

GIS and AHP-Based Identification and Improvement of Groundwater Recharge Zones in Kandahar Province, Afghanistan

Fida Mohammad Sahil^{*1}, Ali Mohammad Rahmani¹

ABSTRACT

Purpose:

Groundwater is the principal source of water for domestic, agricultural, and industrial uses in Kandahar Province. Increasing groundwater abstraction, rapid urbanization, prolonged drought, and limited natural recharge have significantly stressed available groundwater resources. This study aimed to identify and map groundwater recharge potential zones using an integrated Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) approach to support sustainable groundwater management.

Method:

Eight hydrogeological and environmental factors, including rainfall, slope, drainage density, soil texture, geology, land use/land cover (LULC), lineament density, and aspect, were selected based on their influence on groundwater recharge. Spatial datasets obtained from satellite imagery and secondary sources were processed in a GIS environment to generate thematic layers. The relative importance of each factor was determined using the AHP pairwise comparison method, and the resulting weights were integrated through weighted overlay analysis to produce a groundwater recharge potential map. The consistency of the AHP matrix was evaluated using the Consistency Ratio (CR).

Results:

The integrated GIS-AHP framework successfully delineated groundwater recharge potential zones across Kandahar Province. The resulting recharge potential map classified the study area into four categories (low, moderate, high, and very high). Areas characterized by gentle slopes, permeable soils, Quaternary formations, low drainage density, and favorable land-use conditions exhibited the highest recharge potential. The very high and high recharge classes covered 18.2% and 26.7% of the province, respectively, and were concentrated mainly in the northern and central parts of Kandahar, whereas mountainous, desert, and urbanized areas generally exhibited lower recharge suitability. The acceptable consistency ratio (0.038) confirmed the reliability of the weighting process.

Practical Implications:

The generated groundwater recharge potential map provides a scientific basis for groundwater exploration, artificial recharge planning, land-use management, and water resource conservation in Kandahar Province. The methodology can also be applied in other arid and semi-arid regions with similar hydrogeological conditions.

Originality/Novelty:

This study provides a province-scale GIS-based MCDA assessment of groundwater recharge potential in Kandahar Province by integrating multiple hydrogeological and environmental datasets within an Analytical Hierarchy Process framework. The developed approach provides a reproducible spatial decision-support tool for sustainable groundwater resource management in data-scarce environments.

Keywords: Groundwater recharge; Geographic Information System (GIS); Analytical Hierarchy Process (AHP); Multi-Criteria Decision Analysis (MCDA); Groundwater management; Kandahar Province

Author Affiliations:

¹Department of Water and Environmental Engineering, Engineering Faculty, Kandahar University, Kandahar, Afghanistan.

^{*}Corresponding e-mail: fida.sahil@yahoo.com

1. Introduction

Groundwater is one of the world's most valuable freshwater resources and plays a fundamental role in sustaining domestic water supply, agricultural production, industrial activities, and ecosystem services, particularly in arid and semi-arid regions where surface



water resources are limited [1,2]. Increasing population growth, rapid urbanization, climate variability, and unsustainable groundwater abstraction have intensified pressure on groundwater resources worldwide, resulting in declining groundwater levels, reduced aquifer storage, and increasing water scarcity [2,3]. Consequently, identifying, protecting, and sustainably managing groundwater recharge areas are important components of integrated water resources management [3].

Afghanistan is characterized by an arid to semi-arid climate in which groundwater serves as the primary source of freshwater for domestic, agricultural, and municipal uses. The country has experienced increasing pressure on groundwater resources because of prolonged droughts, irregular precipitation, rapid population growth, expanding agricultural activities, and inadequate groundwater management [4,5]. Groundwater is particularly important because surface water availability is highly variable both spatially and seasonally, while many communities depend on wells, springs, and traditional karez systems for water supply [5].

Kandahar Province, located in southern Afghanistan, has experienced substantial population growth and agricultural expansion over recent decades, leading to increased dependence on groundwater for municipal supply, irrigation, and domestic consumption. Continued groundwater abstraction combined with limited natural recharge has raised concerns regarding groundwater sustainability and long-term water security. Despite the strategic importance of groundwater resources, comprehensive assessments of groundwater recharge potential remain limited for Kandahar Province, thereby constraining evidence-based groundwater planning and resource management.

Groundwater recharge is governed by the interaction of climatic, geological, hydrological, topographical, and land surface characteristics [1,6]. Factors including rainfall, slope, geology, soil texture, drainage density, lineament density, land use/land cover (LULC), and aspect collectively influence infiltration, runoff generation, percolation, and aquifer replenishment. Because these controlling factors exhibit considerable spatial variability, conventional field investigations alone are often insufficient for regional-scale groundwater recharge assessment [3,7].

Recent advances in Geographic Information Systems (GIS) and remote sensing have substantially improved the ability to integrate diverse spatial datasets and efficiently evaluate groundwater recharge potential across large geographic areas. GIS enables the integration, processing, visualization, and analysis of multiple hydrogeological datasets, while remote sensing provides consistent and cost-effective information on terrain, land cover, drainage networks, and other environmental variables that influence groundwater recharge [3,7-9].

Numerous studies have successfully integrated GIS with Multi-Criteria Decision Analysis (MCDA) techniques to delineate groundwater potential and recharge zones across diverse hydrogeological settings [10-12]. Among the available MCDA methods, the Analytical Hierarchy Process (AHP), originally developed by Saaty [13], is one of the most widely applied approaches because it systematically determines the relative importance of multiple criteria through pairwise comparisons while evaluating the logical consistency of expert judgments. The integration of GIS and AHP enables spatial information and expert knowledge to be combined into reliable groundwater recharge suitability maps that support evidence-based decision-making [3,4,13].

Previous studies conducted in India, Pakistan, Iran, and Afghanistan have demonstrated that GIS-based AHP approaches effectively identify zones of groundwater recharge potential and support groundwater exploration, artificial recharge planning, and sustainable water resource management [3,4,7]. However, province-scale groundwater recharge assessments integrating GIS and MCDA remain scarce for Kandahar Province. The limited availability of hydrogeological data and the absence of spatial decision-support tools continue to constrain groundwater planning within the province.

Therefore, this study aims to identify and map groundwater recharge potential zones in Kandahar Province using Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) framework. Eight groundwater recharge conditioning factors, rainfall, slope, drainage density, soil texture, geology, land use/land cover, lineament density, and aspect, were selected based on their hydrological significance and data availability. These thematic layers were prepared within a GIS environment, weighted using the AHP technique, and integrated through weighted overlay analysis to generate a groundwater recharge potential map. The resulting spatial information is intended to support groundwater exploration, artificial

recharge planning, sustainable groundwater management, and long-term water resource planning in Kandahar Province.

2. Literature Review

2.1 Groundwater Recharge Assessment

Groundwater recharge is the process by which water infiltrates the land surface and percolates through the unsaturated zone to replenish aquifers [6,14]. Recharge is a critical component of the hydrological cycle because it replenishes aquifer storage and can sustain groundwater discharge to streams and ecosystems [2,6]. The quantity and spatial distribution of groundwater recharge are controlled by climatic, geological, hydrological, topographical, and land surface characteristics, including precipitation, evapotranspiration, soil texture, lithology, land use, and terrain slope [1].

In arid and semi-arid regions, groundwater recharge is commonly limited and episodic because precipitation is low and variable, and evaporative demand is high [1,6]. Consequently, identifying groundwater recharge zones has become a key requirement for sustainable groundwater development, artificial recharge planning, and integrated water resources management [2].

Conventional groundwater investigations commonly use hydrogeological mapping, borehole observations, pumping tests, and geophysical or field investigations [1,14]. Although these methods provide reliable local-scale information, they are often expensive, labor-intensive, and unsuitable for regional-scale groundwater assessments, particularly in developing countries where hydrogeological data are limited [1].

2.2 Application of GIS and Remote Sensing in Groundwater Studies

Geographic Information Systems (GIS) and remote sensing have become indispensable tools for groundwater investigations because they enable efficient integration, visualization, analysis, and management of large spatial datasets. Satellite imagery, digital elevation models (DEMs), and remotely sensed environmental datasets facilitate the derivation of thematic layers such as slope, drainage density, lineament density, land use/land cover (LULC), rainfall distribution, and terrain characteristics that strongly influence groundwater recharge [8,9].

Remote sensing offers important advantages for regional groundwater studies by providing synoptic spatial coverage and repeat observations that can be integrated with GIS-based hydrogeological analysis [8]. When combined with GIS, these datasets can be integrated into spatial models that improve groundwater recharge assessment and support evidence-based groundwater management [15].

Recent advances in satellite technology, including the availability of Sentinel-2 imagery, ALOS Digital Elevation Models, and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), have significantly enhanced the accuracy of groundwater recharge mapping by providing higher-resolution spatial information [16,17].

2.3 Multi-Criteria Decision Analysis and the Analytical Hierarchy Process

Groundwater recharge is influenced by multiple interrelated environmental factors that vary spatially and differ in their relative importance. Multi-Criteria Decision Analysis (MCDA) provides a systematic framework for integrating these diverse factors into a single decision-making model [18]. MCDA has become one of the most widely adopted approaches for groundwater suitability assessment because it enables decision-makers to evaluate multiple criteria simultaneously while accounting for their relative importance.

Among MCDA techniques, the Analytical Hierarchy Process (AHP), developed by Saaty [13], is widely applied in groundwater potential and recharge mapping. AHP employs pairwise comparisons to determine the relative importance of each criterion, computes normalized weights, and evaluates the consistency of expert judgments through the Consistency Ratio (CR). A CR value below 0.10 is generally considered acceptable and indicates that the assigned weights are logically consistent [13].

The integration of GIS with AHP provides a structured and reproducible framework for groundwater recharge assessment by combining spatial criteria with expert-derived relative weights [7,11,13,18]. Numerous studies have demonstrated that rainfall, slope, geology, soil texture, drainage density, lineament density, land use/land cover, and aspect are among the most influential variables affecting groundwater recharge potential [3,19].

2.4 Critical Comparison of Previous Studies

Recent advances in Geographic Information Systems (GIS), remote sensing, and Multi-Criteria Decision Analysis (MCDA) have substantially improved groundwater recharge assessment worldwide. Among the available MCDA techniques, the Analytical Hierarchy Process (AHP) remains

the most widely adopted weighting approach for its transparency, ease of implementation, and ability to assess the consistency of expert judgments [3,19].

Studies conducted in India consistently demonstrate that rainfall, lithology, slope, drainage density, and land use/land cover are the dominant factors controlling groundwater recharge. However, the number and weighting of conditioning factors vary considerably across studies, depending on the hydrogeological setting, climatic conditions, and data availability, indicating that no universal weighting scheme exists [3,19,20].

In Iran and Pakistan, GIS and AHP models have shown that Quaternary alluvial deposits, permeable soils, gentle slopes, and fractured geological formations are the principal controls on recharge potential. These studies also emphasize that integrating structural features such as lineament density significantly improves recharge prediction in fractured aquifer systems [9].

Recent studies in Afghanistan have demonstrated the applicability of GIS-based groundwater recharge mapping under data-scarce conditions. For example, Singh and Noori [9] successfully delineated groundwater recharge potential zones in the Kabul Basin using eight hydrogeological conditioning factors integrated through GIS and AHP. Their results confirmed that rainfall, geology, slope, and drainage density were the most influential variables, highlighting the suitability of GIS and AHP approaches for arid environments similar to Kandahar Province.

Several review studies published since 2022 have critically evaluated groundwater recharge mapping methodologies. Maghribi et al. [19] reviewed 31 GIS–MCDA studies and reported that although more than thirty conditioning factors have been used in previous investigations, only eight factors—lithology, rainfall, slope, drainage density, land use/land cover, soil, lineament density, and geomorphology—appear consistently across most studies. Their review also found that AHP remains the dominant weighting technique because of its simplicity and reproducibility.

Maghribi et al. [19] further noted that groundwater recharge estimation is increasingly incorporating climate-change scenarios and emphasized that future recharge assessments should integrate climatic uncertainty rather than relying solely on historical datasets.

Recent methodological reviews emphasize that groundwater mapping is more defensible when geospatial modelling is complemented by hydrogeological observations and independent validation; limited field data remain a major source of uncertainty in data-scarce settings [21,22].

Monir et al. [23] reviewed GIS- and data-driven approaches to groundwater-level depletion monitoring and highlighted the value of integrating spatial analysis with data-driven models, while also identifying limitations associated with temporal representation, input data, and model validation.

A recent review by Ali and Bilal [24] showed that land-use and land-cover change can alter groundwater recharge, storage, and quality, supporting the use of multi-temporal remote-sensing information when evaluating groundwater systems.

Similarly, Bennett [21] emphasized that independent validation remains a major weakness in many GIS-based groundwater recharge maps. The review recommended validation using groundwater chemistry, groundwater residence time, stable isotopes, or groundwater-level monitoring to improve the reliability of recharge maps and enhance confidence in spatial decision-support systems.

Collectively, previous studies demonstrate that GIS and AHP provide a robust framework for identifying groundwater recharge potential zones, particularly in arid and semi-arid regions. Nevertheless, several methodological limitations remain common across the literature. First, many studies rely heavily on expert-derived weights, introducing unavoidable subjectivity despite acceptable consistency ratios. Second, field validation is often absent or limited due to insufficient hydrogeological observations. Third, many investigations employ static land-use, rainfall, or geological datasets, thereby overlooking seasonal and long-term environmental changes. Finally, relatively few studies have incorporated uncertainty analysis or compared AHP with alternative MCDA techniques such as Fuzzy AHP, TOPSIS, machine-learning algorithms, or hybrid decision-support models.

These research gaps are particularly evident in Afghanistan, where province-scale groundwater recharge investigations remain limited. Existing studies have primarily focused on groundwater availability or localized hydrogeological characterization rather than comprehensive recharge mapping using integrated GIS–MCDA frameworks. Consequently, there remains a need for scientifically robust, reproducible, and spatially explicit groundwater recharge assessments that support groundwater conservation, artificial recharge planning, and sustainable water resources management in Kandahar Province.

3. Materials and Methods

3.1 Study Area

Kandahar Province is located in southern Afghanistan, between approximately 29°22'–33°45' N latitude and 64°28'–68°31' E longitude (Figure 1). The province experiences an arid to semi-arid climate characterized by low annual precipitation, high evapotranspiration, and prolonged dry seasons. Consequently, groundwater constitutes the principal source of water for domestic consumption, agriculture, and industrial activities because perennial surface water resources are limited [2,25].

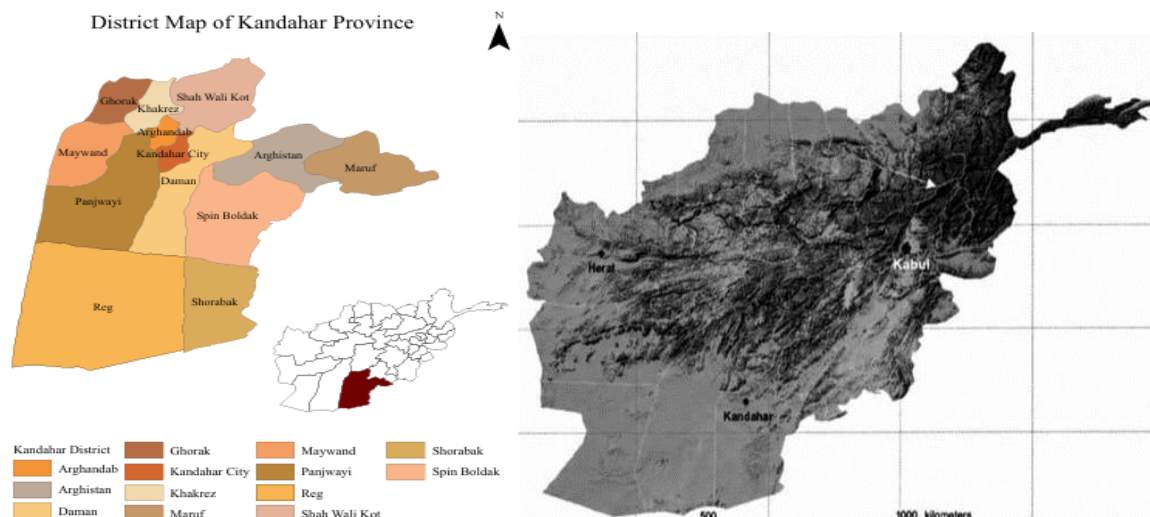


Figure 1. Illustrate the geographical location and spatial extent of Kandahar Province, Afghanistan.

Topography ranges from extensive alluvial plains to mountainous terrain, producing marked spatial variability in runoff generation, infiltration, and groundwater recharge. The geological setting comprises Quaternary alluvial deposits, sedimentary formations, and hard-rock units, each exhibiting distinct hydraulic properties that influence groundwater occurrence and recharge potential [1]. These characteristics make Kandahar Province an appropriate case study for GIS-based groundwater recharge assessment.

3.2 Research Framework

This study adopted an integrated Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) framework coupled with the Analytical Hierarchy Process (AHP) to delineate groundwater recharge potential zones. GIS provides an efficient platform for integrating heterogeneous spatial datasets, while MCDA enables the systematic evaluation of multiple environmental criteria according to their relative importance [18,26].

The methodological workflow comprised five sequential stages, broadly consistent with established GIS-MCDA groundwater mapping workflows [11,12]:

1. Data collection and preprocessing.
2. Preparation of thematic layers.
3. Determination of criterion weights using AHP.
4. GIS-based weighted overlay analysis.
5. Classification and interpretation of groundwater recharge potential zones.

This workflow follows internationally accepted approaches widely applied in groundwater recharge investigations [15].

3.3 Data Collection

Both remotely sensed datasets and secondary spatial data were used in this study. Sentinel-2 multispectral imagery was used for land-use/land-cover mapping due to its 10–20 m spatial resolution and high radiometric quality [17]. Digital elevation information was obtained from the ALOS World 3D Digital Elevation Model, which provides reliable elevation data suitable for hydrological analyses.

Rainfall information was obtained from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset, a globally recognized precipitation product that combines satellite observations with ground-based station data and has been widely applied in hydrological studies [16].

Soil texture information was obtained from a harmonized global soil dataset and processed as a thematic layer for hydrological analysis.

Geological information was obtained from the U.S. Geological Survey geologic map of Afghanistan [27], while administrative boundary data were obtained from Kandahar Municipality.

Before analysis, all spatial datasets were projected into a common coordinate reference system, resampled where necessary to a consistent spatial resolution, and converted into raster format to ensure compatibility during spatial multi-criteria analysis [18].

3.4 Preparation of Thematic Layers

Eight thematic layers representing the principal factors controlling groundwater recharge were prepared:

- Rainfall
- Slope
- Drainage Density
- Soil Texture
- Geological Formation
- Lineament Density
- Land Use/Land Cover
- Aspect

These variables were selected because comparable combinations of climatic, terrain, geological, drainage, soil, structural, and land-cover criteria are widely used in groundwater potential and recharge mapping [3,10-12,19].

Slope and aspect were derived from the Digital Elevation Model using standard terrain analysis tools. Drainage density was calculated from extracted drainage networks, while lineament density was generated from structural features interpreted from remotely sensed imagery. Land use/land cover was classified from Sentinel-2 imagery using standard image processing procedures [17]. Each thematic layer was standardized and reclassified into groundwater-recharge suitability classes before integration, consistent with GIS-based MCDA practice [7,9,18].

3.5 Multi-Criteria Decision Analysis (MCDA)

Groundwater recharge is controlled by multiple environmental variables, which differ in importance and frequently interact with one another. MCDA provides a structured framework for integrating these diverse criteria into a single suitability model by assigning relative weights to each factor [18]. The conceptual workflow of applying MCDA in this study is shown in Figure 2.



Figure 2. Conceptual workflow of MCDA

3.6 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), originally proposed by Saaty [13], was employed to determine the relative importance of the eight groundwater recharge conditioning factors.

The procedure involved:

- Pairwise comparison of all criteria.
- Construction of the comparison matrix.
- Matrix normalization.
- Calculation of priority weights.
- Consistency evaluation using the Consistency Ratio (CR).

3.7 Multi-Criteria Decision Analysis (MCDA)

The normalized criterion weights obtained through AHP were assigned to the corresponding thematic layers within the GIS environment, following the weighted linear-combination logic commonly used in GIS-MCDA [18]. A weighted linear combination (Weighted Overlay Analysis) was then performed according to:

$$\text{Recharge Index} = \sum(W_i * X_i) \dots\dots\dots[\text{Equation 1}]$$

where:

W_i represents the normalized weight of criterion *i*.

X_i represents the standardized suitability score of criterion *i*.

Weighted overlay analysis is widely used in GIS-based groundwater suitability studies because it integrates standardized thematic criteria into a composite spatial index [11,12,18,26,28].

The resulting recharge index raster was classified into four groundwater recharge potential categories, namely, low, moderate, high and very high.

3.8 Consistency Assessment

The reliability of the AHP weighting procedure was evaluated using the Consistency Index (CI) and Consistency Ratio (CR) as proposed by Saaty [13].

$$CI = \frac{\lambda_{max} - n}{n - 1} \dots\dots\dots[\text{Equation 2}]$$

where λ_{max} is the maximum eigenvalue and *n* is the number of criteria.

The Consistency Ratio was computed as:

$$CR = \frac{CI}{RI} \dots\dots\dots[\text{Equation 3}]$$

where RI denotes the Random Index.

Following Saaty [13], a CR value below 0.10 indicates acceptable consistency and confirms that the pairwise comparison matrix is suitable for spatial decision analysis.

4. Results and Discussion

4.1 Overview of Groundwater Recharge Conditioning Factors

Eight groundwater recharge conditioning factors were evaluated to delineate recharge-potential zones across Kandahar Province. Each thematic layer was standardized and assigned a relative weight using AHP, after which the weighted layers were integrated in GIS to generate the final groundwater recharge potential map. The following subsections describe the spatial pattern and hydrogeological relevance of each conditioning factor.

The selected factors represent the major hydrogeological, topographical, climatic, and land surface conditions controlling groundwater recharge. Their individual influence on recharge potential is discussed in the following subsections.

4.2 Rainfall

Rainfall is a major source and controlling factor of groundwater recharge in arid and semi-arid environments [6,9]. Spatial analysis showed noticeable variation in precipitation across Kandahar Province, resulting in corresponding differences in recharge potential (Figure 3). The annual rainfall ranged from 187 mm, mostly in the southern parts of the province, to 488 mm in the north. Areas receiving relatively higher rainfall exhibited greater recharge suitability because increased precipitation enhances infiltration and aquifer replenishment. Conversely, regions receiving lower annual rainfall were characterized by limited recharge potential due to reduced water availability for infiltration. Similar relationships between rainfall and groundwater recharge have been widely reported in previous GIS- and remote sensing-based investigations. For example, Abijith et al. [20] demonstrated that rainfall was one of the most influential parameters controlling groundwater recharge potential in southern India, with high-rainfall zones consistently corresponding to high recharge classes. More recently, Kumar et al. [29] reported that increasing annual rainfall significantly improved groundwater recharge suitability in semi-arid watersheds of India because greater precipitation promoted infiltration and reduced water stress. Likewise, Mohammadi et al. [30] found that precipitation variability strongly governed recharge distribution in dry regions of Iran, where areas receiving higher rainfall consistently exhibited greater groundwater recharge potential.

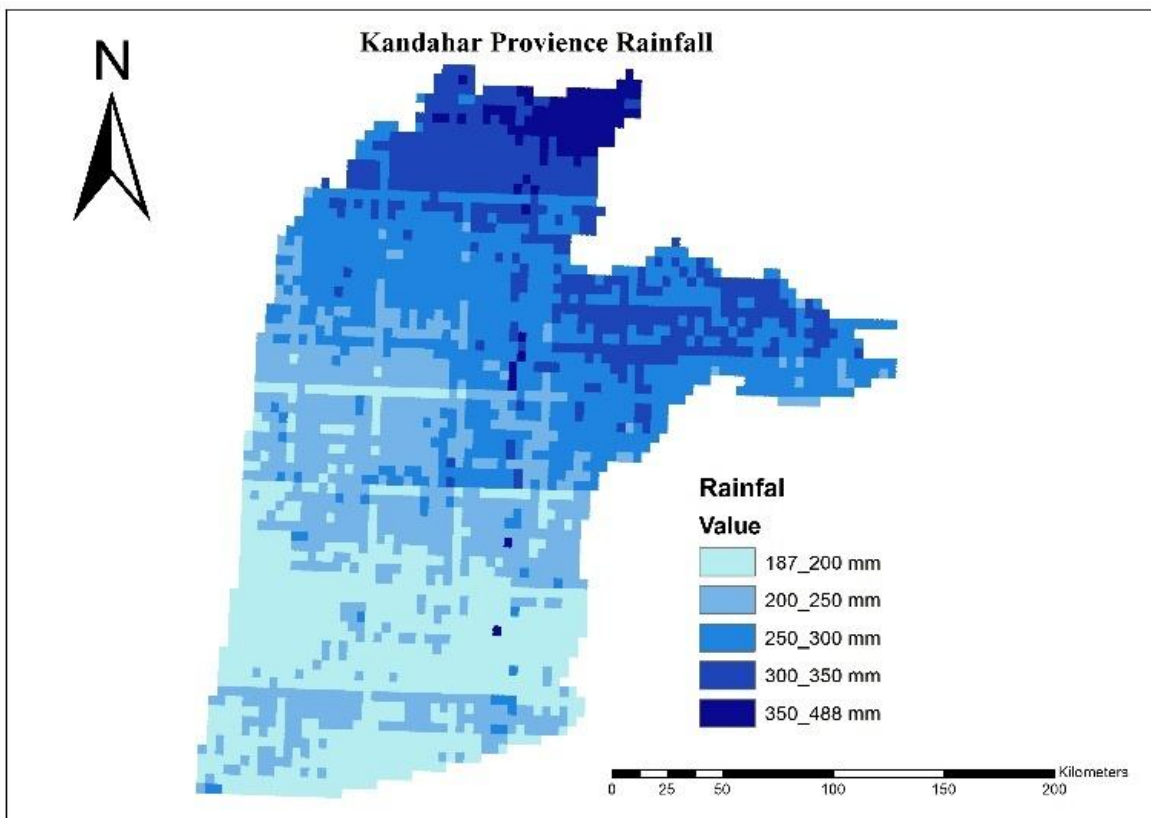


Figure 3: Kandahar Province rainfall map from 2011 to 2025 (average data)

4.3 Slope

Slope strongly influences infiltration and runoff partitioning and is therefore widely used in recharge-potential assessment [7,9]. Gentle slopes provide longer residence time for rainwater, allowing greater infiltration into subsurface formations. In contrast, steep slopes promote rapid surface runoff, thereby reducing groundwater recharge.

The generated slope map showed noticeable variation across Kandahar Province (Figure 4), indicating that relatively flat and gently sloping areas possess favorable recharge conditions, whereas mountainous regions exhibit comparatively low recharge potential. These observations agree with established hydrological principles and previous groundwater recharge studies.

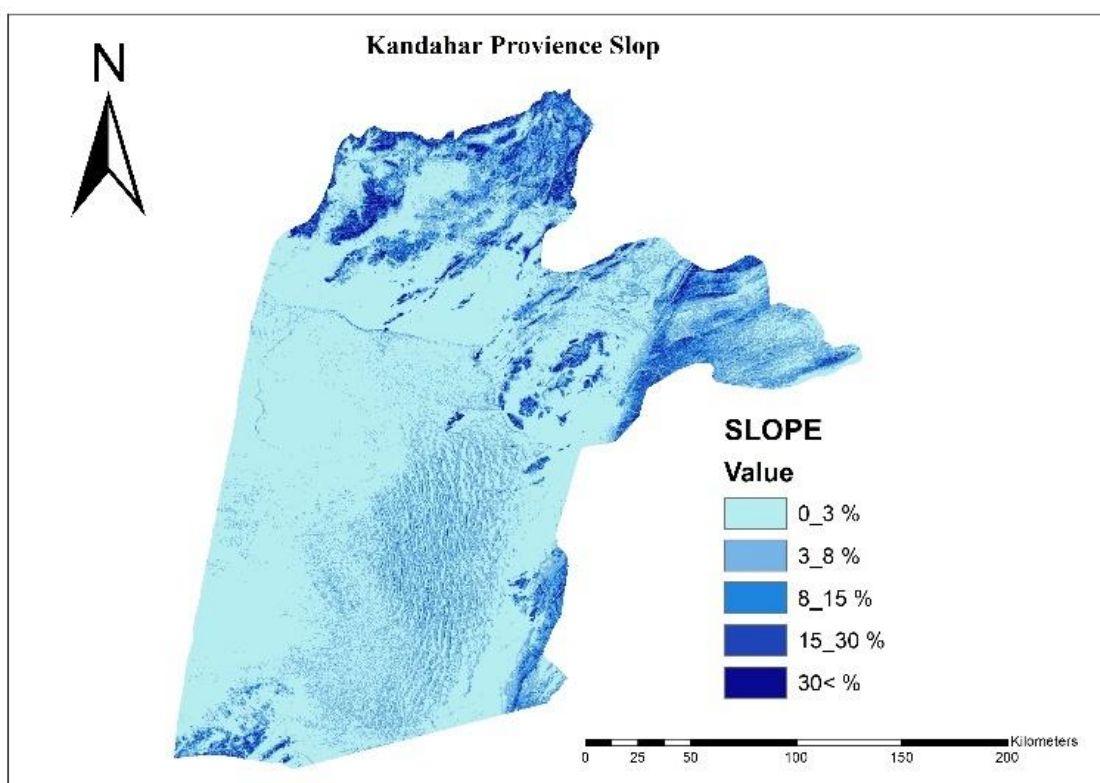


Figure 4: Kandahar Province slope map derived from DEM data

Slope strongly influences infiltration and runoff partitioning and is therefore widely used in recharge-potential assessment [7,9]. Gentle slopes provide longer residence time for rainwater, allowing greater infiltration into subsurface formations. In contrast, steep slopes promote rapid surface runoff, thereby reducing groundwater recharge. The generated map shows that a large part of the province has a gentle slope of less than 8% (Figure 4). Relatively flat, gently sloping areas have favorable recharge conditions, whereas mountainous regions have comparatively low recharge potential. These observations agree with established hydrological principles and previous groundwater recharge studies. Mohammadi et al. [30] found that slope was one of the most influential topographic factors controlling groundwater recharge in the arid regions of Iran, with gentle slopes consistently corresponding to high- and very-high-recharge zones. Similarly, Kumar et al. [29] reported that low-slope areas exhibited significantly higher groundwater recharge potential in a semi-arid watershed because reduced runoff enhanced infiltration and soil moisture retention.

4.4 Drainage Density

Drainage density reflects the degree of surface dissection and is commonly used as an indirect indicator of infiltration and recharge conditions [7,9]. In groundwater-potential mapping, lower drainage density is generally interpreted as more favorable for infiltration than dense, highly dissected drainage networks, although the relationship remains dependent on lithology and terrain [7,9,10,12]. Conversely, high drainage density facilitates rapid runoff, limiting groundwater recharge. Figure 5 shows that the drainage density in the central part of the province is relatively low, indicating favorable infiltration conditions that promote groundwater recharge. In contrast, areas with higher drainage density exhibit lower recharge potential due to the rapid removal of runoff through well-developed stream networks. These findings are consistent with previous groundwater recharge investigations. Mohammadi et al. [30] found that regions characterized by sparse drainage networks had significantly greater groundwater recharge potential because reduced channelization allowed more precipitation to infiltrate into the subsurface. Similarly, Kumar et al. [29] reported that drainage density was inversely related to groundwater recharge potential in a semi-arid watershed, with low drainage density areas exhibiting greater infiltration and higher recharge suitability.

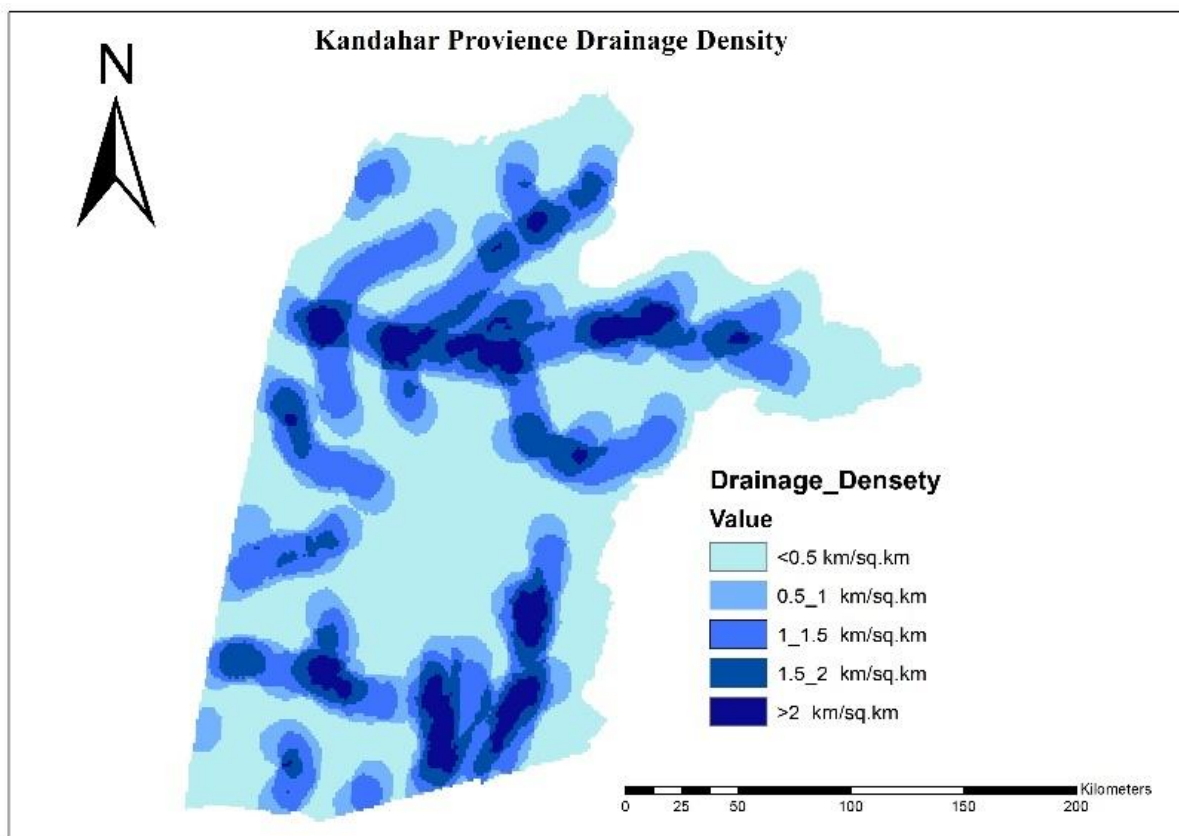


Figure 5: Kandahar Province drainage-density map

4.5 Soil

Soil texture plays a fundamental role in regulating infiltration and percolation [1,7]. Sandy and coarse-textured soils generally have higher hydraulic conductivity than fine, clay-rich soils and can therefore favor infiltration where other hydrogeological conditions are suitable [1,14].

The soil map of Kandahar province in Figure 5 demonstrates spatial variation in recharge suitability according to soil texture. The dominant mapped soils in Kandahar Province include calcareous soils across much of the arid plains; their recharge behavior depends on texture, structure, and hydraulic conductivity [1]. The eastern parts of the province contain extensive Lithosol units. These are shallow, stony soils associated with bedrock or strongly weathered parent material (Figure 6). Fluvisols are near water bodies. Alluvial soils along major river valleys can provide favorable recharge conditions where deposits are sufficiently permeable [1]. Coarse-textured desert soils can exhibit relatively high infiltration but low water-holding capacity [1].

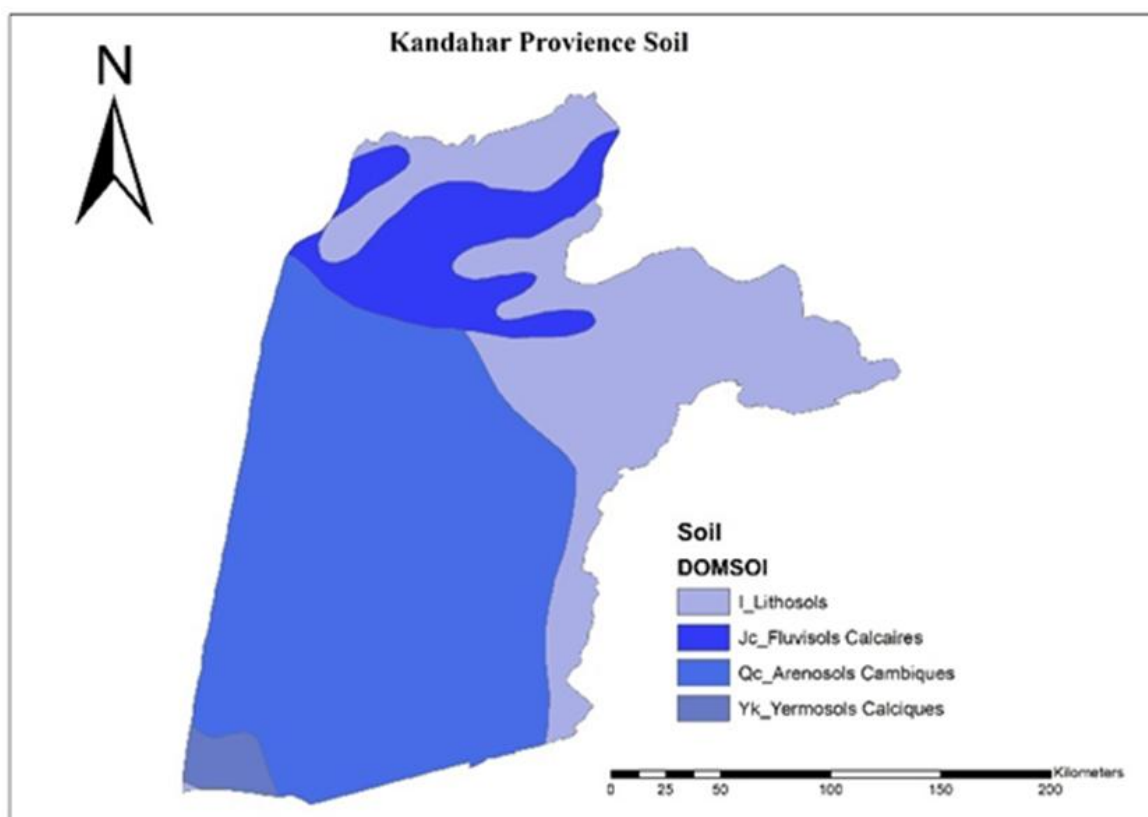


Figure 6: Kandahar Province soil map

4.6 Geological Formation

Geological formations significantly influence groundwater storage and movement because lithological characteristics determine porosity, permeability, and fracture development [1,14].

The geological analysis of Kandahar province in Figure 7 shows that the geological formation of the province has Q (Quaternary Sediments), Qs (Quaternary Soils), Ks (Cretaceous Sandstone), Mi (Miocene Formation), N (Neogene Sediments), Ts (Tertiary Sediments), JTr (Jurassic-Triassic Rocks), Jms (Jurassic Marine Sequence), PTr (Permian-Triassic Rocks), TrPr (Triassic-Permian Rocks), KJs (Cretaceous-Jurassic Sediments), Pg (Paleogene Rocks), TKim (Tertiary Igneous-Metamorphic), Ti (Tertiary Intrusives) and Tv (Tertiary Volcanics). The Quaternary alluvial deposits along the Arghandab River and its valley systems were assigned high recharge suitability because unconsolidated alluvial materials typically exhibit greater primary porosity and permeability than consolidated bedrock [1,27]. In contrast, consolidated sedimentary and igneous formations (JTr, Jms, PTr, TrPr, KJs, Pg, TKim, Ti, Tv) generally exhibited lower recharge suitability because of reduced primary porosity and permeability, although secondary fractures may locally enhance recharge.

Tufa et al. [31] demonstrated that geological formations with high permeability and significant pore connectivity contributed to higher groundwater recharge potential, whereas massive volcanic and metamorphic rocks were associated with low-recharge zones. These findings support the present study and confirm that geological formation is a key controlling factor in groundwater recharge assessment, particularly in arid and semi-arid regions.

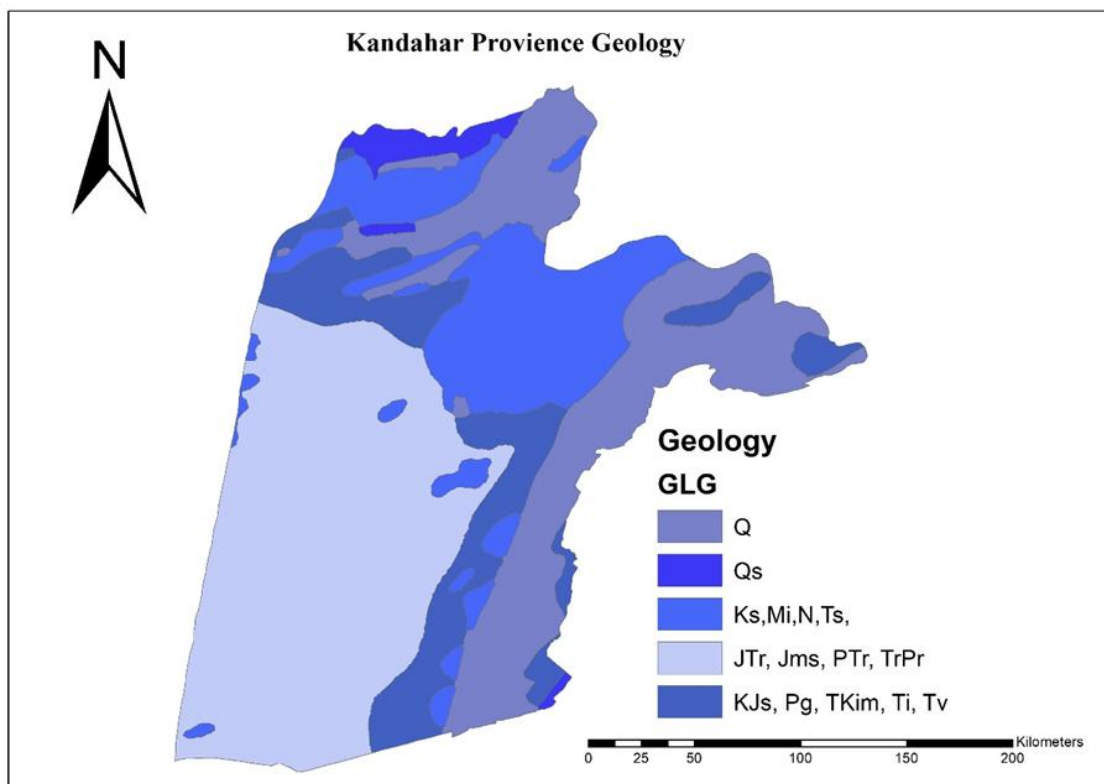


Figure 7: Kandahar Province geological map

4.7 Lineament Density

Lineaments represent structural discontinuities such as faults and fractures that can enhance secondary permeability and groundwater movement; consequently, lineament density is frequently included in GIS-based groundwater potential models [3,9-12].

The generated lineament density map in Figure 8 reveals that areas with relatively high lineament density are located in the northern parts of the province. Larger lineament density exhibits greater groundwater recharge potential because fractures provide preferential pathways for infiltration. Conversely, areas with sparse mapped structural features were assigned lower structural recharge suitability, consistent with the use of lineament density as a proxy for secondary permeability in GIS-based groundwater studies [3,9].

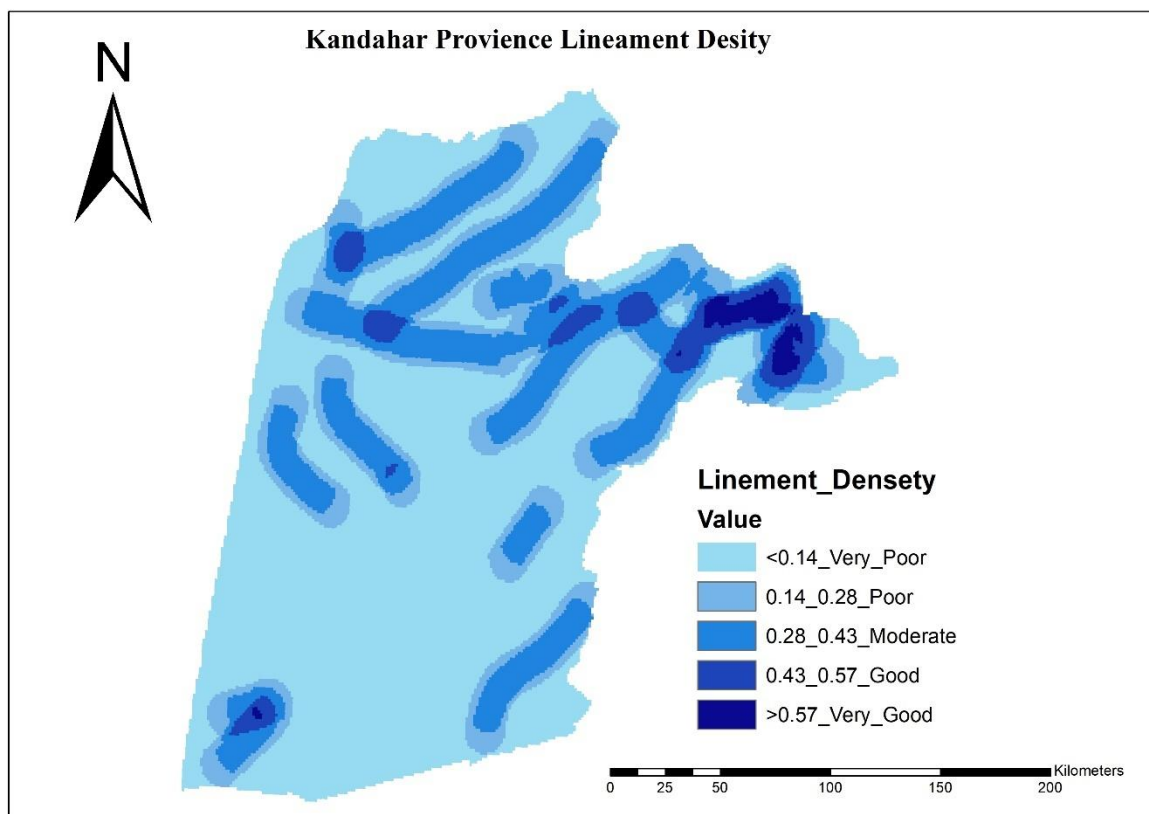


Figure 8: Kandahar Province lineament-density map

4.8 Land Use/Land Cover (LULC)

Land use and land cover influence infiltration, evapotranspiration, and surface runoff and are therefore commonly included in groundwater recharge-potential mapping [3,19]. Agricultural land and vegetated areas generally enhance infiltration by improving soil structure and reducing runoff velocity. Conversely, built-up areas contain extensive impervious surfaces that restrict groundwater recharge. Vegetation can modify infiltration and soil-water processes, although its net effect on recharge depends on rooting depth, soil properties, and evapotranspiration [19].

A supervised classification was performed in ArcMap to derive the LULC layer. The imagery was classified into six LULC classes: water bodies, rangeland, crops (agricultural land), bare ground, built-up area, and trees (forests), as shown in Figure 9. Agricultural and vegetated lands exhibit relatively high recharge potential, whereas urban and barren lands generally display lower recharge suitability.

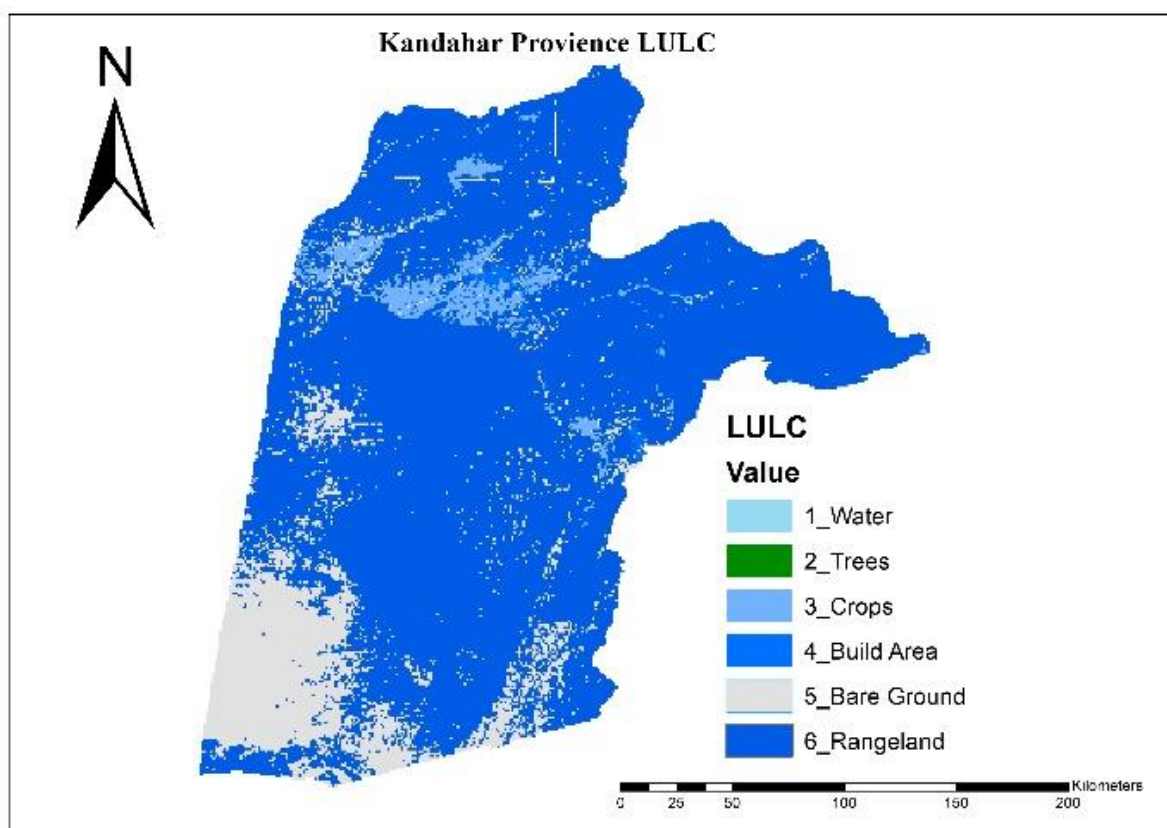


Figure 9: Kandahar Province land-use/land-cover map

4.9 Aspect

Aspect affects solar radiation, soil moisture, evapotranspiration, and vegetation growth, thereby indirectly influencing groundwater recharge. The aspect analysis indicates that relatively shaded slope orientations retain more soil moisture and consequently exhibit higher recharge suitability than sun-exposed slopes, which experience greater evaporative losses. In this model, aspect was assigned a smaller influence than rainfall, geology, and slope; its inclusion reflects potential differences in solar exposure, soil moisture retention, and evapotranspiration among slope orientations.

The aspect map was derived from the ALOS DEM and classified into five aspect classes. Flat areas and slopes facing north to east were identified as having very high groundwater recharge potential because they receive less direct solar radiation, resulting in lower evapotranspiration and greater soil moisture retention. East- to southeast-facing slopes exhibited high recharge suitability, while south- to southwest-facing slopes showed low recharge potential owing to increased solar exposure and higher evaporative losses. West-to-southwest facing slopes were classified as having very low recharge potential, whereas west-to-north-facing slopes exhibited moderate recharge suitability (Figure 10). In conclusion, since Kandahar is in the Northern Hemisphere, north- and northeast-facing slopes generally retain more moisture, while south- and southwest-facing slopes receive greater solar radiation and experience higher evapotranspiration. Similar observations have been reported in previous groundwater recharge studies. Kumar et al. [29] found that north- and northeast-facing slopes generally exhibited higher groundwater recharge potential than south-facing slopes because reduced solar radiation enhanced soil moisture retention and infiltration.

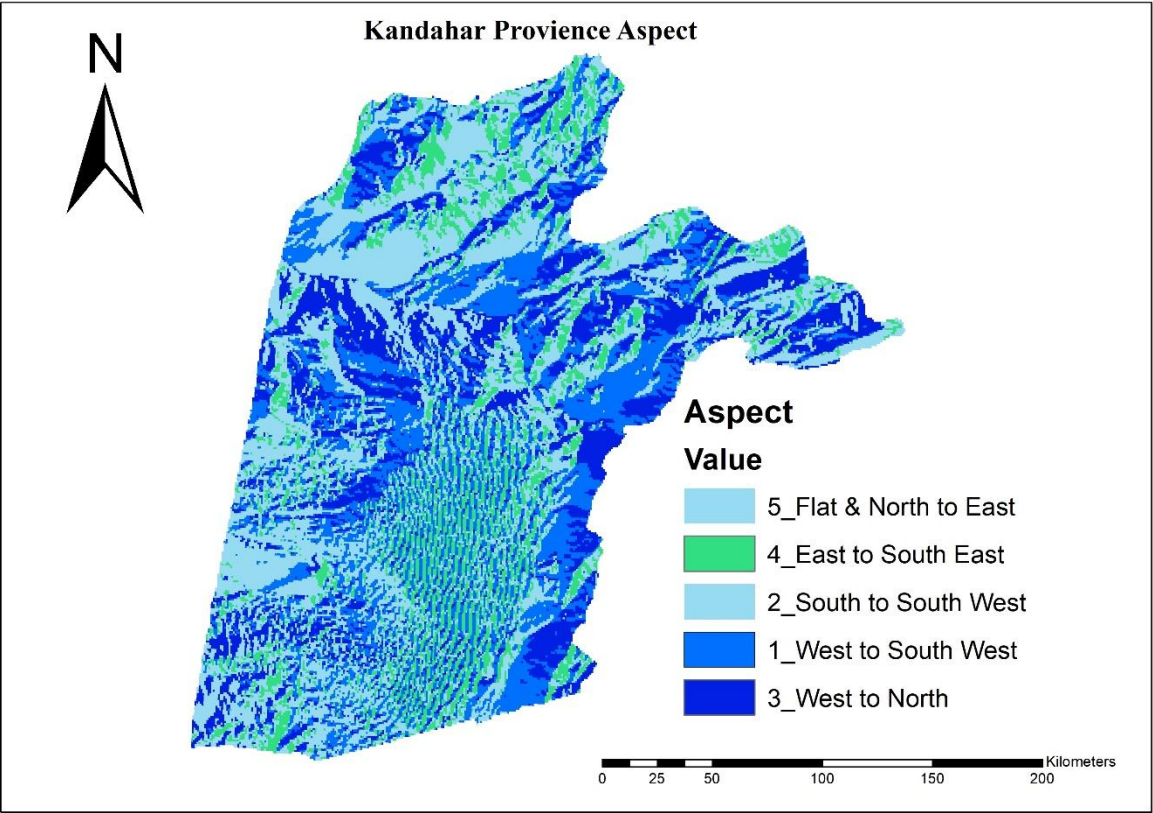


Figure 10: Kandahar Province aspect map

4.10 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) was used to quantify the relative importance of the eight groundwater recharge conditioning factors. A pairwise comparison matrix was constructed using Saaty’s 1–9 scale, where 1 indicates equal importance, and 9 indicates extreme importance of one criterion over another. The pairwise comparison matrix and normalized criterion weights are presented in Tables 1 and 2, respectively. Rainfall received the highest weight (32.63%), followed by slope (22.71%), drainage density (15.69%), and land use/land cover (10.81%). Together, these four criteria account for 81.84% of the total weight. Consistency was evaluated using the maximum eigenvalue, Consistency Index (CI), and Consistency Ratio (CR) (Table 3). The calculated CR was 0.038, which is below the commonly accepted threshold of 0.10, indicating acceptable internal consistency of the pairwise judgments [13].

Table 1: Pairwise comparison matrix of 8 groundwater prospecting factors for the AHP process [32].

Layer	R	S	DD	LULC	ST	G	LD	A
Rainfall (R)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	9.00
Slope (S)	0.50	1.00	2.00	3.00	4.00	5.00	6.00	8.00
Drainage density (DD)	0.33	0.50	1.00	2.00	3.00	4.00	5.00	7.00
Land use/land cover (LULC)	0.25	0.33	0.50	1.00	2.00	3.00	4.00	6.00
Soil texture (ST)	0.20	0.25	0.33	0.50	1.00	2.00	3.00	5.00
Geology (G)	0.17	0.20	0.25	0.33	0.50	1.00	2.00	4.00
Lineament density (LD)	0.14	0.17	0.20	0.25	0.33	0.50	1.00	3.00
Aspect (A)	0.11	0.13	0.14	0.17	0.20	0.25	0.33	1.00
SUM	2.70	4.58	7.43	11.25	16.03	21.75	28.33	43.00

Table 2: Normalized weights for each thematic layer

Layer	R	S	DD	LULC	ST	G	LD	A	Average Weight (%)	Rank
Rainfall (R)	0.37	0.44	0.40	0.36	0.31	0.28	0.25	0.21	32.63	1
Slope (S)	0.18	0.22	0.27	0.27	0.25	0.23	0.21	0.19	22.71	2

Drainage density (DD)	0.12	0.11	0.13	0.18	0.19	0.18	0.18	0.16	0.16	15.69	3
Land use/land cover	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.11	10.81	4
Soil texture (ST)	0.07	0.05	0.04	0.04	0.06	0.09	0.11	0.12	0.07	7.43	5
Geology (G)	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.09	0.05	5.12	6
Lineament density	0.05	0.04	0.03	0.02	0.02	0.02	0.04	0.07	0.04	3.59	7
Aspect (A)	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	2.02	8

Table 3: Determination of consistency ratio

Layer	Weight	Weighted sum	Vector	λ	λ_{max}	CI	CR
Rainfall (R)	0.33	2.80		8.57	8.38	0.054	0.038
Slope (S)	0.23	1.96		8.62			
Drainage density (DD)	0.16	1.34		8.56			
Land use/land cover (LULC)	0.11	0.91		8.42			
Soil texture (ST)	0.07	0.61		8.26			
Geology (G)	0.05	0.42		8.13			
Lineament density (LD)	0.04	0.29		8.07			
Aspect (A)	0.02	0.16		8.17			

4.11 Groundwater Recharge Potential Map

The weighted overlay analysis integrated all thematic layers into a composite groundwater recharge potential map. The final recharge map classified Kandahar Province into four groundwater recharge potential categories, namely, very high, high, moderate, and low (Figure 11).

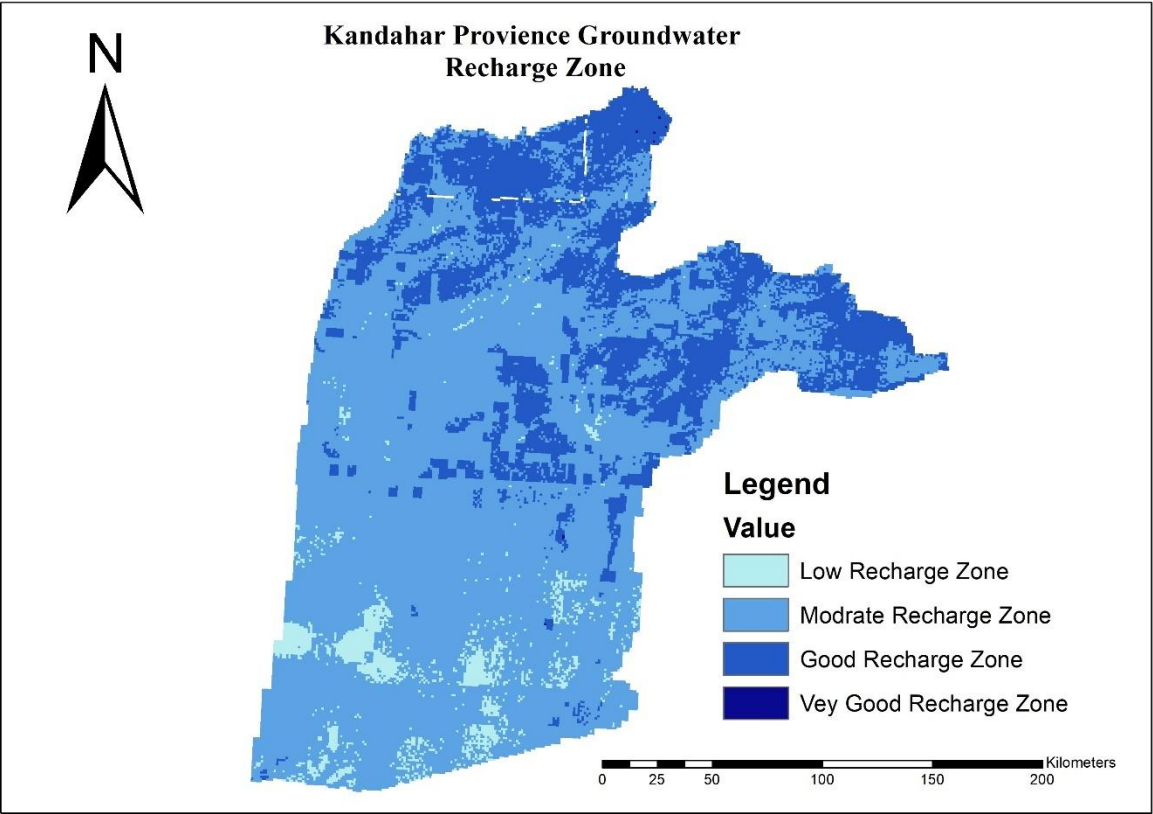


Figure 11: Kandahar Province groundwater recharge-potential map

Areas characterized by high rainfall, gentle slopes, permeable soils, Quaternary sediments, low drainage density, and favorable land use exhibited the highest groundwater recharge potential. In contrast, mountainous terrain, urbanized areas, steep slopes, and impermeable geological formations generally corresponded to low recharge potential. The very high and high recharge classes cover 18.2% and 26.7% of Kandahar Province, respectively. The remaining area is classified

as moderate or low recharge potential, with extensive lower-potential zones occurring in the southern desert areas (Table 4).

The generated recharge map can serve as a spatial decision-support layer for groundwater exploration, managed aquifer recharge screening, watershed management, and groundwater planning [7,9,22].

Table 4: Area of groundwater recharge classes for Kandahar Province.

Recharge Class	Area (km ²)	Area (%)
Very High	9832	18.2
High	14423	26.7
Moderate	26632	49.3
Low	3133	5.8

4.12 Discussion

The GIS-AHP framework produced a spatially explicit classification of groundwater recharge potential in Kandahar Province, consistent with applications of these methods in Afghanistan and other data-scarce settings [3,7,9]. The spatial patterns obtained agree with the fundamental hydrogeological principle that groundwater recharge is controlled by the interaction among climatic conditions, topography, lithology, soil characteristics, structural features, and land use.

The findings are consistent with previous studies demonstrating that rainfall, slope, geology, soil characteristics, and land use are among the dominant controls on groundwater recharge in arid and semi-arid regions [3,9,19,20]. Furthermore, the satisfactory AHP consistency ratio ($CR < 0.10$) indicates that the pairwise comparisons are logically consistent and that the derived criterion weights are reliable, supporting the robustness of the adopted GIS–AHP framework for groundwater recharge potential assessment [33].

The resulting groundwater recharge potential map offers valuable scientific information for groundwater conservation, artificial recharge planning, groundwater abstraction management, and future land-use planning within Kandahar Province. Moreover, the integrated GIS–AHP framework can be readily adapted to other data-scarce regions with similar environmental conditions.

The findings of this study have several practical implications for groundwater management and water resource planning, such as:

- The groundwater recharge potential map can support government agencies in identifying priority areas for artificial groundwater recharge.
- The generated spatial information can assist planners in selecting suitable locations for groundwater development and monitoring.
- The results provide a scientific basis for integrating groundwater recharge considerations into regional land-use planning and watershed management.
- The methodology provides a comparatively data-efficient decision-support framework for regional groundwater screening in data-scarce environments.

5. Conclusion

This study identified groundwater recharge potential zones in Kandahar Province, Afghanistan, by integrating Geographic Information Systems (GIS) with the Analytical Hierarchy Process (AHP) within a Multi-Criteria Decision Analysis (MCDA) framework. Eight groundwater recharge conditioning factors, namely, rainfall, slope, drainage density, soil texture, geology, land use/land cover (LULC), lineament density, and aspect, were analyzed and combined using weighted overlay analysis to generate a spatial groundwater recharge potential map.

The AHP weighting process produced a satisfactory Consistency Ratio ($CR < 0.10$), indicating that the pairwise comparisons were logically consistent and that the derived criterion weights were suitable for spatial decision analysis. The generated recharge map classified the study area into four categories of groundwater recharge potential: low, moderate, high, and very high. Areas characterized by relatively high rainfall, gentle slopes, permeable soils, Quaternary alluvial deposits, lower drainage density, and favorable land-use conditions exhibited the highest groundwater recharge potential, whereas steep mountainous terrain, impermeable geological formations, and densely built-up areas generally demonstrated lower recharge suitability.

The results demonstrate the practical utility of integrating GIS and AHP for regional recharge-potential screening, consistent with previous GIS-MCDA applications [3,7,9]. The resulting recharge potential map provides valuable spatial information that can support groundwater exploration, artificial recharge planning, land-use planning, watershed management, and sustainable groundwater resource development in Kandahar Province. Furthermore, the methodology developed in this study is transferable to other arid and semi-arid regions with limited hydrogeological data.

This study is subject to limitations related to secondary spatial datasets, expert-dependent AHP weighting, temporal variability, and limited field validation. These limitations are important because GIS-MCDA suitability results can vary with criterion selection, weighting assumptions, data resolution, and validation strategy [22,28]. Future research should incorporate higher-resolution datasets, additional hydrogeological factors, comprehensive field validation, alternative multi-criteria decision-making methods, and assessments of climate change and land-use impacts to improve the reliability of groundwater recharge mapping.

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