY

3.1 Data Collection

RS and ancillary data on the study area were collected from different Iraqi governmental agencies. A Landsat 8 image (spatial resolution of 30 m) of the study area was acquired on February 28, 2015. The digital elevation model (DEM, 30 m × 30 m) used in this study was adopted from the DEM model of the Shuttle Radar Topography Mission (SRTM) of the United States Geological Survey (http://www.usgs.gov/). Climatological data (average rainfall data) covering a 15-year period (2000–2014) were collected from the Iraqi Meteorological Organization and Seismology. An exploratory soil map of Iraq at a 1:000,000 scale was obtained from the Ministry of Agriculture of Iraq.

3.2 Selection of Thematic Layers

On the basis of the literature on identifying suitable RWH sites, thematic layers were selected using the available data. In this study, the following four criteria were adopted to determine the suitable RWH regions in Kirkuk: runoff, slope, drainage, and LULC. Rainfall is the primary factor that generates runoff depth along with other factors [12]. LULC is the main criterion for surface runoff generation [14]. Different LULC classes, such as bare soil, farmland, grassland, water body, and built-up area, have different effects on the generation of runoff depth and the calculation of CNs. Slope is an important criterion for mapping and implementing RWH technology, and drainage plays a vital role in RWH [20]. According to the literature, the suitability of zones for RWH increases when land slope decreases, and vice versa. The most important layers are runoff depth, slope, and drainage density. The suitability of zones for RWH increases when drainage density decreases [21]. As for soil type, it remains an important factor in RWH planning; specifically, soil type maps can be used as basis in determining the infiltration characteristics and soil texture of a certain area [16].

3.3 Thematic Layer Preparation

Four thematic layers were produced in the ArcGIS 10.3 and ENVI 5.1 software. As several zones lacked point measurements of rainfall, we used an inverse distance weighting (IDW) algorithm to estimate the amount of rainfall in the study area. The interpolation result revealed that the average annual rainfall of the study area was 360 mm for the period of 2000–2014. To increase yields economically, the amount of normal precipitation should be between 300 and 600 mm annually [22] [23]. Figure 2 illustrates the average rainfall in the study area for the period of 2000–2014.

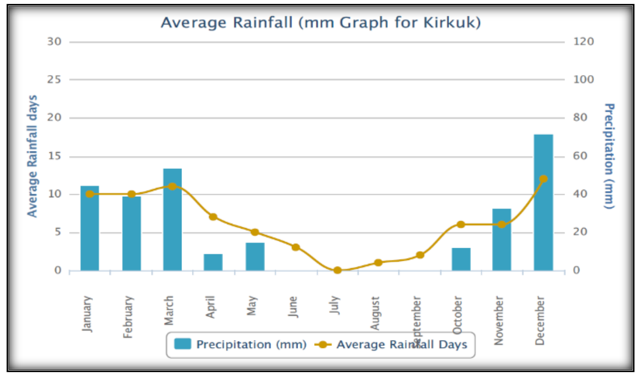


Figure 2 Average rainfall in the study area in 2000–2014

The slope of the study area was derived from the SRTM DEM downloaded from the United States Geological Survey website. According to the FAO slope classification, five slope classes exist in the study area. Figure 3 shows the percentage of slope classes.

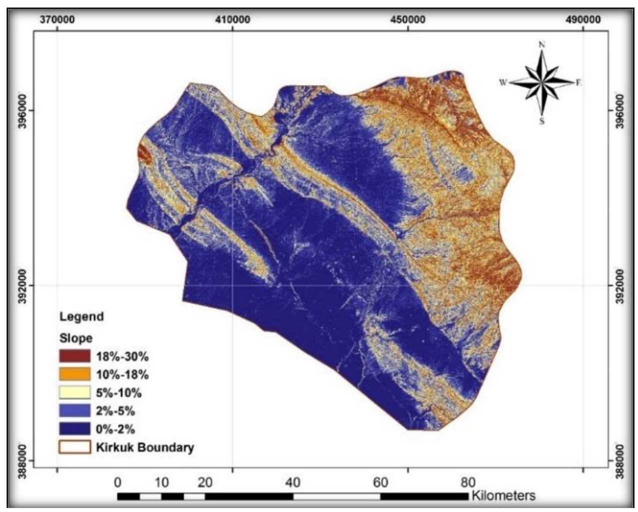


Figure 3 Slope classification map of the study area

The digitizing and georeferencing of the soil map was performed in the ArcGis 10.3 software. The resulting soil map was then converted to a vector layer. Many hydrological factors, such as drainage, flow accumulation, and slope, can be derived from DEMs using ArcGIS 10.3. Figure 4 presents the distribution of drainage streams in the study area. Drainage streams play a crucial role in identifying RWH sites.

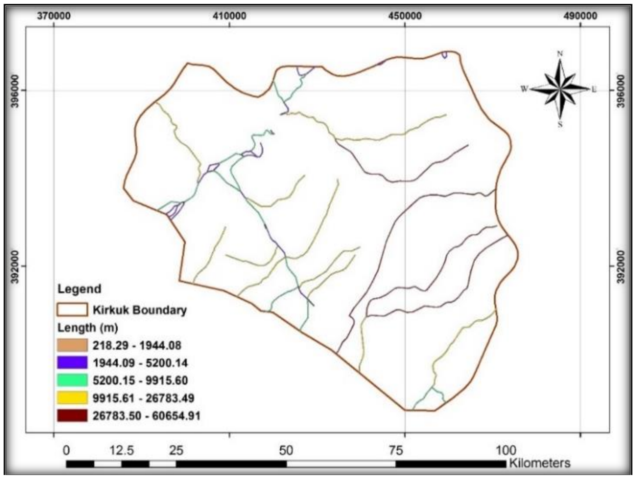


Figure 4 Drainage (streams) of the study area.

LULC was classified by conducting a supervised classification in the ENVI 5.1 environment. A maximum likelihood algorithm was used to classify the Landsat image, as shown in Figure 5. The training sites were obtained from Google Earth with high resolution to achieve an accurate assessment.

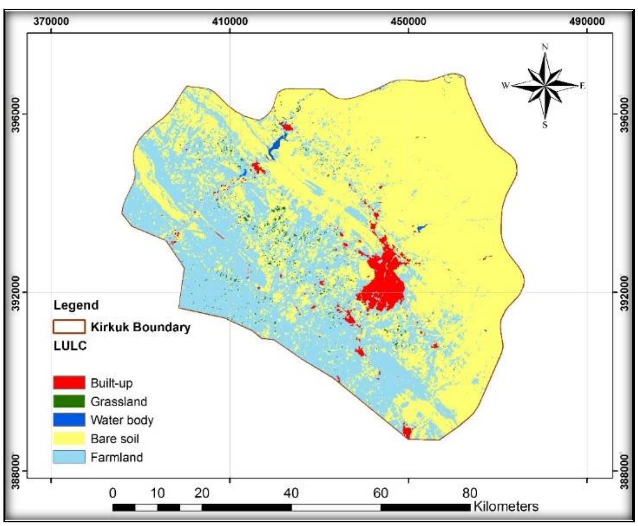


Figure 5 Land cover/land use in the study area.

3.4 Estimation of Runoff Depth

Runoff depth is an important factor in identifying RWH sites. It is used to estimate the water supply during a water event. The Soil Conservation Service model can be expressed mathematically according to Equation (1) [26] to calculate the runoff depth within the GIS environment:

$$Q = \frac{(P - I_s)^2}{(P - I_a) + S} \qquad (1)$$

where *Q* is the runoff depth (mm), *P* is the amount of rainfall (mm), *S* is the potential maximum retention after runoff starts (mm), and I_a is the initial abstraction (mm).

$$S = \frac{25400}{CN} - 254 \qquad (2)$$

CN was estimated per pixel in the study area by matching the soil map and LULC inside the GIS environment with vector data layers. Prior to the estimation, the soil types were classified in the hydrological soil group on the basis of soil texture and the infiltration rates for each soil type. CNs are dimensionless and range from 1 and 100. A CN of 100 indicates low rainfall infiltration and high runoff value, whereas a CN of 1 indicates high rainfall infiltration and low runoff value. The maximum potential retention (*S*) for each pixel, which indicates the initial abstraction of rainfall via vegetation and soil, can be calculated by using Equation 2. We could then easily calculate the runoff depth by utilizing Equation 1. The calculated runoff depth ranged from 160 mm to 490 mm a year, as illustrated in Figure 6 [12], [24].

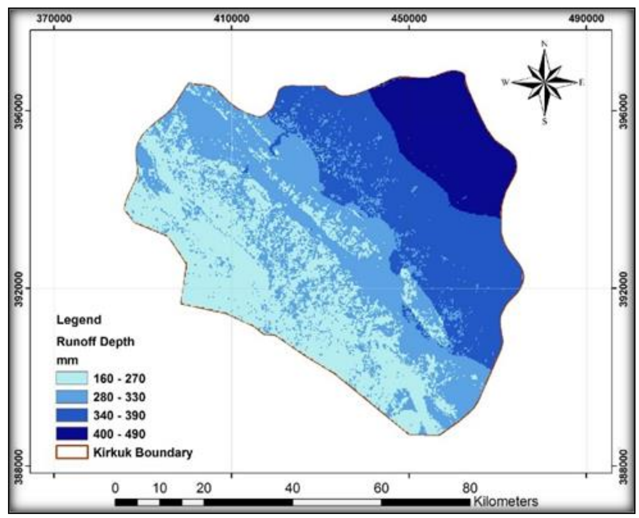


Figure 6 Runoff depth potential map for the study area

To ensure the suitability of zones for RWH, the minimum value of runoff depth should be 300 mm per year [25], [17] .

3.5 Rainwater Harvesting Potential Suitability Map

The overall process of identifying RWH sites is illustrated in Figure 7. The SRTM DEM was used to extract the land slope and drainage characteristics of the study area. Satellite image (Landsat OLI) data were used to produce an LULC cover map of the study area. This map was then used with the soil map to produce the CN layer. The CN layer was in turn utilized to estimate the runoff depth in the study area. All the produced layers were combined with the weights from the literature to produce the RWH potential suitability map.

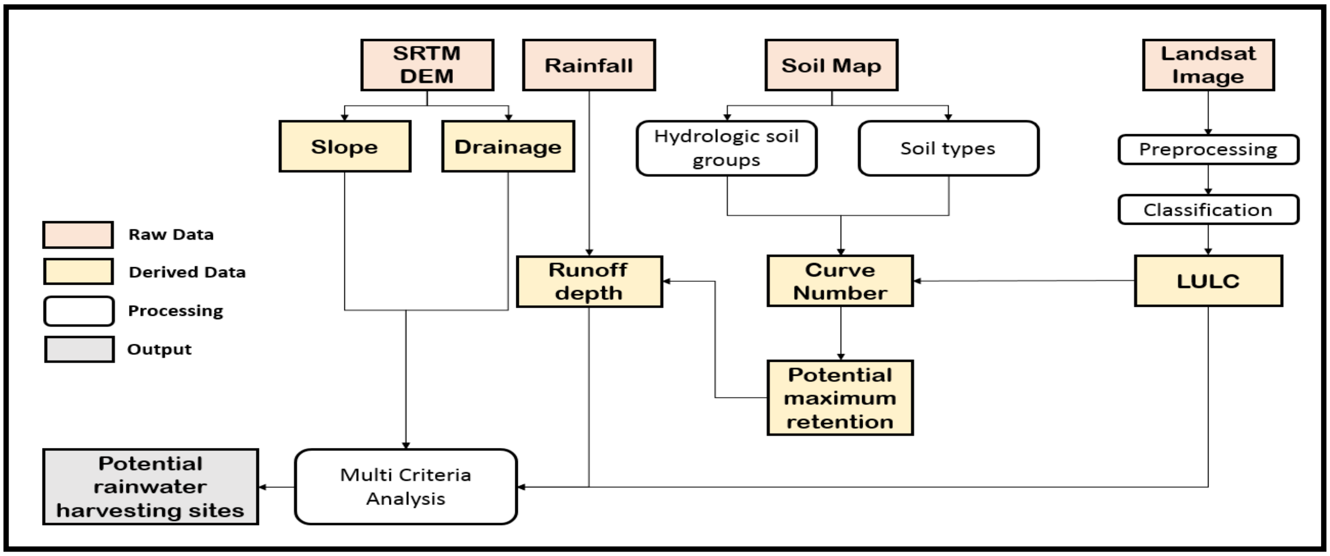


Figure 7 Overall process for identifying potential RWH zones

AHP-based multi-criteria decision analysis and GIS techniques were used in this study to delineate the RWH potential suitability map of the study area. The selected thematic layers (runoff depth, slope, drainage, and LULC), as well as their features, were assigned weights on a scale of 1 to 9 [27]. While assigning the weights, the influence of each thematic layer and its feature on the potentiality of harvesting rainwater was considered. Once the weights of the four thematic layers and those of their features were finalized, pairwise comparison matrices of the assigned weights were constructed using the AHP method. The consistency ratio of this study was 2 %, which is less than 10% and thus indicates that the comparison between the factors is acceptable. Table 1 shows the pairwise comparison matrix for identifying RWH zones and the weight of each criterion.

Table 1 Pairwise comparisons among objectives/alternatives

Criteria/factors	Runoff depth	Slope	Drainage	LULC	Weights
Runoff depth	1.00	2.00	4.00	5.00	0.4896
Slope	0.50	1.00	3.00	4.00	0.3054
Drainage	0.25	0.33	1.00	2.00	0.1264
LULC	0.20	0.25	0.50	1.00	0.0786

Finally, the RWH potential suitability map was generated, as shown in Figure 8.

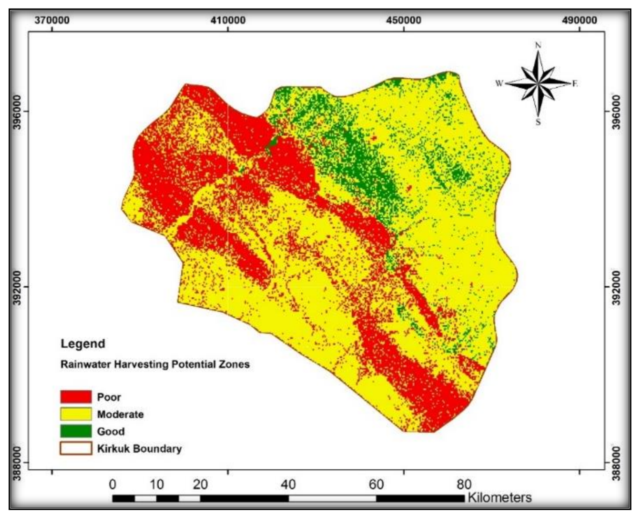


Figure 8 Potential sites for rainwater harvesting.

3.6 Proposed RWH Structures

This study considered the suitability of sites for constructing farm ponds and check dams. To achieve this goal, the suitability criteria for individual RWH structures were finalized on the basis of the results in Table 2.

Table 2 Suitability criteria used for identifying sites for RWH structures (adopted from [21], [28], [29])

Farm pond	Check dam
Land slope: <3%	Land slope: <15%
Land use/land over: Agriculture	Soil: Fine textured soil
Soil: Fine textured soil	Drainage order: Second and third

On the basis of the hydrologic and geomorphologic parameters of the study area, we identified suitable sites for the RWH structures. Figure 9 shows the generated suitability map for different RWH structures.

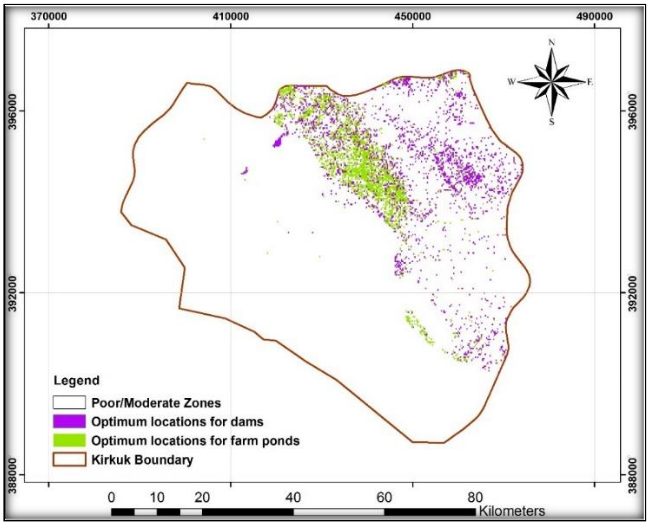


Figure 9 Suitable sites for various RWH structures

4.0 RESULTS AND DISCUSSION

A high positive correlation was found between runoff depth and the amount of rainfall. The linear relationship can be expressed as $y = 1.3909x - 186.54$, where x is the annual mean rainfall and y is the runoff depth. The coefficient of determination (R^2) value was more than 92.24%. Figure 10 illustrates the strong correlation between the two factors. Soil texture as the main parameter was used along with the other parameters to calculate the runoff depth using the CN approach. Runoff depth can reasonably be considered of high priority and weight because it was derived from the main parameters.

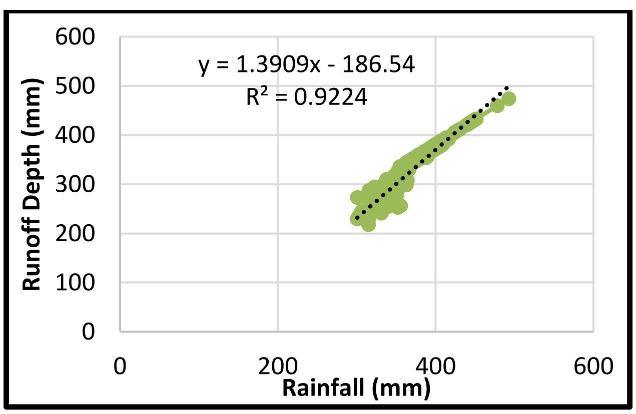


Figure 10 Runoff–rainfall relationship

An easy and accurate detection of suitable RWH zones was achieved by utilizing the integrated approach comprising RS, GIS, and MCDA techniques. The results revealed three classes of RWH, namely, high suitability zone, moderate suitability zone, and poor suitability zone. The high suitability zone is located north of the study area. This northern region is characterized by fluctuating terrain, the slope of which ranges from steep in the northeast and flat in the north. The most suitable RWH zones were identified as the moderate and poor suitability zones. These zones are located in the middle and southern part of the study area, less than 10% of which is made up of slopes. Moreover, slope and runoff depth showed greater influence than the other factors because of their high weights. According to the results, the high suitability, moderate suitability, and poor suitability zones cover about 8.2% (399.75 km^2), 63.4% (3,090.7 km^2), and 28.4% (1,384.5 km^2) of the study area, respectively.

The suitable sites for RWH structures can also be identified according to the RWH suitability map. In this study, the optimal RWH sites for farm ponds and check dams were identified and then presented in Figure 9. These sites are located in the high suitability zone because such zone features high runoff depth, as well as slopes and soil texture of high suitability. One of the important criteria for selecting zones suitable for farm ponds is that land use should be focused on agriculture (Table 1), particularly because farm ponds are necessary when providing supplementary irrigation for crop lands. This part of the study area had been used for agriculture. However, the lack of precipitation in previous years eventually degraded this part of the study area to bare soil. The areas suitable for farm ponds are mostly located in the central north parts of the study area. The total areas suitable for farm ponds and check dams were found to be 181.6 km^2 (3.7% of the total study area) and 197 km^2 (about 4% of the total study area). These recharge structures can augment surface storage and groundwater recharge in the study area. Most of the check dams are located on steep slopes below 15%. These structures are used for the efficient planning and management of water resources in the study area, which in turn can ensure a sustainable water supply in the context of climate change. Sustainable water management strategies, such as that described in this study, are undoubtedly crucial in ensuring that water needs are addressed.

5.0 CONCLUSIONS

This study used RS and GIS techniques to select suitable RWH sites in Kirkuk, Iraq. These techniques were integrated with the MCE method and then employed along with other criteria to obtain the best decision. The selection of suitable RWH sites depends on the quality and precision of the available data, including the methods used to collect, process, and deliver such data. High-quality data and the allocation of weights provide highly reliable and efficient outputs. Furthermore, the identification and allocation of weights for different criteria affect the quality of the estimated map because they influence the multi-criteria analysis. The runoff depth was estimated in this study by using the CN approach, which was employed using the mean annual rainfall data of Kirkuk for the period of 2000–2014. A significant amount of annual runoff depth data were collected in the zones that recorded runoff depth values above 300 mm. The maximum runoff depth in the northern part exceeded 490 mm, whereas the minimum runoff depth in the southern part was approximately160 mm.

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