A Geospatial & Multi-Criteria Analysis Approach for Potential Rainwater Harvesting. A Case Study of Rawalpindi & Chakwal District

Yasmeen, Z.[1,2], A. Javed[3], B. A. Siddiqui[3]

Abstract

Pakistan is an agricultural country and the agriculture sector has an essential role in the GDP. Agriculture production is dependent on the availability of water. Climate change adversely impacts agriculture production and the water sector. This research attempts to put forward such a framework for identifying potential sites for Rain Water Harvesting (RWH) in the area to mitigate the water requirement for crop irrigation. The Rawalpindi and Chakwal district are selected for RWH site selection which are located in the Pothohar region and their climate is Semi-Arid. At present, the area is under water stress conditions due to low rainfall and extensive deforestation. There are a number of famous lakes like Kallar Kahar, Uchali, Khabeki and Jhallar that have problems with water quality and storage. A Multi-Criteria Decision (MCD) method was used on Earth Observation (EO) dataset and weather data for the suitable site selection of RWH for domestic and agriculture. The thematic maps were extracted such as Soil map, land use /land cover, vegetation cover, drainage network and drainage density. The suitable site for RWH was developed in Analytical Hierarchy Process (AHP). Five layers were selected slope, rainfall depth, drainage density, LULC and HSG. This shows that the soil and rainfall depth are the most important variables for RWH. The suitability map indicated that highly suitable sites are found where the soil with low infiltration rate. The RWH suitability map presented can assist decision-makers, hydrologists, and natural resources planners in finding appropriate locations for constructing the RWH system.

Keywords: RWH, MCDM, LULC, EO, Drainage density, NDVI.

Background and Introduction

Water is a natural resource and its role is very important for the socioeconomic development of the country. Pakistan is an agricultural country and the agriculture sector has an important role in the country's economy. It contributes 24% of the Gross Domestic Product (GDP). The growth of population, rapid urbanization and climate change are the factors to increase the water scarcity problem in Pakistan (Zhang et al.,2021). Climate change adversely impacts agriculture production and the water sector. According to the Pakistan Statistics Bureau data from 2010 -2020, canals and tube wells are the major water source for irrigation in Pakistan.

The effects of climate change are gradually being noticed globally. As the IPCC, 2014 reports climate change has a significant impact on farmer income across the globe. Developing countries like Pakistan are vulnerable due to climate change. The country suffers from Hydro-meteorological hazards such as flood, drought and water depletion. The agricultural sector is influenced by climate change both positively and negatively (M.A. khan & A. Tahir, 2018). Water is important for agriculture production and domestic use as well. Bhandari, 2021, concludes that climate change has a significant effect on the availability of freshwater resources. Punjab is the biggest province of Pakistan for agriculture production. According to Pakistan Statistics Bureau data from 2010 to 2020 the canals and the tube well are the major sources of water for irrigation in Punjab. Increasing urbanization and climate crisis are affecting freshwater resources.

Water-saving technologies are the basic need of this era due to the depletion of groundwater and freshwater resources. RWH is one of the predominant features of water conservation techniques (Gireesh et al., 2021). Rainfall and rainwater harvesting have a good relation and water harvesting play a good role in agro-production (Chinazor, O.F. and Eslamian, S. 2021). The RWH is the practice of storing surface runoff for

[1] Zeenat.raza@yahoo.com
[2] Pakistan Meteorological Department
[3] University of Engineering & Technology, Taxila

various productive uses such as agriculture and environmental management. RWH is not a new technology it has been used for centuries in nations such as Israel, the United States, and Australia. To save water, rainwater harvesting is a viable option. Rainwater collection is becoming more widespread, resulting in environmental protection and effective use of a natural resource.

The temperature, slope, and soil of the region all have a role in the adoption of RWH methods. RWH are dependent on rainfall, and the soil in the catchment should be appropriate for producing surface runoff (Helmreich & Horn, 2009). According to a number of research on RWH methods for agricultural and domestic use, RWH is the best for groundwater recharge as well. When this method is used on a wide scale, it may help to mitigate climate change, increase crop yields, reduce soil degradation by decreasing surface run-off, produce energy, food, and biomass, and preserve local rainfall (Bores & ben-Asher, 1982). According to experts and numerous studies, Pakistan is now experiencing one of the world's greatest water crises. Small dams and RWH techniques could help the country increase its water storage capacity. This method has many benefits, including preserving water resources and the environment, reducing pollution, assisting with flood control, and reducing the effect of climate change.

Aim of the study

Pakistan is an agricultural country; it is situated in arid and semi-arid regions. The average rainfall trend of Pakistan is approximately 1800 millimetres in the area latitude 32 to 34 and 300 mm of Gilgit-Baltistan, Southern Punjab, Sindh and Baluchistan (CDPC, 2019). The primary objective of this research is to find acceptable locations for RWH for agricultural purposes via the use of a Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA). Numerous investigations on RWH approaches for agricultural and household purposes have concluded that RWH is the most acceptable technology for groundwater recharge. The Geographic Information System (GIS)-based MCDA is more famous to find appropriate locations for RWH for agricultural purposes (Huang et al., 2011). This research aims to find out suitable sites for RWH to mitigate the water scarcity problem of this area.

Data and Methodology

Study Area

The Rawalpindi and Chakwal districts have an area of 5,286 km2 and 6524 km2 respectively, and lie in Pothohar in north Punjab (see fig.1). The region is bounded by two major rivers Jhelum River on the East and the Indus River on the West (Sarah et al., 2019). The topography of the area is varying from 712 to 7460 ft. (217 to 2274 meters) from the plain of Chakwal to the hills of Murree. Low-lying area is dominated by urban structure and crop forms. The Pothohar plateau generally called Barrani land (rain feed area) is the agro-ecologically zone of Pakistan (Kazmi and Rasul 2009). The Agricultural activities of both districts mainly depend on the precipitation. Rawalpindi's climate is humid subtropical, with long, hot summers, a monsoon season, and short, moderate, and rainy winters. The precipitation comes from both western and eastern (monsoon) winds. Rawalpindi and Chakwal's geographical characteristics include plantation and agricultural land that helps in food production. The research area's soil types are mostly classified as calcareous and non-calcareous. These soils are typically sandy in texture (silty, loamy, clayey and loamy & clayey). Rainwater harvesting techniques are widely used around the world and are more suitable for catchments that depend on irrigation rainwater. Three main factors are important for adopting Rainwater Harvesting techniques climate, slope and soil of the area. RWH depend on rainfall and the soil of the catchment should be suitable for surface runoff production (Aladenola, & Adeboye, 2010). The climate of the study area is generally cold and humid. It receives both westerly and easterly (monsoon) precipitation. The land features of Rawalpindi and Chakwal are cultivated rain-fed and agricultural land and contribute to food production.

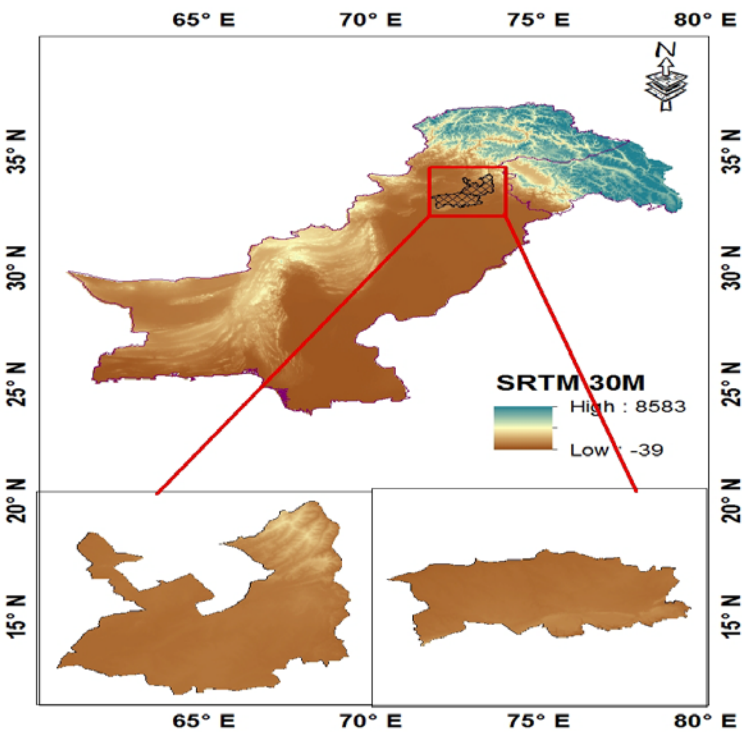

Figure 1: Location of the Study Area

Data

Topographic Data

The elevation, surface slope and drainage information were extracted from the Shuttle Radar Topography Mission (SRTM) 1 arc sec at 30-meter spatial resolution Digital Elevation Model (DEM), and the data was downloaded from(www.earthdata.nasa.gov/). The DEM has been an essential element in hydrological and watershed management studies. The drainage density map was created to reveal the number of channels in watershed areas of the Rawalpindi and Chakwal districts. The soil data were extracted from the soil survey map of Punjab.

Climatic Data

We have acquired the annual average precipitation and temperature data from a meteorological station at Rawalpindi and Chakwal. The 11 years of data were used for the period from 2009 to 2019 because the meteorological station data for Chakwal is available from 2009.

Satellite Data

We have obtained the Earth Observation (EO) data of LANDSAT 8 OLI/TIRS sensor to map out the Land use / Land cover (LULC), Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI). The EO cloud-free imagery was downloaded from the United State Geological Survey (http://earthexplorer.usgs.gov/).

Methods

To develop the suitable site selection of RWH, there were some necessary steps to be done, (Fig. 2) depicts the step-by-step methodology of watershed delineation using ArcGIS model builder.

A Drainage Density (DD) and slope layer were developed for the suitability criteria of RWH sites using the Arc-Hydro tool. The method started with the collection of topographic, satellite, and observed climate data. The watershed database was created using geographical information system (GIS). The watershed and stream network delineation were done using Digital Elevation Model (DEM) and Arc Hydro extension. The necessary information on basins was computed such as river length, river slope, basin slope, and longest flow path.

The soil information of the area was extracted from the Soil survey map of Punjab and was freely available. The soil texture layer was digitized after the geo-referenced downloaded JPEG image and assigned a coordinate system to map. A hydrological Soil Group (HSG) map was then prepared to show different classes of soil; A, B, C, and D. The land use and land cover, Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index have been extracted from LANDSAT 8 satellite data after pre-processing of imagery. The NDVI was calculated using Near Infra-red (NIR) and a red band. Normalized difference Water Index makes use of a near-infrared band (NIR) and a short-wave infrared band (SWIR). Wherever water has a high absorption coefficient, the short-wave infrared band between 1500 and 1750 nm is employed. Precipitation data is essential for RWH. Inverse Distance Weighted (IDW) interpolation was performed on mean monthly precipitation and temperature data. The in-situ climate data is available in point format after interpolation the raster maps of precipitation and temperature were generated.

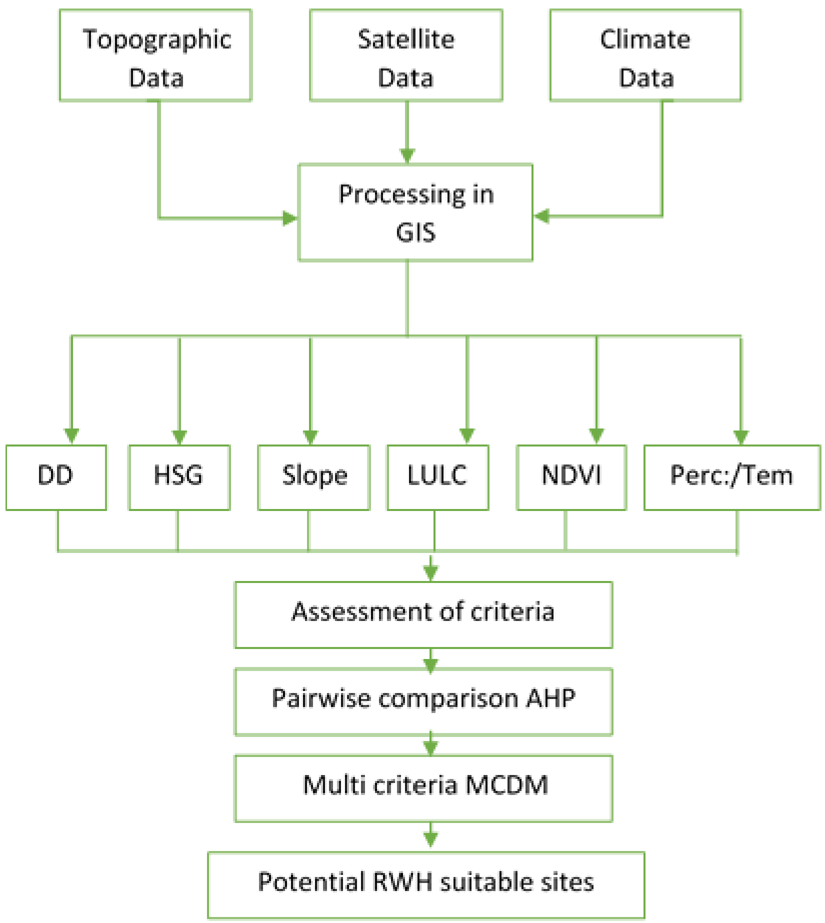

Figure 2: Step by Step Methodology

All the thematic layers were reclassified into 5 classes to carry out the weighted overlay method. In order to weighted criteria selection, the Analytic Hierarchy Process (AHP) method was used. AHP follows the Multi-Criteria Decision Making (MCDM) method which is useful to describe the relationship between the factors. Matrices were created to check the relationship between the slope, HSG, average rainfall, NDVI, DD and LULC. Scale values vary from 1 to 9 equal importance to extreme importance. Finally, MCDM analysis was used as a process to combine and convert spatial data into a decision. The procedure of MCDM consists of rules to define the relationship between the input and output data. The weighted Overlay tool was used to identify potential RWH sites. The ArcGIS has good tools to support planning and decision-making to choose and select suitable areas.

Results and Discussion

As already noted, Pakistan is an agricultural country, the most of the crops depend on natural rainfall. Due to climate change, the variability of rainfall is expected. Drought and flood conditions are directly related to rainfall. Rasul et al;2012 stated, based on precipitation and temperature data from 1960-2010, that drought and flood conditions are expected in future so we would need science-based policies. RWH technique is suitable to mitigate the drought. It is a special technique to store water-saving for Irrigation. RWH is beneficial for those areas where the water distribution through channel/Canals are unavailable. Topography, land use and rainfall directly affect RWH. The hydrological parameters flow direction, flow accumulation, stream networks, catchment grid delineation, drainage points, drainage line, drainage density and slope were derived from the Digital Elevation Model. In (Fig. 3) the elevation, slope and Drainage Density are shown.

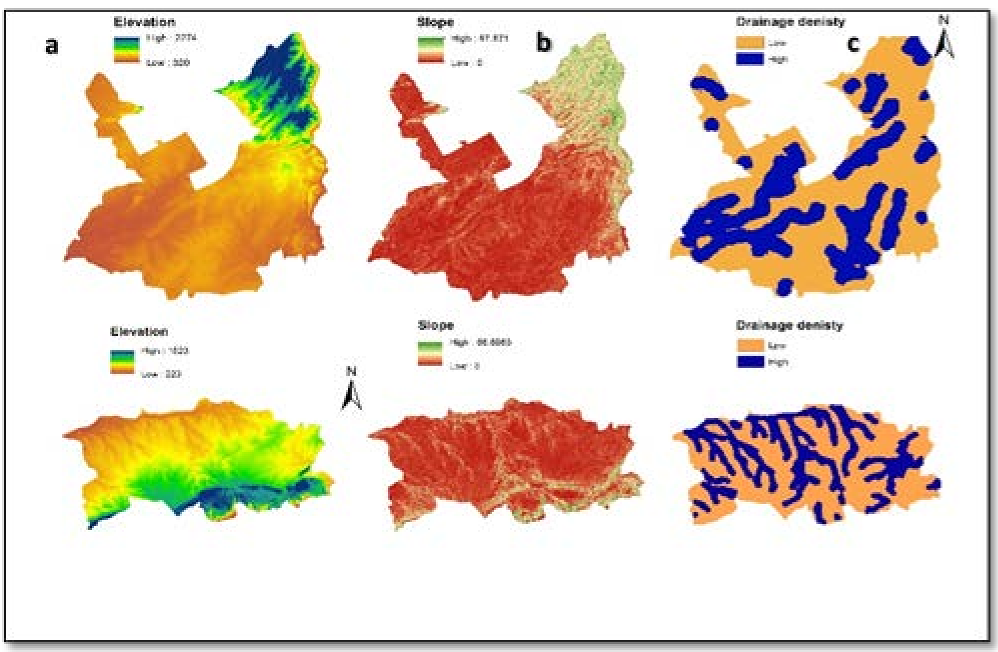

Figure 3: a. Elevation, **b.** Slope, and **c.** Drainage Density of Rawalpindi & Chakwal

The drainage density defined as the total length of the drainage network of the basin is divided by the area of the catchment. It can be seen from the drainage density map (Fig.3 c) that the study area has a good drainage density. It is worth mentioning that the area having high surface drainage density is less favourable for harvesting rainwater on the land surface, and hence the area having low surface drainage density is usually preferred from the rainwater harvesting viewpoint. Low drainage density is favourable for RWH.

The soil texture and its properties are very important for water harvesting research. RWH depend on rainfall and the soil of the catchment. Both factors are suitable for surface runoff production. Fig.4, shows the Soil texture of Chakwal and Rawalpindi. The soil data were digitized by the Soil Survey Map of Punjab.

The 1978 the map was downloaded from (European Soil Data Center) . The soil texture within the study area was found mainly to be silty, loamy and clayey soil.

Soil texture is important because it identifies the uptake infiltration rate and storage of water in the soil. The soil map for five soil texture classes was developed in ArcGIS 10.1. Six different soil classes were identified in the region namely clayey, Gullied land, loamy, loamy and clayey, mountainous land and silty soil. Soil texture is different in the plain and the mountain regions. The texture of soils in the plain regions mainly consists of loamy clayey, loam, and silt clay. The classification of soil into hydrologic soil groups depends on infiltration rates and the soil texture. The soil was reclassified into Hydrological Soil Groups (HSG) based on the United State Department of Agriculture (USDA) Hydrological soil Group Method classified into categories to D shown in (table.1). The area under study mainly B, C and D HSG were found.

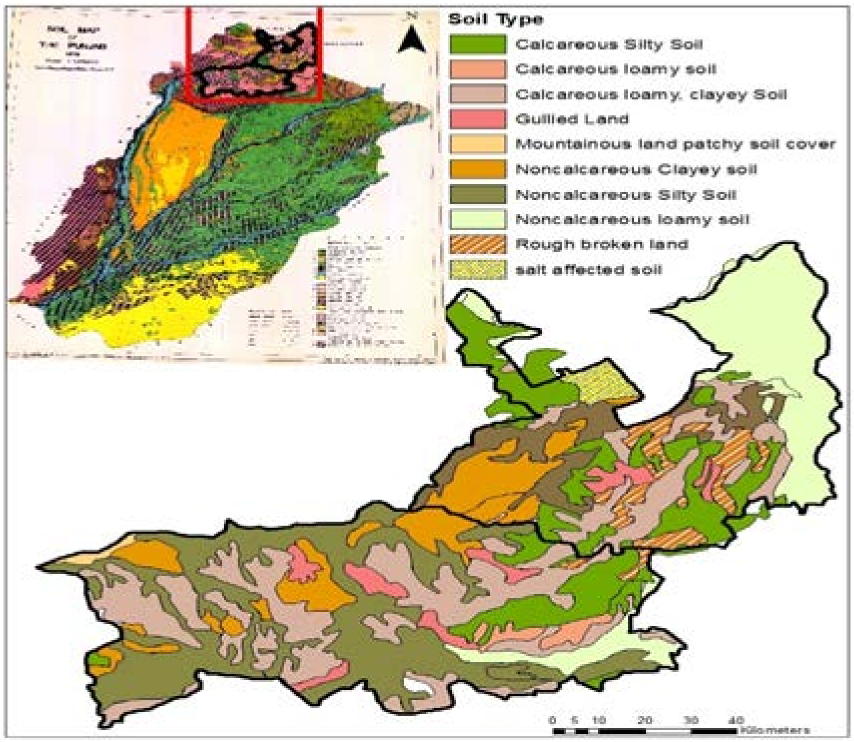

Figure 4: Soil Texture Map of Punjab 1978 (Published by of Dt. Direction of Dr. M. Bashir Choudhry, DG Soil Survey of Pakistan

Table 1: Hydrological Soil Group USDA

HSG	Runoff Description Soil texture
A	Low runoff potential because of high infiltration rates. (Sand, loamy sand and sandy Loam)
B	Moderately infiltration rates leading to a moderately runoff potential (Silty loam and loam)
C	High / moderate runoff potential because of slow infiltration rates (Sandy clay loam)
D	High runoff potential with very low infiltration rates (Clay loam, silty clay loam, sandy clay, silty, clay, and clay)

The HSG and LULC maps are useful to calculate the rainfall losses of the area. For the RWH site selection the Slope, HSG and LULC are the significant parameters in order to calculate the losses of rainfall for a RWH site.

The LULC has a significant impact on the hydrological response of watersheds. The LANDSAT satellite data were classified in ERDAS imagine software; the supervised classification method was used to map the LULC (Fig. 5). Based on the ground knowledge the area is classified into the forest, vegetation, soil, water and built-up land. It is noted that the vegetation and barren land covers are more than other features. The Curve Numbers (CN) were generated with the help of HSG and LULC for the soil permeability of both districts. The Curve Number method was originally developed by the Soil Conservation Services in 1964; 1972. The method is widely used all over the world, especially for watersheds where no runoff has been measured. The CN method has two phenomena, initial abstraction and retention. The initial abstraction is the losses of rainfall before the runoff such as interception, and infiltration. The retention loss of rainfall after runoff is called actual retention. Soil water retention is essential for land productivity and soil health.

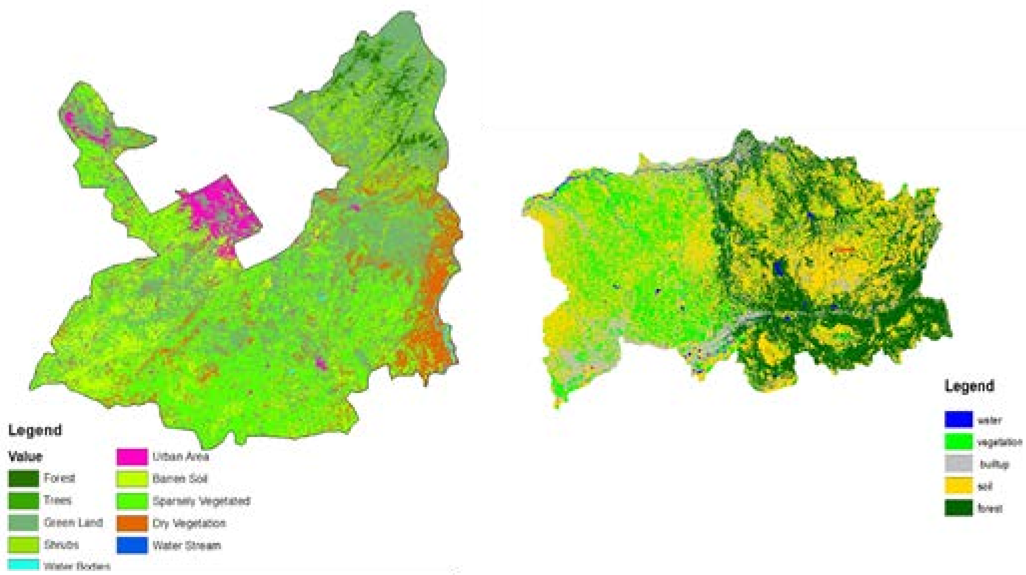

Figure 5: Land use and Land Cover Map

Evaluation of rainwater harvesting sites

Based on the literature review; we apply appropriate criteria for site selection. The suitable site for RWH was developed in Analytical Hierarchy Process (AHP). Five layers were selected which include slope, rainfall depth, drainage density, LULC and HSG. All the layers do not have the same importance for the determination of potential rainwater harvesting areas. Therefore, different weights were identified for the different factors. Site suitability for rainwater depends on the determination of the best site from a set of potential sites by analysing all the characteristics of the candidate sites. Pairwise comparison was used to estimate the weights of criteria, known as the Analytical Hierarchy Process (AHP). This method follows the Multi-Criteria Decision Making. The analytical hierarchy process selects the best rainwater sites by using the Multi-Criteria Evaluation (MCE) module. The ArcGIS has good tools to support planning and decision-making to choose and select suitable areas.

There are different methods to combine the decision criteria in multi-criteria decision analysis. In this study, a Weighted Linear Combination (WLC) is used. This weighted linear combination is employed to calculate the sum of the weighted criteria. To execute the Weighted Linear Combination method, an analytic hierarchy process is used, known as a pairwise comparison. The weighted linear combination is executed in two steps within the GIS environment; firstly, the weights associated with the criteria map's layers are determined. Secondly; the priority for all hierarchical levels including the level representing alternatives is combined. The (TL. Saaty, 1990) introduced the fundamental scale for pairwise comparison to determine the relative importance of each criterion.

Table 2: Scale for Pair-wise Comparison (Fundamental Scale of TL. Saaty, 1990)

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate
3	Moderate importance
4	Moderate strong
5	Strong
6	Strong to very strong
7	Very strong
8	Very strong to extremely strong
9	Extreme importance

Table 3: Pair-wise Comparison Matrix Showing the relative importance of the criteria

Factors	Soil	Rainfall Depth	DD	LULC	Slope
Soil	1	2	3	4	5
Rainfall Depth	1/2	1	2	3	4
DD	1/3	1/2	1	2	3
LULC	1/4	1/3	1/2	1	2
Slope	1/5	1/4	1/3	1/2	1
Column Sum	2.25	4.05	6.8	10.5	15

The relative importance of all layers in (Table.3) was assigned based on a scale of 1 to 9 (Table.2) and the pair-wise comparison matrix was proposed. The relative importance numbers of each column are divided by the sum of the total columns and add the element of each resulting row. As the weight calculation of each criterion shown in (Table.4) shows that the soil and rainfall depth assign the most and the slope has the least important criteria in RWH potential site selection.

Table 4: computation of criterion weight

Factors	Soil	Rainfall Depth	DD	LULC	Slope	Weight
Soil	0.437	0.489	0.439	0.38	0.333	0.42
Rainfall Depth	0.218	0.244	0.292	0.285	0.266	0.26
DD	0.145	0.122	0.146	0.19	0.2	0.16
LULC	0.109	0.081	0.073	0.095	0.133	0.1
Slope	0.087	0.061	0.048	0.047	0.066	0.06

In the final step after the combination of the MCDA and GIS techniques on the five-criterion layer, we mapped the suitable potential site for RWH in Rawalpindi and Chakwal shown in (fig.6). The potential suitable site of RWH is found where the D hydrological soil group was dominated and the soil has low infiltration characteristics.

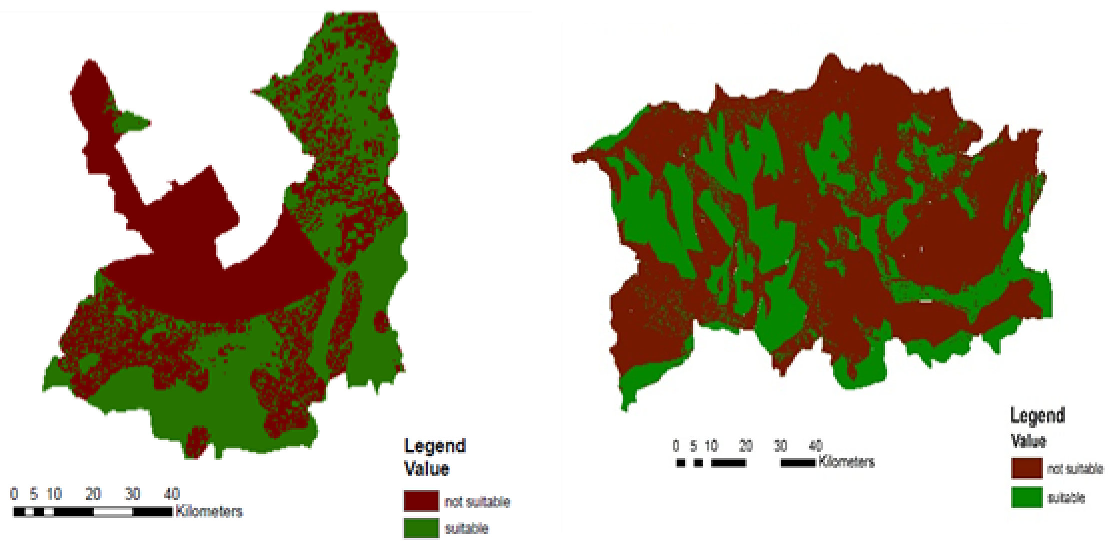

Figure 6: Rainwater Harvesting Potential Zone Map

To delineate RWH suitable sites, all the biophysical layers with their corresponding normalized weights, were integrated using ArcGIS software. The final map is categorized into two categories suitable and not suitable for RWH. The low-lying area of Rawalpindi is most suitable for RWH sites. The area where the higher drainage density value is mostly not suitable for the RWH. The outcome of RWH sites of Chakwal showed that the hilly region of easterly and south-easterly of Chakwal is also suitable for RWH due to the deep drainage network it might be the higher runoff in this area.

Figure 7 shows the area irrigated in Punjab with different sources of water. Data were downloaded from the Pakistan Statistical Bureau from 2010 to 2020. The farming system of Punjab depends on tube wells and canals water directly or indirectly (Qureshi, A.S., 2020). In Pakistan, a large amount of groundwater (73%) and surface water (275) is used for irrigation (Zhang et al., 2021). RWH techniques are good to recharge the groundwater to help the level of water in tube wells. It is recommended that surface water store in this area to minimized the use of groundwater for farming.

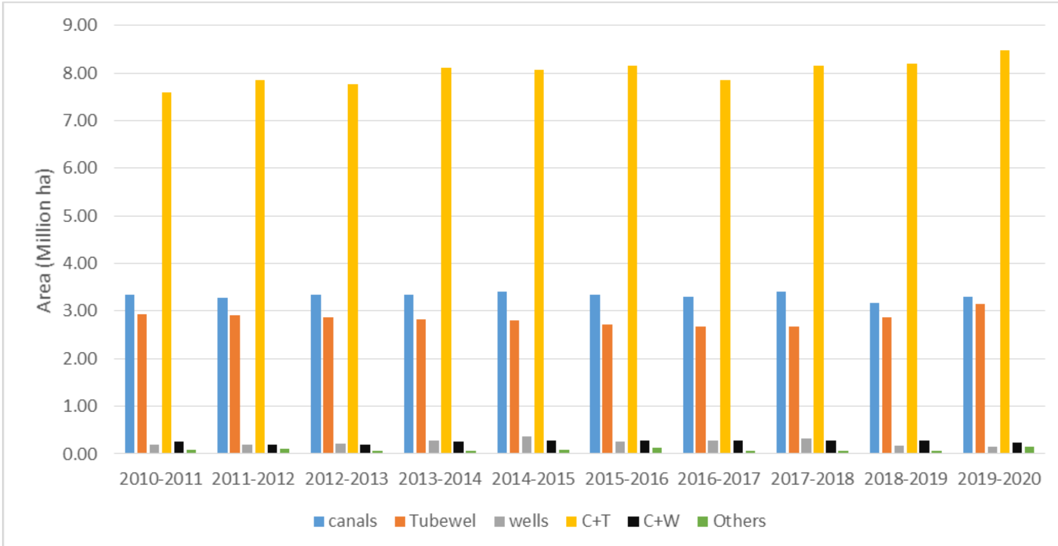

Figure 7: Source of water for Irrigation in Punjab (Source: Pakistan Statistical Bureau)

Conclusion

The area under study is situated in the Pothohar Plateau and the area is generally called barrani land. The agriculture of this area is dependent on the rainfall and the variability of the rainfall has an impact on agricultural production. The RWH is the possible solution for water scarcity in rain-fed areas. The remote sensing and GIS techniques were used, and the result of the proposed approach can be used in determining and selecting the most appropriate site for rainwater harvesting, where evaporation losses are minimized. The suitable site for RWH was developed in Analytical Hierarchy Process (AHP). Five layers were selected slope, rainfall depth, drainage density, LULC and HSG. This shows that the soil and rainfall depth was the most important variable for RWH. The suitability map indicated that highly suitable sites are found where the soil with low infiltration rate. The RWH suitability map presented can assist decision-makers, hydrologists, and natural resources planners in finding appropriate locations for constructing the RWH system.

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