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Potential Sites for Rainwater Harvesting Focusing on the Sustainable Development Goals Using Remote Sensing and Geographical Information System

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Abstract: An innovative way to combat water scarcity brought on by population increase and climate change is rainwater harvesting (RWH), particularly in arid and semiarid areas. Currently, Pakistan is facing major water issues due to underprivileged water resource management, climate change, land use changes, and the sustainability of local water resources. This research aims to find out the suitable sites and options for RWH structures in the Quetta district of Pakistan by integrating the depression depth technique, Boolean analysis, and weighted linear combination (WLC) with hydrological modeling (HM), multicriteria analysis (MCA), a geographic information system (GIS), and remote sensing (RS). To find suitable sites for RWH, a collection of twelve (12) thematic layers were used, including the slope (SL), land use land cover (LULC), subarea (SA), runoff depth (RD), drainage density (DD), lineament density (LD), infiltration number (IFN), distance from built-up area (DB), distance from roads (DR), distance from lakes (DL), maximum flow distance (MFD), and topographic wetness index (TWI). The Boolean analysis and WLC approach were integrated in the GIS environment. The consistency ratio (CR) was calculated to make sure the assigned weights to thematic layers were consistent. Overall, results show that 6.36% (167.418 km^2), 14.34% (377.284 km^2), 16.36% (430.444 km^2), 18.92% (497.663 km^2), and 18.64% (490.224 km^2) of the area are in the categories of very high, high, moderate, low, and very low suitability, respectively, for RWH. RWH potential is restricted to 25.35% (666.86 km^2) of the area. This research also identifies the five (5) best locations for checking dams and the ten (10) best locations for percolation tanks on the streams. The conducted suitability analysis will assist stakeholders in selecting the optimal locations for RWH structures, facilitating the storage of water, and addressing the severe water scarcity prevalent in the area. This study proposes a novel approach to handle the problems of water shortage in conjunction with environmental and socioeconomic pressures in order to achieve the sustainable development goals (SDGs).

Keywords: RWH; GIS and RS; Boolean approach; WLC technique; AHP; suitability; optimal structures; SDGs

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1. Introduction

Climate change and population growth have made water scarcity an urgent global issue that is especially affecting arid and semiarid regions [1]. Furthermore, it is expected that, by the year 2025, approximately 1.8 billion population will reside in regions experiencing severe water shortage globally [2,3]. The decline in global freshwater supplies because of rapid industrialization, urbanization, and excessive groundwater extraction makes RWH efficient to implement water management strategies at the watershed level [4–6]. RWH is a good and eco-friendly strategy to increase freshwater resources, especially in arid and semiarid regions [4]. Additionally, RWH structures are effective in addressing water shortages and promoting sustainable water use in the current climate change situation. Therefore, the sustainable management of water resources that aligns with the United Nations' SDGs is vital to meet current and future water needs in response to changing environmental conditions [7–9].

GIS and RS techniques have been widely used for the suitability of RWH sites by numerous studies because of their effectiveness [5,9–17]. Several studies have employed soil conservation models to calculate runoff from rainfall for RWH [4,14,18–21]. Moreover, the MCA approach and HM techniques are also combined with the soil conservation service curve number (SCS-CN) technique to find out the suitability of RWH [1,14,16,20–23]. Numerous studies have also utilized the analytical hierarchy process (AHP), which is an example of MCA [1,5,19,20,23,24]. Boolean analysis was utilized for the suitability of RWH structures [14]. Besides, the WLC approach combined with Boolean analysis has been utilized for the suitability of RWH [1,20,21]. The aforementioned approaches apply the integration of socioeconomic (distance from roads, settlements or lakes, etc.) and biophysical (RD, LULC, etc.) parameters to improve the site suitability of RWH [3,9,25]. The majority of relevant studies concluded that an AHP-based MCA is a reliable method for RWH suitability.

In Pakistan, some studies have been conducted for the selection of RWH sites using GIS and the RS technique with fewer thematic layers [15,26]. However, some socioeconomic aspects (such as IFN, TWI, etc.,) and also biophysical parameters (RD, IFN, TWI, etc.) were not mentioned in previous studies. RWH mapping requires us to consider the socioeconomic impacts [20,26]. Boolean analysis (suitable and unsuitable areas), the depression depth technique (suitable options for RWH), and the achievement of SDGs were also not emphasized. Various other studies also explored the RWH sites considering the limited criteria. For instance, Mitra et al. [27] considered land use and runoff in Kasai basin, Purulia, India; Kolekar et al. [28] considered runoff and SL; and Kar et al. [29] studied the soil, land use, drainage network, and SL as primary criteria for different parts of Purulia District, India. Thus, the reliability of RWH sites depends upon the selection of appropriate criteria [26,29–31]. IFN, LULC, SL, DD, LD, DR, DL, DB, and runoff coefficient parameters are important for the suitability of RWH sites [21,32]. Thus, there is a capacity to improve the AHP-based analysis by selecting a more comprehensive set of standards. Furthermore, the previous studies explored the suitable RWH sites utilizing various approaches; however, the validation of proposed sites remains unexplored [1,5,19,20,23,24]. Therefore, the innovation of the current study is to improve the methodology considering various factors in the AHP and validating the proposed sites with the existing one. Moreover, the current study links with multiple SDGs to manage various sustainability problems (such as water scarcity, socioeconomic problems, and environmental problems).

The determination of the suitable locations for RWH is essential for land and water management in arid and semiarid regions, which rely on RWH facilities [21]. Therefore, this study is conducted to find out the suitability of RWH in the Quetta District, Pakistan by integrating GIS, RS, HM, MCA, and the Boolean approach. This study also aims to provide suitable options for RWH structures, such as percolation tanks (along the streams and on the ground), check dams, nala bunds, and farm ponds, which are proposed by combining the depression depth technique with the WLC approach. Additionally, this research validates the existing structures and links the achievable objectives of the SDGs with RWH.

Study Region

Quetta District is located in Balochistan, southwest of the country of Pakistan, having a latitude of 30.183 N and a longitude 66.996 E, as shown in Figure 1. The area of Quetta (2653 km^2) encompasses a sequence of valleys that function as a natural fortress, encircled by hills known as Chiltan, Takatoo, Murdar, and Zarghun. Quetta is the 5th largest city in Pakistan, and it is also recognized as the fruit garden of Pakistan due to the variety of plant and animal wildlife. Quetta is the only high-elevation main city in Pakistan, standing at a height of 1680 m (5500 feet) above mean sea level. The topography of Quetta is characterized by diverse landscapes and features, and it encompasses a mix of mountainous terrain, valleys, and plains, contributing to the region's overall geographic complexity.

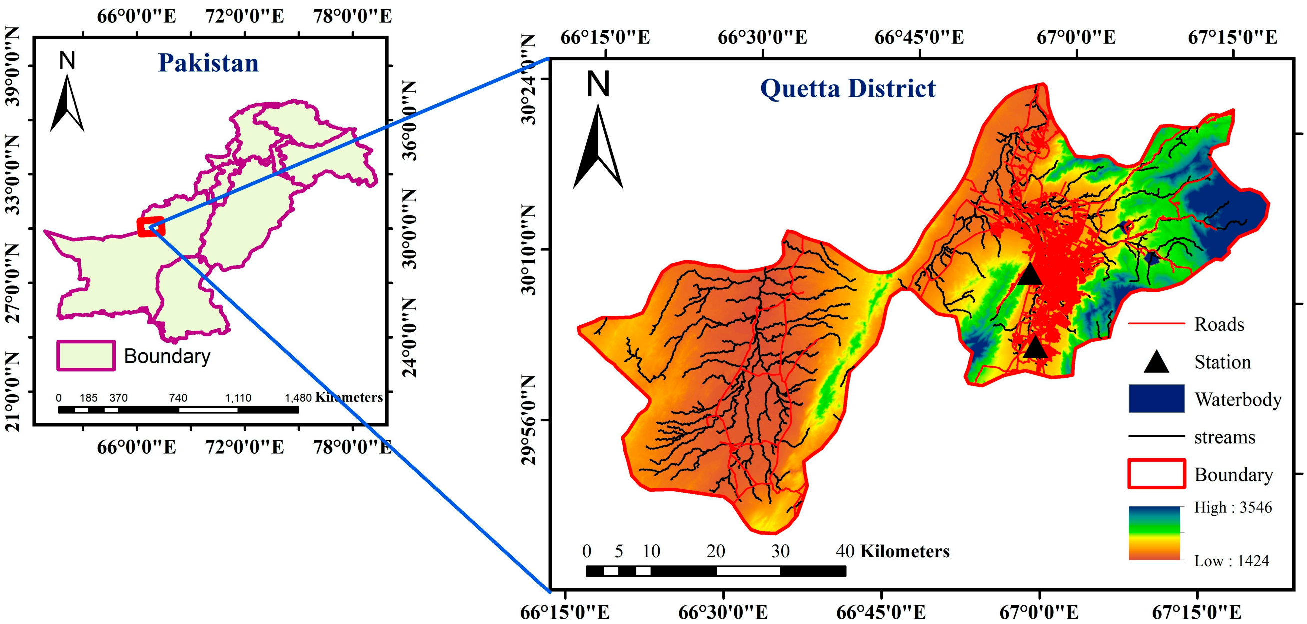

Figure 1. Quetta District location with roads, meteorological stations, streams, and elevation.

Quetta has experienced recurring droughts, flash floods, and seismic activity, creating an urgent need for constructing delay and check dams to address the rapidly declining water table [33]. The area also faces socioeconomic challenges due to its growing population and ongoing water shortages, especially during low rainfall periods [34]. In Quetta District, groundwater is the only source of water for domestic, industrial, and agricultural needs, and karezes (traditional underground water channels that are the source of water supply) have now dried up [34]. The average ground water level reached up to 183 m in 2021 compared to 91.43 m in 2010 [35].

Climatically, the region falls in a cold semiarid climate zone, according to the Köppen–Geiger climate classification. It has a semiarid and dry climate with less humidity, mild to extremely cold winters, and hot summers. The mean monthly temperature is 24.2 °C with maximum recorded temperatures of 42 °C in summer and −18.3 °C in winter. The annual rainfall varies from 100 to 300 mm with low precipitation in winter and higher evapotranspiration in summer [33].

2. Materials and Methods

2.1. Dataset

2.1.1. Topographic Data

The shuttle radar topography mission (SRTM) digital elevation model (DEM) of 30 m resolution was used. The DEM was obtained from the USGS Earth Explorer website. Table 1 provides a list of datasets used in this study.

Table 1. The datasets gathered for this study.

Category	Dataset	Source
Topography	DEM (SRTM 30 m resolution)	https://earthexplorer.usgs.gov/ (accessed on 4 September 2023))
Meteorological	Rainfall (1980–2020)	Pakistan meteorological department (PMD)
Soil	Digital soil map (10 m resolution)	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ (accessed on 5 November 2023)
Land use land cover	Current land use (10 m resolution)	https://livingatlas.arcgis.com/landcoverexplorer/ (accessed on 31 December 2023)
	Current lineament density (Landsat 8 OLI/TIRS 30 m resolution)	https://earthexplorer.usgs.gov/ (accessed on 30 October 2023)
	Current built-up area and lakes (Sentinel-2 10 m resolution)	ESRI image https://livingatlas.arcgis.com/landcoverexplorer/ (accessed on 31 December 2023)
Land use and soil	Curve number grid map (250 m resolution)	Jaafer et al. [36] (accessed on 2 January 2024)
Vector data	Roads	https://www.openstreetmap.org/ (accessed on 30 November 2023)

2.1.2. Meteorological Data

The observed daily rainfall data for Quetta stations (Sheikhmanda and Sariab) were collected from the Pakistan Meteorological Department (PMD) covering the period from 1980 to 2020.

2.1.3. Land Use Land Cover Data

The LULC data of sentinel-2 image (10 m resolution) were sourced from the ESRI website (Table 1). This high-resolution dataset provides detailed and accurate information on LULC patterns across the study region. The study region was classified into six (6) classes; rangeland, water bodies, agriculture land, trees, built-up area, and barren land. Most of the LULC of study region covers a rangeland. Moreover, the data were also used to extract biophysical data such as lakes boundaries. The LD data of 30 m resolution based on Landsat 8 were sourced from the USGS website. Furthermore, the data were subsequently processed in the GIS environment.

2.1.4. Soil Data

The Food and Agriculture Organization (FAO) provided the global soil data. The soil map was extracted for the study region. Most of the region is covered by two soil types: clay and loam.

2.1.5. Land Use and Soil Data

The curve number (CN) grid map of 250 m resolution was sourced from Jaafar et al. [36]. The dataset provides widespread information, which is crucial for understanding surface runoff potential and HM. Also, the map enables the accurate analysis of the impact of watershed characteristics, soil infiltration rates, and land use on hydrology. Utilizing these data, it is possible to enhance the accuracy of hydrological assessments and develop more effective water management strategies.

2.1.6. Socioeconomic Data

The roads network was sourced from an open street map website for the study region. The LULC (Sentinal-2: 10 m resolution) data were used to extract the built-up area of the region. The dataset source is presented in Table 1.

2.2. Selecting and Preparing Thematic Layers

The suitability of RWH sites was assessed across a variety of previous research considering the analysis based on various thematic layers [1,7,10,21,22,26,27,30,37]. Matomela et al. [1] focused on the site suitability of RWH using six (6) thematic layers, such as SL, DD, DL, DR, CN, and DB. Additionally, Boolean criteria were used for the suitable options of RWH. Singh et al. [17] also emphasized the site suitability of RWH using five (5) thematic layers, such as LULC, SL, DD, soil, and contour. Roy et al. [20] also evaluated the potential sites for RWH structures using nine (9) thematic layers, such as runoff coefficient, SL, LULC, soil texture, DD, stream order, geology, LD, and depth of ground water. The layers SL, LULC, runoff, and soil type were chosen by Tiwari et al. [4].

Twelve (12) thematic layers to enhance the site suitability with additional criteria for the suitable options of RWH were chosen for this study. Layers including the DD, SL, LULC, MFD, RD, IFN, DB, DR, DL, LD, SA, and TWI were undertaken for WLC analysis.

The selected factors affect the suitability of RWH sites. The RD factor is crucial, as it indicates the volume of water that can be collected from a specific area after rainfall [1]. Areas with higher RD are ideal for harvesting, as they have the potential to yield more water, making them suitable for RWH structures [21]. SL influences the movement and accumulation of water, with an SL less than 5% being the most suitable for RWH [38]. Moreover, an SL more than 5% is not recommended for RWH due to the uneven distribution of runoff; it also requires substantial earthwork, which leads to high costs [39]. LULC plays a crucial role in influencing both runoff and its potential for RWH in a region [23,40,41]. Certain land covers, such as barren land or rangeland, are more suitable for RWH, because such covers can be easily modified to store water. RWH is limited in urban and agricultural zones because of safety concerns and economic factors, respectively [1]. DD refers to the ratio of total length of all the streams and rivers in the area of the basin. DD plays a crucial role in determining the suitability of areas for RWH and optimal sites for storage structures [21,42]. The areas with high DD are more beneficial to RWH [43], since it produces higher levels of runoff generation and reduced infiltration and permeability [44]. Lineaments are linear features in the landscape that often represent zones of structural weakness, such as faults or fractures, which can influence groundwater movement. Areas with high LD are likely to have increased groundwater recharge potential, making them favorable for RWH [37]. DR is important for the accessibility and maintenance of RWH structures. Sites that are closer to roads are easier to access for construction, maintenance, and monitoring, making them more practical for implementation. Built-up areas often have impervious surfaces, which increase surface runoff, reduce infiltration, and are generally not ideal for RWH; hence, understanding their location is important to avoid placing structures where water collection might be inefficient or where space for implementation is limited. A 1000 m buffer zone around the lake is omitted, because it is within the feeding area for habitats [1]. Areas near lakes might already have natural water storage, so identifying locations away from these water bodies can help distribute water harvesting efforts more effectively across the landscape. TWI indicates areas of potential water accumulation based on the landscape's topography. The areas with a TWI greater than 15 exhibit high capacities for flow concentration, making them ideal choices for RWH [45]. The stream frequency and DD are multiplied to determine the IFN; a high IFN shows a high capability for RWH [21]. The MFD shows how water flows across a landscape considering multiple directions of flow. The greater the MFD, the greater the potential for RWH [16]. The SA helps in the more precise planning and implementation of RWH structures, ensuring that specific hydrological characteristics are taken into account [21]. Increasing the SA enhances the rainwater collection volume, which leads to the elevation of the peak flood discharges [46].

These various thematic layers were produced using Arc GIS 10.7 (ESRI, 2016) for selecting the sites. The DEM of the study area was delineated and was used to prepare the SL map, TWI map, and stream order within the boundary. The stream order was applied to compute the stream density. The Euclidean distance tool in the GIS environment was used to create a map of the DR, DB, DL, and distance from faults. The watershed modeling system (v.10.1) was used to divide the study region into SAs and for developing the MFD map [47]. The IFN values were computed for each SA and interpolated for the entire area. The DD and SA were calculated using HEC-HMS model v.4.11 for each SA and then incorporated in the GIS environment. The ArcGIS 10.7 (ESRI, 2016) and Geomatica (PCI 2016) platforms were utilized for preparing the thematic layer of the LD. The CN grid map was sourced from Jaafar et al. [36] and assigned for each SA in the GIS environment for further utilizing in HEC-HMS. The CN, lag time, initial abstraction, and rainfall data for each SA were utilized in the HEC-HMS model to calculate the RD.

All the thematic layers and their features were allotted their own weight, according to their level of suitability for RWH locations (Table 2). Various research also applied such criteria and weights [1,4,9,14,20,21,39]. However, this research updated the weights to the criteria and also removed the inconsistency in the weight allocation to ensure a more accurate and reliable identification of potential RWH sites. This approach not only enhances the precision of the results but also sets a benchmark for future studies in the field, contributing to more sustainable water resource management strategies. The Boolean technique was used to exclude redundant locations from the RWH site selection that were selected through the WLC method [1,20,21]. The Boolean criteria are discrete and indicate true or false conditions. Four constraint layers were used, namely DR, DL, DB, and distance from faults, to enhance the site suitability. The criteria for the Boolean approach are listed in Table 3, and an overall flowchart of the adopted methodology is illustrated in Figure 2.

Table 2. The assigned weights of thematic layers along with the classifications of their features.

Thematic Layer and Its Weight	Feature Class	Suitability Class	Sub Classes Weight
Runoff depth (mm) (9)	≥81.58 ≤83.49	Very high	9
	≥79.76 <81.58	High	8
	≥78.23 <79.76	Moderately	7
	≥76.32 <78.23	Low	6
Slope (%) (8)	<3	Very high	8
	≥3 <8	High	7
	≥8 <15	Moderately	5
	≥15	Low	3
Land use land cover (7)	Barren land	High	7
	Rangeland	Low	3
	Water bodies	Restricted	0
	Agriculture	Restricted	0
	Trees	Restricted	0
	Built-up area	Restricted	0
Subarea (km^2) (6)	≥357.09 ≤522.07	Very high	7
	≥270.43 <357.09	High	6
	≥195.43 <270.43	Moderately	4
	≥97.1 <195.43	Low	3

Table 2. *Cont.*

Thematic Layer and Its Weight	Feature Class	Suitability Class	Sub Classes Weight
Maximum flow distance (km) (6)	≥28.48 ≤38.04	Very high	7
	≥21.73 <28.48	High	6
	≥13.82 <21.73	Moderately	4
	≥5.54 <13.82	Low	2
Drainage density (km/km^2) (5)	≥0.59 ≤0.95	Very high	7
	≥0.44 <0.59	High	5
	≥0.31 <0.44	Moderately	3
	≥0.03 <0.31	Low	2
Topographic wetness index (5)	≥12.12 ≤24.54	Very high	7
	≥8.51 <12.12	High	5
	≥6.23 <8.51	Moderately	3
	≥2.09 <6.23	Low	2
Lineament density (4)	≥0 <0.44	Very high	6
	≥0.44 <0.88	High	5
	≥0.88 <1.32	Moderately	3
	≥1.32 ≤1.76	Low	2
Infiltration number (4)	≥0 <0.12	Very high	6
	≥0.12 <0.29	High	5
	≥0.29 <0.58	Moderately	3
	≥0.58 ≤1.29	Low	2
Distance from built-up area (m) (3)	<2000 ≥500	Very high	5
	<3000 ≥2000	High	4
	≥3000	Moderately	3
	<500	Low	2
Distance from roads (m) (3)	<1000	Very high	5
	<1500 ≥1000	High	4
	<2000 ≥1500	Moderately	3
	≥2000	Low	2
Distance from lakes (m) (2)	≥4000	Very high	5
	<4000 ≥3000	High	4
	<3000 ≥1500	Moderately	3
	<1500	Low	2

Table 3. Thematic layers for the Boolean approach along with their classification of features.

Thematic Layer	Feature Rank	Suitability Class	Weightage
Distance from built-up area (m)	<250	Unsuitable	0
	>250	Suitable	1
Distance from roads (m)	<250	Unsuitable	0
	>250	Suitable	1
Distance from faults (m)	<250	Unsuitable	0
	>250	Suitable	1
Distance from lakes (m)	<1000	Unsuitable	0
	>1000	Suitable	1

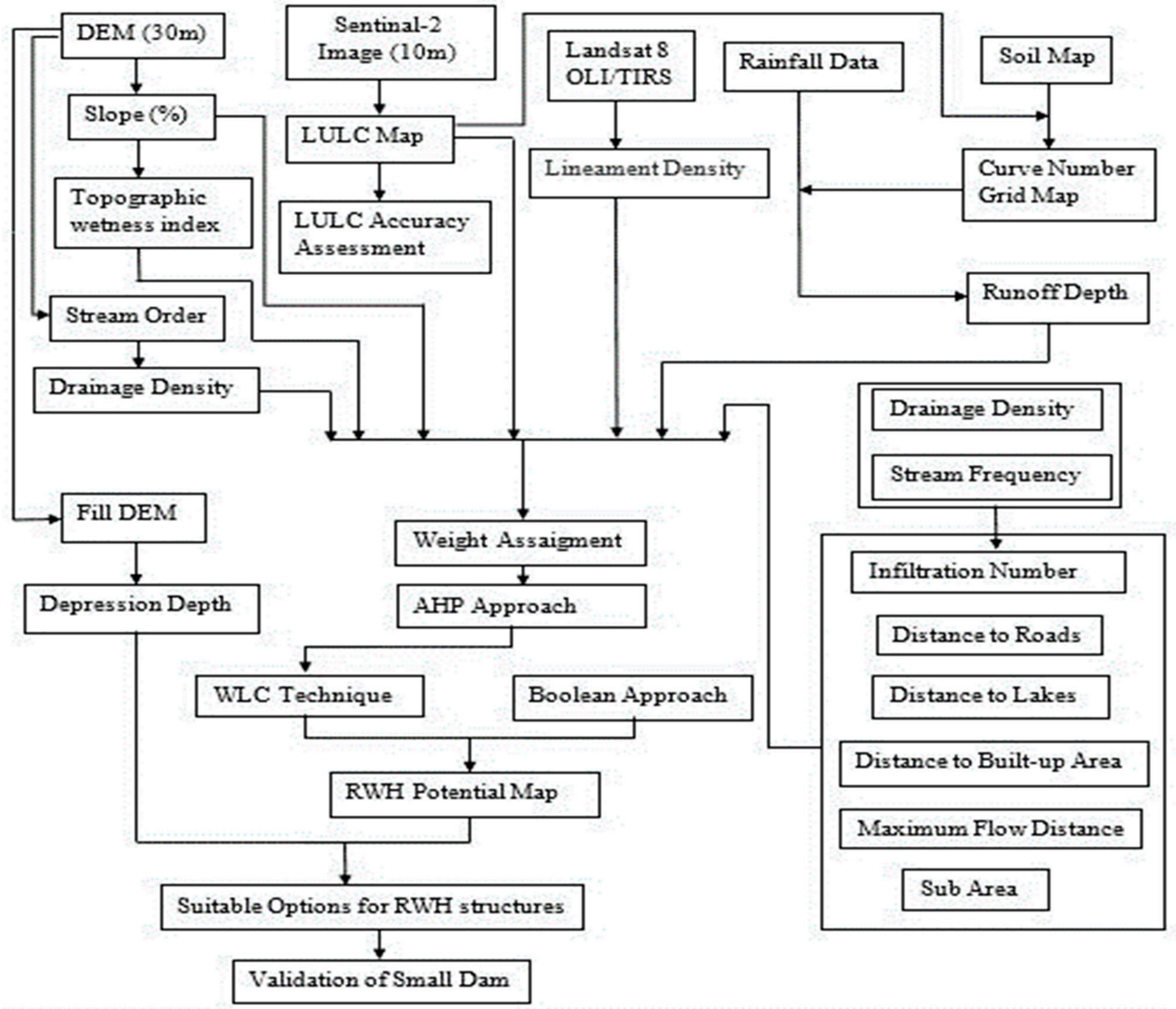

Figure 2. Adopted methodology flowchart for the study.

2.3. MCA Analysis

The spatial data were converted into a raster format for MCA. The qualitative data were converted into quantitative through a pairwise comparison matrix using Saaty's scale [48]. Furthermore, weights were assigned to each thematic layer and normalized utilizing Saaty's analytic hierarchy process (AHP). Moreover, to make sure the weights were consistent, the CR was calculated using the methodology suggested by Wind and Saaty [49]. The CR can be expressed by the following equation:

$$CR = \frac{CI}{R_{CI}} \tag{1}$$

where CI stands for consistency index, and R_{CI} stands for random consistency index. CI can be acquired as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where n is the total number of layers (criteria), and λ_{max} is the crucial eigenvalue. The assigned weights need to be changed to maintain consistency if the CR is greater than 0.1 [49]. R_{CI} depends on the number of criteria, and its value was chosen as 1.54 against the twelve thematic layers, as listed in Table 4.

Table 4. Random consistency index (R_{CI}) [50].

Number of Criteria	3	4	5	6	7	8	9	10	11	12	13	14	15
Random consistency index (R_{CI})	0.58	0.89	1.12	1.26	1.36	1.41	1.42	1.49	1.52	1.54	1.56	1.57	1.59

2.4. Runoff Estimation

The SCS-CN method (SCS, 1956) was employed for the estimation of annual direct runoff utilizing a rainfall–runoff model HEC-HMS 4.11 [51]. The efficiency of using rainfall data to estimate direct runoff has been demonstrated by numerous studies [1,4,14,15,21,22,26,37,52,53]. The correct computation of dimensionless CN is a critical component that determines the accuracy of the SCS-CN approach. The estimation of CN depends on several factors, such as the hydrologic soil group (HSG) and LULC, in order to obtain reliable results. Using Equation (5), the weighed curve number (CN_w) was estimated for the entire area. The following formula can be used to estimate runoff from rainfall using the SCS-CN approach [54]:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad where \;\; P > 0.2S \tag{3}$$

where Q is the direct surface RD (mm), S is the maximum potential water abstraction by soil (mm), and P is the total precipitation (mm). The expression for S is as follows:

$$S = \frac{25400}{CN_w} - 254 \tag{4}$$

where CN_w is the weighted curve number for the entire area, and it can be calculated as follows:

$$CN_w = \frac{\Sigma(CN_i \times A_i)}{\sum A} \tag{5}$$

where A_i and CN_i are the area and CN of each SA, and A represents the entire area.

2.5. Suitability Analysis of RWH

The combined maps were created in the GIS environment using the WLC technique. WLC has been broadly applied in the mapping of suitability in the GIS environment and MCA. The WLC method and Boolean factors were combined with each other to exclude some features from the site selection and create the resultant suitability map of RWH. The following equation was employed to express the suitability of RWH:

$$\begin{aligned} RWHPI = {} & RD_{nw} * RD + SL_{nw} * SL + LU_{nw} * LU + SA_{nw} * SA + MFD_{nw} * MFD + DD_{nw} * \\ & DD + TWI_{nw} * TWI + LD_{nw} * LD + IFN_{nw} * IFN + DB_{nw} * DB + DR_{nw} * DR + DL_{nw} * \; DL \end{aligned} \tag{6}$$

where $RWHPI$ is the RWH potential index, and SL_{nw}, LU_{nw}, SA_{nw}, RD_{nw}, DD_{nw}, LD_{nw}, FN_{nw}, DB_{nw}, DR_{nw}, DL_{nw}, MFD_{nw}, and TWI_{nw} are the normalized weights of slope, land use, SA, RD, LD, IFN, DB, DR, DL, MFD, and TWI, respectively. Moreover, *SL, LU, SA, RD, DD, LD, IFN, DB, DR, DL, MFD*, and *TWI* are the weights for respective thematic layer.

Equation (6) generated a grid map showing the suitability of the RWH sites in the study area. *RWHPI* is a unitless value derived from the abovementioned Equation (6). The *RWHPI* was categorized into distinct classes (very low to very high) to find out the suitability level of RWH sites. Numerous studies utilized this method and verified its utility successfully [1,4,14,21,22,39]. The Boolean analysis (unsuitable area) for RWH was combined into a single layer, which was later integrated with the WLC method, resulting in a final RWH suitability map.

2.6. Optimal Locations for RWH Structures

The optimal locations of RWH structures, such as percolation tanks, farm ponds, and check dams, depend on the topography, soil characteristics, and LULC of the study region.

The selection criteria of optimal locations are shown in Table 5. In order to determine the best locations for check dams and percolation tanks on the stream, a buffer zone of 50 m around second and third order streams was marked in the GIS environment [1,14,21,22]. The depression depth was determined from the initial DEM and filled DEM using the minus tool in the GIS environment. The depression depth and Boolean analysis maps, along with the final output layer from the WLC, were integrated for optimal locations. The locations were also validated with pre-existing structures located in the research area.

Table 5. Criteria for selecting sites of RWH and replenish structures [14].

Thematic Layer	Percolation Tank (Along the Stream)	Percolation Tank (on the Ground)	Farm Pond	Check Dam	Nala Bunds
Slope (%)	<5%	<3%	<3%	<15%	<10%
Land use land cover	-	Degraded forest, wasteland	Agriculture	-	Barren land
Soil texture	Coarser	Coarser	Fine	Fine	Fine
Stream order	2nd and 3rd order	-	-	2nd and 3rd order	-

3. Results and Discussion

3.1. Thematic Layers of RWH for Suitability Mapping

Several thematic layers were chosen for their effectiveness in determining RWH suitability. The analysis of these layers is presented in the subsequent sections, ensuring that the study captures all relevant factors.

3.1.1. Runoff Depth Map

Effective RWH requires a detailed understanding of the spatial variability in RD across the study area. The classification of RD identifies regions with the highest potential for capturing and storing rainwater, thereby optimizing the placement of harvesting structures. Figure 3a presents an RD map showing that 18.5% of the area (493.42 km^2) was highly suitable for RWH, while 40.42% (1077.78 km^2) and 41.07% (1095.15 km^2) had moderate and low suitability, respectively, for RWH. The maximum RD (83.49 mm) occurred mostly in the eastern parts of the study area, and the minimum RD (76.32 mm) occurred in the northern and southern parts. The greater the RD, the greater the suitability of those regions for RWH. Conversely, lower RD indicates less potential for water RWH in the northern and southern regions. These variations in RD emphasize the need for strategic planning in the placement of RWH structures to maximize efficiency.

3.1.2. Slope Map

Understanding the slope of the terrain is critical for the effective implementation of RWH strategies, as it directly influences water flow and accumulation. Steep slopes may lead to rapid runoff, while gentle slope areas are more conducive to water retention and infiltration. Figure 3b shows the slope map of the study area. The slope varies from gentle to steep because of the mountainous landscape of the study region. A significant portion of the study area, 36.93% (995.45 km^2), falls under the gentle slope category, which is conducive to RWH. The moderately sloped and nearly flat areas cover 17.60% (474.35 km^2) and 16.08% (433.59 km^2) of the region, respectively. The nearly flat areas with slopes below 3% are considered the most suitable for RWH, because of the maximum water retention capacity, and they occur in the middle of the study area. Conversely, steep slopes covering an area of 29.42% (793.01 km^2) mostly occur in the western part, which is the least suitable because of the rapid runoff generation. According to the slope map, 53.01% (1228.98 km^2) of the area is suitable for RWH. This significant portion of land offers promising potential for effective water conservation.

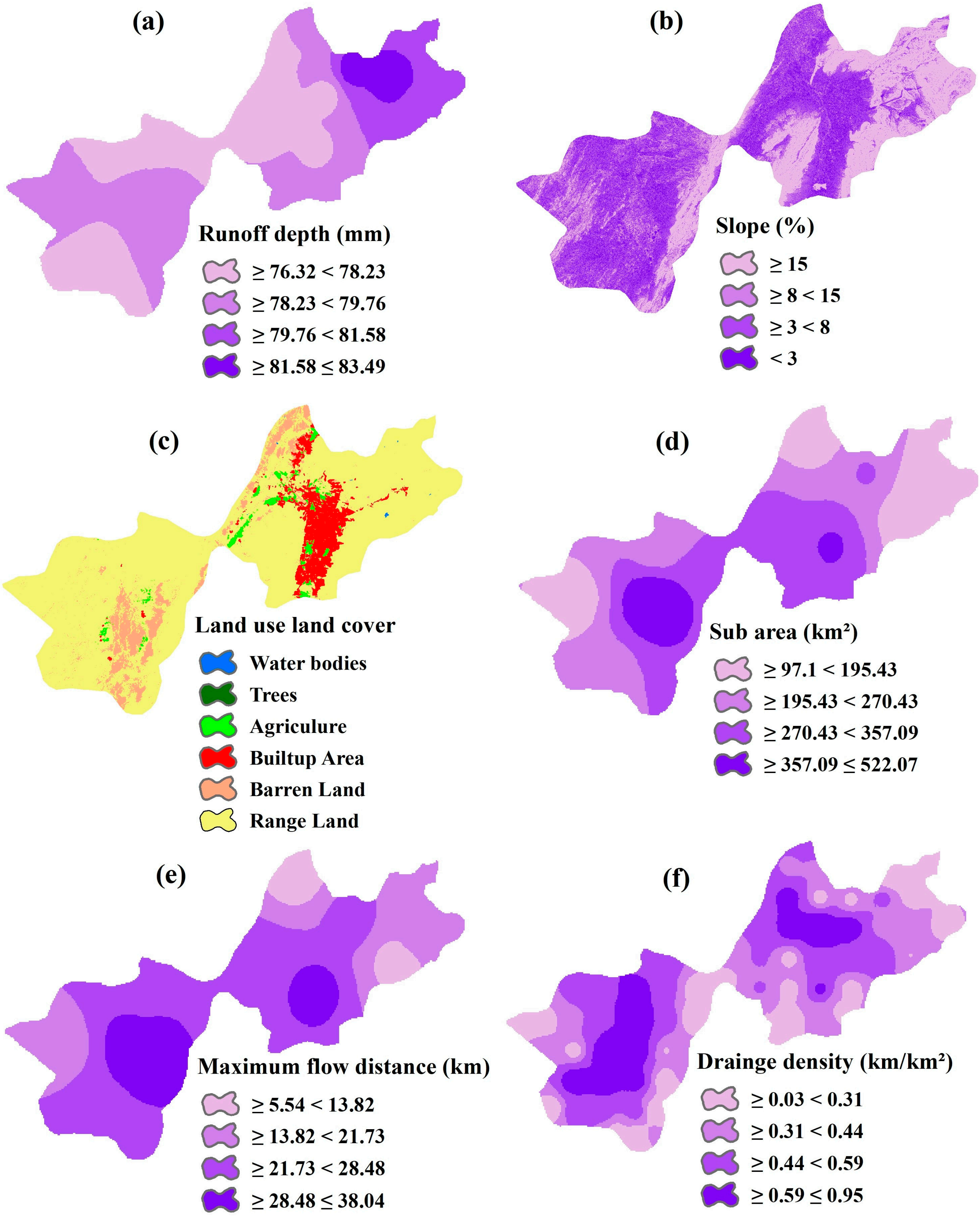

Figure 3. *Cont.*

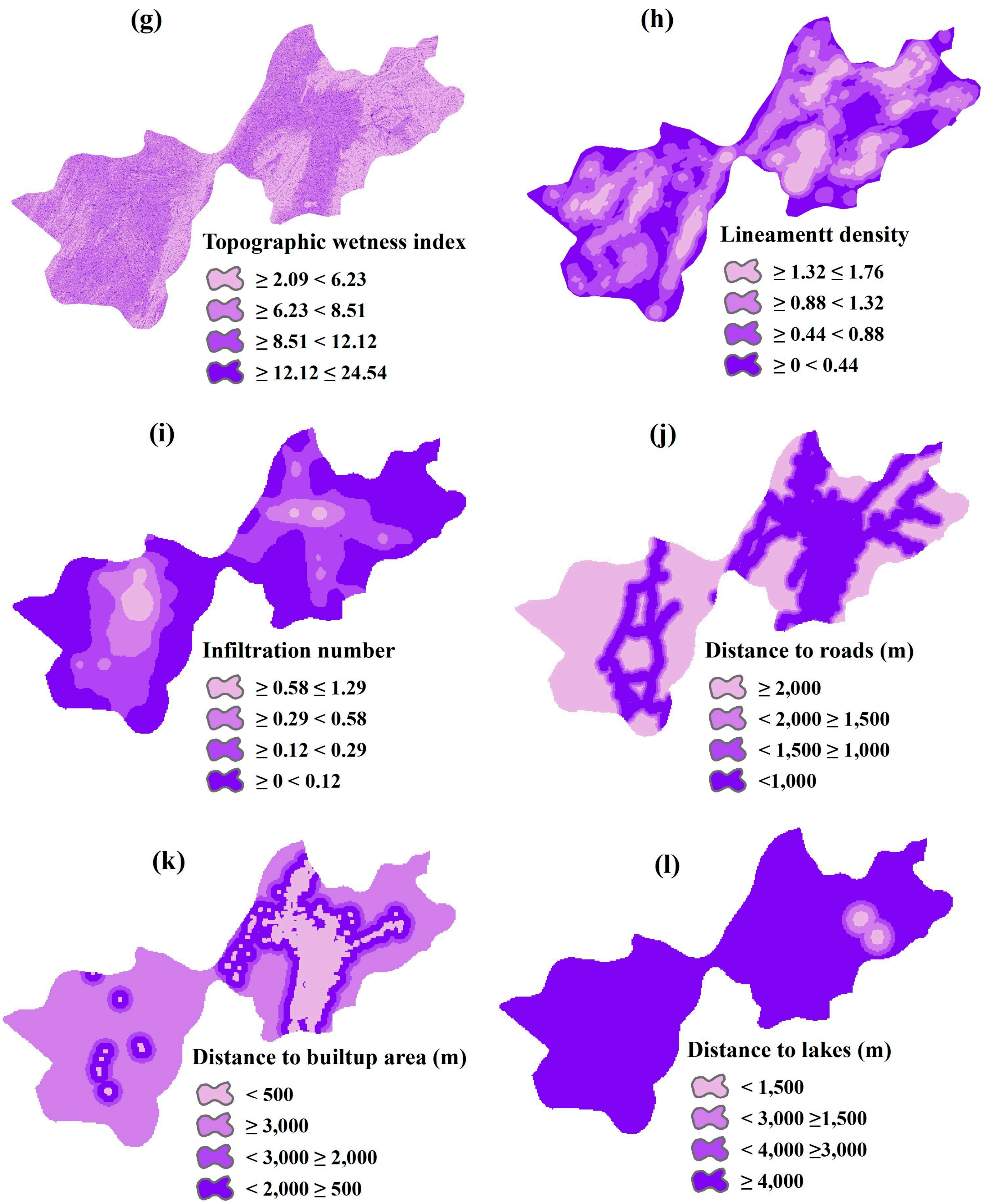

Figure 3. (**a**) RD map, (**b**) SL map, (**c**) LULC map, (**d**) SA map, (**e**) MFD map, (**f**) DD map, (**g**) TWI map, (**h**) LD map, (**i**) IFN map, (**j**) DR map, (**k**) DB map, (**l**) DL map.

3.1.3. Land Use Land Cover Map

The accurate mapping and classification of LULC is essential for understanding the spatial distribution of different land types and their potential for water retention and storage. The LULC map validation through ground truthing produced satisfactory results, as shown by the Kappa coefficient presented in Table 6. Figure 3c presents the LULC map of the study region. The majority of the area comprises rangeland with an area of 82.06% (2187.72 km^2). Other land use includes water bodies, trees, agriculture, built-up areas, and barren land, with areas of 0.03% (1.06 km^2), 0.01% (0.0003 km^2), 1.95% (52.06 km^2), 7.72% (206.04 km^2), and 8.24% (219.87 km^2), respectively. Among these, barren land is identified as the most suitable for RWH due to its minimal vegetation and high potential for water retention, while rangeland is deemed moderately suitable. According to the LULC map, an extraordinary portion of the study area covering 2407.59 km^2 (90.3%) is classified as suitable for RWH, highlighting the significant potential for implementing water conservation strategies in the study region.

Table 6. Land use land cover accuracy assessment.

Feature Class	Water Bodies	Agriculture	Built-Up Area	Barren Land	Rangeland	Total	User Accuracy	Kappa Coefficient
Water bodies	0	0	0	0	0	0	0	0
Agriculture	0	1	0	1	0	2	0.5	0
Built-up area	0	0	20	0	1	21	0.95	0
Barren land	0	0	0	21	2	23	0.91	0
Rangeland	1	0	0	8	25	254	0.96	0
Total	1	1	20	30	25	300	0	0
Producer accuracy	0	1	1	0.7	0.99	0	0.96	0
Kappa coefficient	0	0	0	0	0	0	0	0.85

3.1.4. Subarea Map

The SA map provides a valuable insight for varying sizes of different regions within the study area, which directly influences the potential for water accumulation and storage. Figure 3d presents the SA map of the study region. The smaller area lies in the northeastern and western parts, and the larger area is in the middle parts of the study region. According to the SA map, 1161.01 km^2 (43.54%) of the area has high suitability; 836.31 km^2 (31.36%) moderate suitability; and 669.04 km^2 (25.09%) low suitability for RWH. A larger SA is more suitable for RWH, while a smaller SA is less suitable [46]. The spatial distribution of these areas highlights the need to adapt interventions for maximizing water storage in the most favorable locations.

3.1.5. Maximum Flow Distance Map

Figure 3e shows the MFD map of the study region. The MFD map shows that 68.12% (1817.84 km^2) of the area has high suitability, while 25.06% (668.91 km^2) of the area moderate suitability, and 6.80% (181.47 km^2) of the area low suitability for RWH. Notably, aligning with the terrain and hydrological characteristics of the region, the MFD is greater in the central parts of the study area and lower in the northeastern regions. The outcomes of the MFD analysis exhibit a strong correlation with the SA, as illustrated in Figure 3d. These results underscore the importance of considering MFD in conjunction with other factors, such as slope and land use, to develop a comprehensive strategy for RWH.

3.1.6. Drainage Density Map

DD is a key hydrological parameter that significantly influences the runoff and infiltration rates across a landscape. The DD map of the study area is shown in Figure 3f. According to the DD map, 1293.17 km^2 (48.48%) of the area has high suitability for RWH and lies in the central part of the study area. Moreover, the moderate and low suitability areas for RWH are 798.93 km^2 (29.95%) and 575.11 km^2 (21.56%) and are located in the southwestern and eastern parts of the study region, respectively. These findings underscore the importance of DD in the spatial planning of RWH structures, as areas with higher DD offer considerable potential for water collection, particularly in regions where surface runoff is the primary source of water. By integrating DD analysis with other hydrological and topographical factors, this study provides a robust framework for optimizing RWH site selection.

3.1.7. Topographic Wetness Index Map

The TWI is a critical indicator for understanding the spatial distribution of soil moisture and plays a vital role in the suitability of sites for RWH. The TWI is particularly useful in identifying areas where water is likely to accumulate. Figure 3g presents the TWI map of the study region. The TWI map shows that 923.53 km^2 (34.26%), 1256.52 km^2 (46.62%), and 515.74 km^2 (19.12%) of the area have low, moderate, and high suitability for RWH, respectively. The areas identified as highly suitable are likely to experience greater water accumulation, making them ideal for RWH structures.

3.1.8. Lineament Density Map

Lineaments include fractures, rock cleavages, and faults and are natural pathways for water infiltration and groundwater recharge. Figure 3h shows the map of LD of the study area. The analysis revealed that more than half of the study area (59.44–1608.21 km^2) has a low LD, which is highly suitable for RWH due to its smaller infiltration process. Furthermore, 28.62% (774.18 km^2) of the area has moderate LD, while 11.94% (323.01 km^2) has high LD, and both are less suitable for RWH due to their greater infiltration capacity. According to the LD map, moderate and high lineament occurs in the central part of the study area, while low lineament occurs in the eastern and western parts. By focusing on areas with low LD, which offer less infiltration potential, the placement of RWH structures can be optimized to maximize water retention and recharge.

3.1.9. Infiltration Number Map

The IFN is an important metric that reflects the ability of an area to absorb and store water. Understanding the variation in infiltration rates across different parts of the study area helps in identifying the optimal locations for RWH structures. The IFN map of the study area is presented in Figure 3i. Most of the area (87.02–2321.14 km^2) has a low infiltration rate, and 12.96% (346.06 km^2) area has low suitability for RWH; this area lies in the middle parts of the study region. The study area has limited potential for RWH due to its poor water absorption capabilities. The results emphasize the significant impact of infiltration rates on RWH suitability. Areas with low infiltration rates are more effective for capturing and storing rainwater, while those with higher rates offer less potential for water conservation.

3.1.10. Distance from Built-Up Area Map

The DB is a critical factor in determining the suitability of RWH sites. Figure 3j presents the DB map of the study region. A distance less than 500 m from a built-up area was marked in the low suitability class for the effectiveness of RWH, since it is more prone to contamination, there is limited space for constructing the RWH structures, and urbanization disrupts the natural flows. The results show that 60.45% (1612.37 km^2) of the area is moderately suitable, and 25.533% (681.28 km^2) area is highly suitable for RWH sites.

According to the criteria, most of the area is suitable for RWH. Most of the built-up area located in the middle of the study region has low suitability for RWH sites.

3.1.11. Distance from Roads Map

The DR is an important factor influencing the suitability of RWH sites. Roads can affect the water flow and access to an RWH site, making it crucial to consider distance for planning and implementing these structures. Sites closer to roads may experience better accessibility and infrastructure support but may face issues such as runoff contamination and increased erosion. The DR map is shown in Figure 3k. The results show 46.11% (1248.04 km^2) of the area has low suitability, and 46.04% (1246.14 km^2) of the area has high suitability for RWH sites. The road area mostly occurs in the middle of the study region and presents low suitability. Moreover, approximately half of the study area is appropriate for RWH.

3.1.12. Distance from Lakes Map

DL can influence the effectiveness of RWH structures by affecting local hydrology and water quality. Sites closer to lakes might benefit from better water availability but could also face challenges related to contamination and competing water uses. Figure 3i shows the DL map of the study region where 97.55% of the area (2602.02 km^2) was identified as having high suitability, and 0.720% (19.22 km^2) of area was found to have low suitability for RWH. This ensures that RWH sites are less likely to experience negative impacts from nearby lakes, such as contamination.

3.2. Thematic Layers Weights and MCA

The weights to each thematic layer and their aspects were assigned numbers from 1 to 9, as shown in Table 2. Normalized weights were assigned to each thematic layer and their respective feature classes using the AHP and eigenvector technique [55]. Table 7 presented a pairwise comparisons matrix and the CR of 0.0001 was determined within the threshold limit, which is up to 0.1. The low CR confirms the validity of the assigned weights and supports the accuracy of the overall evaluation process [48]. Hence, the chosen criteria for the thematic layers were considered to be consistent, reliable, and robust for the analysis.

Table 7. Pairwise comparison matrix of the selected thematic layer.

Thematic Layer	RD	SL	LULC	SA	MFD	DD	TWI	LD	IFN	DB	DR	DL	NW
RD	1.00	1.13	1.29	1.5	1.5	1.8	1.8	2.25	2.25	3	3	4.5	0.15
SL	0.89	1.00	1.14	1.33	1.33	1.6	1.6	2	2	2.67	2.67	4	0.13
LULC	0.78	0.88	1.00	1.17	1.17	1.4	1.4	1.75	1.75	2.33	2.33	3.5	0.11
SA	0.67	0.75	0.86	1.00	1.00	1.2	1.2	1.5	1.5	2	2	3	0.1
MFD	0.67	0.75	0.86	1.00	1.00	1.2	1.2	1.5	1.5	2	2	3	0.1
DD	0.56	0.63	0.71	0.83	0.83	1.00	1.00	1.25	1.25	1.67	1.67	2.5	0.08
TWI	0.56	0.63	0.71	0.83	0.83	1.00	1.00	1.25	1.25	1.67	1.67	2.5	0.08
LD	0.44	0.5	0.57	0.67	0.67	0.8	0.8	1.00	1.00	1.33	1.33	2	0.06
IFN	0.44	0.5	0.57	0.67	0.67	0.8	0.8	1.00	1.00	1.33	1.33	2	0.06
DB	0.33	0.38	0.43	0.5	0.5	0.6	0.6	0.75	0.75	1.00	1.00	1.5	0.05
DR	0.33	0.38	0.43	0.5	0.5	0.6	0.6	0.75	0.75	1.00	1.00	1.5	0.05
DL	0.22	0.25	0.29	0.33	0.33	0.4	0.4	0.5	0.5	0.67	0.67	1.00	0.03

Note: SL, LULC, SA, RD, DD, LD, IFN, DB, DR, DL, MFD, and TWI represent slope, land use land cover, subarea, runoff depth, drainage density, lineament density, infiltration number, distance from built-up area, distance from road, distance from lake, maximum flow distance, and topographic wetness index, respectively.

3.3. Mapping RWH Suitability

The RWH suitability was mapped using the WLC technique within the GIS environment by the developed criteria, as shown in Table 2. The resulting maps are different from other studies, and also, the process to compute the regional map for a particular layer was different; for example, DD was computed for each SA and interpolated for whole area. Figure 4a shows the suitability map for the RWH sites. The RWH suitability map was classified into five (5) categories: very high (5.467–6.564); high (5.031–5.466); moderate (4.662–5.030); low (4.278–4.661); and very low (3.306–4.277). The classification allows for a clear and actionable understanding of the spatial distribution of the RWH potential throughout the study region.

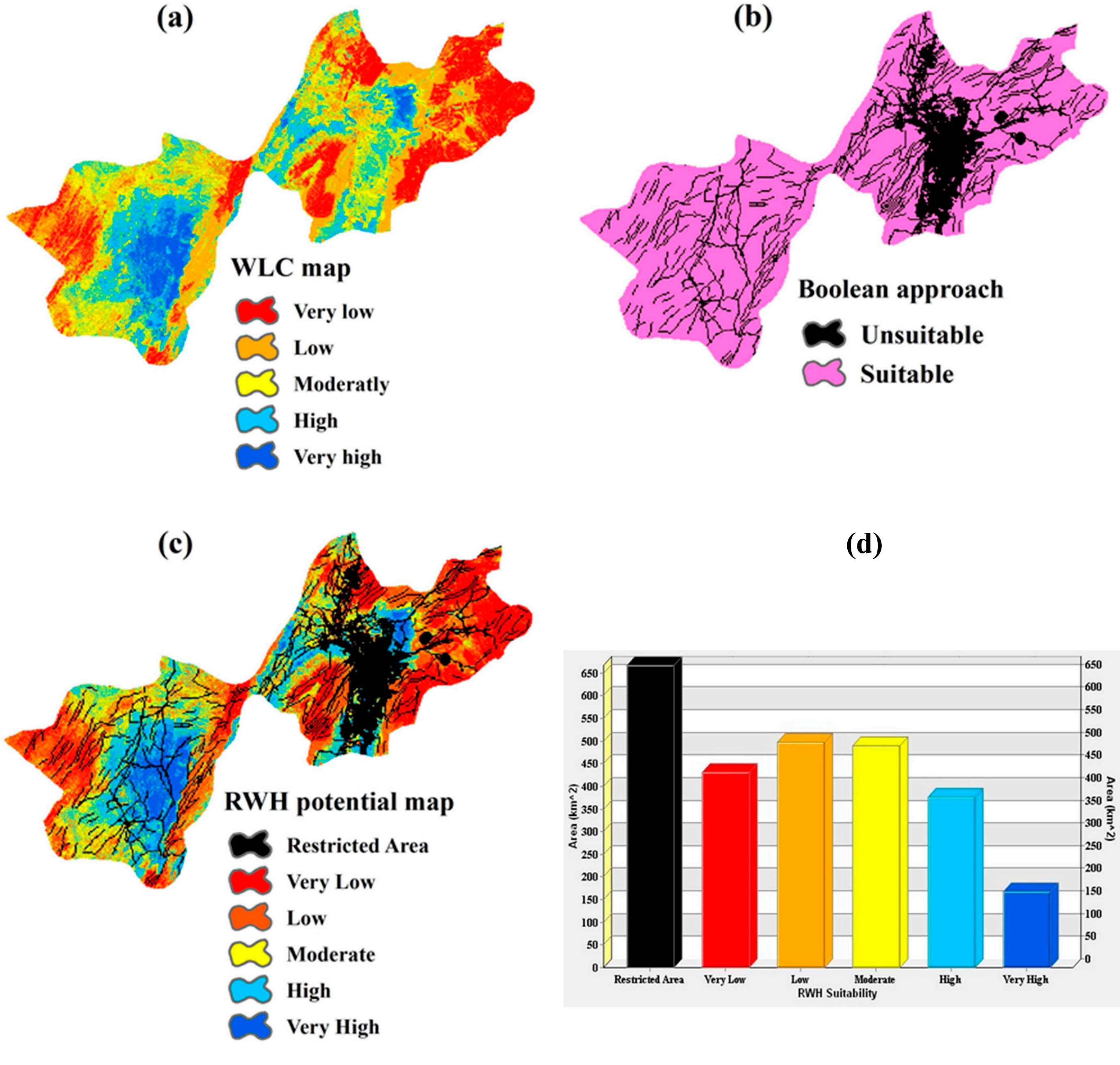

Figure 4. (**a**) WLC map, (**b**) Boolean approach, (**c**) RWH potential map, (**d**) RWH suitability histogram.

Besides, to enhance the suitability of RWH sites, Boolean analysis was used to eliminate some locations. The resulting map comprises suitable (1) and unsuitable (0) areas based on

Boolean analysis, shown in Figure 4b. The integrated map by Boolean and WLC analysis is shown in Figure 4c. Figure 4d shows the overall area histogram of various suitability classes of RWH. The results show that 6.36% (167.418 km^2) and 14.34% (377.284 km^2) of the area falls in the categories of very high and high suitability, respectively, for RWH sites. Notably, most of the streams in the study area come under very high and high classes. The suitability map also showed that 16.36% (430.444 km^2), 18.92% (497.663 km^2), and 18.64% (490.224 km^2) of the area shows very low, low, and moderate suitability for RWH sites, respectively. RWH potential was restricted to 25.35% (666.86 km^2) of the study area as a result of built-up areas, lakes, and roads. Moreover, the results also demonstrate that the area of high suitability is in the middle, and low suitability is in the eastern and western parts for RWH. The areas including those with a hilly landscape and steep slopes are responsible for the distribution of RWH suitability [1,4,17,20,21]. The stream areas have been identified as the best for RWH sites because of gentle slopes, more runoff, and ease of access.

3.4. Suitable Options of RWH Structures

The suitable options for RWH structures were determined using Boolean analysis, as shown in Table 5. The area in the high and very high suitability classes was integrated with the depression depth to determine the RWH structures. In this research, the criteria for five (5) types of RWH structures were specified, such as farm ponds, percolation tanks on the stream and on the ground, nala bunds, and check dams. The effectiveness of this approach was confirmed by examining existing structures, which are located at the convergence points of depression depths and areas classified as highly suitable or very highly suitable. Furthermore, the incorporation of these RWH structures into broader water management strategies helps to maximize water conservation across the region. This comprehensive approach has contributed significantly to addressing water scarcity challenges and improving water security in the study region. Figure 5 presents various types of RWH structures.

The results show that five (5) sites are suitable for the check dam, two (2) in the eastern and three (3) in the western side of the study area. The results have also located ten (10) optimal sites for percolation tanks on the streams. The possible area identified as suitable for percolation tanks on the ground is 1.320% (35.22 km^2), which occur in the western and northern parts of the study area. Furthermore, the areas suitable for farm ponds and nala bunds are 0.178% (4.76 km^2) and 0.173% (4.62 km^2), respectively. These areas are near to built-up areas and roads and are economical for the development of the study region [21]. In addition to these findings, it is crucial to prioritize the construction of these RWH structures to ensure their timely implementation. The proximity of these zones to built-up areas and roads not only makes them economically viable but also facilitates easier access for construction and maintenance. Engaging local communities in the development and maintenance of these structures can further enhance their effectiveness and sustainability. Regular assessments of these sites should be conducted to monitor their performance and adapt to any changing environmental conditions. Ultimately, the successful implementation of these RWH structures will play a significant role in mitigating water scarcity in the Quetta District. To relieve the current water shortage and raise the district of Quetta's living standards, a number of the planned structures are well placed close to roadways and built-up areas. Additionally, the regions surrounding the proposed structures distanced from current habitats are opportunities for future settlements. Although the socioeconomic factors have been accurately integrated in the study, it is still imperative to carefully explore the potential upstream and downstream consequences of implementing RWH systems. These potential effects include changes in water availability for existing agricultural practices, impacts on local biodiversity, and shifts in water flow patterns. Therefore, a balanced approach that considers both the benefits and potential risks of RWH systems is essential.

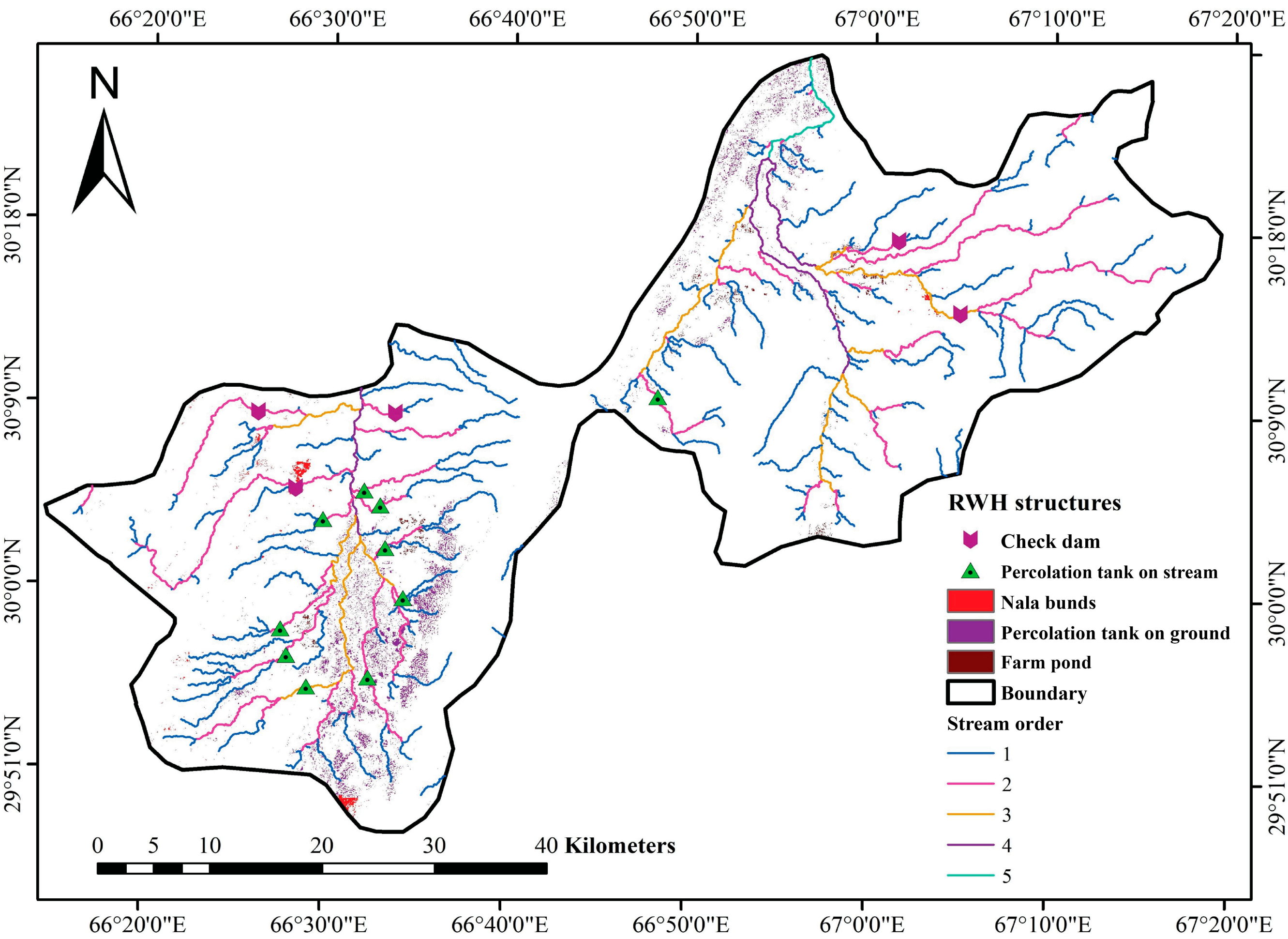

Figure 5. Various suitable options for RWH structures.

3.5. Validation of RWH Structures

In validating RWH structures within the study area, the WLC technique serves as a robust approach. By employing WLC, the effectiveness and suitability of RWH structures can be systematically evaluated, taking into account various spatial factors and criteria such as slope, land use, soil type, and proximity to water resources. The validation by ground truthing for two dams located in the study region (Quetta District) exhibits their exact occurrence in a very high-class area, as shown in Figure 6. This method enables the integration of multiple parameters and their respective weights for providing a comprehensive assessment of the RWH structure. Furthermore, the successful validation of existing dams in areas with very high suitability also strengthens the reliability of the method. Since the study region continues to face challenges related to water scarcity, the insights gained from this validation process can guide future efforts in expanding RWH infrastructure. By adopting the aforementioned methodology, stakeholders can be confident in selecting the sites to maximize water collection and contribute to long-term water sustainability in the region. Through meticulous analysis and validation using WLC, researchers can ascertain the optimal location and design of RWH structures, ensuring their efficacy in addressing water scarcity challenges across the globe. The utilization of WLC adds consistency and reliability to the validation process, offering valuable insights for policymakers, water resource managers, and stakeholders involved in sustainable water management initiatives [56].

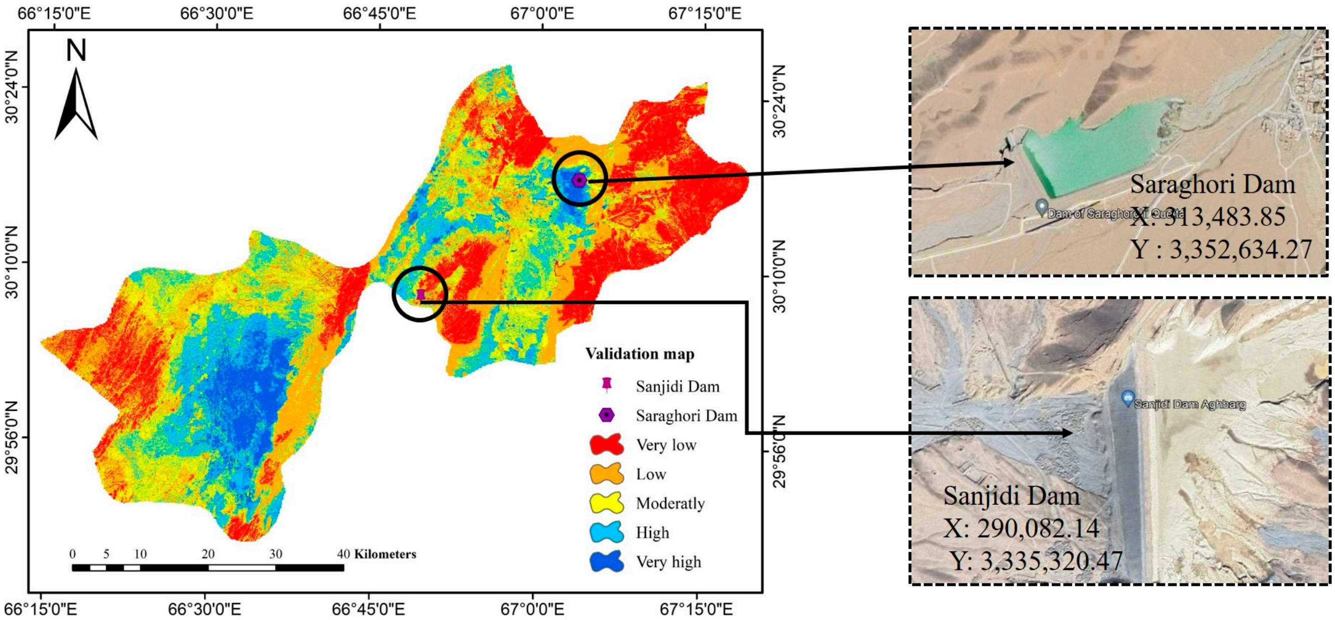

Figure 6. Validation of WLC approach results with existing RWH structures.

3.6. Strategy for Sustainable RWH

The development plan for any region needs to be in agreement with the SDGs and should be performed using sustainable approaches [7]. With this objective, this research outlines the sustainable RWH plan that addresses the SDG targets. By establishing connections between the findings and the SDGs, the research also provides sustainable solutions to the primary challenges encountered by the citizens of Quetta District.

The topic, RWH, is a significant component of sustainable development in the area, covering the SDG Targets 6.5 and 12.2, which emphasize integrated water resource management and sustainable natural resource management. Moreover, it aligns with the SDGs, particularly 6A (Enhance water harvesting), 6.6 (Replenish aquifers), and 6.4 (Mitigate water scarcity). This research contributes to mitigating water scarcity through the implementation of RWH systems and groundwater recharge initiatives. By installing the RWH structure (percolation tank), groundwater replenishment can be facilitated, and ultimately, drinking water can be made available for local inhabitants. Ensuring equitable access to these structures for all who live in the area contributes to achieving Target 6.1 (Universal water access).

Several SDG targets, including 2.3 (Increase agricultural productivity), 2.4 (Adopt resilient agricultural practices), and 15.3 (Stabilize desertification), depend greatly on agriculture. To achieve these targets, the proposed farm ponds and check dams are crucial to expand cultivated land and control desertification. Furthermore, it is critical to use advanced irrigation methods such as sprinkler and drip irrigation as well as crops with minimal water requirements. In addition to raising food productivity, income levels, and job opportunities, this agricultural expansion strategy also satisfies targets such as 2.1 (Zero hunger), 9.1 (Facilitate economic growth), 8.3 (Foster employment opportunities), and 1.2 (Decrease poverty by 50%).

Energy needs for home and agricultural use can be met in an environmentally responsible way by using renewable energy sources, such as solar energy. Target 7.2 (Increase the utilization of renewable energy) is one of the SDGs that ensures everyone has access to cheap and clean energy. Goal seven (7) of the SDGs is all about ensuring these things. Farm ponds and lakes can be economically equipped with solar panels to supply electricity needs and minimize evaporation loss, even upstream of check dams.

Climate change in the context of global change is covered by the SDGs by adapting and reducing its impact. SDG targets, such as 1.5 (Mitigate extreme events related to climate variability), 13.1 (Improve resistance to climate-related risks), and 11B (Adjustment to climate variability), underscore the importance of climate resilience programs. Given the vulnerability of the study area to climate-change-induced natural disasters such as flash floods, constructing RWH structures serves as a proactive measure to mitigate such risks. These structures not only safeguard tourism in the study area (Hanna Lake, Spin Karez, Bolan Pass, Ziarat, and others) but also the main roads, which will be useful to achieve Target 8.9 (Fostering tourism).

The sustainable development of Quetta District depends on the local people's participation in water management, as highlighted in Target 6B, and the raising of public awareness of sustainable development, as outlined in Target 12.8. A variety of mass communication techniques, such as field visits and training sessions, can be employed to raise public awareness of the significance of RWH systems. Additionally, the district must actively participate in the development and execution of water management advantages that may lead to the construction, conservation, and maintenance of the RWH structures by this cooperative approach.

In conclusion, there are several ways in which this research might support the socioeconomic and environmental SDGs. The RWH strategy offers long-term answers to the various problems that community members face. Furthermore, the methodology outlined in this study and its findings can support planners and water managers in identifying the best locations for RWH structures and resolve concerns raised by the local community. The employed approach uses most of the publicly available data and is particularly suitable for arid and semiarid areas where the observed data are lacking.

4. Conclusions

This research aims to achieve the SDGs through the development and implementation of sustainable RWH strategies. Employing a combination of HM, MCA, GIS, and the depression depth approach ensured the precision of the results, and also, some other maps were added for the enhancement of site suitability. This study, conducted in the Quetta District region, identified appropriate sites for RWH and determined optimal locations for RWH structures. Biophysical factors, such as runoff, SA, SL, and LULC, along with socioeconomic parameters, such as DB, DL, and DR, were considered. The reliability of the established criteria was demonstrated by the CR of these variables. The primary outcomes of this study are summarized below:

- The results indicate that 6.36% (167.418 km^2), 14.34% (377.284 km^2), 16.36% (430.444 km^2), 18.92% (497.663 km^2), and 18.64% (490.224 km^2) of the total area fall into the categories of very high, high, moderate, low, and very low suitability for RWH, respectively. RWH potential was restricted to 25.35% (666.86 km^2) of the area of the watershed. Overall, most of the area was located in the very high and high suitability zones along the stream.
- The results also locate ten (10) optimal sites for percolation tanks and five (5) optimal sites for check dams along the streams. The areas identified as suitable for nala bunds, farm ponds, and percolation tanks on the ground are 0.173% (4.62 km^2), 0.178% (4.76 km^2), 1.320% (35.22 km^2), respectively.
- Implementing the sustainable RWH plan holds considerable significance for the advancement of Quetta District. The proposed strategy offers various benefits for both individuals and society. It aligns closely with the objectives outlined in SDG 6, Targets 6.1 (which include making sure that everyone has access to water), 6.4 (which addresses water shortages), 6A (which calls for increasing water harvesting activities), and 6.6 (which calls for rehabilitating aquifers). Therefore, deploying the suggested RWH systems not only offers sustainable solutions to water scarcity but also contributes to achieving the targets set in the SDGs.
- This research supports a number of the SDGs by providing long-term fixes for environmental, social, and economic problems including growing agricultural activities to create jobs and using solar energy.

For those looking to improve Quetta District's future development initiatives, this agenda provides invaluable assistance to water engineers, planners, and managers. The RWH site selection method requires less time, cost, and effort than traditional methods, which depend on collecting large amounts of field data. Moreover, this approach is versatile and applicable to diverse regions grappling with water scarcity challenges. This study focuses on RWH site identification and structure type. However, the storage of various RWH structures can also be determined to help water engineers, planners, and managers create a future development plan for Quetta District. The detailed site characterizations and in-depth field assessments of the suggested RWH locations need to be completed before the RWH system can be implemented in order to assess and track surface flooding operations. Moreover, it is also suggested to consider various methods, such as machine learning models (artificial neural network, support vector machine, and random forest), AHP, and fuzzy logic, to assess the site suitability of RWH, and an optimal technique needs to be recommended based on the validation of these results.

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