

## DELINEATION OF GROUNDWATER POTENTIAL ZONES USING GIS, REMOTE SENSING AND MULTI INFLUENCING FACTOR TECHNIQUES IN BANNU DISTRICT, KHYBER PAKHTUNKHWA

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DOI: <https://doi.org/10.5281/zenodo.18677642>

### Keywords

Groundwater potential zones, Remote Sensing, Weighted overlay, Multi-influence factor, Remote sensing, Geographic information system

### Article History

Received: 24 November 2025

Accepted: 05 January 2026

Published: 21 January 2026

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### Abstract

Effective recognition of potential areas is essential for efficient groundwater utilization, planning, and management. In this particular study, the goal was to evaluate the potential for groundwater in Bannu district, Khyber Pakhtunkhwa Province, Pakistan. The research employed Spatial Multi-Criteria Decision Analysis (S-MCDA) method, incorporating seven influencing factors: drainage, lineament density, rainfall, gradient, soil types, geological structure and land use/land cover. Each influencing factor was assigned a weight and score through the (MIF) technique. Depending on how each subclass affected aquifer recharge and groundwater potential, each influencing factor was assigned a weight: (A) for primary effects and (B) for secondary effects. The relative effect was determined by adding the respective weights of the primary and secondary effects (A and B). This yielded the score for each subcategory within each influencing parameter. These all parameters were then combined using a weighted overlay analysis in ArcGIS 10.8 to delineate groundwater potential regions, which are divided into five categories: very low, low, good, high, and very high potentiality. The results indicated that very high groundwater potential zones enclosed 26.17% of the area (306 km<sup>2</sup>), high potential covered 21.47% (251 km<sup>2</sup>), moderate potential covered 17.53% (205 km<sup>2</sup>), poor potential covered 21.72 % (254 km<sup>2</sup>) and very poor potential covered 13.08 % (153 Km<sup>2</sup>) of the total area. This study can be a helpful resource for upcoming investigation plans and offers insightful information for efficient groundwater harvesting and management.

## INTRODUCTION

### 1.1 Scientific Background

Bannu district is focus of study in this research work, which is located in the southern part of Pakistan's Khyber Pakhtunkhwa province. It is positioned in the eastern section of the historic Bannu Valley bordered on the West by North Waziristan district, on the South by Karak district, and on the East by Lakki Marwat district (Arain et al., 2014).

The Bannu district is situated within the Bannu valley and is characterized by its low-lying structure. This valley is positioned between the longitudes of

70°22" and 70°57" East and the latitudes of 32°43" and 33°06" North. The district is divided into four tehsils and 49 union councils. For the purpose of investigation, the study would be focused on the two primary tehsils, namely Bannu and Domel. Surrounding a total area of 1227 square kilometers, district Bannu is densely populated, with an average of 552 individuals per square kilometer. This region experiences a hot and arid climate (Shakoor et al., 2022). The geographical layout of district Bannu is shown in Figure 1.

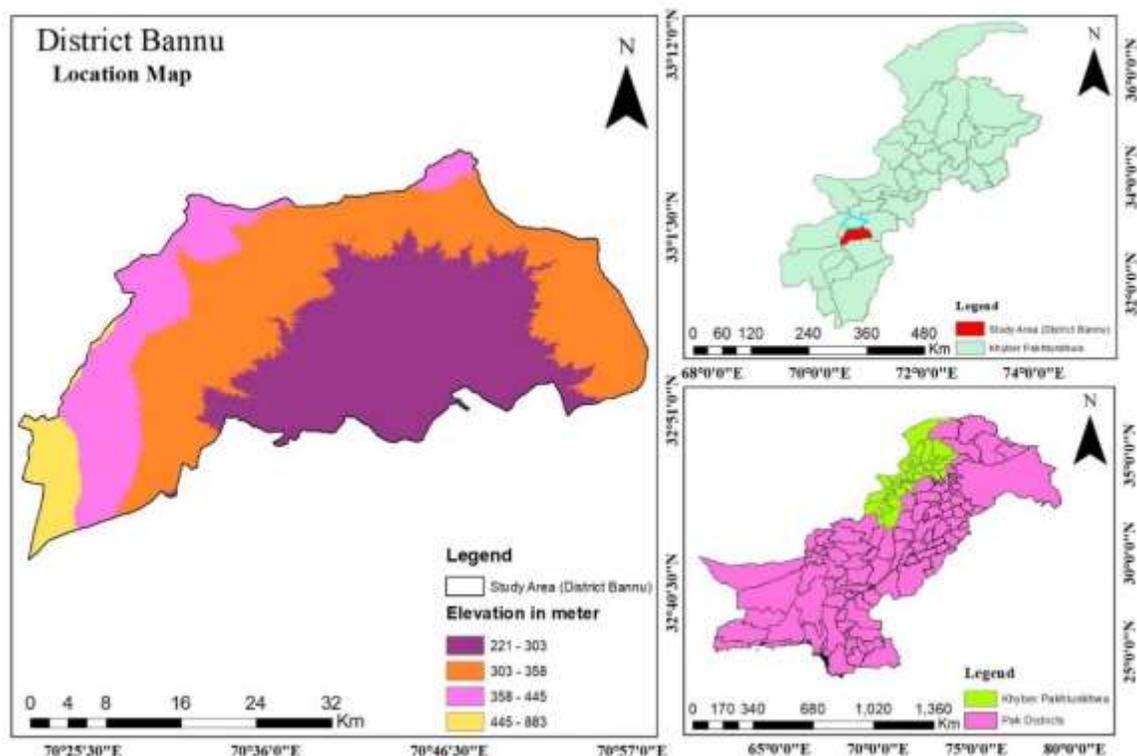


Figure 1.1 Study area map location

The worldwide distribution of groundwater relies on various factors including porosity, density of lineaments, geological compositions, weathering, and drainage density, (Sallwey et al., 2019; Saravanan et al., 2021). In the past, groundwater aquifers have been investigated using a variety of field-based geophysical and hydrogeological approaches, (Panahi et al., 2020) but these methods are time-consuming and uneconomical, especially at regional dimensions. (Bai et al., 2022). Moreover, these techniques mainly

focus on a single factor affecting groundwater recharge, which narrows their role in predicting regional groundwater mapping. Additionally, the major focus of these strategies is on a single component that affects groundwater recharge, which limits their use in estimating regional groundwater mapping. Groundwater research and the study of other natural resources both have been greatly benefited in recent decades from the widespread use of RS & GIS instruments like Environmental

Monitoring, Agriculture, Disaster Management, Urban Planning and Infrastructure, Forestry and Natural Resource Management etc. (Alam et al., 2021; Panahi et al., 2020).

The use of RS data spanning wide spatial and temporal scales enhances our understanding of the hydrological system, its changes, and its interactions with various factors, including climate change and human activities. This knowledge is essential for effective water resource management, disaster mitigation, ecosystem conservation, and sustainable development (Alam et al., 2022; Hoffmann & Sander, 2007; Rajesh, et al., 2021; Senthilkumar et al., 2019; Suliman et al., 2022). Several studies utilized GIS-based qualitative approaches like Analytical Hierarchical Process and Multi-Influencing factors to evaluate groundwater potential zones. These approaches are research based and depend on the researcher's experience in related fields. In addition to the above-mentioned methods, several researchers used quantitative techniques such as frequency ratio, (Doke et al., 2020), entropy weighting (Rahmati et al., 2022), support vector machine (SVM) (Prasad et al., 2020), random forest (RF) model (Chen et al., 2020), and logistic regression (Chen et al., 2018). These methods, which are based on mathematical equations, optimize the data processing environment in dynamic or unpredictable situations.

In the southern region of Khyber Pakhtunkhwa province, the status of groundwater table is under stress (Suliman et al., 2022). The region has a sub-tropical to semi-arid climate, and there are a lot of irregularities in both spatial and temporal distribution of rainfall (Farid et al., 2017). Due to the area's limited surface water resources and because of being poorly developed, ground water resources in the research area are largely utilized for irrigation and household purposes. Due to increase in population, the demand of groundwater resources of the expansion of agricultural fields have led to overuse of groundwater and a decline in water quality. In the semi-arid region, the mapping of potential zones of groundwater is also important for rainfall conservation programs, and development of groundwater. The ultimate task of this research work is to use the MCDA approach to identify GWPZs sites in the Bannu district.

The district has limited rainfall pattern, with an average annual rainfall ranging between 200 to 300 millimeters. The monsoon season, typically occurring between June and September, witnesses the highest amount of rainfall. Due to the low rainfall and high evaporation rates, groundwater plays a crucial role as a reliable source of water in district Bannu (Din et al., 2023). From a hydrogeological standpoint, Bannu lies within the main aquifer system of Pakistan; the Indus Basin. The aquifers in the area mainly consist of alluvial deposits, with sand and gravel formations acting as the primary reservoirs for groundwater. Many of these aquifers are unconfined, indicating they lack impermeable layers that separate them from the surface (Kumari et al., 2022).

Groundwater recharge in district Bannu primarily occurs through, rainwater infiltration, and irrigation return flows. However, maintaining proper recharge rates is challenging due to the region's low rainfall and high evaporation rates. Consequently, sustainable groundwater management is crucial to ensure the availability of this vital resource. The study area's reliance on groundwater extends to various sectors. Agriculture is the main economic driver, with farmers heavily relying on wells and tube wells for irrigation. Groundwater is also essential for household water supplies, serving as a common source of drinking water and other domestic needs. Furthermore, the industrial, building, and mining sectors depend on groundwater for their operations (Das et al., 2017). Understanding the hydrogeological features, groundwater potential, and recharge mechanisms in district Bannu is crucial for effective water resource management. By comprehensively studying the study area, including its geology, land use, and hydrological characteristics, informed decisions can be made to ensure the sustainable utilization and conservation of groundwater resources (Senapati et al., 2022).

## 1.2 Objectives

The purpose of this study is to use geospatial technologies (MIF approach) to locate groundwater potential zones in district Bannu, Khyber Pakhtunkhwa, Pakistan. The specific objectives this study would be focused on are presented below:

- To prepare thematic map of influencing factors like drainage density, slope,

lineament density, geology, soil, LULC and rainfall.

- To develop a detail map of groundwater zones in the study region using MIF technique.
- To validate groundwater potential map using well data.

### 1.3 Significance

In order to map the potential water supply zone, observe, and preserve this essential resource, study of groundwater is now essential. People in the province of Khyber Pakhtunkhwa, particularly in Bannu, depend on groundwater for home and agricultural applications. Furthermore, excessive groundwater excavation and insufficient preparation have made this vital asset scarce in the research region (Khan et al., 2013). Consequently, in order to maintain these renewable substances, scientific approaches as well as management are vital. In order to ensure ecologically sound use and adequate advancement of the underground water reserve within the locality, the recognition of GWPZs in the district Bannu, Khyber Pakhtunkhwa, Pakistan will be significant and beneficial for organizers and appropriate officials in drafting the policies, as well as for regional groundwater supplies and highly imaginative authorities, such as the Water and Sanitation Authority (WASA) and Water Resources Research Centre Bannu (WRRCB). The development of useful policies and practices for sustainable utilization of underground water supplies would obtain assistance from this investigation.

### 1.4 Integration of Geospatial and MIF Techniques

Finding groundwater potential zones requires an efficient scientific methodology. Water resource management may be improved by using an integrated strategy that combines geospatial and ground-based methods (Waikar et al., 2014). The use of geospatial approaches is widespread around the world to analyze groundwater potential zones more quickly and accurately with ground truth confirmation. These are superior to other conventional approaches for identifying groundwater resources because they are straight forward, reliable, affordable, and time-effective (Raju et al., 2019). By employing some of the regulating characteristics, including geology,

lineament and drainage density, soils, rainfall, slope, and LULC, it produces accurate findings by lowering the likelihood of human errors (Etikala et al., 2019). Additionally, the integration of GIS and RS approaches is advantageous.

In the past, several researchers from all over the world have utilized RS and GIS to identify GWPZs using a variety of techniques, including the multi-influence factor (MIF) (Chaudhary et al., 2018; Das et al., 2017; Nasir, Khan et al., 2018; Sashikkumar et al., 2017). Groundwater may be quickly and accurately identified using the MIF approach (Rajasekhar et al., 2019). Additionally, the MIF approach is very productive and highly valid for the identification of GWPZs. As a result, the MIF approach was used to find GWPZs in the area under study. Additionally, the globally utilized the geospatial and MIF technique was employed to cross-validate the groundwater potential zones.

### Literature Review

A literature review on groundwater delineation using Geographic Information Systems, Remote Sensing, and multi-influence techniques would reveal a significant body of research aimed at improving our understanding of groundwater resources and their sustainable management. In Pakistan's Khyber Pakhtunkhwa province, specifically in the Bannu district, groundwater holds significant importance as a precious natural asset serving a variety of purposes. Given the district's arid to semi-arid conditions characterized by little rainfall and substantial evaporation, groundwater becomes especially crucial as a dependable water source (Suliman et al., 2022). The main economic driver of district Bannu is agriculture, and irrigation for agricultural production relies heavily on groundwater. For their agricultural purposes, farmers significantly rely on wells and tube wells to draw groundwater, maintaining the productivity and sustainability of their fields. The presence of groundwater directly affects the agricultural livelihoods and crop productivity of the area (Rajasekhar et al., 2019).

Groundwater is crucial for home water supplies in addition to agriculture, especially in locations with insufficient or poor surface water sources. Groundwater wells are a common source of drinking water, cooking, and other household necessities in

district Bannu. As a result, the availability and quality of groundwater directly affect the local population's well-being and means of subsistence (Arain et al., 2014). Additionally, district Bannu industrial, building, and mining sectors frequently demand large volumes of water for their activities. These industries rely on groundwater as a dependable supply, certifying their continued operation and economic expansion. Since groundwater in district Bannu is essential for industrial, domestic, and agricultural operations. The regions of groundwater potential zones must be understood and evaluated. With the use of this information, groundwater resources may be planned, managed, and used sustainably, assuring their long-term availability and lowering the dangers connected to overuse or poor management techniques (Ahmed et al., 2021).

Groundwater, probably the most important naturally available resource, has a major impact on civilization's development and socio-economic activities (Arshad et al., 2020). It provides a huge amount of freshwater worldwide for drinking, industrial use and agricultural, (Panahi et al., 2020). The serious issue of groundwater is day by day depleting of the environment, society, and ecosystem (Rajesh et al., 2021). Pakistan is considered as the fourth largest groundwater puller in the world since its pumpage rate exceeds its recharge rate (Qureshi et al., 2020). Groundwater is depleting day by day in different parts of the country due to climate change, rapped urban sprawl, and poor water management (Majeed and Piracha, 2011). Unscientific exploitation and poor water policy utilization are further potential contributing issues (Suliman et al., 2022). Therefore, characterization of the groundwater resource type and availability becomes critical for effective management in the world's major cities.

According to (Abijith et al., 2020), Asia's groundwater resources are mostly the result of rainfall that seeps into the aquifer. GIS, RS, and MCDM have been used by to evaluate GWPZs in a semi-arid area of Rajasthan, India. On the basis of their importance appropriate weights have been assigned to seven different thematic levels. Utilizing MCDM and AHP techniques, weights assigned to all thematic levels have been normalized. The tube well depth data in the research region have been used to corroborate the final produced

groundwater potential map. In the Goghat-II block of West Bengal, India, (Das and Pal, 2019) an attempt was made to visualize groundwater recharge potential zones using the fuzzy-AHP approach. Six influencing criteria have been developed, with weights given based on the fuzzy- AHP method, to help identify the possibility for groundwater recharge.

Using data of the depth of the water table in the research region, the generated groundwater potential model has been validated (Andualem and Demeke, 2019). Used RS, GIS, and MCDA methods to try to determine GWPZs in Ethiopia's upper Blue Nile Basin. By combining a variety of thematically impactful layers, the GWPZs map was developed. According to the MCDA approach, weights were allocated and normalized to each thematic layer. Geospatial and MIF have been employed by to assess the geographical distribution of GWPZs in the Afghan province of Kabul (Nasir et al., 2021). The determining elements for GWPZs include geology, slope, LULC, rainfall, soil type, lineament, and drainage density. The MIF approach has been used to assign weights and rankings to each element. Numerous studies have been conducted in Pakistan to discover GWPZs, but none has attempted to evaluate the GWPZs in the context of the current research (Chaudhary et al., 2021).

Geospatial and Multi-Criteria Decision Analysis (MCDA) approaches were employed to assess Groundwater Potential Zoning (GWPZs) by considering seven influencing factors: soil, geology, rainfall, land use and land cover (LULC), slope, lineament, and drainage density (Muhammad and Khalid, 2017). The study area's GWPZs regions were evaluated using geophysical techniques (an electrical resistivity survey). With the use of GIS and the analytical hierarchical process (AHP), have an attempt has been made to identify advantageous groundwater potential recharge zones. The Analytic Hierarchy Process (AHP) method in Geographic Information Systems (GIS) is a decision-making approach that employs a structured process to evaluate and prioritize various criteria and alternatives, facilitating effective spatial analysis and decision support (Arshad et al., 2020). The study was conducted in Punjab; province an agro-urban area of Pakistan.

According to each layer's effect, ranks and weights were assigned, and the layers themselves were

established. The location of the water and GWPZs regions in the Upper Thal Doab, Punjab, Pakistan, was established by conducting a comprehensive geospatial analysis and utilizing various data sources and methodologies (Bodrud and Doza et al., 2019). For groundwater modelling, an integrated strategy combining RS and GIS has been acquired. Based on their effect, weights were assigned to each of the several contributing elements, such as rainfall, geology, soil, LULC, etc., projecting GWPZs calculation for the Kohistan area of Sindh's Ramshorn district. The study was conducted in dry climate zones that frequently experience unexpected droughts and floods. GIS and RS approaches were employed in the study to identify GWPZs (Abudeif et al., 2022).

### 2.1 Problem Statement

The problem at hand is the need for an accurate and comprehensive delineation of groundwater resources in district Bannu. Insufficient knowledge of groundwater availability and potential zones hinders sustainable water resource management in this region. Addressing this challenge requires a thorough assessment using modern geospatial techniques such as GIS and Remote Sensing, coupled with a multi-influence approach, to identify and map groundwater potential zones essential for agricultural, domestic, and industrial purposes. Identification of groundwater potential zones in district Bannu implies a research or investigative task aimed at determining areas within district Bannu where there is a probability of finding groundwater resources. This is a common geospatial and hydrogeological study that would be conducted to support various purposes, including water resource management, urban planning, and agricultural development. In semi-arid to arid regions like Bannu, where surface water supplies are often transient, the only reliable source of water for industrial, household, and agricultural needs is groundwater. Due to population increase and the extension of agricultural land, groundwater resources are under growing pressure, which has resulted in resource miss use and a reduction in water quality. The problem is even worse in some arid parts of Bannu where the water table continues to drop quickly drying off wells and springs and destroying orchards. Due to several variables including industrial

development, economic growth, and other related issues, rural-urban migration is a significant phenomenon in the modern era. Because it lowers the amount of greenery inside and surrounding the cities, this rapid urban expansion is extremely complicated in nature. To recharge groundwater and maintain sustainable production, the situation proposes new strategies combined with integrated watershed management. The suitable locations for groundwater recharging must be found in the research region in order to manage the water table's condition. Why is it essential to identify groundwater potential aquifers for the future planning and development of the study region? For the study region's future planning and development, it is also essential to identify groundwater potential aquifers.

### Materials and Method

#### 3.1 Data collection

The present study research data requirements are gathered from a variety of sources. The 12.5m resolution digital elevation model data are obtained from ALOS PALSAR (<https://asf.alaska.edu>). The slope, Drainage and lineament density map are generated from Dem. To determine land use and land cover, Sentinel 2 data are being acquired from Copernicus Open Access Hub (<https://scihub.copernicus.eu/>). The geological map is created from the geological survey of Pakistan. A soil map is created using the soil survey data from Khyber Pakhtunkhwa. The rainfall data are downloaded from the Climate Research Unit of the time period of 2010 to 2020. When utilizing GPS and physically monitoring the water level using a rope tape to gauge the depth of the groundwater table, these methods may both be used to obtain this information during a field survey and collected the data of tube wells.

#### 3.2 Methodology

The methodology used in this study could serve as a plan for similar studies in other regions facing groundwater challenges. The approach of integrating GIS, RS, and MIF techniques can be applied to various contexts worldwide. Overall, the outcomes of this study could contribute to better understanding the spatial distribution of groundwater potential in Bannu district, Pakistan. The present study research

data requirements are gathered from a variety of sources. The 12.5 m resolution digital elevation model data are obtained from ALOS PALSAR (<https://asf.alaska.edu>). From the digital elevation model (DEM), topographic parameters including altitude, angle, slope and stream network are obtained. To determine land use and land cover, Sentinel 2 data are being acquired from Copernicus Open Access Hub (<https://scihub.copernicus.eu/>).

Supervised image classification techniques are used to classify the entire pixels based on their spectral signatures. In a supervised image classification, algorithm of Maximum Likelihood Classification (MLC) is used. A total of 150 training samples are taken from each sub class. The sentinel 2 image are employed for the purpose of classification. The MLC relies on their spectral signatures, where pixels are allocated to specific classes based on the likelihood of their association with those classes. The fundamental elements of MLC are the mean vector and covariance measures, which can be extracted from the training data. The outcomes of the classification indicate that MLC is a highly resilient method, minimizing the likelihood of misclassification occurrences.

The geological map is created from the geological survey of Pakistan. After geo-referencing, the lithological units are converted into digital format using information extracted from a geological map at a scale of 1: 650,000 that was issued by the Geological

Map of North Pakistan. A soil map is created using the soil survey data from Khyber Pakhtunkhwa. After Georeferencing, the soil types are converted into digitized layers. The rainfall layer is produced by the interpolating method, and the precipitation data is downloaded from the Climate Research Unit of the time period of 2010 to 2020, using the inverse distance weighting (IDW) approach. This method is better suited for areas with limited data availability. IDW involves assigning weights to neighboring observed values according to their proximity to the interpolation location, resulting in the interpolated value being a weighted average of these observations. The rankings are generated based on various primary and secondary interactions between the factors that affect the GWPZs. Using the minor and major effects of each element, the recommended relative rates for groundwater potentiality are calculated once weights have been assigned. Based on understanding of the researcher of study region's hydrological characteristic, the relevance of each element is evaluated in this analysis. The proposed score of each individual factor will then be derived using the relative score, as shown in equation (3.1).

$$S_i = \frac{j+n}{\sum (j+n)} \times 100 \quad (3.1)$$

Where  $j$  and  $n$  are the major and minor influence factors, respectively, and  $S_i$  is the suggested score of a factor.

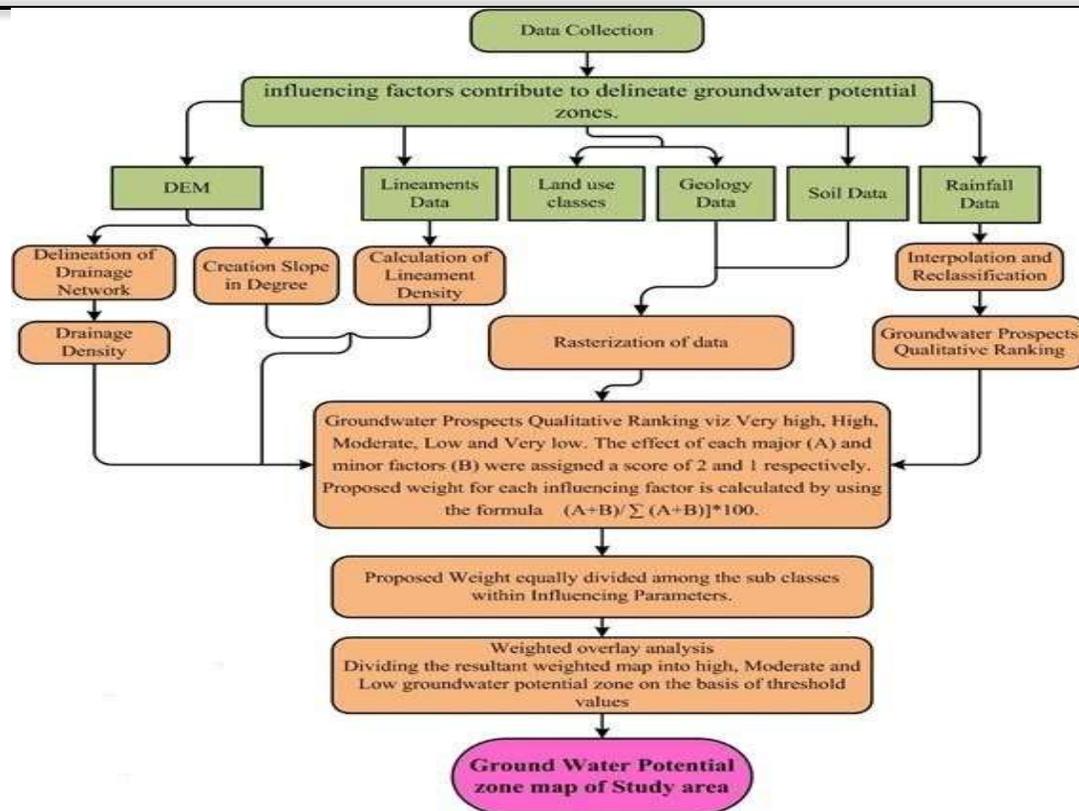


Figure 3.1 Flowchart which shows how groundwater potential is calculated

### 3.2.1 Geology

Geology has a major impact on groundwater flow and occurrence, and different kinds of rocks have a significant impact on groundwater infiltration and accessibility (Allafta and Opp, 2021). The Geological Map of North Pakistan, based on Peshawar, Khyber Pakhtunkhwa, provided the 1:650000 geological map of Pakistan. The geological map is in raster format; it has been georeferenced and digitized then viewed in ArcGIS 10.8. The research region was extracted on the map using the Spatial Analyst Tools > Extract > Clip tool. Digitally, the study area was divided into sedimentary rocks. Different values were given to different rock types based on infiltration capacity and the possibility of groundwater recharge, as indicated in Table 3.2.

### 3.2.2 Slope

GWPZs is commonly found by measuring the slope, sometimes referred to as the rate of elevation change. The steeper slope may result in faster soil erosion as well as greater surface runoff (Rather et

al., 2022). The slope is essential for surface water penetration and groundwater recharge. A steep slope makes infiltration difficult since there is a lot of runoff, which leads to a low GWPZs (Kanagaraj et al., 2019). A moderate slope actually speeds water infiltration while reducing runoff. The research area's slope was mapped using ArcGIS 10.8 tools and a DEM with 12.5 m accuracy.

### 3.2.3 Drainage density

The term "Drainage density" describes the spatial arrangement of stream channels. The degree of drainage has an impact on the amount of water permeation in a particular area (Akinlalu et al., 2017). Using the correct application in ArcGIS 10.8, the drainage system was retrieved out of the DEM with a scale of 12.5 m, and a drain density graphic was created employing the line density instrument of the geospatial analyst tool. The drainage density is calculated by dividing the total area by the sum of all waterway's sections in the region. (Allafta et al., 2021).

$$D_d = \sum_{i=1}^n \frac{DI}{A} \quad (3.2)$$

Where A is the area of the research region and  $\sum_{i=1}^n DI$  is the sum of all stream lengths (measured in meters). For watercourse measurements, the waterway line demarcation technique was used with 1000 units.

### 3.2.4 Rainfall

The majority of places with potential for groundwater are identified by the penetration rate, which is sustained by slope and precipitation distribution (Sarwar et al., 2021). The rainfall layer is produced by the interpolating method, and the precipitation data is downloaded from the Climate Research Unit of the time period of 2010 to 2020. A rainfall map was then produced using Spatial Analyst Tools > Interpolation and then IDW using precipitation data that had been submitted to the ArcGIS 10.8 for interpolation. The study area's rainfall map was obtained using the Spatial Analyst Tools>Extraction>Obtain by Extraction by Mask tool. The research region was divided into five rainfall regions—very low, low, moderate, high, and very high, as a result of the interpolation of rainfall data. Each has been given the appropriate weight.

### 3.2.5 Soil type

According to concepts, the soil has a significant impact on the rate of aquifer infiltration (Anbazhagan et al., 2005). Depending on the size, shape, arrangement, and pore system of the soil grains as well as how they are linked together, water can move both vertically and laterally (Allafta et al., 2021). A soil map of Pakistan at a scale of 1:2,000,000 was provided by the Soil Survey of Pakistan. The research region was removed from the map using the Spatial Analyst Tools > Extract > Clip tool after it had been georeferenced and uploaded to

ArcGIS 10.8. The research area was divided into the following subcategories using computerized tools: 1. mainly loamy, clay & saline, 2. mainly noncalcareous, loamy & clay, 3. mainly loamy, shallow & gravel.

### 3.2.6 Landuse/ Landcover

According to reports, LULC has an impact on a region's groundwater availability and growth. Surface runoff and infiltration are regulated by regional land cover patterns (Scanlon et al., 2005). Forests and other types of vegetation increase water penetration while reducing runoff. Built-up areas often have worse infiltration because their surfaces are less porous (Allafta et al., 2021).

To determine LULC, Sentinel 2 data are acquired from Copernicus Open Access Hub (<https://scihub.copernicus.eu/>). It was decided upon the research area, the time period for 2022, and the datasets > sentinel 2> of Level-1. In order to obtain images with the least amount of cloud cover, we selected Scene Haze Shelter and Land Cloud Cover, which is less than 15% from the list of "Additional Criteria". Using the tools found under Spatial Analyst Tools > Extract > Clip, the study part was obtained from the collected pictures once they had been uploaded into ArcGIS 10.8, the appropriate program. We select Picture Classification > Maximum Likely Hood Classification when categorizing photos. Many polygons were created during the supervised classification of the zone of interest (particular land use category) in order to construct the signature files. All polygons were combined to create a unique class for the type of land use. Several classes that represent various types of land use were created using the same procedure.

Table 3.1. Relative rates and the score of each influencing factor Major (A) and Minor (B)

Influencing Factor	Major (High) Effect (A)	Minor (Low) Effect (B)	Proposed Relative Rates (A + B)	Proposed Score of Each Influencing Factor (MIF)
Geology	2	1+1+0	4	10
Drainage density (m)	2+2	1	5	15
Rainfall (mm)	2+2	1	5	14
Lineament density (m)	2	1+0+0	3	16
Soil	2	0+0+0	2	15
Slope(°)	2+2	1	5	15
LULC	2+2+2	1+1	8	15
			Σ32	Σ100

3.3 Assigning of Weights and Ranks.

Using the (MIF) approach, the rankings of each subclass of influencing factor were established, as well as the weights of each influencing parameter. The author's experience and a literature review were both used to identify the relationships between the different feature classes and give rankings to each feature's sub-classes. Primary impact labels (A) and MIF=((Minor+Major))/((Minor+Major))×100 (3.3) Where MIF stands for "multi-influencing factor," "A" for "primary effect," and "B" for "secondary effect" between two influencing factors.

3.4 Weighted Overlay Analysis

The estimated weights and qualitative as well as quantitative rankings were assigned to all seven parameters examined in the study. The "weighted overlay" tool from the overlay toolbox with in ArcGIS 10.8 spatial analyst tools were utilized. This tool allocated weights and rankings to each of the seven parameters, along with their respective sub-categories, as illustrated in Table 3.1. Subsequently, an integrated analysis was performed using weighted overlay analysis to combine all the parameters. The Groundwater Potential Index (GWPI) was calculated using equation (3.5), as presented below.

$$GWPI = GwGr + RfwRfr + SlwSlr + DDwDDr + SwSr + LULCwLULCr + LDwLDr \dots\dots\dots(3.5)$$

In other words, "GWPI" represents the groundwater potential index, which is influenced by various factors such as geological characteristics ("G"),

scores of 2 were assigned to significant influencing factors, whereas minor influencing elements acquired a secondary effect label (B) and a score of 1. The cumulative sum of the primary (A) and secondary (B) impacts is used to determine the suggested relative rates (A+B) of each influencing factor. The following calculation is used to determine the recommended score.

$$MIF=((A+B))/((A+B)) \times 100 \quad (3.4)$$

rainfall ("Rf"), slope ("Sl"), drainage density ("DD"), soil type ("St"), land use and land cover ("LULC"), and lineament density ("LD"). The notation 'w' indicates the weight assigned to each thematic layer, which is calculated using the MIF (Multi influence factor) method as shown in column "4" of (Table 3.2). Similarly, 'r' represents the ranking of subclasses within each layer, as presented in column "5" of (Table 3.2).

After compiling data for the thematic layers, these layers were transformed into raster datasets using spatial analyst tools. This conversion was essential for subsequent weighted overlay analysis and other operations. To maintain consistency, the WGS\_1984\_UTM\_Zone\_43 coordinate system was utilized throughout the study. This choice was made because all raster's need to share the same coordinate system before conducting weighted overlay analysis.

The weighted overlay tool facilitated the comparison of multiple rasters on a standardized scale, assigning weights based on their respective importance. The

resulting output layer values ranged between “1” and “5”. Groundwater potential zones (GWPZ,s) were categorized using this scale: zones with a value of “1” signified minimum potential, while those with a value of “5” indicated maximum high potential.

To classify variables like slope, drainage density, lineament density, rainfall, and land cover layers, a five-category classification system was employed. This allowed the effective categorization of these variables.

To validate the devloped model, existing tube wells data were used. Total of 61 tube wells data were collected of their latitude, longitude and depth of water. This data was overly on the GWPZ,s map to verify the result of the model.

**Table 3.2 The weight and ranks assigned to each parameter influencing the groundwater recharge within a thematic layer**

Parameters	Sub categorized within influencing parameter	Groundwater prospects (qualitative rank)	Suggested mass of to each influencing factor $[(A+B) \sum (A+B)] \times 100$	Groundwater Predictions quantitative score
Slope in degree	00-15	Very high	15	15
	16 – 30	High		11
	31 – 45	Moderate		07
	46 – 60	Low		03
	61- 78	Very low		00
Drainage density in km/ km <sup>2</sup>	1.7–3.0	High	15	15
	3.1- 4.5	Moderate		11
	4.6-6.1	Low		07
	6.2-7.3	Very low		04
Geology	Sedimentary rocks	High	10	10
		Moderate		06
		Very low		04
Rainfall in (mm)	206–234	Very high	14	14
	176–205	High		10
	147–175	Moderate		06
	118–146	Low		04
	86.2–117	Very low		01

Soil	Mainly non calcareous. Loamy & clay	High	15	15
	Mainly loamy shallow & gravel soil	Moderate		10
Land use/land cover	Water body	Very high		15
	Vegetation	High		10
	Urban	Moderate	15	05
	Barren land	Low		01
Lineament density in Km	1.5–1.8	Very high		16
	1.2–1.4	High	16	12
	0.72–1.1	Moderate		08
	0.37–0.71	Low		04
	0–0.36	Very low		00

## Results and Discussions

### 4.1 Thematic Layers

Geographic Information Systems (GIS) technology enables researchers and other users to combine various portions of information into distinct 'themes'. These thematic data layers consist of datasets sharing a common feature or characteristic, organized within a single layer of spatial data. Thematic layers aggregate metrics (like counts, quantities, percentages, and numeric data) and associate them with colors based on geographical divisions. These layers are like heat maps, but they display clustered patterns outlined by geographical borders rather than highlighting specific hotspots. The fundamental components essential for creating a thematic map contain, the statistical information employed to analyze and represent the chosen phenomenon within a particular area; and a base map acting as the foundational reference for the geographical context where the particular phenomenon is taking place.

The study area's groundwater potential zones (GWPZs) were determined by analyzing seven different thematic layers: geological composition (G), soil characteristics (SC), incline or slope (S), land use and land cover (LULC), rainfall patterns (R), density of drainage networks (Dd), and

lineament density (Ld). The following sections provide a comprehensive explanation of each of these thematic layers.

#### 4.1.1 Geological Composition

Geological formations play a crucial role in influencing the volume and quality of groundwater within a region. In fact, it is the most prominent factor in all mentioned seven parameters. Examining the structural significance, physiography, and diverse landforms in the research area is essential for comprehending their impact on the capacity of water infiltration. Understanding the geological characteristics of an area is considered essential to influencing the replenishment of groundwater. It is helpful to understanding the structural importance, rock composition, and diverse geological attributes within the study area in relation to their capacity to grip and allow the passage of water (Raza et al., 2022). The geological aspect significantly forms groundwater dynamics, and the diverse rock varieties play a crucial role in determining the quantity and movement of groundwater resources (Allafta et al., 2021). The composition, characteristics, and permeability of rocks and soil have a substantial influence on water infiltration and the

replenishment of groundwater reserves. Permeability and porosity dictate the ability of

rocks to store energy.

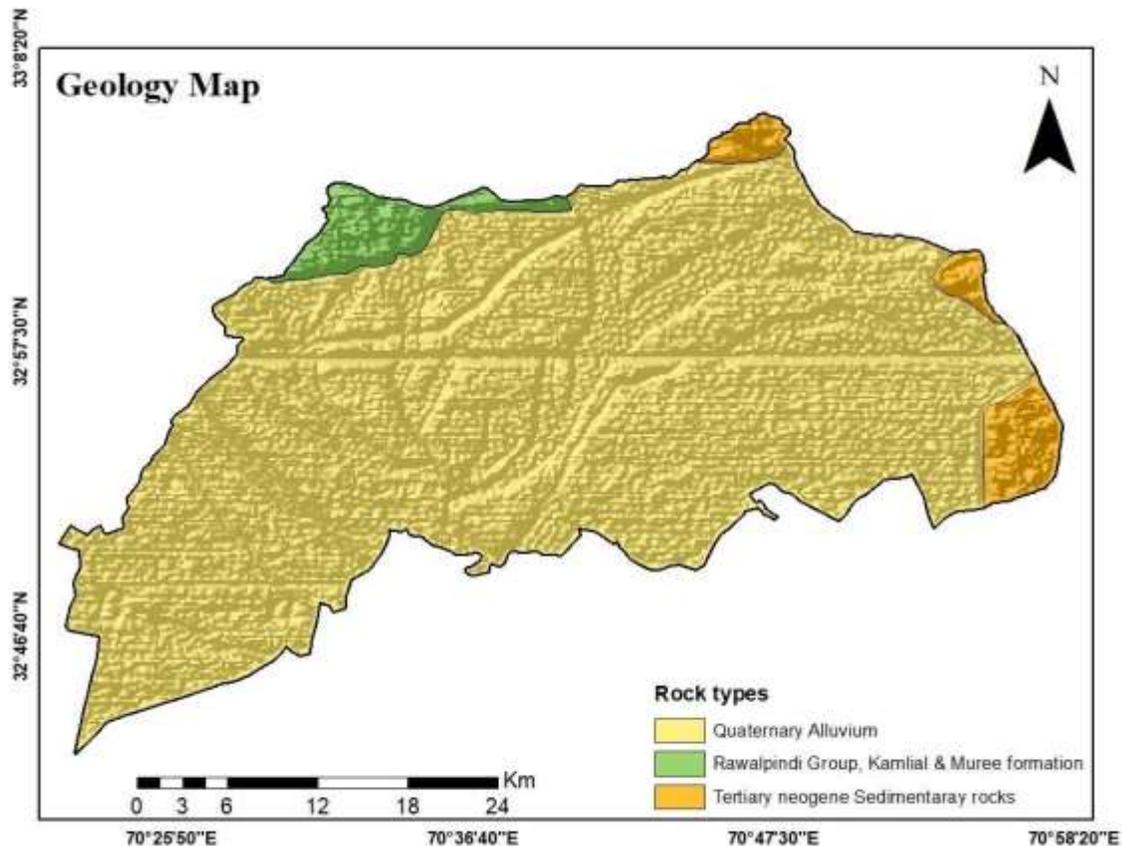


Figure 4. 1 Geological decomposition of study area

The fluid conductivity or porosity of the geological framework determines the fluid slopes that water moves in, from places of groundwater recharge to discharge zones (Nasir et al., 2021). In the context of this investigation, sedimentary rocks constitute the major portion of the region. The composition of sedimentary rocks is quaternary alluvium, Rawalpindi group, Kamliail & Muree formation and tertiary Neogene sedimentary rocks as shown in (Figure 4.1) (Tani and Tayfur, 2021). The quaternary alluvium is poorly sorted organic material, clay, sand, and rounded pebbles and cobbles. The Rawalpindi Group is a geological formation that is part of the Paleocene to Eocene-aged rocks. It primarily consists of sedimentary rocks, including sandstones, siltstones, mudstones, and conglomerates. The Rawalpindi Group, with its

distinct sedimentary characteristics, is a key geological formation in Bannu district. Its role in shaping the hydrogeological landscape makes it a significant focus of interest for researchers, geologists, and professionals involved in land and water management in the region. In Kamliail formations include various sedimentary rock types, such as sandstones, siltstones, mudstones, and conglomerates. The Muree Formation comprises interbedded sequences of sandstones, shales, and conglomerates. Sedimentary rocks provide favorable conditions for the existence of groundwater potential zones (GWPZs).

#### 4.1.2 Spatial Distribution of Slope

The slope of the land plays a vital role in the movement of water, the process of recharge, and the runoff on the surface. The gradient of a

location directly affects how water is absorbed into the ground; steeper slopes lead to reduced recharge as quick surface discharge provides a shorter period for water to seep into the subsurface for ultimate replenishment of groundwater (Sarwar et al., 2021). Areas with

level terrain are considered to have the highest groundwater recharge due to enhanced infiltration. Conversely, regions with gentle slopes are believed to have optimal groundwater recharge due to greater subsurface water penetration and minimal surface runoff.

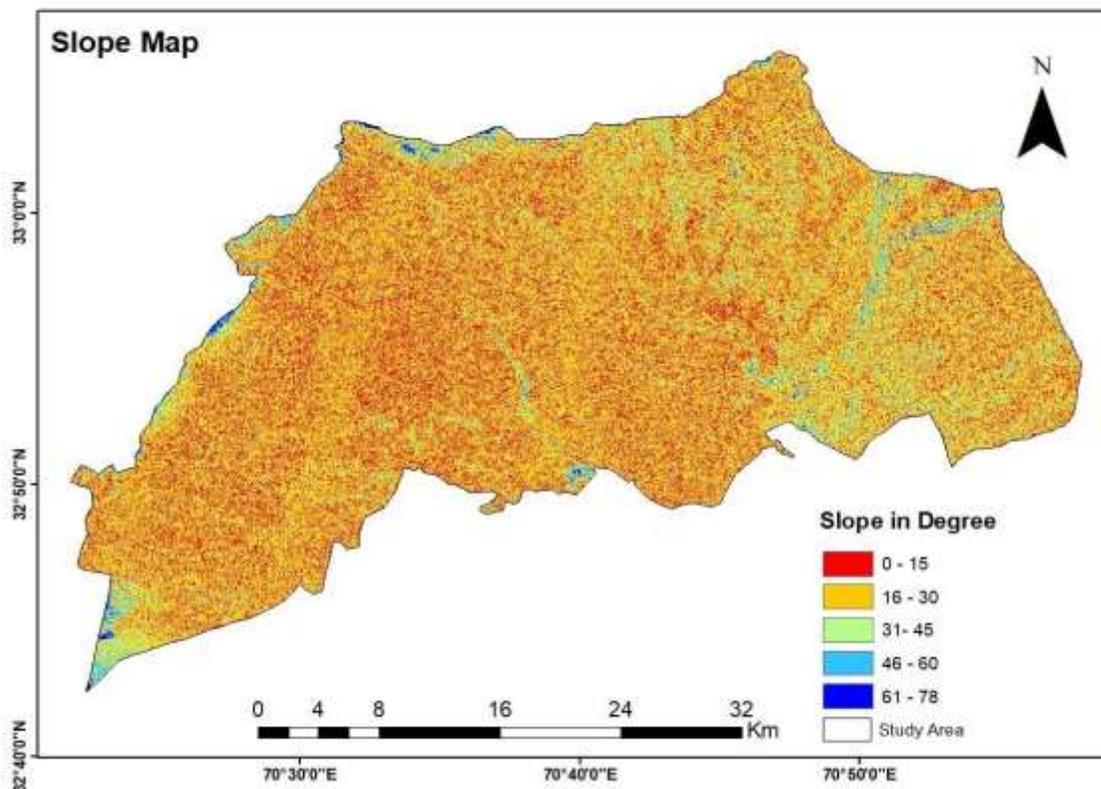


Figure 4.2. Spatial distribution of slope in the study area

The slopes within the study area are categorized into four groups: extremely low ( $0^{\circ}$  to  $15^{\circ}$ ), slopes falling within this category have a very gentle gradient, ranging from flat to a slight incline. These areas are generally considered flat or nearly flat. They are suitable for a variety of land uses, including agriculture, urban development, and infrastructure projects. Low ( $16^{\circ}$  to  $30^{\circ}$ ), slopes in this category represent a moderate incline. While not excessively steep, these areas may have enough slope to influence water runoff and drainage patterns. Depending on other factors such as soil type, low slopes can still be suitable for various land uses. Moderate ( $31^{\circ}$  to  $45^{\circ}$ ), slopes classified as moderate have a steeper

incline. These areas may present challenges for certain types of development and agriculture. Proper engineering and land management practices are often required to address issues related to erosion and stability. High ( $46^{\circ}$  to  $60^{\circ}$ ), high slopes are relatively steep, requiring careful consideration in land-use planning. These areas may be prone to erosion and landslides, and infrastructure development becomes more challenging. Sustainable land management practices become increasingly important in high-slope areas and very high ( $61^{\circ}$  to  $78^{\circ}$ ) gradients as shown in (Figure 4.2), very high slopes are characterized by steep inclines, often approaching the limits of what is practical for human

development. These areas are prone to erosion, landslides, and other natural hazards. They are typically unsuitable for most types of development.

#### 4.1.3 Spatial Distribution of Drainage density in the Study Area

The arrangement of water courses reflects the progression of the earth's crust. As a result of the distinct underground and surface characteristics of each region, there exists an inverse correlation between groundwater and drainage density (Mandal et al., 2021). Drainage density, which is inversely linked to permeability, has implications for the storage of groundwater. Areas with low drainage density are more likely to undergo groundwater replenishment, whereas high drainage density leads to substantial runoff, reducing the rate of infiltration and hindering effective groundwater recharge. The study area was categorized into five classes based on drainage density in "km": very low (0.27–1.6),

low (1.7–3.0), moderate (3.1–4.5), high (4.6–6.1), and very high (6.2–7.3) values (as depicted in Figure 4.3). Drainage density (Dd) is calculated by dividing the entire length of the stream segments by the unit area. The drainage density refers to the concentration of rivers, streams, or water channels within a given area. A very low drainage density values indicates that there are relatively few rivers or streams per unit area. Low drainage density suggests a slightly higher concentration of water channels compared to the very low category. However, the overall density is still considered low, indicating that the area may have fewer watercourses. Areas with moderate drainage density have a more balanced distribution of water channels. This category implies a moderate concentration of rivers and streams, suggesting a more developed drainage network. High drainage density indicates a significant concentration of water channels in the area. This may result in a well-developed and interconnected network of rivers and streams.

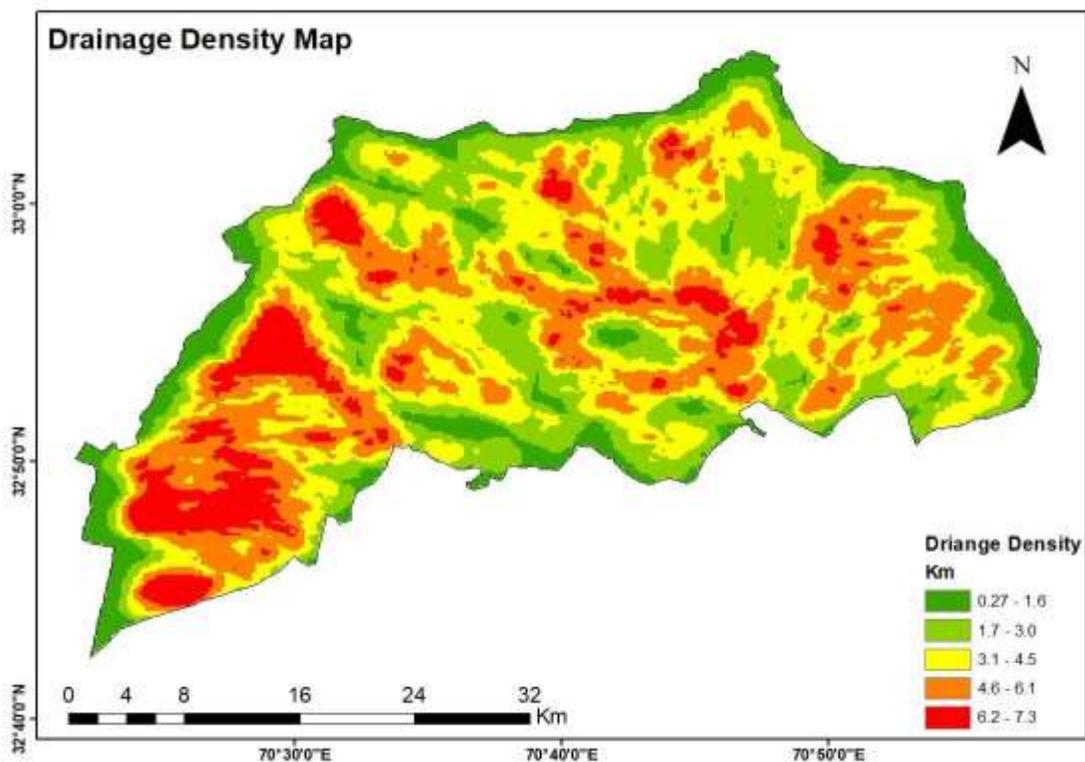


Figure 4.3. Drainage density map

#### 4.1.4 Rainfall Pattern in Study Area

Rainfall plays a significant role in shaping the water cycle and holds particular importance for the replenishment of groundwater. The rate of infiltration, predominantly influenced by the distribution of rainfall and the gradient of the terrain, has a decisive impact on the majority of groundwater potential zones (Sarwar *et al.*, 2021). The amount and temporal-spatial spread of

precipitation significantly affect the hydrological characteristics of a given area (Tani and Tayfur, 2021). The intensity of rainfall is a determining factor in the classification of groundwater potential zones, in conjunction with other vital variables. As rainfall levels increase, the likelihood of the presence of groundwater potential zones also increases in a region.

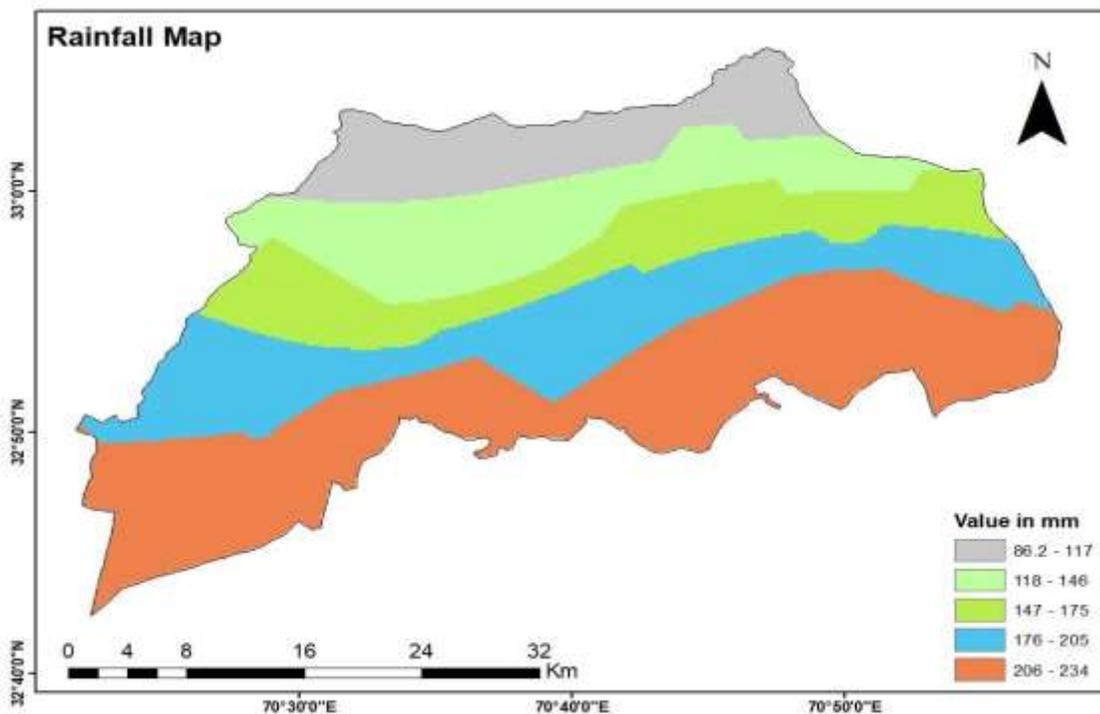


Figure 4.4. Rainfall pattern in study area

The historical ten-year average of rainfall map is categorized into five distinct/zones classes in mm (86.2–117), this zone represents areas with the lowest average annual rainfall. Locations falling within this range typically experience relatively dry conditions, and water availability may be limited. Vegetation and agriculture in these areas might be adapted to lower moisture levels. (118–146), Areas in this zone receive a slightly higher average annual rainfall compared to lowest average annual rainfall. While still considered relatively low, the increased rainfall may contribute to improved water availability and slightly more favorable conditions for

certain crops and ecosystems. (147–175), This zone signifies moderate average annual rainfall. Areas falling within this range experience a moderate level of precipitation, providing better conditions for vegetation growth, agriculture, and sustainable water resources. (176–205), this zone indicates areas with a relatively high average annual rainfall. Locations in this zone are likely to have more abundant water resources, supporting diverse ecosystems, agriculture, and other water-dependent activities and (206–234), This is the zone with the highest average annual rainfall. Areas in this zone receive a substantial amount of rainfall, leading

to lush vegetation, well-developed watercourses, and a generally high level of water availability as demonstrated in Figure 4.4.

#### 4.1.5 Spatial Distribution of Lineament Density in Study Area

Lineaments are representations of linear features such as faults and fractures that possess distinctive linear characteristics. Due to their

capacity to facilitate the movement of groundwater, these lineaments carry significant hydro-geological importance (Magesh et al., 2012). The density of lineaments serves as an indicator of their role in influencing groundwater migration. A higher lineament density corresponds to a greater potential for groundwater availability. Lineaments serve as markers for zones that are more permeable.

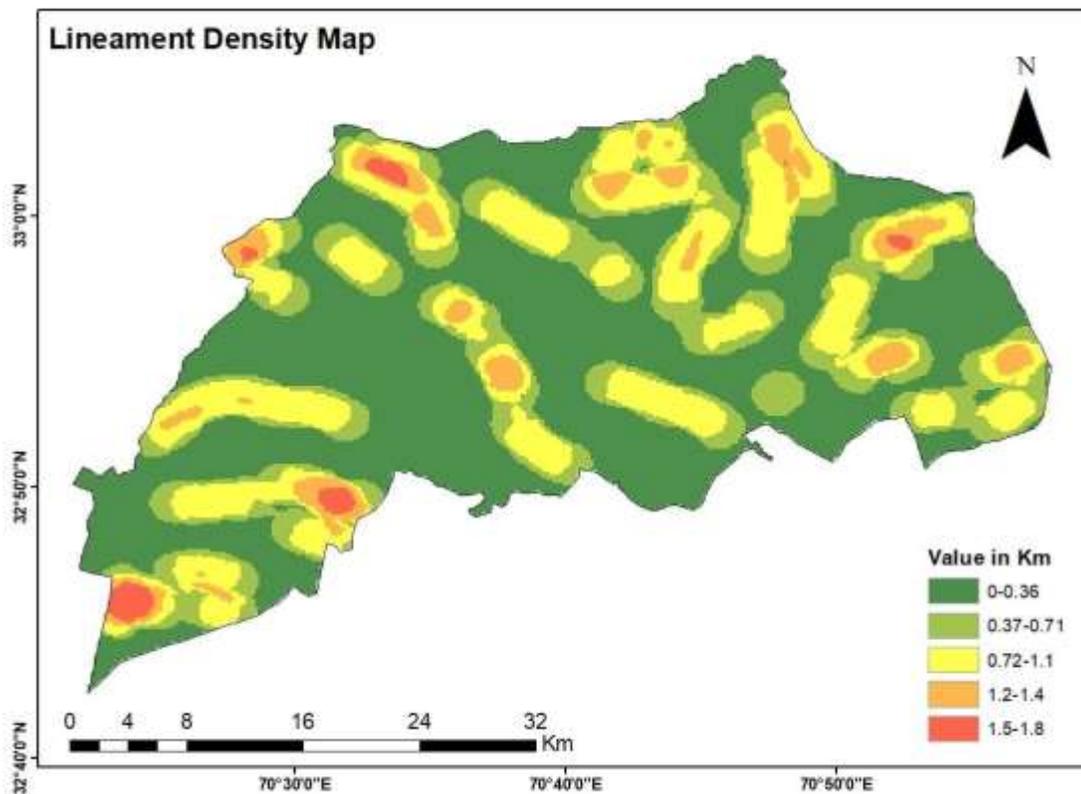


Figure 4.5. Lineament density map

The lineament density map of the study area can be categorized into five classes in “km”: very low (0–0.36), this class represents areas with a minimal concentration of linear features. This range indicates that these areas have very few identified lineaments per square kilometer. Low (0.37–0.71), Areas in this class have a slightly higher lineament density compared to the very low class. Moderate (0.72–1.1), This class signifies a moderate concentration of lineaments. The range from 0.72 to 1.1 km suggests a more

pronounced presence of linear features, indicating geological structures that may influence the local landscape. High (1.2–1.4), Areas falling within this class have a high density of lineaments. This range indicates a significant occurrence of linear features, which may have implications for geological processes and landform development and very high (1.5–1.8), The very high class represents areas with the highest lineament density. The range from 1.5 to 1.8 km suggests an extensive occurrence of linear

features, indicating a complex geological setting with potentially diverse structural elements. Locations with a high lineament density are designated as having elevated groundwater potential, thus receiving a higher weighting in the assessment.

#### 4.1.6 Spatial Distribution of Soil Types

The type of soil plays a key role in determining both the quality and speed of penetration into aquifers (Anbazhagan et al., 2005). Particle size, shape, water absorption capacity, and saturation level collectively influence the effective porosity of the soil (Thapa et al., 2017). The specific soil composition holds importance in the identification of groundwater potential zones. The study area is characterized by three distinct soil types: 1. loamy, clay and saline, 2. mainly noncalcareous loamy and clay, 3. mainly loamy, shallow and gravel as shown in Figure 4.7. After assessing the characteristics and water-holding capacity of each soil type, corresponding weights

were assigned to them. Loamy soil has a balanced composition of sand, silt, and clay, offering good fertility and drainage, shallow soil has a limited depth, which can affect plant root development and water-holding capacity, the presence of gravel indicates larger, coarse particles in the soil. While gravel improves drainage, it may also affect water retention. Clay soil is characterized by fine particles and is often rich in nutrients. However, it tends to have poor drainage and aeration, and it can become compacted easily. Saline soil contains elevated levels of salts. Excessive salinity can negatively impact plant growth by affecting water absorption. It often requires special management practices to improve its suitability for agriculture. Each of these soil compositions has specific implications for agriculture, land use planning, and environmental management. Understanding the characteristics of different soil types is crucial for making informed decisions regarding crop selection, irrigation practices, and sustainable land use.

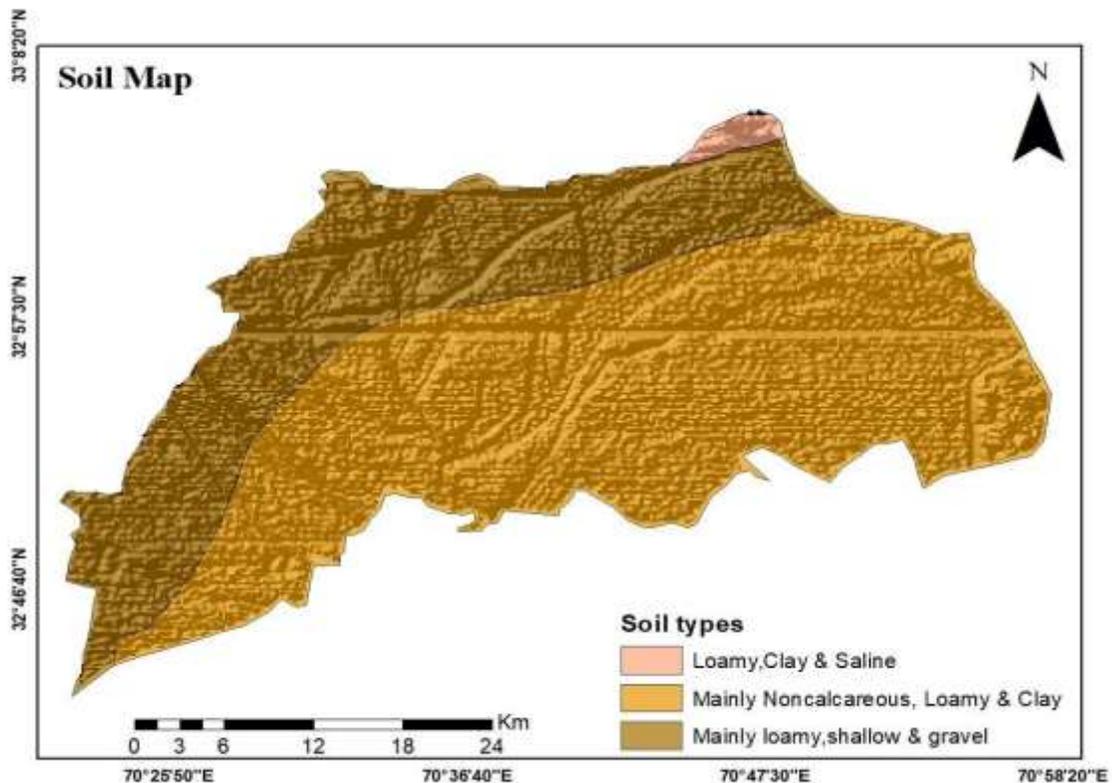


Figure 4.6. Soil map

#### 4.1.7 Landuse/Landcover in Study Area

Remote sensing data, such as satellite imagery, is processed and analyzed to create land use/land cover maps of the research region. This information helps identify different land use types, such as water bodies, urban land, vegetation cover, and barren land. Land use/land cover data provides insights into the distribution of surfaces that impact groundwater recharge and availability. The arrangement of land cover across a region governs the processes of infiltration and surface runoff. Vegetation, including forests, acts to slow down runoff and enhance the penetration of water into the

ground. In contrast, urban areas typically exhibit reduced infiltration rates due to surfaces with lower permeability (Allafta et al., 2021). Therefore, understanding the specific characteristics that encompass the study area is crucial for conducting groundwater potential research. To accomplish this, a supervised classification technique was employed, categorizing the research region into four distinct groups: vegetation, barren ground, urban land, and water bodies, as depicted in Figure 4.7. The classification process was carried out using ArcGIS 10.8.

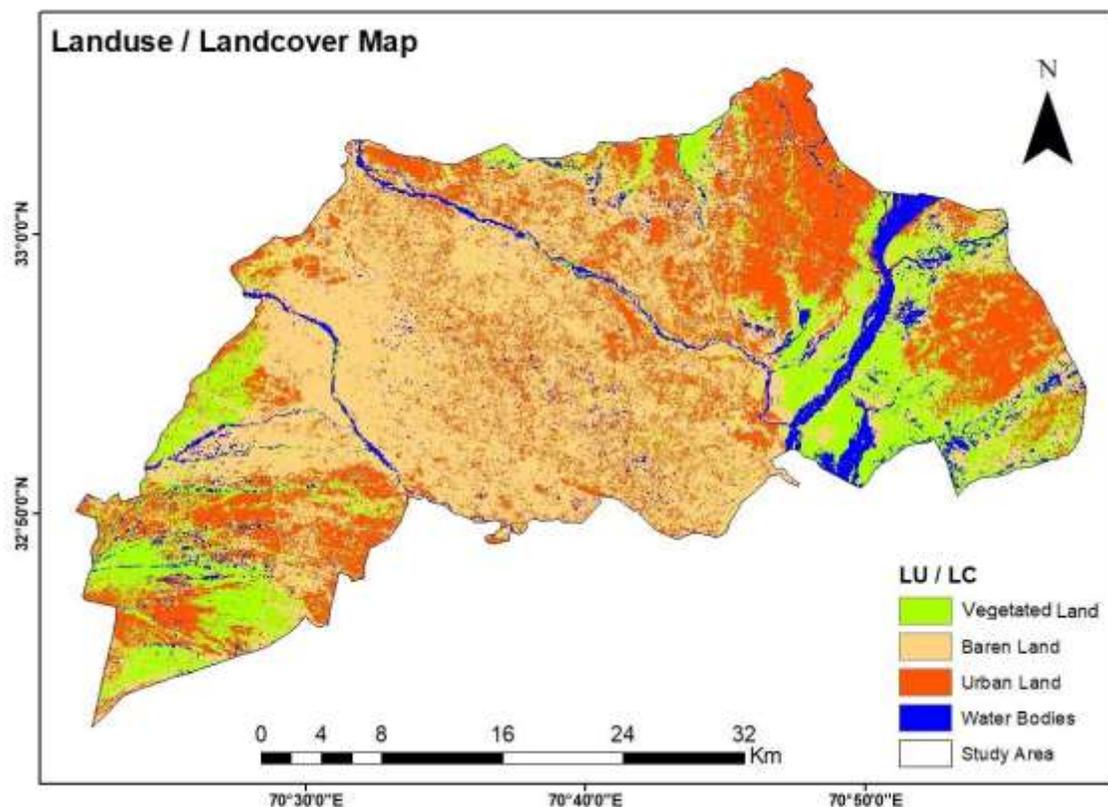


Figure 4.7. Landuse/Landcover in Study Area

#### 4.2 Groundwater influencing factors

The combined use of Geographic Information System (GIS) and Remote Sensing (RS) data facilitated a detailed analysis of various parameters influencing groundwater distribution. Satellite imagery provided valuable information on land cover, while GIS enabled the spatial

integration of diverse datasets, enhancing the overall accuracy of the groundwater delineation. The incorporation of multi-influence techniques involved the simultaneous analysis of geology, soil types, land use, lineament and drainage density, rainfall and slope. This multi-parametric approach allowed for a nuanced understanding

of the factors influencing groundwater occurrence and movement within the study area. To validate the accuracy of satellite data and tube well information, a comprehensive field survey was conducted using Global Positioning System (GPS) technology. Ground-truth points were established during the survey, serving as reference data for comparison with remote sensing data and tube well measurements. The spatial accuracy of the delineated groundwater zones was evaluated by comparing the final result map with the GPS ground-truth points. This assessment provided insights into the reliability of the spatial distribution of groundwater and identified areas where adjustments or fine-tuning of the model might be necessary. The integration of field survey data through GPS ground-truthing significantly enhanced the overall accuracy and reliability of the groundwater delineation results. The validation process ensured that the model outcomes aligned closely with the actual conditions on the ground, providing stakeholders with trustworthy information for decision-making. The delineation of groundwater in district Bannu, Pakistan, using GIS, RS, and multi-influence techniques, benefitted from the inclusion of field survey data through GPS ground-truthing. This approach not only validated the satellite and tubewell data but also contributed to a more accurate and reliable understanding of the groundwater dynamics in the region.

The nature of rocks determines the porosity and permeability of sediments to store and permit groundwater. In the study area, various types of sedimentary rocks have been reported from geological maps including sandstone, clays limestone, and quaternary alluvium deposits. 95 % of the area is covered by alluvium deposits while 5% of the area is covered by other sedimentary rocks. The results show that alluvium deposits near the stream channels have a high capacity of groundwater as compared to other zones. These quaternary sediments comprised of sand, silt, clay, and gravel from

recent river deposits are promising because they offer good permeability and potential for holding water. Assigning importance to these rock types depends on their specific hydrogeological qualities.

LULC encompasses the soil composition, arrangement of residential zones, presence of water bodies, and the extent of vegetation in a specific region. This plays a crucial role in influencing how groundwater is replenished, its occurrence, and overall availability. Employing supervised image classification, a categorization process was carried out to recognize and label different LULC types. A supervised image classification algorithm was used to develop a land use and land cover map and categorized into four distinct LULC classes, which include urban areas, vegetation, water bodies, and barren expanses. Urban land and barren land cover about 70 % of the total area while water bodies and vegetation cover 30 %.

Lineament density map illustrates that closely disseminated lineaments are predominantly found along the Kurram River, likely due to considerable destruction downstream. These regions with higher lineament density are considered favorable for groundwater prospects in the landscape. Examining the map reveals that a major portion of the study area exhibits poor and very poor lineament density. The slope has a direct impact on rainfall penetration and is an important component in evaluating potential groundwater supply. The terrain is made up of the sharpest slopes and escarpments, which are mostly located in the northeast. The type of soil in a location affects how quickly rainfall seeps in and how much water it can hold. As a result, it may be regarded as one of the crucial elements in defining the zones of potential groundwater. The research area is primarily covered by loam soil, which makes up 58.12% of the area coverage, followed by clay, clay loam, and sandy clay loam, which make up 34.34%, 8.09%, and 0.45% of the area coverage, respectively. These soil types exhibit varying degrees of infiltration properties.

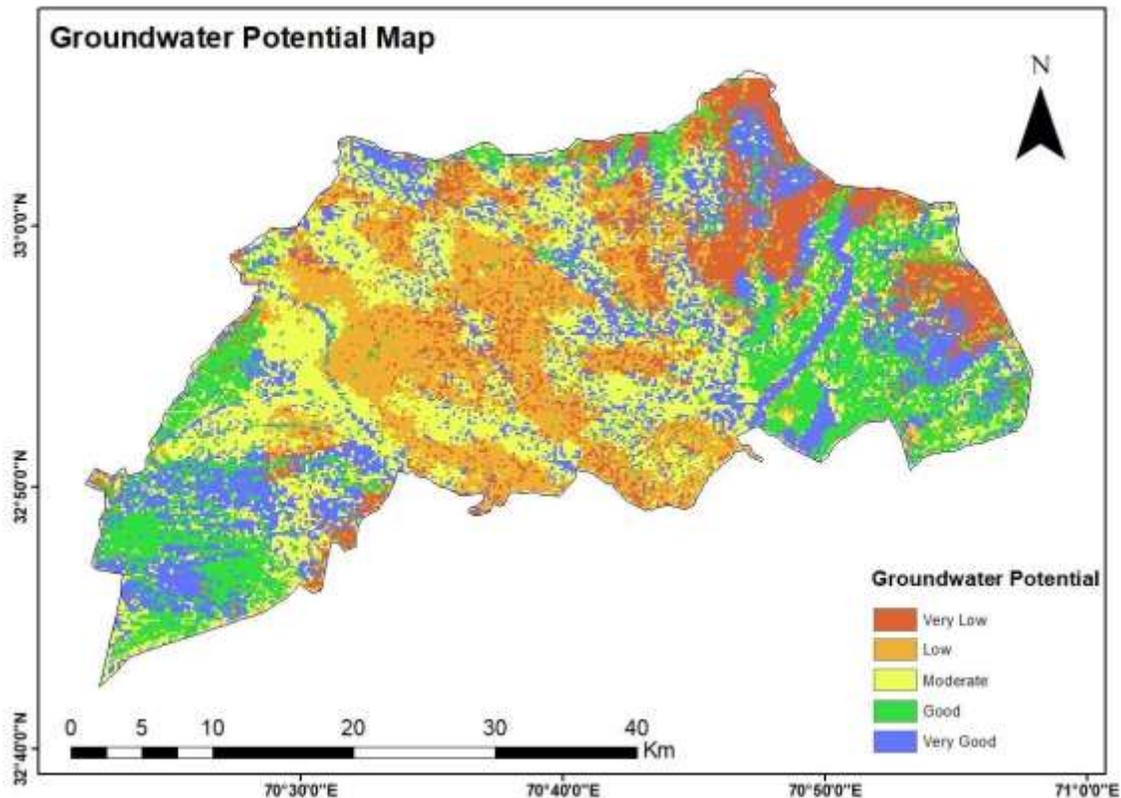


Figure 4.8. GWPZs map of the study area

The resulting groundwater situation map for the research area is represented in Figure 4.8. After employing remote sensing (RS), geographic information system (GIS), and multi-criteria decision analysis (MIF) techniques, the research region displayed groundwater availability across five classifications: incredibly inadequate, low, moderate, substantial, and highly elevated. The results from the GWPZ map indicate that a significant portion of the study area exhibits

limited and exceptionally low groundwater availability. About 1169 km<sup>2</sup> of the study region's total area falls within this range. Out of the entire research region, 153 km<sup>2</sup> (13.08%) are located in the "very low" GWPZ, 254 km<sup>2</sup> (21.72 %) area falls under 'low' GWPZ, 205 km<sup>2</sup> (17.53%) area falls under 'moderate' GWPZ, 251 km<sup>2</sup> (21.47%) area falls under 'high' GWPZ and 306 km<sup>2</sup> (26.17%) of the study area fall under 'very high' as shown in (table 4.1).

Table 4.1. GWPZs covered area

GWPZs	Area (sq. km.)	Percentage%
Very low	153	13.08%
Low	254	21.72%
Moderate	205	17.53%
High	251	21.47%
Very High	306	26.17%

There is a total of five GWPZs categories for the current investigation territory: extremely poor, poor, moderate, good, and very good. The top area of GWPZs in the north-eastern and north-western portions of the research field is dominated by the arrangement of surficial deposits, watercourse deposits, and land use areas having a substantial water absorption capability, as shown in the GWPZs diagram as shown in (Figure 4.8). The conclusion implies that the gradient, LULC, along with topography are important variables affecting the replenishment of groundwater. Furthermore, the arrangement of geomorphic terrain, patterns of precipitation, lineage volume, drain volume, and soil properties all have an impact on the underground water mechanism's capacity for assimilation. Precipitation penetrating the ground is closely linked with how the land is utilized, making it a crucial factor for the development of aquifers. In areas undergoing urbanization and industrialization, such as construction zones, the ability of water to infiltrate is restricted, resulting in a maximum flow rate on the surface. Conversely, alluvium in waterways exhibits a notable ability to absorb water. As the small holes within the dirt allow liquid to be ingested and retained via the roots, they soften the topsoil and sediments, allowing water to percolate more easily into agricultural regions. On the other hand, because of their higher water flow potential and absence of permeable material, built and vacant terrain minimize leakage. Thus, fields with crops and bodies of water are seen to be appropriate for recharging waterways, while populated areas and arid regions are thought to have a restricted capacity to do so. Due to average rainfall, the southern Bannu regions have a significant potential for groundwater recharge. The method created in this research can be applied to identify GWPZs in other regions of the province by appropriately incorporating relevant factors, assigning rankings, and determining weights. Consequently, the model we have created will assist competent authorities in devising effective strategies and protocols for the sustainable management of water resources.

### 4.3 Validation of the Framework

#### 4.3.1 Utilizing information collected from tube wells

The prototype developed to identify GWPZs was put to the test by comparing it to the actual water table depths in the district Bannu, using data collected from several tube wells and boreholes. We collected data on water table levels and depths from a total of 62 tube wells and recorded their coordinates using handheld GPS devices to validate the results of our current study. We categorized the water depths in the tube wells into five groups: very high 18 meters (20-60 feet), high 27 meters (61-90 feet), moderate 48 meters (91-160 feet), deep 73 meters (161-240 feet) and extremely deep 97 meters (241-320 feet). This tube well data was overlaid onto the map of the selected GWPZs, serving as a reference point to assess the accuracy of groundwater depths, as shown in Figure 5.3. Among the tube wells, 28 (26.17%) fell within the extremely high groundwater potential zone, 8 (21.47%) within the good groundwater potential zone, 7 (17.53%) within the moderate groundwater potential zone, 8 (21.72%) within the poor groundwater potential zone and 12 (13.08%) within the very poor groundwater potential zone. A comparison between the tube well data and the GWPZs map generated by GIS revealed that 7 out of the 62 tube wells did not align with the GWPZs map. However, despite these discrepancies, the overall accuracy of the results exceeded 87%. Consequently, the groundwater potential map identified for the research area, which was created using RS, GIS, and MIF methodologies, has been validated.

There are two main parts of the MIF technique, the first part is to find out the projected score of each influencing factor based on the interrelation with other factors and second part is weighted overlay analysis. The determination of the groundwater potential zone has been influenced by seven parameters. The MIF techniques are used to calculate the inter relationships between various variable. Each variable is weighted depending on its direct and indirect strength, and subclasses are assigned based on a literature of relative relationship. Both most important and

small influencing factor is given a weightage of “1” and “5”, respectively. A component with a higher weight value has a bigger influence, while a factor with a lower weight value has a less influencing factor on the delineation of the

groundwater potential zone which is shown in (table 3.1). The formula, of weighted overly for each influencing parameters calculated which is shown in equation (3).

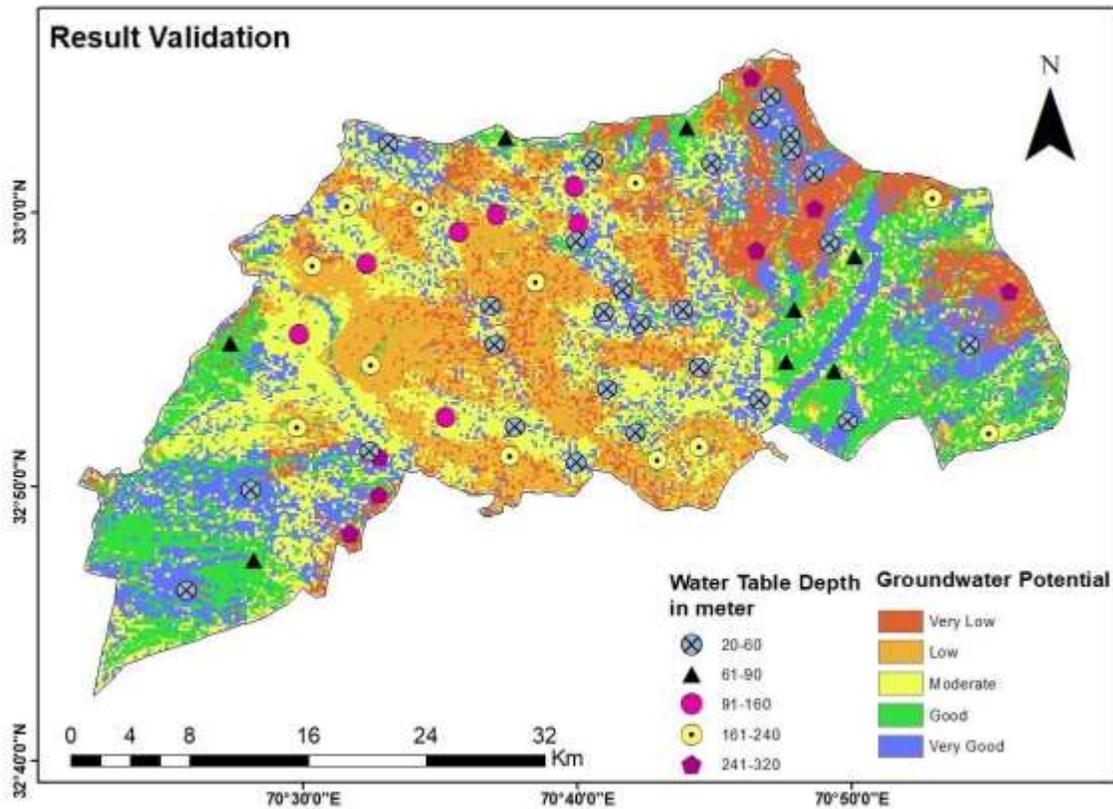


Figure 4.9. GWPZs map of the Bannu, overlaid by tube wells depth

### 5.2 Discussion

The integration of GIS and remote sensing techniques provided a holistic understanding of the hydrogeological system. The combination of these technologies enabled the simultaneous analysis of multiple parameters, resulting in a more comprehensive and accurate delineation of groundwater resources. The study's findings have direct implications for water resource management in district Bannu. Policymakers can utilize the information to formulate strategies for sustainable groundwater extraction, pollution prevention, and land-use planning to safeguard water quality. Identification of vulnerable zones, influenced by anthropogenic activities, highlights

the need for targeted interventions. These may include stricter regulations in high-risk areas and the implementation of best practices in agriculture and urban development to mitigate potential groundwater contamination. Understanding the influence of rainfall patterns on groundwater recharge contributes to climate-resilient water resource management. This knowledge is instrumental in adapting to changing climatic conditions and ensuring the sustainability of groundwater supplies in the face of potential climate variability. Future research could focus on refining the model through real-time monitoring and validation. Additionally, exploring the impact of climate change on

groundwater dynamics and assessing the effectiveness of artificial recharge strategies would enhance the robustness of groundwater management practices. The delineation of groundwater in district Bannu using GIS, RS, and multi-influence techniques provides actionable information for sustainable water resource management. The findings contribute to the ongoing efforts to ensure the availability and quality of groundwater in the region for current and future generations.

### Conclusion

The arid conditions in Bannu result in unpredictable annual rainfall, making groundwater the primary water source for domestic and agricultural needs. The region faces challenges due to population growth, urbanization, low precipitation, and inefficient groundwater use. To address these issues and ensure sustainable water resources, it is crucial to identify groundwater potential zones (GWPZs) using a scientific approach. Researchers globally have utilized various techniques to locate GWPZs, and the current study aims to employ geospatial and multi-influence factor methods for this purpose.

Thematic layers, encompassing geology, slope, soil, lineament and drainage density, LULC and rainfall, were developed using remotely sensed and secondary data processed in a GIS. Weighted overlay analysis with MIF was applied to assign weights and rankings to all influencing thematic layers. The study area was divided into five zones (very high, high, moderate, low, and extremely low) based on GWPZs. Model validation was conducted through two methods, one involving the measurement of water table gravity from current tube wells in the region. The generated map was validated through field visits to collect water table depth data, achieving a total accuracy of over 87%, confirming the reliability of the study. The use of geospatial and MIF methods for identifying groundwater potential zones in Bannu remained valid, time-efficient, and cost-effective. The study's outcomes hold significance for planners, authorities, and regional groundwater management entities such as the Water

Resources Research Center Bannu (WRRCB) and Water and Sanitation Authority (WASA). The results will provide policy formulation and contribute to sustainable groundwater resource management and development in Bannu, Pakistan.

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