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Water Recharges Suitability in Kabul Aquifer System within the Upper Indus Basin

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Abstract: Groundwater is the main source of water for drinking, household use, and irrigation in Kabul; however, the water table is dropping due to the excessive extraction over the past two decades. The groundwater restoration criteria selection mainly depends on the techniques used to recharge the aquifer. The design of infiltration basins, for example, requires different technical criteria than the installation of infiltration wells. The different set of parameters is relevant to water being infiltrated at the surface in comparison with water being injected into the aquifers. Restoration of the groundwater resources are complicated and expensive tasks. An inexpensive preliminary investigation of the potential recharge areas, especially in developing countries such as Afghanistan with its complex Upper Indus River Basin, can be reasonably explored. The present research aims to identify the potential recharge sites through employing GIS and Analytical Hierarchy Process (AHP) and combining remote sensing information with in situ and geospatial data obtained from related organizations in Afghanistan. These data sets were employed to document nine thematic layers which include slope, drainage density, rainfall, distance to fault, distance to river channel, lithology, and ground water table, land cover, and soil texture. All of the thematic layers were allocated and ranked, based on previous studies, and field surveys and extensive questionnaire surveys carried out with Afghan experts. Based on the collected and processed data output, the groundwater recharge values were determined. These recharge values were grouped into four classes assessing the suitability for recharge as very high (100%), high (63%), moderate (26%), and low (10%). The relative importance of the various geospatial layers was identified and shows that slope (19.2%) is the most important, and faults (3.8%) the least important. The selection of climatic characteristics and geological characteristics as the most important criteria in the artificial recharge of the aquifer are investigated in many regions with good access to data and opportunities for validation and verifications. However, in regions with limited data due to the complexities in collecting data in Afghanistan, proper researching with sufficient data is a challenge. The novelty of this research is the cross-disciplinary approach with incorporation of a compiled set of input data with the set of various criteria (nine criteria based on which layers are formed, including slope, drainage density, rainfall, distance to fault, distance to river channel, lithology, ground water table, land cover, and soil texture) and experts' questionnaires. The AHP methodology expanded with the cross-disciplinary approach by adding the local experts´ questionnaires survey can be very handy in areas with limited access to data, to provide the preliminary investigations, and reduce expenses on the localized expensive and often dangerous field works.

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1. Introduction

With the depletion of groundwater resources and substantial losses in surface water reservoirs through evaporation, the restoration of groundwater aquifers can be a strategy to enhance the sustainability of the groundwater resources in the Kabul Plain aquifer within the Upper Indus River Basin (UIRB) (Figure 1). Previous studies show a decreasing trend in groundwater levels and deteriorating groundwater quality [1–12]. Therefore, improved groundwater management is needed to ensure an adequate water supply to the expanding city. One of the most appropriate ways to enhance the condition of the aquifer is to use the managing aquifer recharge (MAR) technique, which is widely used for different regions [13–18]. Regional recharge studies in the Kabul aquifer have been limited to traditional approaches to groundwater and recharge exploration which only utilized drilling and geophysical methods in some small areas sporadically due to the expensive field work investigations and the regional complexity with confrontations and wars [19]. The traditional field geophysical works are costly, time-consuming, and can be deployed in only limited areas [20,21]. The RS techniques and GIS tools are helpful in investigations and provide the opportunity to prepare the first-order, preliminary estimates with less expense and avoid the complexities of field investigations in developing or war-torn countries [22,23]. The RS-GIS based methodologies with utilization of global datasets can be applied in many regions throughout the world, particularly in areas where in situ data is insufficient and accessibility is limited. The RS-GIS based models like DRASTIC (depth to water-table, recharge, aquifer media, soil media, topography, impact of the vadose zone, hydraulic conductivity) have been previously used in groundwater pollution risk assessment [24,25]. The support methodologies to identify potential recharge areas are in development, and include, for example, the frequency ratios method [26], logistic regression model techniques [27], random forest models [28], and artificial neural networks [27]. The RS-based methods allow quick and replicable coverage of entire regions, making it a useful tool for obtaining short-term spatiotemporal information from large areas [29,30]. GIS is able to effectively handle complicated spatial-temporal data and various datasets for the same geographical location [31]. Several researchers have used RS and GIS approaches for delineating potential sites and identifying artificial groundwater recharge areas [32–37]. Other methods are based on bivariate and multivariate statistical analysis with decision making in prioritization of the collected information [38,39]. The RS-GIS based techniques in combination with the AHP methodology have been increasingly popular to obtain spatial plans and resource allocations for addressing various water resource management issues in the last several decades [40]. Lack of access to reliable data and to financial resources often make large-scale geophysical exploratory surveys in the region impossible. The AHP has been employed as a well-organized technique to specify the groundwater potential sites in some other areas [41–44]. We expand applications of RS-GIS and AHP approaches to combine hydrogeological, geomorphological and climatic data to delineate sites for groundwater recharge potential in the UIRB area, Kabul aquifer system.

This study aims to develop a method using RS and GIS overlays and AHP techniques to delineate potential sites for groundwater recharge. Specific objectives include identifying potential locations for groundwater recharge and determining the relative importance of the various Geospatial attributes based on their impact on groundwater recharge.

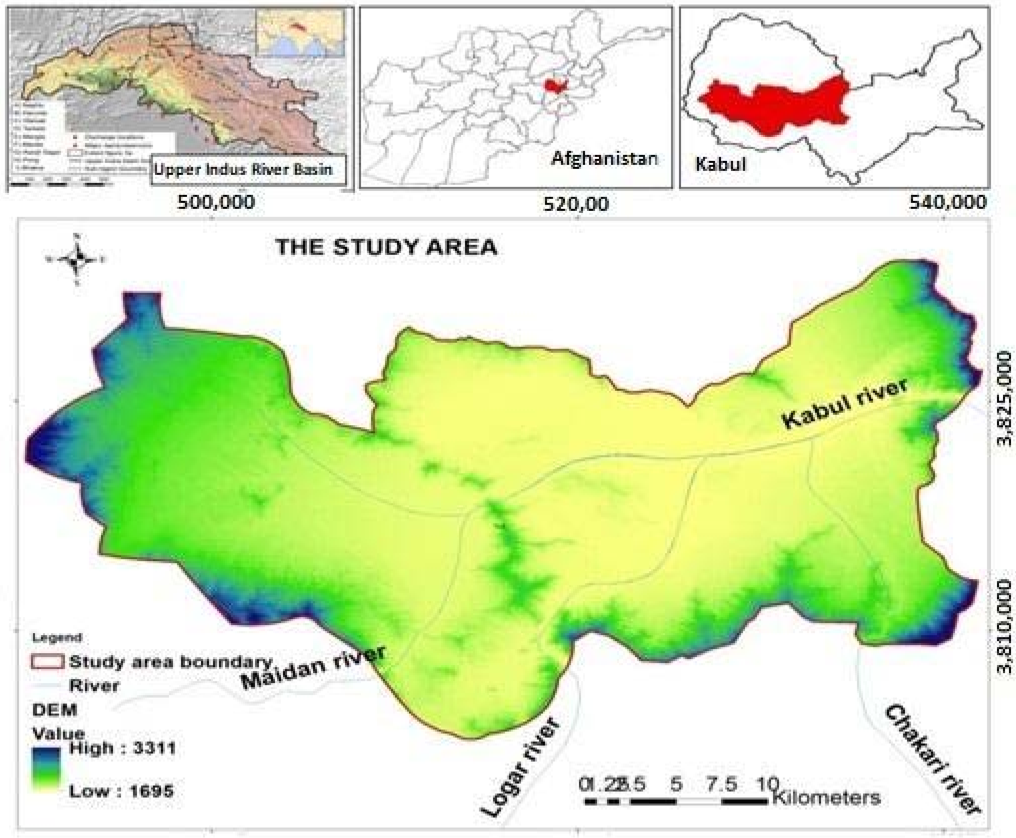

Figure 1. Location of the study area within the Upper Indus Basin.

2. Materials and Methods

2.1. The Study Area Description

The study area, the Kabul Plain, is located in the central part of Kabul province in Afghanistan, which lies at 69°24′37.38″ E to 69°9′16.50″ E longitude and 34°32′3.37″ N to 34°35′5.71″ N latitude, and which covers a total of 926.48 km^2 within the UIRB (Figure 1). The relief of the study area is around 1600 m and ranges between 1695 m and 3311 m above sea level (a.s.l.). The study area is enclosed by mountain ranges which divide the catchment into two sub-basins in the NW-SE direction. The climate of the study area is categorized into arid and semi-arid with air temperature ranging from a mean monthly high in July of 32 °C to an average monthly low in January of −7 °C. Average annual precipitation and potential evapotranspiration rate is 330 mm/year and 1600 mm/year, respectively. There is no permanent river flows in the study area. However, surface water due to flooding during the cold seasons is the major source for groundwater recharging. Three rivers enter the Kabul city region: the north-flowing Kabul River and its two tributaries, the Paghman and the Logar rivers (Figure 1). The Kabul River ultimately flows eastward and enters Pakistan. Geologically, the fluvial and aeolian sedimentary rocks form a major part of the lithology of the study area. The results obtained from pumping tests conducted in the Kabul Plain were employed to validate the results of this study. The values of hydraulic conductivity are between 2 and 112 m per day [45].

2.2. Overall Methodology

To delineate a potential site for recharging the Kabul Plain aquifer, a set of GIS tools were employed. The applied methodology is presented in Figure 2, which involves the following major steps:

1. Identifying criteria and preparing thematic layers,
2. Ranking the thematic layers,

3. Weighting of the criteria (layers),
4. Analyzing the overlay,
5. Generating the suitability map

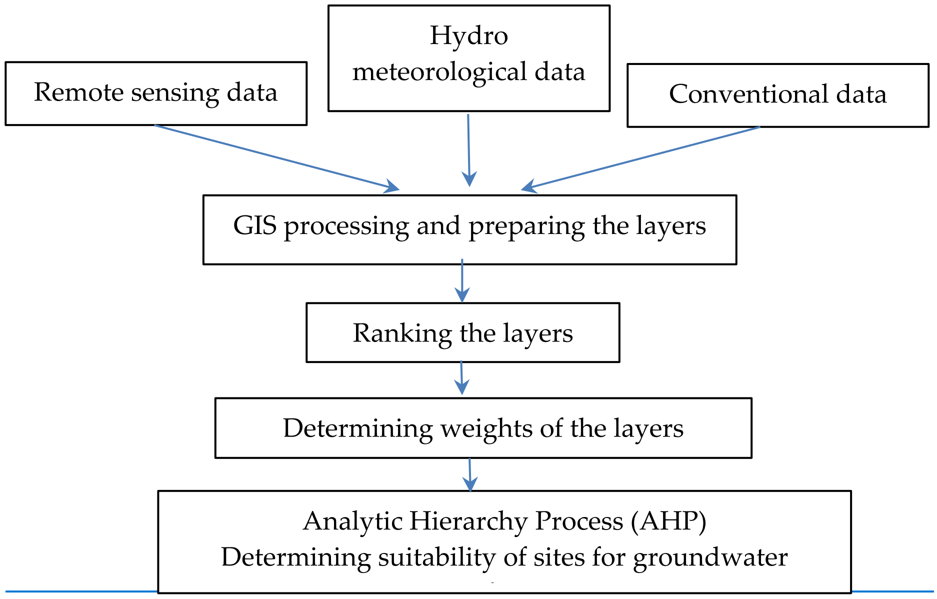

Figure 2. The flowchart of the overall methodology.

2.3. Identify Criteria and Preparation of Thematic Layers

Three main category datasets, which included RS, hydrometeorological, and conventional data were used to develop the map of suitable recharge sites. The data used include slope, distance from faults, land use, drainage network, soil texture, lithology, depth to groundwater table, distance from river, and precipitation amount. These datasets were gathered from the previous studies and followed the international guidelines in the identification of suitable recharge sites [46]. Each criterion was represented as a thematic layer created from satellite images, data from relevant sources, and conventional field data. The analysis of these data was completed employing QGIS 3.22.9.

2.3.1. Remote Sensing Data

Slope and drainage density data were obtained from Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30-m resolution [47]. The slope and drainage density maps (Figure 3a,b) were prepared by using the spatial analyst tool of the QGIS tools. The land use map was extracted using the national land use map of Afghanistan (Figure 3c). The map was received in shape file format from the Afghanistan Ministry of Agriculture, Irrigation and Livestock (MAIL) [48]. The land use maps show that the land is mostly used as rangeland and crop lands (Figure 3c). Figure 3d shows the lineaments, adopted from the U.S. General Services (USGS) work in Afghanistan [49].

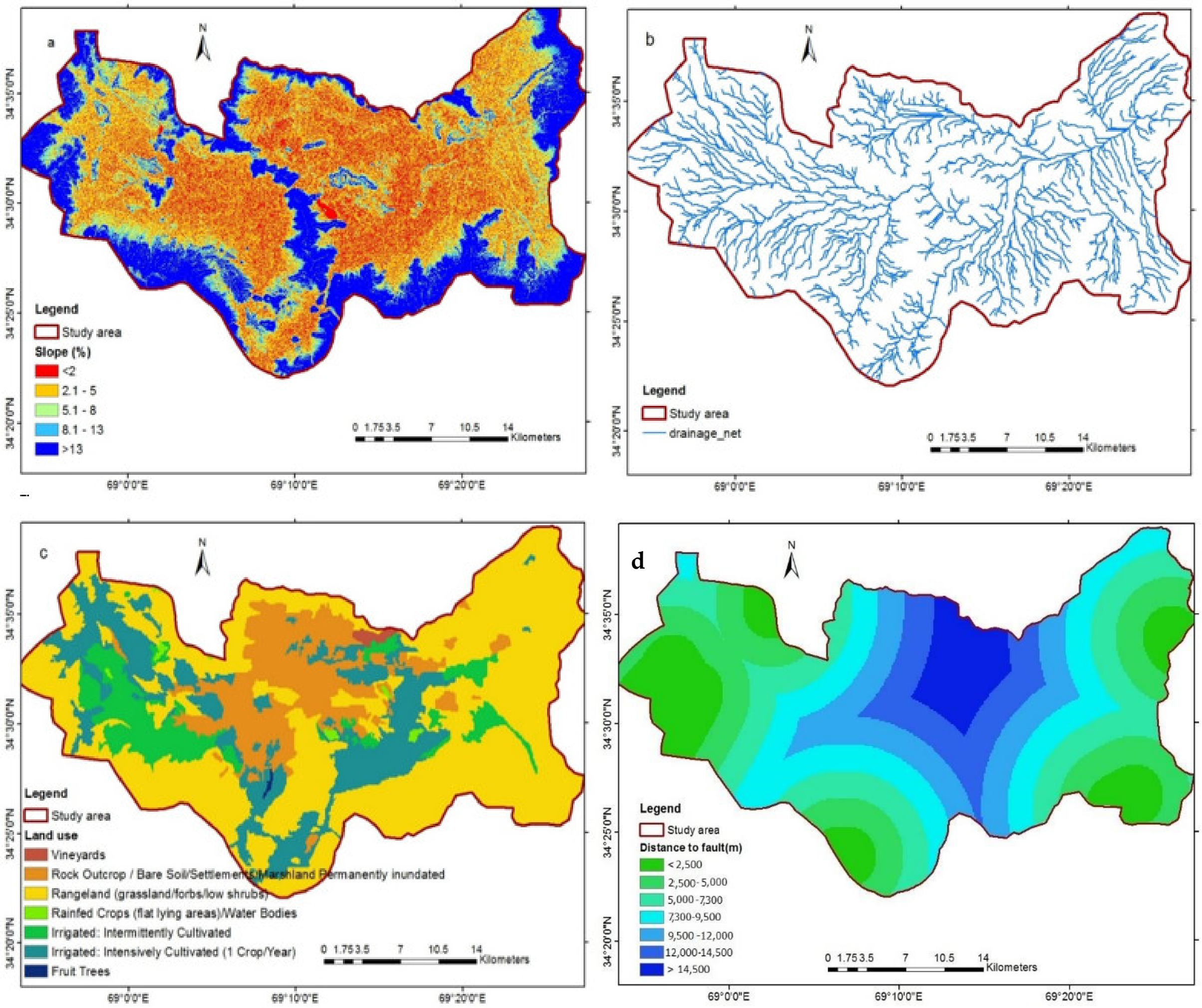

Figure 3. Maps of the remote sensing data: (**a**) slope; (**b**) drainage density; (**c**) land use; (**d**) distance to fault.

2.3.2. Conventional Data

The geology map was extracted from the Geologic and Mineral Resource Map of Afghanistan (scale: 1:250,000) (Figure 4a). The map was obtained in shape file format from the USGS [50]. The Kabul Plain is enclosed by mountain ranges and the Kabul Plain is filled with Quaternary and Neogene deposits (Figure 4) [51]. The mountain ranges mainly consist of a variety of metamorphic rocks and to some extent crystalline rocks [52].

The Kabul Plain is geologically composed of an accumulation of lacustrine and terrestrial deposits. The deposits in the Kabul Plain are categorized into Quaternary and Neogene deposits. The Quaternary deposits are composed of sand and gravel, and are deposited mainly in the river channels. The Neogene sediments consist mainly of clay, siltstones, marls, fine-grained sandstones, and conglomerate (Figure 5a) [53].

The soil texture layer map (Figure 5b) was extracted from the regional soil map of Afghanistan which was prepared by the U.S Department of Agriculture (USDA) [54]. The soil texture map shows five classifications. Included Class -1-Haplocambids with Torriorthents: This type of soil covers a large amount of low slope land of the central portion of the basin. Class -2 Rocky lands with Lithic Cryorthents: cover the eastern and northern parts of the study area in small amounts. Class -3 Rocky land with Lithic Haplocambids; Covers small part of central flat section of the study area. Class -4 Rocky lands with Lithic Haplocryids, Class -5 Xerochrepts with Xerorthents covers a small area of the Kabul Plain to the western.

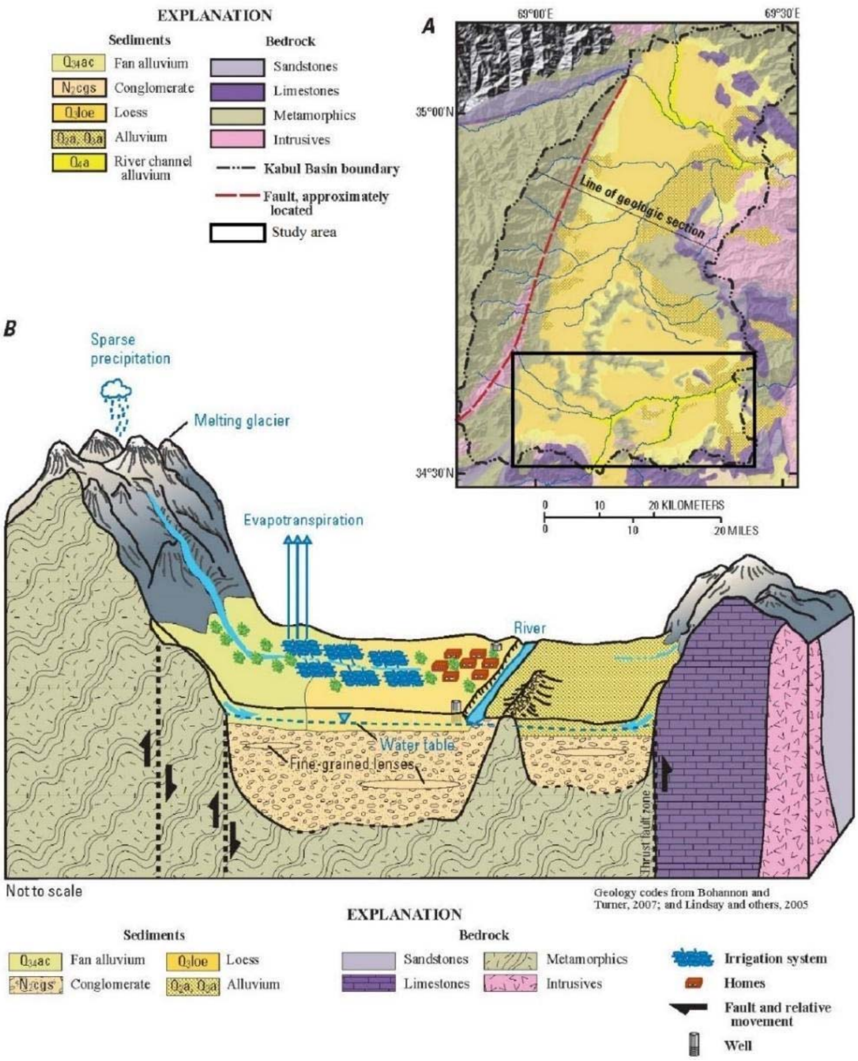

Figure 4. Geology map (**A**) and conceptualized hydro geologic cross section (**B**) of the study area [50].

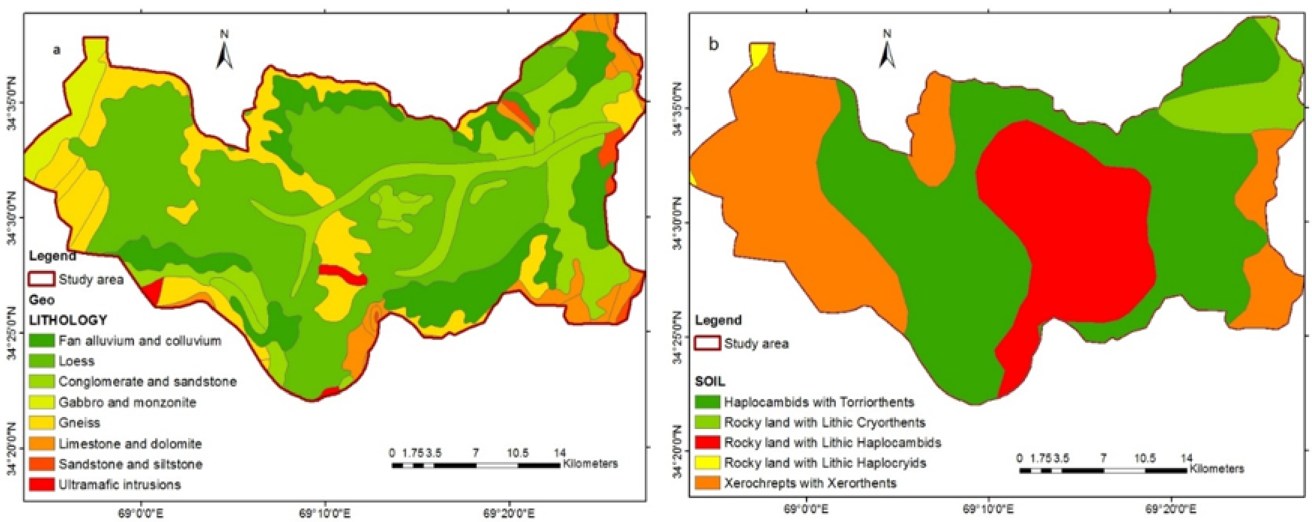

Figure 5. Maps of the conventional data: (**a**) lithology; (**b**) soil texture.

2.3.3. Meteorological Data

Depth to the ground water-table is one of the primary variables for the groundwater recharge system. Water table data of 2017 were received from the hydrogeology department of the National Water Affair Regulation Authority of Afghanistan (NWARA), and Afghanite Geo Engineering Company (AGEC, Kabul, Afghanistan) [55] in digital format. The inverse distance weighting (IDW) approach was employed to interpolate these data for the whole study area. Figure 6a shows the groundwater depth map. Groundwater fluctuations are between 15 and 100 m. The average annual rainfall of the area's three meteorological stations was used to prepare the rainfall thematic layer. The minimum and maximum of the rainfall amount are about 285 mm and 381 mm, respectively. These data are interpolated spatially using the IDW method for the whole study area. Figure 6b illustrates the rainfall distribution map of the study area. Rainfall decreases to the east (Figure 6). Flood water is considered one of the potential sources of water for the groundwater recharge projects, and floods occur on both sides of stream channels. Less distance indicates higher suitability. Figure 6c presents a map of major rivers. The measurements of rivers were received from the Ministry of Energy and Water of Afghanistan.

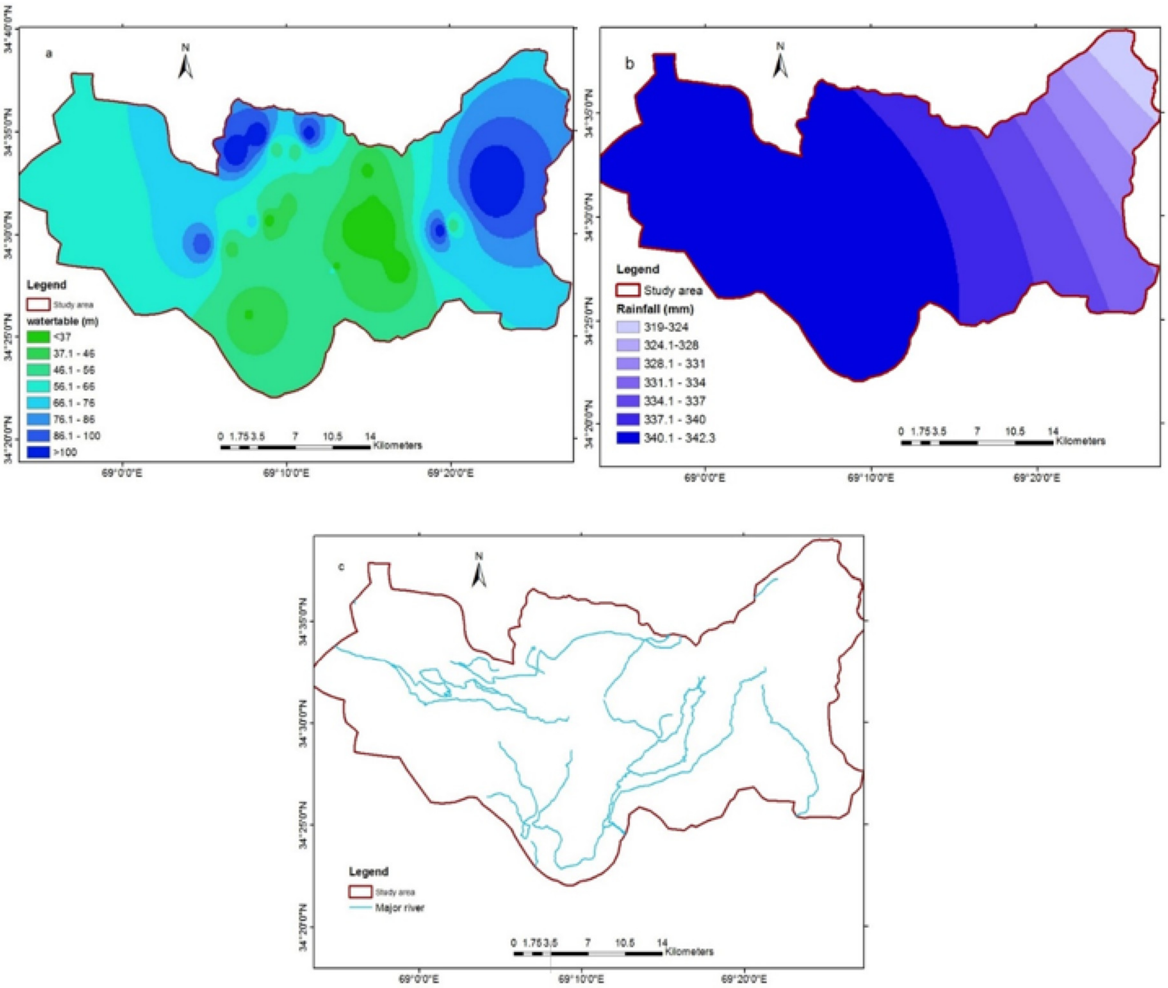

Figure 6. Water resource contribution to the area: (**a**) water table; (**b**) rainfall; (**c**) major river.

2.4. Ranking the Thematic Layers

The different scales on the datasets and the criteria were measured, unified, and converted into the comparable units. The thematic layers were unified with the sample category. The thematic layers were assorted into the classes, according to the groundwater occurrence and recharge approach taken by previous works [33] and recommendations.

For each layer, higher values are dedicated to classes that are more important for locating groundwater recharge. The thematic maps, however, were prepared first and then were re-classed into five suitability classes (1–5) (Figure 7a–i).

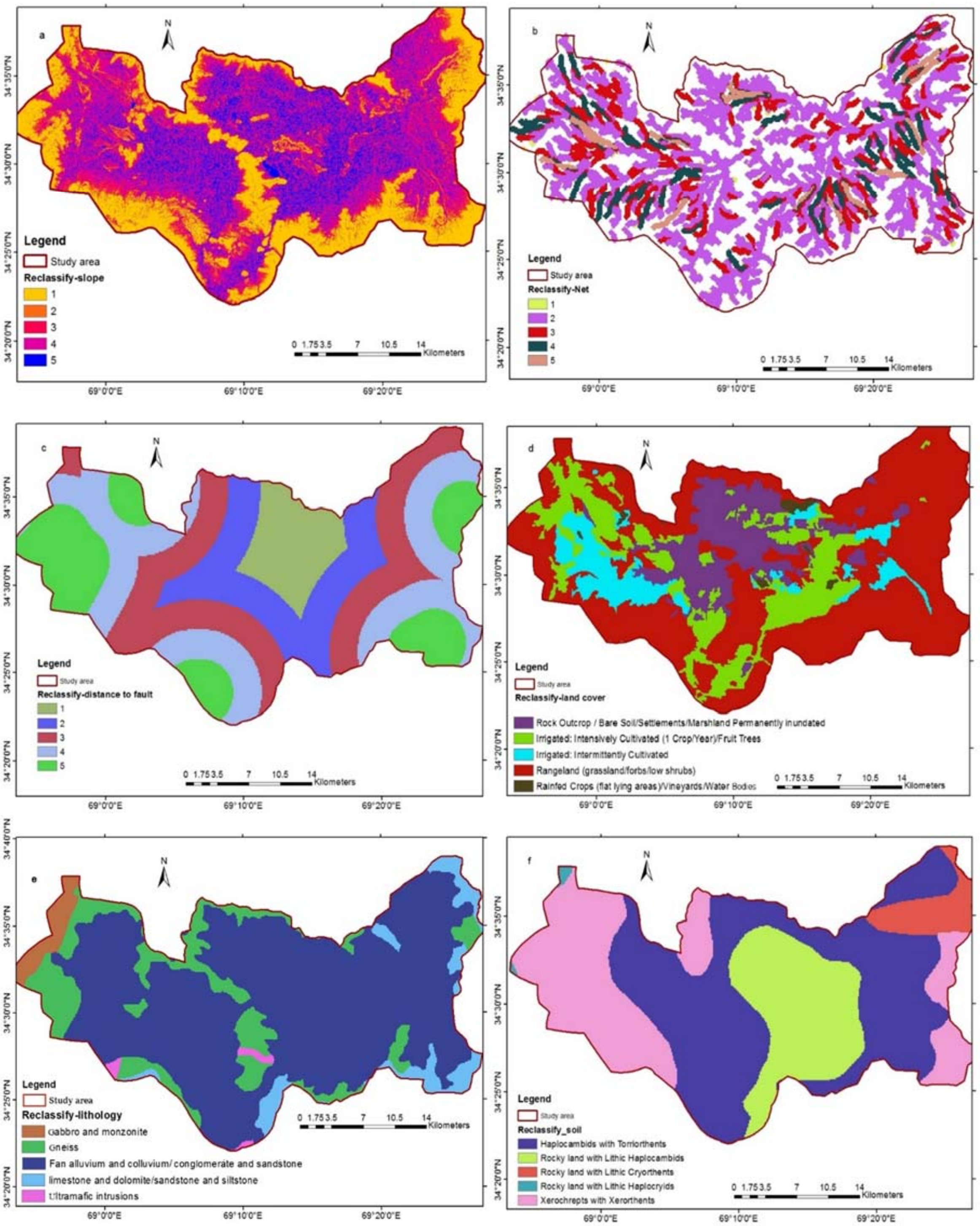

Figure 7. *Cont.*

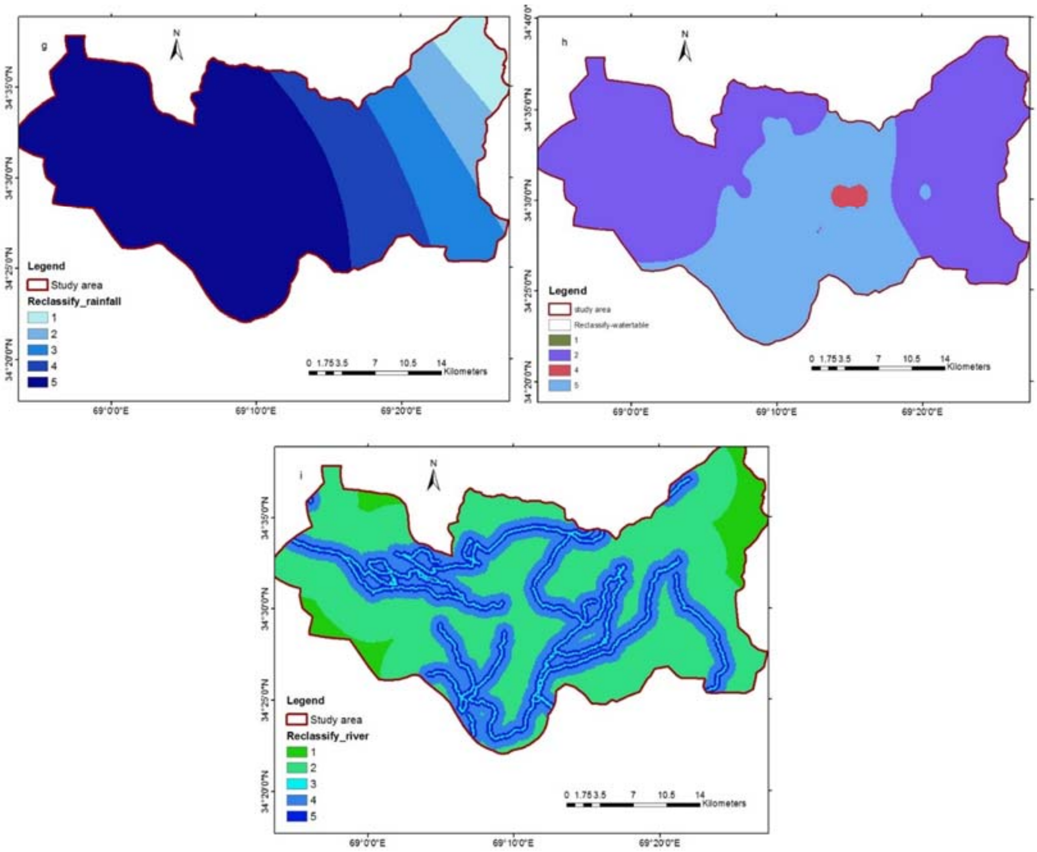

Figure 7. Ranked and reclassified layer maps: (**a**) slope; (**b**) drainage density; (**c**) distance to fault; (**d**) land use; (**e**) lithology; (**f**) soil texture; (**g**) rainfall; (**h**) water table; (**i**) distance to river.

Slope plays an important role in controlling runoff into the subsurface. The slope must be as gentle as possible to favor surface water infiltration. A significant amount of rainwater is commonly percolated in the flat terrain, whereas overflow will occur on steep slope areas. Thus, the slope of the study area is classified into five categories, namely 0–2°, 2.1–5°, 5.1–8°, 8.1–13°, and higher than 13°. Higher infiltration values were allocated to the flat and undulating areas (e.g., 0–2d = 5), whereas less value was assigned to the steep slope areas (Table 1).

Areas with high drainage density can receive excessive runoff and have high recharge potential. Therefore, areas with high drainage density were assigned a high recharge potential, as demonstrated in Figure 7b.

Table 1. Ranking of the suitability variables.

Parameters	Range	Rank
Slope (Degree)	0–2	5
	2.1–5	4
	5.1–8	3
	8.1–13	2
	13.1–77	1
Lithology	Gneiss	1
	ultramafic intrusions	2
	gabbro and monzonite	3
	sandstone and siltstone/carbonates	4
	Fan alluvium and colluvium/loess/conglomerate and fractured sandstone	5

Table 1. *Cont.*

Parameters	Range	Rank
Drainage density	0–0.17	1
	0.17–0.30	2
	0.30–0.46	3
	0.46–0.67	4
	>0.67	5
Land-use	Rock Outcrop/ Bare Soil/Settlements/Marshland Permanently inundated	1
	Fruit Trees/Irrigated: Intensively Cultivated (1 crop/Year)	2
	Irrigated: Intermittently Cultivated/Vineyards	3
	Rangeland (grassland/forbs/low shrubs)	4
	Rain fed Crops (flat lying areas)/Water bodies	5
ground water table (m)	>60	2
	30–60	4
	15–30	5
	<15	1
Rainfall (mm)	319.25–323.86	1
	323.861–328.47	2
	328.4701–333.07	3
	333.078–337.6	4
	337.68–342.3	5
Distance to river (m)	0–50	3
	50–300	5
	300–1000	4
	1000–5000	2
	>5000	1
Distance to fault (m)	0–3500	3
	3500–6600	5
	6600–9800	4
	9800–13,500	2
	>13,500	1
Soil	Haplocambids with Torriorthents	5
	Rocky land with Lithic Haplocambids	4
	Rocky lands with Lithic Cryorthents	3
	Xerorthents and Xerochrepts	2
	Rocky land with Lithic Haplocryids	1

Land-use and land cover affect groundwater potential by affecting runoff, soil erosion, and evapotranspiration [56,57]. The study area contains vineyards, rock outcrops, bare soil, settlements, rangeland, cropland, and irrigated areas. Settlements have a negative consequence on water infiltration to the subsurface with surface coverage of different types of engineering constructions, pavements, and soil condensations. Settlements often restrict the infiltration of precipitation and affect the recharge of the groundwater. Agricultural land and rainfed lands pose high groundwater recharge potential. They have good vegetation cover. The infiltration capacity of soil depends on numerous factors such as moisture content, soil type, organic matter, and vegetative cover. The soil characteristics affecting infiltration and non-capillary porosity are probably the most significant. The porosity determines the storage capacity of soil and influences persistence to flow; thus, infiltration tends to increase with effective porosity. Vegetation cover increases infiltration in comparison with barren soil because (i) it retards surface flow giving the water additional time to percolate the soil; (ii) the root system makes the soil more pervious; and (iii) the foliage shields the soil from raindrop impact and decreases the rain packing of the surface soil. Similarly, other researchers noted that land covered with vegetation is an attractive site for groundwater investigation [21]. Geological features such as faults and lineaments induce secondary porosity and subsequently the permeability of rocks. Groundwater flow in the subsurface is facilitated by faults, fracture, and solution conduits below the land surface. There is a strong positive correlation between the geologic structure and rapid pathways for groundwater recharge and flow to the aquifers [58]. The lineament intersections in an area facilitate the infiltration of surface water to the subsurface. Therefore, areas away from the lineament have a lower potential for groundwater recharge. The type of rock and soil is the most important component for groundwater potential due to the infiltration process primarily depending on the permeability of particular types of rock [59,60]. Fan alluvium and colluvium, loess, conglomerate and sandstone, gabro and monzonite, gneiss, carbonates, siltstone, and ultramafic intrusions are the main geological formations found in the Kabul Basin as shown in Figure 5a. High weight is assigned for fan alluvium, conglomerate, and sandstone, because these formations are highly weathered and fractured. In contrast, low weights were given to ultramafic formations due to their low permeability. Soil is commonly categorized based on the drainage classes. The suburbs of the Kabul Plain are mainly overlayed with well-drained soil, particularly in rangeland. High weight is assigned to a well-drained area. The depth between 15 to 30 m in the water table is considered suitable for recharge. This is in line with artificial groundwater recharge schemes and the interaction between rechargeable water and the aquifer. Groundwater depth fluctuations are between 15 to 100 m. Within 15 to 30 m depth, the groundwater can be held in the targeted aquifer. At a depth of less than 15 m, the lateral drainage may move water downstream. Regarding the precipitation, due to limitations in snow-measuring data only rainfall data were used. Rainfall for the Kabul Plain was divided into five equal classes using GIS tools. The classification of rainfall ranges was completed by considering local precipitation [25,44,61]. In terms of rivers, the areas near them are more suitable to natural and artificial groundwater recharge. However, to prevent the flow of water from the recharged area back to the stream from a groundwater table mound caused by the recharge project, very short distances to surface water have lower values.

The artificial recharge to groundwater usually improves the sustainable yield of the aquifer in areas where over-exploitation has decreased the aquifer storage. The distance between 50 to 300 m from the river is considered very suitable for recharging projects if these natural linear structures are used for this purpose.

2.5. Determining Weights for the Criteria (Layers)

The weighting procedure was completed using the AHP method. The AHP matrix approach is suitable in cases of separating a large number of alternatives to a series of pairwise comparisons followed by synthesizing the results.

In order to identify suitable recharge sites, the AHP approach was applied in four steps: (1) the delineation of effective factors on groundwater recharge sites; (2) a pairwise comparison matrix; (3) estimating relative importance; and (4) calculating matrix consistency. The effective factors are nine thematic layers which include aquifer lithology, soil texture, drainage density, distance to fault, slope, land use, rainfall, distance to river, and depth to the groundwater table.

The relative significance of each variable on groundwater recharge is determined according to the employment of a nine-point scale, as illustrated in Table 2; a score of 1 is given for equal importance between the two factors, and a score of 9 is given for extreme importance of the row theme in comparison with the column factor. According to the number of input factors (reclassified maps of thematic layers) a pairwise comparison matrix, A (m^2), is created. In this research, the pairwise comparison matrix procedure was applied. For pairwise comparison, the factor effects on each other were measured according to Saaty's one-to-nine-point scale (Table 2).

In the matrix, the selection parameter pairs, and the assignment of pair weight were undertaken according to the interconnection between one factor and the others to affect recharge.

Table 2. Saaty's 1-9 scale of relative importance [62].

Intensity of Importance	Interpretation
1	Equal importance
3	Moderate importance
5	Essential
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate value between adjacent scale values

The target population consisted of ten people knowledgeable about Afghanistan's water resources basin, including five experts from the Ministry of Energy and Water, three water resource management engineers of private Afghanistan geoscience companies, and two local people working on water issues in the study area. Ten people were asked to complete the questionnaire which sought information on the following criteria: slope, drainage density, rainfall, distance to fault, distance to river channel, lithology, ground water table, land cover, and soil texture.

For instance, the lithology/land use type pair was assigned 3 (moderate importance) because geological features play a crucial role in the occurrence and distribution of groundwater in any terrain and can recharge the aquifer directly [63]. A value of 1 was assigned to parameters of equal importance.

Table 3 shows a pairwise comparison matrix which was derived from Saaty's nine-point importance scale.

Table 3. Pairwise comparison matrix of parameters.

Parameter	Slope	Geology	Drainage Density	Land Use	Distance to Fault	Water Table	Soil Texture	Distance to River	Rainfall
Slope	1	1.09	1.5	3	5	4.5	2	4	1.63
Geology	0.91	1	2	3	2.5	1.5	2	1.02	2.16
Drainage Density	0.66	0.5	1	1.5	2.5	1.5	2.5	2	3.06
Land use	0.33	0.33	0.66	1	3	5	1.5	2	2.58
Distance to fault	0.2	0.4	0.4	0.33	1	1.6	1.5	2.02	6.96
Water table	0.22	0.66	0.66	0.2	0.62	1	1	1.01	1.07
Soil texture	0.5	0.5	0.4	0.66	0.66	1	1	3	1.26
Distance to river	0.25	0.98	0.5	0.5	0.49	0.99	0.33	1	1.24
Rainfall	0.61	0.46	0.32	0.38	0.14	0.93	0.79	0.80	1
	CI	0.09							

The Consistency index (*CI*) is expressed as ratio of the difference between the principal eigenvalue (λmax) and the number of factors under study from the (n) to ($n-1$) as follows:

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

The *CI* for recharge parameters studied in Kabul Basin was achieved using an overlying method. The consistency index was 0.09, which is less than 1.

3. Results

Map of Groundwater Recharge Potential

The reclassified layers and their corresponding percentages influencing the recharge were integrated using the weighted overlay tool of QGIS tools and generated a spatial distribution map of groundwater recharge within the Kabul aquifer system (Figure 8).

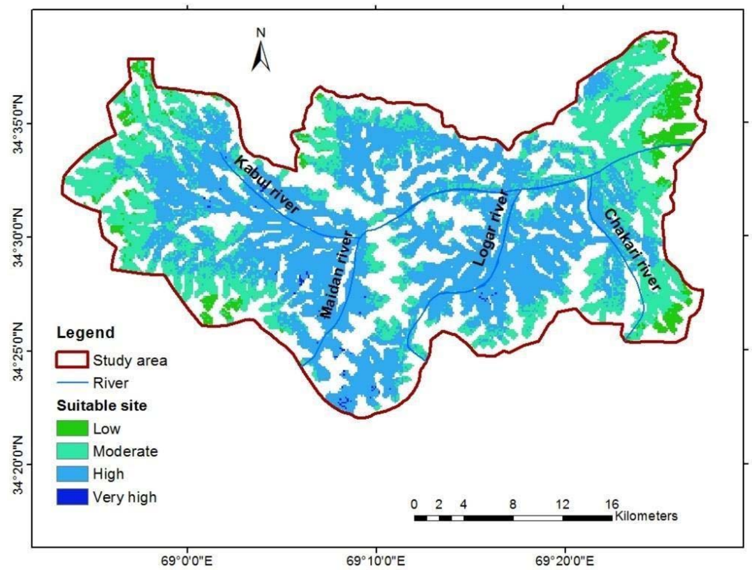

Figure 8. Map of groundwater recharge suitability for the Kabul aquifer.

The Equation (2) is applied to map of groundwater recharge as following;

$$GWRSM = 18.6\% \times RRf + 13.7\% \times RGm + 19.2\% \times RSl + 11.2\% \times RSt + 3.8 \times RLd + 8.2 \times RDd + 10.5 \times RLulc + 6.9 \times Rdr + 7.9 \times RWf \quad (2)$$

where, *RRf* is a reclassified rainfall map, *RGm* is a reclassified geology map, *RSl* is a reclassified slope map, *Rst* is reclassified soil texture map, *RLd* is a reclassified fault distance map, *RDd* is a reclassified drainage density map, *Rlulc* is a reclassified land-use/land-cover map, *Rdr* is a reclassified distance to river map, and *Rwf* is a reclassified distance to groundwater level map.

The spatial distribution of recharge categories (Figure 8) displays that the very high to high areas for groundwater recharge are situated in the central and southern parts of the Kabul Plain, while most of the marginal parts were assigned as moderate to low.

Based on the map of suitable sites, 64% of the study area has high suitability for groundwater recharge (Figure 9). The suitable areas are situated in low altitude areas which are almost flat. These areas are covered by sedimentary units including two major geological formations: alluvium and colluvium fans, limestone, and sandstone. These formations are considered to have a high potential for the recharge process due to their specific characteristics including the porosity values and the nature of +. Twenty-six percent of the study area has moderate suitability and 10% has low suitability (Figure 9).

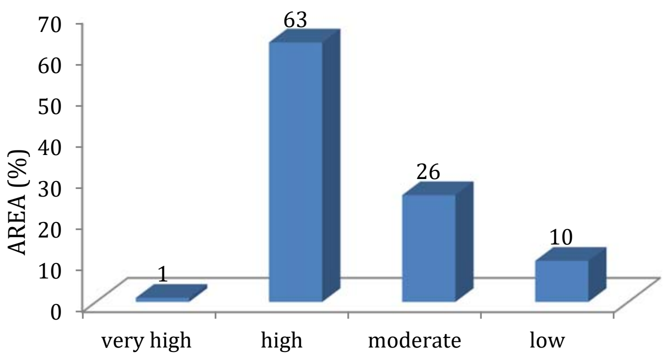

Figure 9. Distribution of suitable areas in the Kabul aquifer.

The mountains are the main part of these areas that are primarily composed of Paleoproterozoic gneiss and ultramafic rocks. The natural characteristics of these formations are not appropriate for groundwater recharge. Also, the suitable areas for groundwater recharge have residential development alongside the rivers.

A map of the groundwater recharge potential was created. The central and southern parts of the Kabul Plain are specified as very high to high potential sites which have rain-fed crops and croplands where the infiltration is high. The areas with the most potential for groundwater recharge that have been identified are: alluvial fans/sandstones/conglomerates, crop lands, and low/flat slope areas, areas near surface water, areas with higher precipitation, and proximity to faults. Based on the map of suitable sites, (Figure 9), 64% of the study area has high suitability for groundwater recharge.

Figure 10 denotes the weights of each layer in AHP. The slope (19.2%) and rainfall (18.6%) are the most important thematic layers and strongly influence the recharge process. Soil texture and land use are also important. The distance to fault (3.8%) layer is the least important.

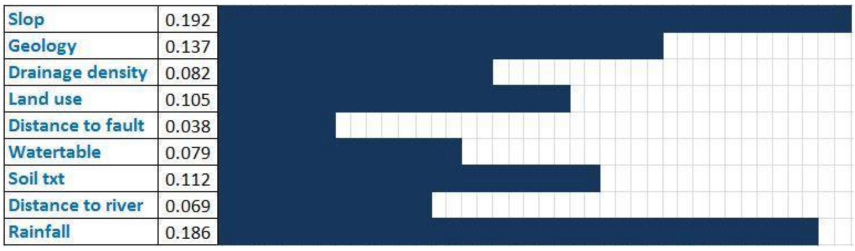

Figure 10. Relative importance of thematic layers.

4. Discussion

4.1. Delineation of Groundwater Potential Recharge Zones

The integration of RS data and the AHP method into the GIS environment to delineate the spatial distribution of recharge within a geographical area has been proven to be both practically and economically feasible [44]. According to the obtained weights of applied layers (Figure 10), recharge is controlled by several different factors. Suitable recharge sites (high and very high classes) correspond to outcrops of the Quaternary (Lataband series) and Tertiary (Kabul series) sediments (Section 2.3.2). These components are highly weathered and fractured. They have high porosity and permeability and they are suitable for recharge. Therefore, the outcrops of the Lataband and Kabul series were allocated a high recharge potential.

Regarding slope characteristics, which shows lithological resistance to weathering and erosion, a large portion of the area has a low slope. A low slope (<5°) can generally be observed in central parts of the Kabul Plain and in the foothills (Figure 3a). Flat to gentle slopes tend to spread overflows and produce considerable groundwater recharge in permeable areas. Therefore, these areas are considered appropriate for groundwater recharge. Higher slopes can be located at the flanks of the hill regions.

The precipitation availability is considered an essential source of groundwater recharge [64,65]. Therefore, rainfall has been assigned as the most significant factor in groundwater recharge after slope. Generally, total rainfall gradually increases with an increase in elevation in the study area from medium (328.5–333.1 mm/year) to high (333.1–337.6 mm/year) and very high (>337.7 mm/year). The eastern and the central part of the study area receives very low (<319.3 mm/year) to low (324–328.5 mm/year) rainfall (Figure 6b). Moving to the east, the rainfall values and groundwater potential decreases.

Areas with dense lineaments are usually considered suitable sites for groundwater recharge. Faults and lineaments also have good potential for recharging groundwater. Areas with a high recharge potential are in the central and southwest of the Kabul Plain aquifer, closer to fault and fracture areas. The aforementioned areas are characterized by the most permeable lithologic units, low to gentle slopes, high drainage density, and thick soil layers with high infiltration capacity, corresponding to reclassified thematic layers of high recharge potentials.

4.2. Validation

The distribution map of established extraction wells was in combination with the created map of the potential recharge areas; the well locations overlap these areas (Figure 11a). Most of the wells exist in the conglomerate, sandstone and loess. This lithology is well known for their high permeability. The central and southwestern regions are high recharge zones and coincide with six recharge sites (Figure 11b) which previously were identified using field work and groundwater investigation. The identified suitable recharge zones include: (1) southwest of the catchment where the Maidan River enters the study area; three zones of the six suitable recharge areas are located along the river; and (2) the alluvial fan situated in the central part of the plain where the Kabul and Maidan rivers connect. The areas with high values of hydraulic conductivity, k (m/day), are in the high recharge zones. In addition, the amount of hydraulic conductivity decreases toward the outlet of the basin. The high recharge zones are seen on conglomerate, sandstone and loess lithology in which the amounts of hydraulic conductivity are highest. Recharge rates fall in regions where lithology properties are confined by the ultramafic intrusions, gneiss and the gabbro and monzonite cover (Figure 11c).

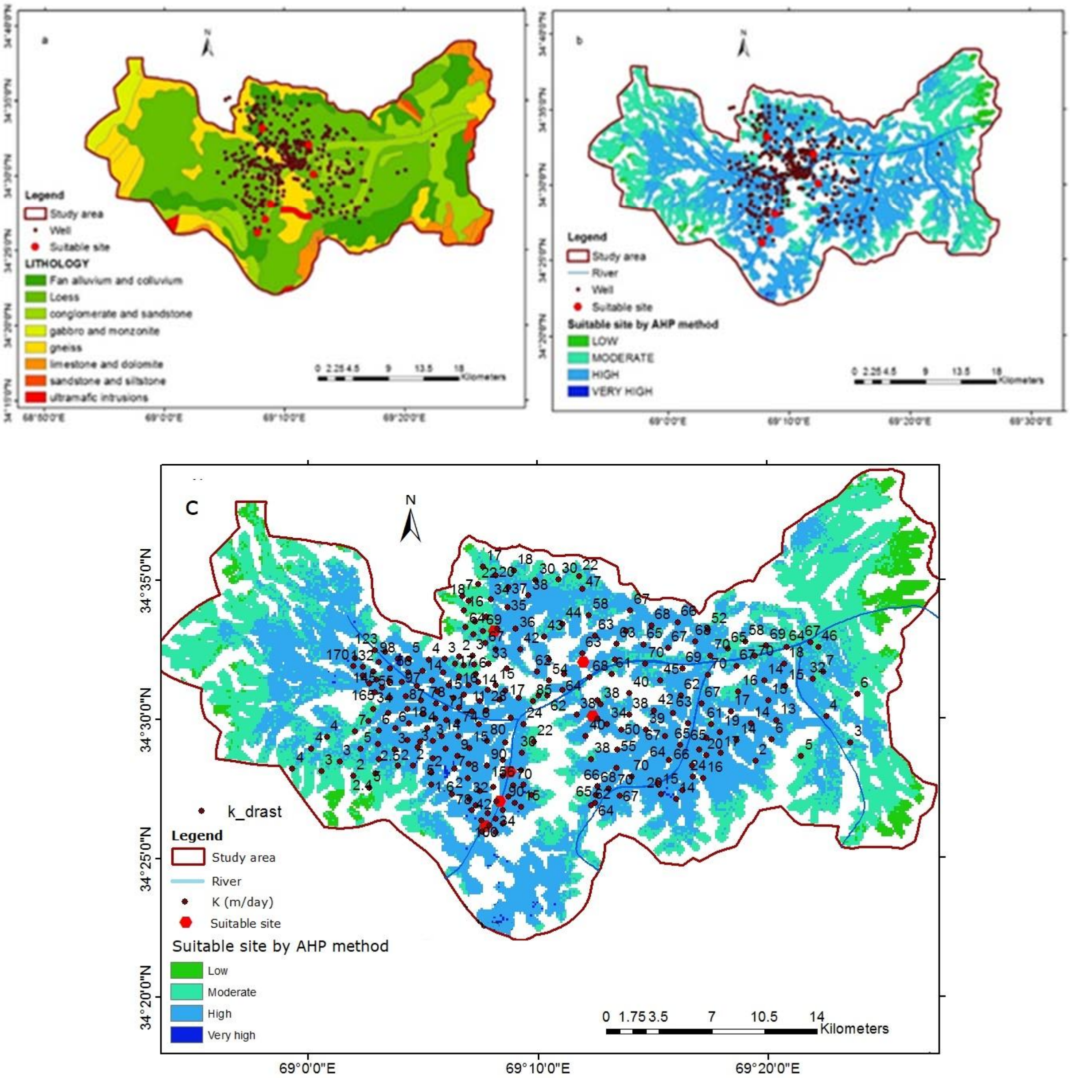

Figure 11. Lithological maps showing location of: (**a**) extraction wells and suitable sites to recharge identified by previous studies; (**b**) groundwater recharge potential zones by AHP method and established extraction wells and suitable sites; (**c**) hydraulic conductivity, k (m/day), distribution in the study area.

5. Conclusions

The expansion and availability of RS and GIS datasets and tools significantly increase opportunities to study the natural environment within a reasonable time and financial expenses. AHP provides support in ranking and weighing the impact of various factors to determine recharge potentiality in the Kabul Plain aquifer. AHP allows for the deriving of the ratio scales from both discrete and continuous paired comparisons of recharge parameters. The present study showed that slope and rainfall are the most influential factors controlling groundwater recharge, followed by lithology in the study area, as confirmed by previous studies. The applied methodology can be used in less-studied regions around the world, particularly in areas where in situ data is inadequate and the accessibility is limited. One of the primary features of our methodology is the utilization of global datasets that are easily and freely available for most of the world's land surface. The implemented methodologies are not a substitute for conventional methods that need extensive in situ datasets, but they could provide first-order estimates for identification of the groundwater recharge areas. The results of this study indicated that areas with a high recharge potential are located in the central and southwest of the Kabul Plain aquifer. The sustainability of water resources and availability are complicated issues worldwide and under stress in developing countries where we are faced with difficulties in providing the proper local research. Many countries have decreased their water resources dramatically and continue to deplete underground water. Underground water resources are not given proper investigation in regards to sustainability supply chains. At the same time, it is important to use groundwater efficiently, as recommended by the UN. Groundwater makes up 99% of all of Earth's fresh water and requires appropriate attention [66]. Managed Aquifer Recharge (MAR) should work for maintaining the required groundwater sustainability, but is difficult to apply in some complicated regions worldwide, including many regions in Afghanistan and Central Asia. The AHP methodology expanded with the cross-disciplinary approach by adding the local experts' questionnaires, which can be very handy in areas with limited access to data, in order to provide the preliminary investigations, reduce expenses and circumvent often dangerous fieldwork. We plan to continue our research in Afghanistan and Central Asia.

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