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GROUNDWATER RECHARGE POTENTIAL MAPPING IN RAWALPINDI DISTRICT USING ARCGIS

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Abstract

Ground water is an important source of fresh water to Pakistan and especially to the fast-growing city like Rawalpindi. However, its long-term availability is threatened by increasing demand, changing land use and climatic variability. In this work Analytic Hierarchy Process (AHP), Remote Sensing (RS) and Geographic Information System (GIS) has been used for demarcation of Groundwater Potential Zones (GWPZs). The five parameters used for the delineation of the groundwater potential zones are rainfall, geology, slope, drainage density, land use and land cover (LULC). The results showed that the "moderate" groundwater potential class occupies 39.52% of the study area and "very high" and "high" potential zones are 1.87%, and 37.49%, respectively. In contrast, the region has "low" and "very low" at 21.04% and 0.09% respectively.

1- Introduction

Groundwater is a vital natural resource, particularly in regions where surface water is scarce. While 71% of the planet is covered in water, just 2.5% of the Earth's surface has freshwater that is accessible for human use [1]. In Pakistan, this precious resource faces acute pressure from rapid urbanization, shifting land use patterns, and persistent climate uncertainty, which collectively threaten the sustainability of aquifers [2]. Specifically, the Rawalpindi district, situated within the Pothohar Plateau, confronts significant challenges regarding groundwater depletion due to increasing extraction demands and diminishing natural replenishment [3]. In this study, an integrated method of Analytical Hierarchy Process and multi-influence factor analysis is used to systematically search for viable recharge sites that can solve these critical water security challenges.[4], [5]. By integrating diverse thematic layers—including geology, soil characteristics, and Drainage density—this research provides a quantitative framework to categorize the district into distinct potential zones for improved water resource management [6]. This methodological integration leverages satellite-derived datasets and spatial analysis to evaluate the hydrological characteristics of the region, facilitating evidence-based decision-making for sustainable extraction [7]. Most groundwater potential investigation techniques, including geophysical methods, ground-based surveys, and exploratory drilling, are often uneconomical and time-consuming, resulting in large data sets [8]. The Mapping of potential groundwater and recharge zone have significant advantage to understand the groundwater resources availability and its spatial distribution. This will be helpful for planning, developing and managing ground water sources in the area of interest. [9], [10], [11]. By synthesizing these multi-criteria thematic layers, this research establishes a robust spatial model that prioritizes the central regions of the district, which exhibit the most favourable characteristics for sustained groundwater storage [12].

The main objectives of this work are to: The objectives of the study are; 1) preparation of thematic layers affecting the development of groundwater recharge potential zones in Rawalpindi District, 2) identification and mapping of suitable groundwater recharge zones through integration of thematic layers using ArcGIS and 3) demonstration of capability and effectiveness of integration of GIS and Remote Sensing (RS) techniques with Analytic Hierarchy Process (AHP) method in groundwater recharge potential zone mapping.

The mapping of groundwater recharge potential zones in Rawalpindi District will assist decision-makers, policy-makers, water resource planners, and stakeholders including individuals, government institutions, and local communities in improving sustainable groundwater resource planning, development, and management for agricultural irrigation, domestic water supply, and the overall economic development of the area.

2- Materials and Methods

2.1- Study Area

Rawalpindi city is one of Pakistan's largest metropolitan regions and 4th largest city of the country. The Rawalpindi District covers a total area of approximately 5,286 square kilometres, characterized by a complex topographic transition between the Potohar Plateau and the Himalayan foothills. The climate of this region is humid subtropical with hot summers and mild to cool winters [13].

Rawalpindi experienced the highest average growth, reaching 3.36 million in 2023 with an annual growth rate of 8.18 % by the 2017 census in Pakistan, intensifying the demand for sustainable water infrastructure to accommodate this rapid demographic expansion.

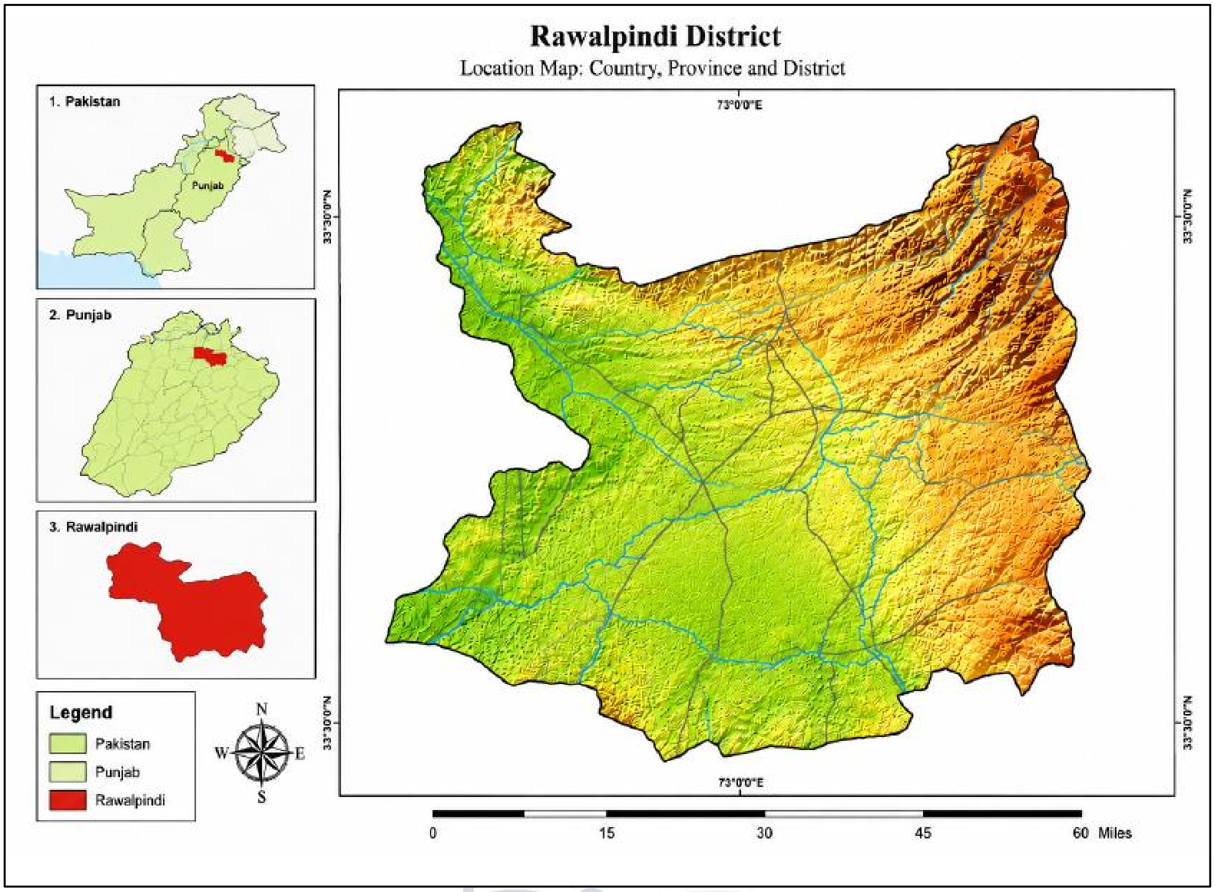


Figure 1 Study Area Location of Rawalpindi District

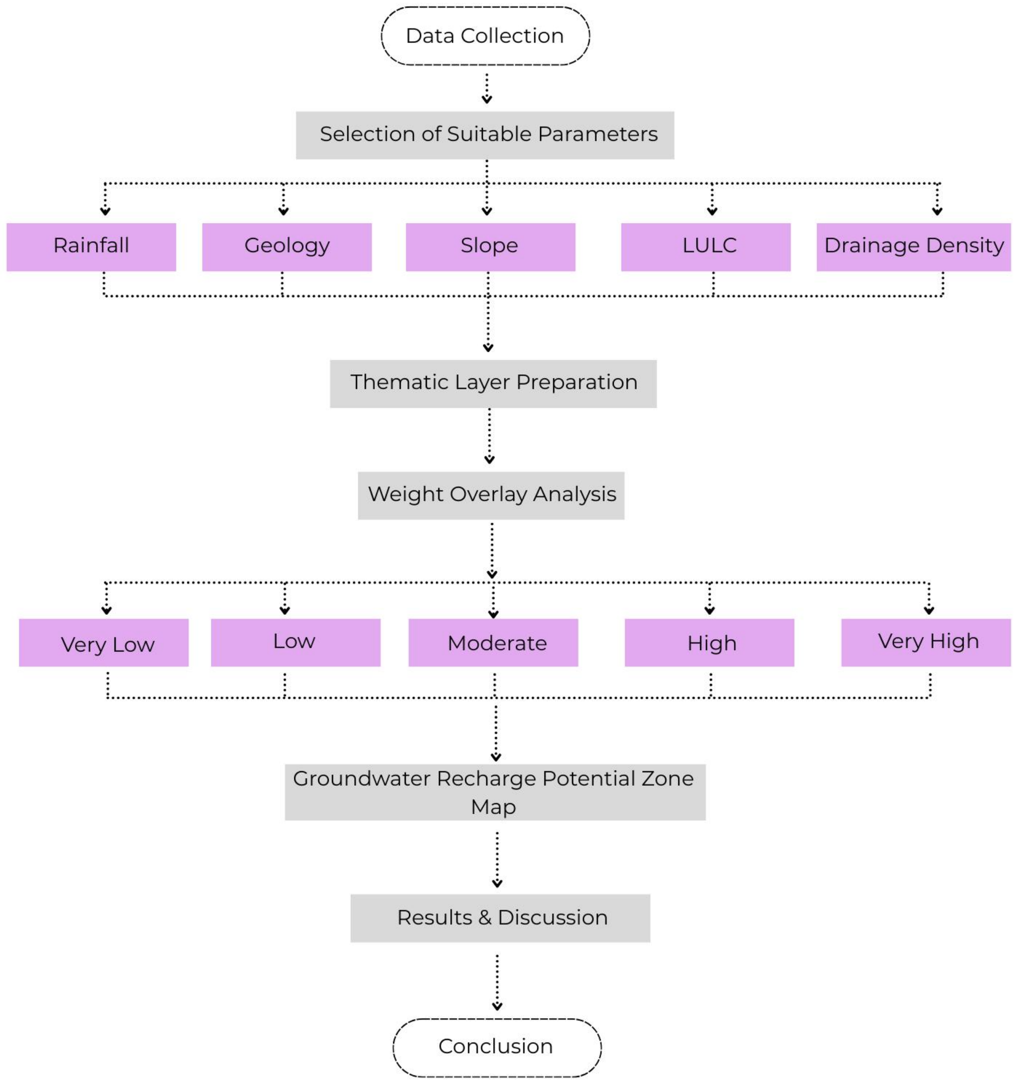
2.2- Data Source

This study evaluated the potential of groundwater and the characteristics of the land surface with the use of various authoritative datasets. Shape file data were collected from DIVA-GIS, accessible through the website (https://diva-gis.org/data.html). Geological data were collected from the Digital Elevation Mode (DEM). Rainfall data were obtained from the Pakistan Meteorological Department (PMD) or Cru Data Rainfall. Drainage density were obtained using a 30-Meter SRTM of Digital Elevation Model (DEM), accessible through the website (https://dwtkns.com/srtm30m/) (accessed on 10 December 2025), Land Use/Land Cover (LULC) data were obtained from Esri Sentinel-2 Land Cover Explorer, accessible through the website(https://livingatlas.arcgis.com/landcoverexplorer/) (accessed on 10 December 2025). Geological data was obtained from the Soil Survey of Pakistan.

3- Methodology:

This research employed a multi-methodology approach including Remote Sensing (RS), Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) for the identification of groundwater recharge potential zones in Rawalpindi District. The whole process comprised of four major steps: (1) data collection and preprocessing, (2) thematic layers preparation, (3) weights assignment by AHP, and (4) weighted overlay analysis in ArcGIS for the final groundwater recharge potential map.

All spatial datasets were projected to a common coordinate reference system (WGS 1984 UTM Zone 43N) and resampled to a common spatial resolution of 30 meters for uniformity across all levels of themes. The final groundwater recharge potential map was classified into five classes: Very High, High, Moderate, Low and Very Low.



Flowchart 1 Methodology Flowchart

Influence Parameter	Classes	Potentiality Rating	Assigned Weight (%)
Rainfall	High	5	30
	Medium	3	
	Low	1	
Geology	High permeability (Alluvium/Loam)	5	25
	Medium (Weathered rock)	3	
	Low (Clay/Hard rock)	1	
Slope (°)	0–5	5	15
	5–15	3	
	>15	1	
LULC	Water Bodies	5	10
	Forest / Trees	4	
	Vegetation	4	

	Crops	3	
	Range Land	3	
	Bare Ground	2	
	Built-up Area	1	
Drainage Density	Low	5	20
	Medium	3	
	High	1	

Table 1: *Assigned Values and Weights of Parameters Influencing Groundwater Recharge Potential*

Thematic Layer Preparation

Five thematic layers were created and utilized as input parameters for the assessment of groundwater recharge potential. Each layer was reclassified on a scale ranging from very low to very high, where very high indicated the most favourable condition for groundwater recharge and very low indicated the least favourable condition.

Rainfall

Precipitation is a key factor for groundwater recharge and is the main source of natural aquifer recharge and the amount of water available for infiltration into subsurface aquifers[14]. Rainfall data of Rawalpindi District was obtained from the Pakistan Meteorological Department (PMD) and CRU gridded climate datasets of duration 2021-2024 . Regions with higher annual precipitation received higher suitability scores for its higher contribution to infiltration and groundwater recharging.

3.1.2- Geology

The geology controls the formation infiltration, permeability and water-holding capacity in the subsurface[15]. The Geological Data for ArcGIS was obtained from the Soil Survey of Pakistan Rawalpindi District. The lithological units were classified in terms of hydraulic conductivity and porosity. Quaternary sediments (Q) are unconsolidated alluvial deposits with Very High recharge potential due to the high permeability and porosity. Neogene and Tertiary sedimentary rocks (N and Ts) have high recharge potential due to moderate to good infiltration in sedimentary sequences. Sedimentary rocks of Paleogene (Pg) have moderate recharge potential because of their intermediate hydraulic conductivity. Triassic metamorphic and sedimentary rocks (Trms) and unsliced Reduced permeability from compaction and partial metamorphism gave Paleozoic rocks (Pz) Low recharge potential. Undivided Precambrian rocks (PC), the oldest and most cemented crystalline basement units, had Very Low recharge potential due to low porosity and near-zero infiltration capability.

3.1.3- Slope (°)

The slope plays an important role in controlling the effect of the infiltration process[16]. Gentle gradients allow for water absorption whereas steep inclines increase runoff, limiting replenishment[17], [18]. As the steepness increased, the percolation rate decreased due to the rapid overland flow[19], [20]. Thus, moderate and level slopes show the existence of strong groundwater recharge potential zones. The slope data in AHP for groundwater potential zoning is applied for the identification of regions prone to significant discharge and favoured for recharge.

3.1.4- Land Use / Land Cover (LULC)

Land use/cover is important factors affecting the groundwater and recharge occurrences. It directly affects the rate of infiltration, soil moisture status, rate of recharge, runoff, and evaporation from the land surface. LULC data for Rawalpindi District were derived from Sentinel-2A (MSI) imagery at 10 m resolution and processed in ArcGIS using standard remote sensing techniques including image stacking, mosaicking, and radiometric enhancement. Seven LULC classes were identified and mapped across the district: Water, Trees, Flooded Vegetation, Crops, Built Area, Bare Ground, and Rangeland.

3.1.5- Drainage Density

This parameter quantifies the total length of streams within a specified area and low drainage density is generally conducive to penetration by increasing the residence time of surface water[21] . In contrast, a higher drainage density entails a higher amount of surface runoff which reduces the time for water to percolate into the subsurface layers, and aquifer recharge[22]. The procedures performed utilized techniques from Spatial Analyst toolkit: Fill, Flow Direction and Flow Accumulation. The drainage density (Dd) is calculated by dividing the sum of the length of all stream channels within the watershed, by the total area of the study as shown in Equation 1.

$$D_d = \frac{\sum_{i=1}^{n} Si}{A} \, (km/km^2) \qquad (1)$$

where, Σni=1 Si is the total length of all stream channels in the watershed (km) and A is the total area of the study watershed (km2).

3.2- AHP Weight Assignment

The relative importance of each thematic layer was calculated with the Analytic Hierarchy Process that involved the construction of a pairwise comparison matrix based on expert opinion. This method allows a systematic quantification of complex variables, by reducing multi-criteria decision making to a series of pairwise assessments[23]. The calculation of the normalized weights of each criterion is based on Saaty's preference scale, so that the final potential map reflects the relative influence of hydrogeological and environmental factors[24]. After this evaluation, the weighted thematic layers were combined using the weighted overlay analysis tool in ArcGIS to create the final groundwater potential map of the study area.

In this study, the AHP approach was used to assess the groundwater potential zoning of the area using normalized weights. The methodology included identification of factors affecting groundwater recharge potential, assigning relative weights (Table 2), construction of a pairwise comparison matrix (Table 3) and calculation of a normalized priority vector (Table 4) to assess the relative importance of the twelve parameters with respect to the objectives of the model (Figure 3).

Score	Importance Intensity	Description
1	Equal Importance	Both factors contribute equally to groundwater recharge
2	Slightly More Important	One factor has a slightly greater influence than the other
3	Moderately Important	One factor has a moderate influence over the other
4	Strongly Important	One factor has a strong influence on groundwater recharge
5	Very Strongly Important	One factor is highly dominant in controlling groundwater recharge

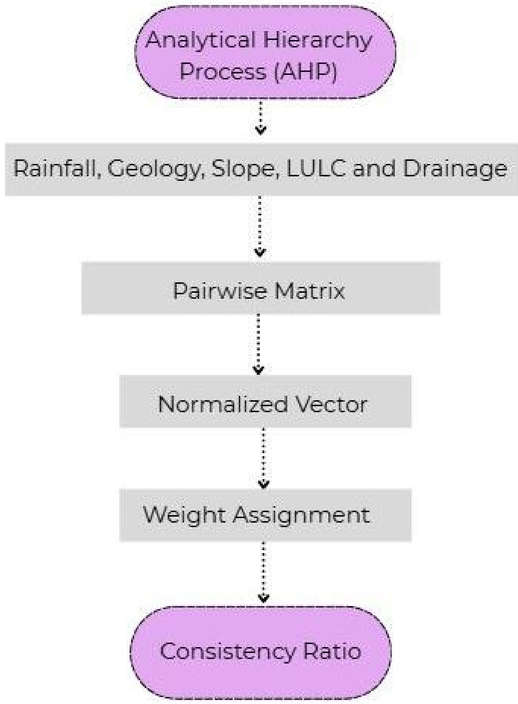
Table 2: *Relative scale Values*

Factors	Rainfall	Geology	Slope	LULC	Drainage
Rainfall	1	3	5	5	3
Geology	1/3	1	3	3	1
Slope	1/5	1/3	1	1	1/3
LULC	1/5	1/3	1	1	1/3
Drainage	1/3	1	3	3	1
Sum	2.066	5.666	13	13	5.666

Table 3: *Pair Wise Comparison Matrix*

Factors	Rainfall	Geology	Slope	LULC	Drainage	Criteria Weights Average
Rainfall	0.484	0.529	0.385	0.385	0.529	0.462
Geology	0.161	0.176	0.231	0.231	0.176	0.195
Slope	0.097	0.059	0.077	0.077	0.059	0.074
LULC	0.097	0.059	0.077	0.077	0.059	0.074
Drainage	0.161	0.176	0.231	0.231	0.176	0.195

Table 4: *Normalized Weight Vector of Groundwater Potential Parameters.*



Flowchart 2 Methodological outline of AHP

3.3- Criteria Weights Assignment

The weight distributions for each theme layer were calculated by applying Analytic Hierarchy Process (AHP) on the basis of established hydrological principles and specific hydrogeological conditions of Rawalpindi District and are presented in Table 1. Rainfall was assigned the highest weight of 30% because it is the most dominant parameter affecting groundwater recharge in the study area where seasonal monsoon precipitation directly controls aquifer recharge. Geology was weighted at 25% to reflect the importance of lithological permeability, with alluvium and loam formations (rating 5) allowing rapid infiltration and clay and hard rock units (rating 1) impeding recharge. The drainage density was given a weight of 20% as the low drainage density areas (rating 5) encourage more infiltration and the high drainage density areas (rating 1) encourage surface runoff and limit recharge. The slope was set at 15% and flat terrain of 0–5° received the highest rating (5) in order to optimize infiltration time. Steep slopes above 15° received the lowest rating (1) because of increased runoff. Land use/land cover was assigned a minimum weight of 10%. Water bodies and woods were rated most favourably with 5 and 4 respectively, while built-up impermeable surfaces were rated with the lowest grade of 1. The total weight of the five characteristics is 100%, which makes the multi-criteria framework for mapping the groundwater recharge potential in Rawalpindi District balanced and internally consistent.

3.4- Consistency Index (CI) And Consistency Ratio (CR)

Consistency Index (CI)

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

$$CI = \frac{5.08 - 5}{5-1}$$

$$CI = \frac{0.08}{4}$$

$$CI = 0.02$$

Consistency Ratio (CR)

$$CR = \frac{CI}{RI}$$

$$CR = \frac{0.02}{1.12}$$

$$CR = 0.018$$

Factor	Rainfall	Geology	Slope	LULC	Drainage Density	SUM	Consistency Index
Rainfall	0.48	0.53	0.38	0.38	0.53	2.30	5.16
Geology	0.16	0.18	0.23	0.23	0.18	0.98	5.07
Slope	0.10	0.06	0.08	0.08	0.06	0.38	5.05
LULC	0.10	0.06	0.08	0.08	0.06	0.38	5.05
Drainage Density	0.16	0.18	0.23	0.23	0.18	0.98	5.07
Average							5.08

Table 5 Priority Vector and Consistency Index (CI)

4- Result

4.1- Spatial Analysis of Parameters

Five thematic parameters namely rainfall, geology, slope, drainage density and land use and land cover (LULC) were developed and integrated using GIS based Analytic Hierarchy Process (AHP) for the demarcation of groundwater recharge potential zones in Rawalpindi District. Each metric was spatially analysed and categorized to represent its relative contribution to recharge potential as follows.

The Rainfall map (Figure 2) was classified into three zones namely Low, Medium and High. In the southern and south-western parts of the area, limited recharge capacity is faced due to less rainfall input. The central zone changes to moderate rainfall and permits moderate seasonal infiltration. Intimate rainfall is limited to the northern highlands adjacent to the Murree Hills, which are favourable for aquifer recharge, but this is slightly reduced by steep gradients leading to rapid surface runoff in these areas.

The geological map (Figure 3) shows a heterogeneous distribution of lithological units with different hydraulic properties. The central valleys and plains are composed of Quaternary alluvial sediments (Q), which have the highest potential for infiltration due to their unconsolidated state and high porosity. The central and southern areas have moderate to good recharge conditions from Neogene and Tertiary sedimentary formations (N, Ts). The southern district is dominated by Paleogene rocks (Pg) with intermediate conductivity and moderate potential, whereas the northern highlands are dominated by Triassic metamorphic rocks (Trms) and Paleozoic rocks (Pz) with poor permeability. The least favourable geological conditions are observed in the extreme northern peripheries where the porosity of the Precambrian crystalline basement rocks (pC) is close to zero.

The slope map (Figure 4) was classified into 3 classes of 0-5°, 5-15° and >15°. The middle and southern parts of the area are gently sloping (0–5°) and this feature allows water to remain on the surface for a longer time and thus help infiltration. Moderate inclines (5–15°) form transitional zones enabling partial repletion. Steep slopes (> 15°) are mainly in the northern highlands and generate rapid overland flow with significant infiltration restriction and the lowest recharge ratings. Similarly, the Drainage Density Map (Figure 5) shows the spatial variation of recharge capacity. The zones of low drainage density in the periphery of the districts are most suitable for recharge as the stream network is sparse and surface water can be accumulated and infiltrated easily. The interior of the district is dominated by moderate drainage density. High drainage density areas have thick channel networks that rapidly transmit precipitation as runoff and inhibit recharge.

The LULC map (Figure 6) derived from Sentinel-2A imagery with a 10 m resolution identified seven land cover classes. Cropland is the largest land class; it is common in the central and southern lowlands. Cropland has a moderate recharge class (3) because it can seasonally infiltrate water. The tree cover (mainly in the northern highlands and in the northeastern peripheries) was rated highly (4) because of its capacity to improve soil permeability and infiltration through root channels. Urbanized areas (in and around Rawalpindi city) were given the lowest grade (1) due to impermeable surfaces that do not allow infiltration and directly contribute to the drainage system through runoff. Rangeland was rated moderate 3, bare terrain was rated 2, and water bodies and flooded vegetation have a positive effect on localized recharging.

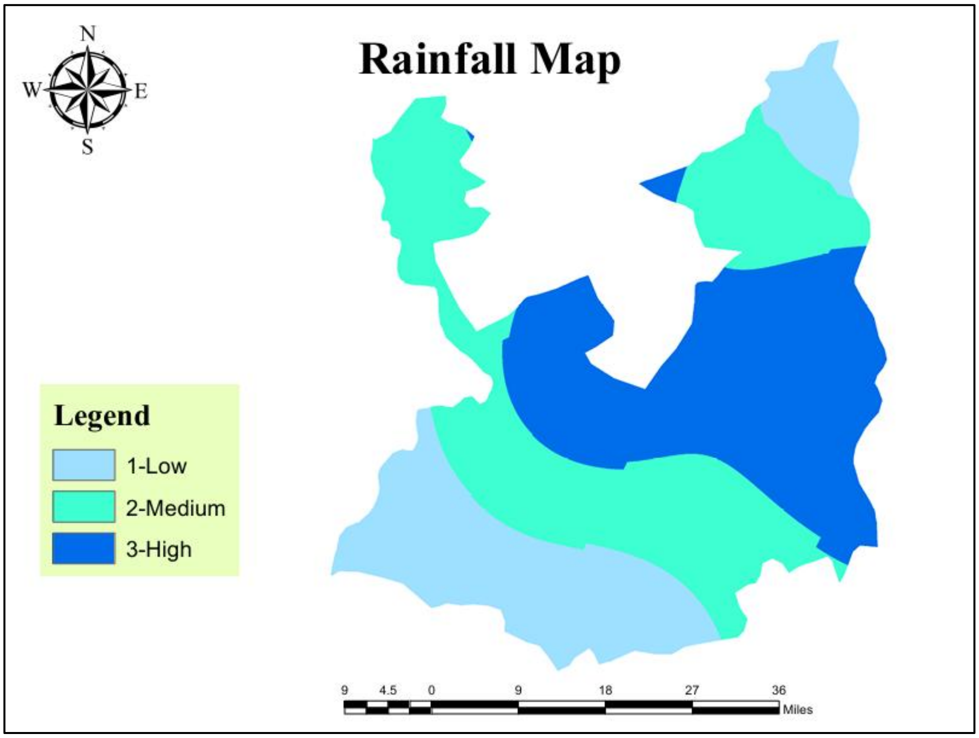


Figure 2 Map of Rainfall (2021-2024)

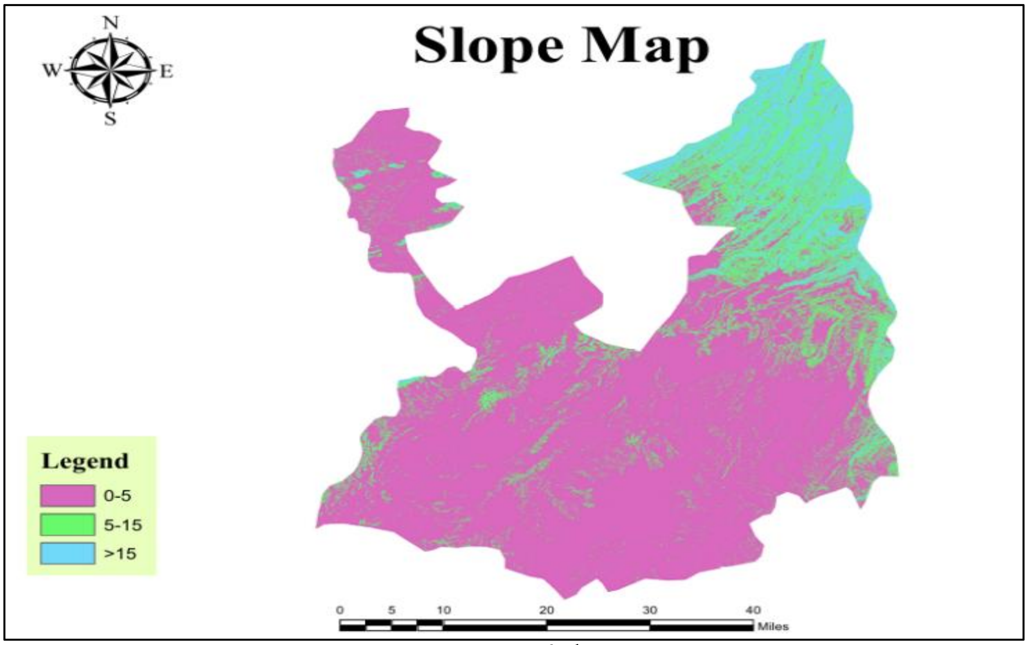


Figure 4 Map of Slope

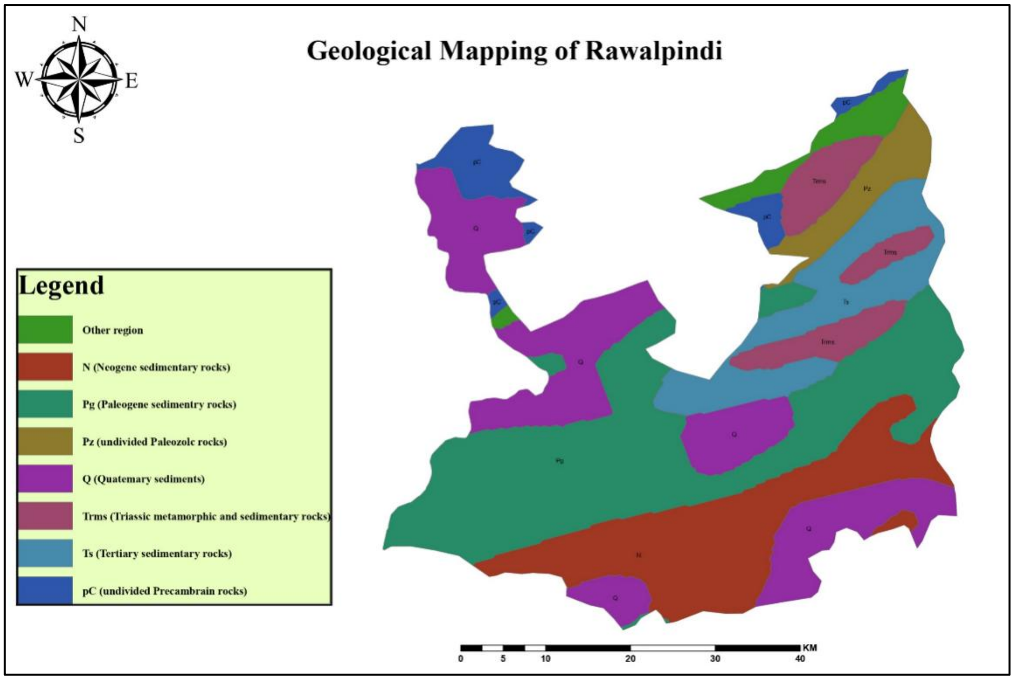


Figure 5 Map of Drainage Density

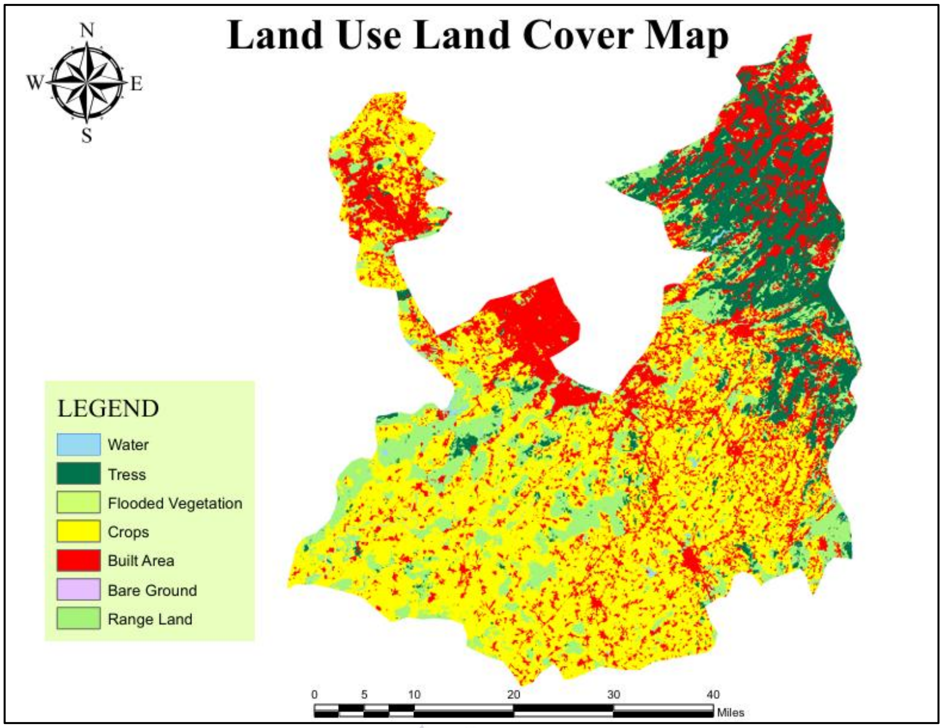


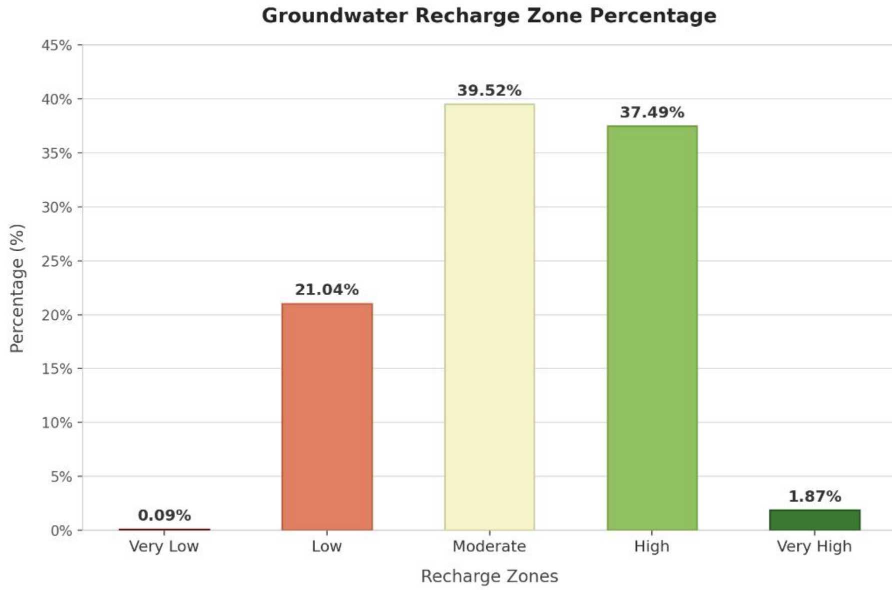
Figure 6 Map of Land Use/Land Cover (LULC)

4.2- Groundwater Recharge Potential Zoning

The spatial distribution of Groundwater Recharge Potential Zones (GRPZs) of Rawal pindi District derived from weight overlay of five thematic characteristics is shown in Figure 7 and the percentage distribution of same is shown in Bar Chart 1. The district was divided into five zones – Very High, High, Moderate, Low and Very L ow – each representing a unique combination of hydrogeological and environmental factors.

The area of Very High recharge potential zone is only 1.87 per cent of the total district area and is characterized by small scattered patches where all the five factors, viz., high rainfall, highly permeable Quaternary alluvial geology, gentle slopes, vegetation or crop cover and low drainage density are well synchronized. The High Potential Zone is much larger, comprising 37.49% of the district, and is located in the central and north-eastern parts where there is moderate to high rainfall falling on permeable sedimentary geology, with gentle topography and agricultural or forestry land cover. These two favourable zones represent about 39.36% of the district area and are the main target for groundwater development and managed aquifer recharge.

The Moderate recharge potential zone is the major spatial classification covering 39.52% of the district. The central Potohar Plateau is characterized by a broad transition zone of moderate rainfall, Paleogene rocks of intermediate permeability, gently sloping topography and a mix of agricultural and urban areas, leading to a variety of uneven recharge conditions. The Low Potential Zone accounts for 21.04% of the total land in the district, mainly in the southern and southwestern parts, where natural infiltration is hindered by scant annual rainfall, impermeable geological formations and extensive areas of developed and barren surfaces. The Very Low zone, which comprises only 0.09% of the district, is limited to steep highland areas at the extreme northern periphery, with an underlying geology of impermeable Precambrian crystalline rocks. The steep gradients, the porosity near to zero, the scanty vegetation and the high drainage density make the conditions basically inadequate for the groundwater recharge. The spatial distribution of GRPZs shows a general trend of good recharge conditions in central and north-eastern parts of the district and a gradual decline of recharge conditions in the southern, south-western and extreme northern parts of the district.



Bar chart 1 Groundwater Recharge Zone %

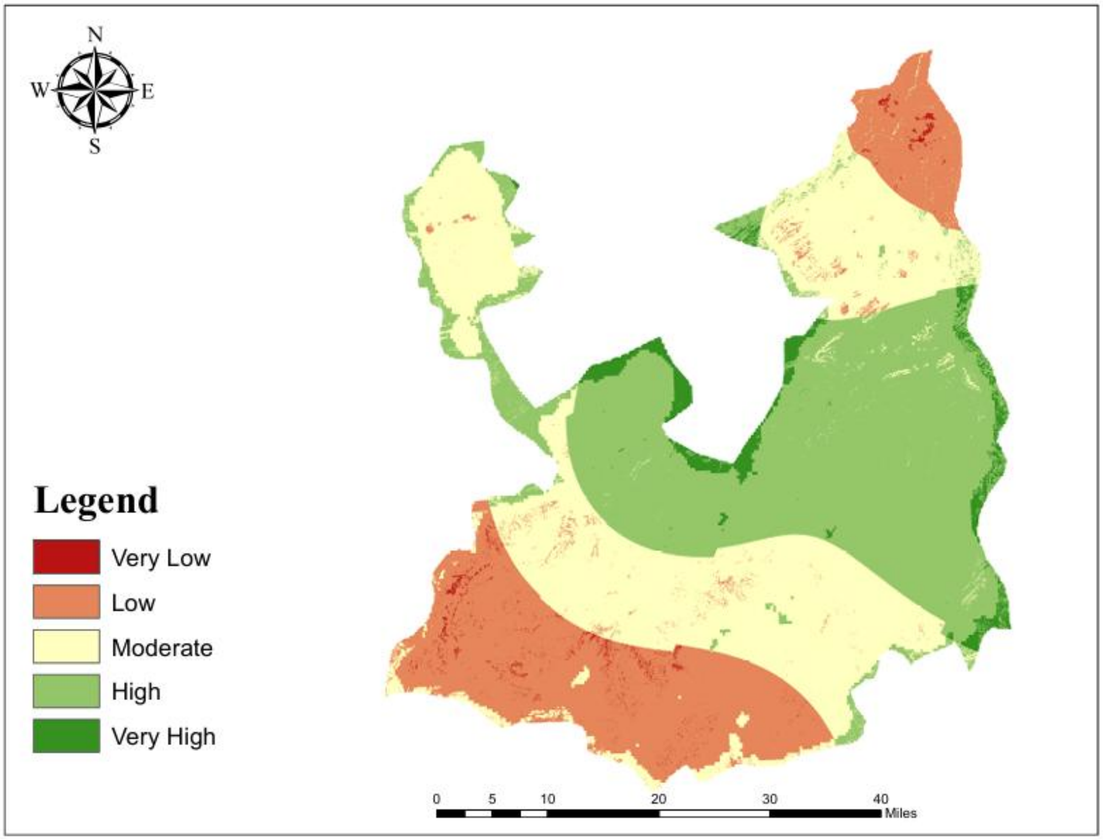


Figure 7 Final Map for Ground Water Potential Zone

5- Conclusion

This research has successfully identified the groundwater recharge potential locations in Rawalpindi District through integration of Remote Sensing, GIS and Analytic Hierarchy Process (AHP). The five thematic characteristics like precipitation, geology, topography, land use/land cover and drainage density were spatially analysed and merged using weighted overlay analysis. The results indicate that the district has around 39.36% very high to high recharge potential with major portion lying in the central and northeastern part having permeable Quaternary alluvial geology, moderate slope and favourable land cover. The moderate zone (39.52 %) is confined to the southern, southwestern and extreme northern peripheries due to impermeable geology, steep topography and urban growth while low and very low zones (21.13 %) are confined to the southern, southwestern and extreme northern peripheries.

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