DELINEATION OF GROUNDWATER POTENTIAL ZONES USING ANALYTICAL HIERARCHY PROCESS AND GIS IN BHILANGANA BLOCK OF TEHRI GARHWAL DISTRICT, UTTARAKHAND, INDIA

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ABSTRACT

Groundwater is one of the most reliable freshwater resources globally, but overexploitation has led to declining water tables, deteriorating water quality, and increased water scarcity. These problems have raised serious questions about how sustainable groundwater management can be achieved. In recent times, geospatial techniques and the Analytical Hierarchy Process (AHP) have been increasingly applied to assess groundwater availability. This research aims to delineate groundwater potential zones in the Bhilangana Block using the above-mentioned methods. Initially, remote sensing data were employed to generate thematic layers, including geomorphology, geology, slope, elevation, drainage density, lineament density, soil, rainfall, and land use/land cover. Subsequently, these layers were integrated using a multi-criteria evaluation approach, and weights were assigned using AHP-based weighted overlay analysis. The resulting groundwater potential zones were classified into five categories: very low and low (over 45 %), moderate (35.05 %), high (16.66 %), and very high (3.81 %). The findings of this research offer insights into groundwater occurrence in the study area, which could be helpful for sustainable groundwater management and long-term planning of water resources.

***Keywords**: AHP (Analytical Hierarchy Process), GIS (Geographic Information System), groundwater potential zones, groundwater sustainability*

INTRODUCTION

Groundwater is one of the most important sources of freshwater for human consumption and agricultural activities worldwide [1]. Groundwater is the water stored in aquifers beneath the surface, accounting for 30 % of total freshwater [2]. Around 2.5 billion people worldwide rely on groundwater for basic daily water needs, including domestic consumption, irrigation, and industrial use [3]. Groundwater is highly unevenly distributed worldwide; this imbalance has been further exacerbated by rapid population growth, resulting in unplanned urbanisation and the drying up of alternative water sources due to climate change. These problems have intensified pressure on existing water resources, leading to severe water scarcity in many parts of the world [4].

Currently, freshwater scarcity has become a significant challenge in many countries, impacting socio-economic development, food security, and ecosystem sustainability [5]. In rural and mountainous regions where alternative water sources are rapidly declining due to climate change and modern techniques for sustainable water resource management are lacking, dependence on groundwater is expected to rise further [6].

Mountain areas exhibit significant diversity in hydrological properties, which affects groundwater flow and transport processes. This distinct hydrological setup in mountain areas requires an accurate delineation of groundwater potential zones. Various studies at the regional, national, and international levels have demonstrated that groundwater potential in mountainous regions can be assessed through geological and hydrological investigations, using drilling data, satellite imagery, and field surveys [7]. These methods have proven reliable, but they are often labour-intensive, time-consuming, and require technical expertise, making them less feasible for large, remote areas.

In recent years, integrating Geographic Information System (GIS) techniques with multi-criteria decision-making (MCDM) approaches has emerged as a cost-effective and efficient method for assessing groundwater potential. Among these approaches, the Analytical Hierarchy Process (AHP) has been widely applied to evaluate and prioritise multiple groundwater-controlling factors, such as geology, slope, drainage density, land use/land cover, soil type, and lineament density. By incorporating satellite imagery and spatial datasets, GIS-AHP-based methods enable systematic analysis and spatial modelling of groundwater potential zones with improved accuracy and reduced field dependency.

Against this backdrop, the present study aims to delineate groundwater potential zones in the Bhilangana Block of Tehri Garhwal District, Uttarakhand, using GIS and AHP-based multi-criteria evaluation techniques. The findings of this research are expected to provide valuable scientific insights to support groundwater resource planning, sustainable utilisation, and policy formulation in this environmentally sensitive Himalayan region.

STUDY AREA

The Bhilangana Block is one of the nine blocks of the Tehri Garhwal District in Uttarakhand. It covers an area of 1,353.91 km^2 (Figure 1). Bhilangana Block is a mountainous block with elevations ranging from about 704 to 6,586 m above mean sea level [8]. This significant variation in altitude plays a crucial role in defining the hydrology, climate, and land-use patterns of the study area.

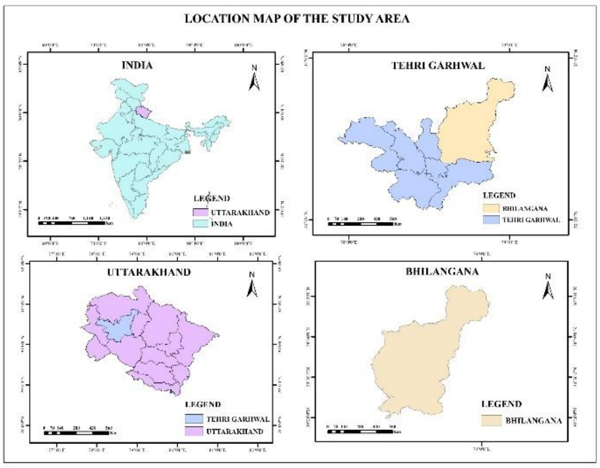

Figure 1. Location map of the study area

Geologically, the Main Central Thrust (MCT) divides this area into the Lesser and Central Himalayan regions [9]. The geology of the study area shows a great diversity of rock types, including gneiss, schist, quartzite, phyllite, epidiorite, and amphibolite, etc. All these rocks have different permeability, porosity, and water-holding capacity, which determine the rate of groundwater infiltration in the study area [10]. Hydrogeologically, in the Central Himalayan zone north of MCT, the aquifers are localised and represent the sole water sources supplying the natural springs in this upper region. Groundwater occurrence in these aquifers is very limited due to the nature of the hard, crystalline rocks, such as gneiss, amphibolite, and quartzite [11]. The lower, Lesser Himalayan part of the study area is characterised by local or discontinuous aquifers, in which groundwater occurs in unconfined, confined, or semi-confined conditions in sedimentary rocks such as limestone and low-grade sedimentary rocks such as phyllite, quartzite, etc. [11].

According to the latest census data, the total population of the Bhilangana Block is approximately 109,756 [12]. The population is predominantly rural, with villages scattered across steep slopes and narrow valleys, often at considerable distances from perennial surface water sources.

Given the region's reliance on groundwater and spring-fed sources, a detailed assessment of groundwater potential is crucial. The scientific assessment of groundwater occurrence in the study area can significantly contribute to the development of future water resource management policies and climate-resilient development strategies.

METHODOLOGY

Different thematic maps, such as slope, drainage density, and elevation, were prepared using Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data with a global resolution of 1 arc-second, acquired from USGS Earth Explorer. Standard GIS methods were used to prepare these datasets, and the Spatial Analyst tool in the ArcGIS software was used to generate the slope, drainage density, and elevation maps. The SRTM DEM data provided the necessary information to compute terrain characteristics, such as slope, while the drainage density and elevation maps were derived from these computed characteristics [13]. The geological and geomorphological datasets used in this study were obtained from the National Remote Sensing Centre Bhuvan geoportal, where thematic layers are generated using remote sensing techniques and are available at a standard scale of 1:50,000. Derived from IRS LISS-III imagery, these datasets provide sufficient spatial detail to delineate lithological and geomorphic controls on groundwater occurrence, making them suitable for groundwater potential zone mapping. Land use land cover (LULC) data were obtained from Environmental Systems Research Institute (ESRI) with a spatial resolution of 10 m, rainfall data from the India Meteorological Department (IMD) as daily gridded data with a spatial resolution of 0.25° × 0.25° [14], and soil data from the National Bureau of Soil Survey and Land Use Planning at a scale of 1:10,000.

Weights for the different thematic layers were assigned using the Analytic Hierarchy Process (AHP), originally proposed by Saaty [15]. The Analytic Hierarchy Process (AHP) is often used in groundwater delineation studies [16]. A pairwise comparison matrix was developed using Saaty's 1 - 9 fundamental scale (Table 1), where 1 indicates equal importance and 9 extreme importance of one factor over another. The pairwise comparison matrix used in the AHP analysis was developed based on hydrogeological relevance, expert judgement, and insights derived from previously published GIS-AHP-based groundwater potential studies. The relative importance assigned to the thematic layers reflects their expected influence on groundwater occurrence and recharge conditions in the Himalayan environment. Parameters such as geomorphology, geology, slope, and elevation were assigned comparatively stronger influence due to their direct control on infiltration, subsurface storage, runoff behaviour, and groundwater movement, whereas parameters such as rainfall, soil, and LULC were given relatively lower weights based on their indirect or locally variable influence.

The matrix structure followed a systematic hierarchical comparison approach commonly adopted in groundwater potential zonation studies using AHP techniques. Similarly, structured pairwise comparison frameworks and expert-guided weighting approaches have also been reported in previous GIS-AHP and Fuzzy-AHP groundwater studies [3, 17 - 19].

Reciprocal relationships within the matrix were maintained in accordance with Saaty's pairwise comparison principles to ensure logical consistency during the weighting process.

After preparing the pairwise comparison matrix, normalised weights were computed (Table 2).

Using this comparison framework, relative weights were computed through the eigenvector (normalisation) method to obtain the final priority weights for each thematic layer (Table 3). The eigenvector indicates the relative influence of the layers on groundwater potential [20]. The maximum weight shows the most influential parameter, and the minimum weight represents the least influential parameter. Various weights were finalised following a field survey, a review of the existing literature, and expert advice in mountain hydrogeology.

Table 1. Pairwise comparison matrix

Factor	Geomorphology	Geology	Slope	Elevation	Lineament density	Drainage density	Soil	Rainfall	LULC
Geomorphology	1	2	4	4	5	5	6	7	8
Geology	1/2	1	2	3	4	4	5	6	7
Slope	1/4	1/2	1	2	3	3	4	5	6
Elevation	1/4	1/3	1/2	1	2	3	4	5	6
Lineament density	1/5	1/4	1/3	1/2	1	2	3	4	5
Drainage density	1/5	1/4	1/3	1/3	1/2	1	2	3	4
Soil	1/6	1/5	1/4	1/4	1/3	1/2	1	2	3
Rainfall	1/7	1/6	1/5	1/5	1/4	1/3	1/2	1	2
LULC	1/8	1/7	1/6	1/6	1/5	1/4	1/3	1/2	1

Table 2. Calculation of normalised weights

Factor	Geomorphology	Geology	Slope	Elevation	Lineament density	Drainage density	Soil	Rainfall	LULC
Geomorphology	0.3546	0.4141	0.4561	0.3497	0.3071	0.2621	0.2323	0.2090	0.1905
Geology	0.1773	0.2070	0.2281	0.2622	0.2457	0.2096	0.214	0.1936	0.1791
Slope	0.0887	0.1035	0.1140	0.1748	0.1843	0.1572	0.1549	0.1493	0.1429
Elevation	0.0887	0.0683	0.0570	0.0874	0.1229	0.1572	0.1549	0.165	0.162
Lineament density	0.0709	0.0518	0.0376	0.0437	0.0614	0.1048	0.1161	0.1194	0.1190
Drainage density	0.0709	0.0518	0.0376	0.0288	0.0307	0.0524	0.0774	0.0896	0.0952
Soil	0.0587	0.0414	0.0285	0.0219	0.0203	0.0262	0.0387	0.0597	0.0714
Rainfall	0.0496	0.0331	0.0228	0.0175	0.0154	0.0173	0.0194	0.0299	0.476
LULC	0.0426	0.0290	0.0182	0.0140	0.0123	0.0131	0.0128	0.0149	0.0238

Table 3. Influence and score values of each thematic layer

Factor	Weight	Influence	Domain of effect	Score
			River	5
			Valley glacier	2
			Piedmont slope	2
Geomorphology	0.308	31	Glacial valley	2
			Younger alluvial plain	4
			Active floodplain	2
			Medial moraine	2
			Highly dissected structural hills and valleys	2
			Quartzite, Schist/Phyllite and Amphibolite	5
			Epidiorite	2
			Unmapped	1
			Biotite gneiss, Quartzite and Schist	4
			Amphibolite	4
Geology	0.207	21	Porphyroblastic garnet gneiss	1
			Gneiss, Kyanite schist, Quartzite, Calc-silicate	4
			Porphyritic non-foliated granite	2
			Basic metavolcanics	4
			Quartzite band	3
			Quartzite, Schist, Carbonaceous phyllite and Limestone	5
			Very low	1
			Low	2
Lineament density	0.080	8	Moderate	3
			High	4
			Very high	5
			0 - 15	5
			15 - 25	4
Slope	0.141	14	25 – 34	3
			34 – 44	2
			44 – 77	1
			Very low	5
			Low	4
Drainage density	0.059	6	Moderate	3
			High	2
			Very high	1
			704 - 1,788	5
			1,788 - 2,550	4
Elevation	0.114	11	2,550 - 3,473	3
			3,473 - 4,558	2
			4,558 – 6,589	1
			Crops	4
			Bare ground	1
LULC	0.020	2	Water	5
			Snow/Ice	1
			Trees	3
			Built-up area	3
			Rangeland	3
			Water	5
			1,316 - 1,419	1
			1,419 - 1,487	2
Rainfall	0.028	3	1,487 - 1,537	3
			1,537 - 1,588	4
			1,588 - 1,677	5
			Rock outcrops	1
Soil	0.040	4	Glaciers	2
			Loamy	3
			Sandy	4

After deriving the weights, the consistency of the judgements was assessed using the Consistency Index (CI) and Consistency Ratio (CR). The principal eigenvalue (λ_{max}) was used to compute the CI, and the CR was calculated as CI divided by the Random Consistency Index (RI) [17]. To verify the consistency of the assigned weights, the Consistency Index (CI) was first calculated, followed by the calculation of the Consistency Ratio (CR).

$$CI = (\lambda_{max} - n) / (n - 1) \qquad (1)$$

l - principal eigenvalue
n - number of factors
CI = (9.42 – 9) / (9 – 1) = 0.0525

$$CR = CI/RI \qquad (2)$$

CI - Consistency Index
RI - Random Consistency Index
CR = 0.0525 / 1.45 = 0.036

To maintain consistency in the weight assessment, the CR value must not exceed 0.1 [17]. The consistency ratio for the study was 0.036, which is < 0.10. This confirms the consistency of the assigned weights.

With GIS, all layers were integrated. The groundwater potential index (GWPI) was calculated using the formula below:

$$GWPI = \sum_{j=1}^{m} \sum_{i=1}^{n} (w_j \cdot X_i) \qquad (3)$$

m - total number of thematic layers (themes),
n - total number of classes (features) within a theme,
w_j - normalised weight of the *j*-th thematic layer
X_i - assigned score of the *i*-th feature within the thematic layer.

RESULTS AND DISCUSSION

In this study, geomorphology, geology, slope, elevation, lineament density, drainage density, soil, rainfall, and LULC layers were selected as key factors because they influence infiltration, runoff generation, subsurface flow paths, and ultimately groundwater potential in mountainous areas [21]. For example, in the Shivalik-type terrain and the Himalayan foothills, studies have shown that geomorphology and geology strongly influence the location and yield of springs, while lineament density and drainage patterns govern the distribution of fractures and recharge zones [21]. Layers such as the depth of the water table, fracture orientation, and aquifer thickness were not included in this study due to limited data availability and their relative insignificance compared to the above-mentioned indicators. In shallow, topography-driven mountain systems, which are mostly spring-fed, groundwater potential is more directly controlled by surface-hydrogeomorphic features such as slope, lineaments, and geology, rather than a stable, regionally mapped water table depth. This requires a dense monitoring network and multiple seasonal measurements to be meaningfully incorporated. Fracture orientation undoubtedly serves as an important indicator in structurally dominated aquifers. In the selected study area, which is a largely young, deformed and heterogeneous rock mass terrain, fracture-orientation data are scarce due to scattered outcrops. In these areas, lineament density serves as a proxy for the presence and intensity of the fracture networks [22]. Aquifer thickness is an important parameter for 3D modelling in a well-defined sediment-filled basin, but in this study area, groundwater occurs in shallow, highly variable, and often discontinuous bodies controlled by slope position and bedrock fractures rather than in thick, laterally continuous aquifers [11]. Comprehensive thickness data would require extensive geophysical profiling or borehole sections, which were not available at the required scale and resolution for a thematic layer-based GIS analysis.

Geomorphology

The study of landforms in a region can help track groundwater presence in that area [23]. Geomorphology in the area includes younger alluvial plains, valley glaciers, snow cover, rivers, piedmont alluvial plains, piedmont slopes, medial moraines, glacial valleys, and other features. Based on their groundwater potential, these classes were given different weights. Alluvial plains and rivers have been considered the most valuable for groundwater recharge, while dissected hills and valleys have been given the lowest value due to their tendency toward surface runoff production (Figure 2) [24].

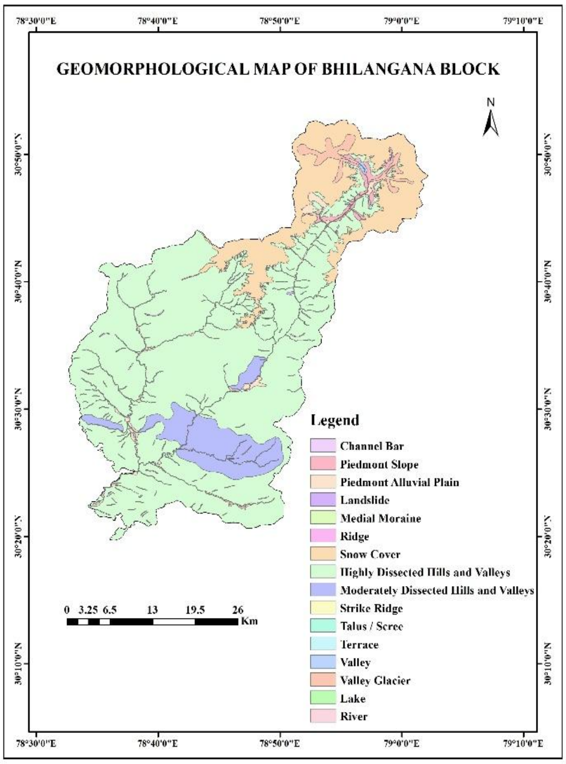

Figure 2. Geomorphology

Geology

The geology of an area governs the infiltration rate of surface water into the subsurface [25]. It directly controls the infiltration, movement, and accumulation of water [26]. Bhilangana Block has diverse rock types, including basic metavolcanics, phyllite, biotite gneiss, quartzite, and slate. Due to their high porosity, dolomite, limestone, quartzite, silt, and clay were assigned high weights. It is important to note that, in the study area, clay-dominated units are interpreted as storage-type locally saturated thin layers that trap perched water tables and enhance local water retention, thereby contributing to the overall groundwater storage potential at the local scale. Although these clay materials commonly act as hydrological barriers, restricting horizontal and vertical groundwater flow, their role in sustaining near-surface saturation justifies their high weight. Nonfoliated granite, mica, and schist were assigned low scores due to their lower permeability to surface water. These rocks act as a hydraulic boundary, limiting further downward baseflow movement (Figure 3) [27].

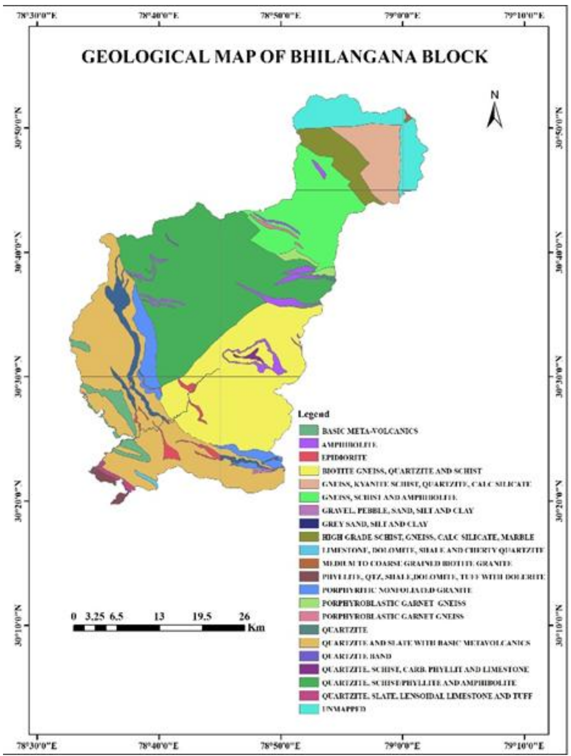

Figure 3. Geology

Slope

Changes in elevation over a specific area determine the slope [28]. Steep slopes result in higher surface runoff, while moderate or flat slopes produce lower surface runoff, thereby increasing groundwater recharge. The slope in the study area was divided into five groups: flat (0° - 15°), gentle (15° - 25°), mild (25° -

34°), steep (34° - 44°), and very steep (> 45°). In the study, flat and mild slopes were given higher weights due to their significance in groundwater recharge, while steep slopes were assigned lower weights (Figure 4).

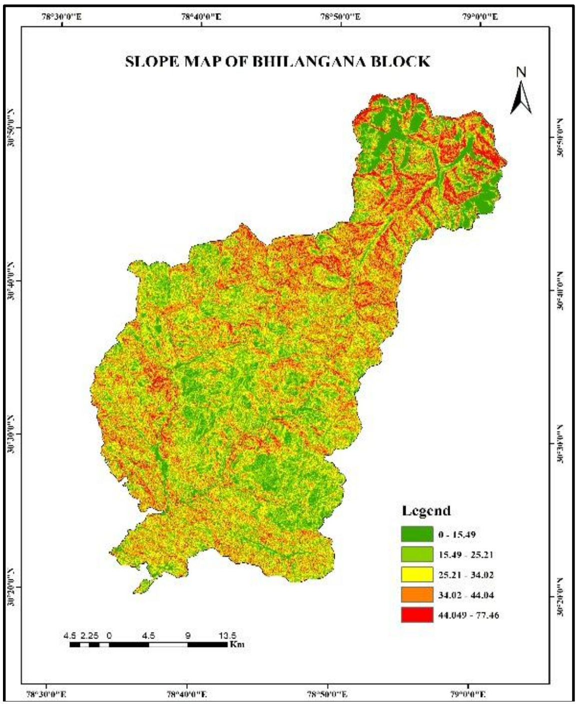

Figure 4. Slope

Elevation

Elevation, coupled with slope, influences the direction of surface water runoff. Changes in elevation also affect weather patterns, resulting in variations in precipitation. In the study area, elevation was classified into five categories: very low (704 - 1,788 m), low (1,788 - 2,550 m), moderate (2,550 - 3,473 m), high (3,473 - 4,558 m), and very high (4,558 - 6,589 m). Low elevation was prioritised more than high elevation (Figure 5).

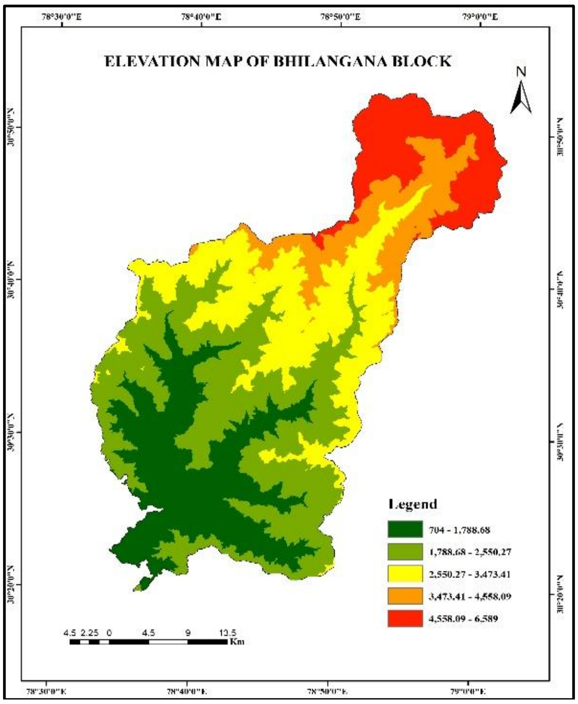

Figure 5. Elevation

Lineament density

Straight or curved features visible at the Earth's surface are called lineaments. They are often regarded as "lines of the landscape" [29]. Lineaments are primarily zones of fractures in bedrock that allow water to infiltrate easily, resulting in significant groundwater recharge. In the Himalayas, these fractures create preferential flow paths, which are critical for "Mountain Block Recharge," where water travels through deep bedrock to emerge in lower-elevation springs or valley aquifers [30]. However, high lineament density does not always translate into significant groundwater recharge, as many fractures in hard rock terrains are either clogged, shallow, or disconnected [31]. In the Bhilangana Block, high (0.42 - 0.57) and very high (0.57 - 0.90) lineament density does not have a significant impact on groundwater recharge. For better groundwater infiltration, lineaments must co-occur with favourable conditions such as permeable soils, gentle slopes, and vegetation [32]. Medium lineament density (0.28 - 0.42) accounts for 31.73 % of the total area, while low (0.11 - 0.28) and very low (0 - 0.11) jointly account for 50.35 % of the total area (Figure 6).

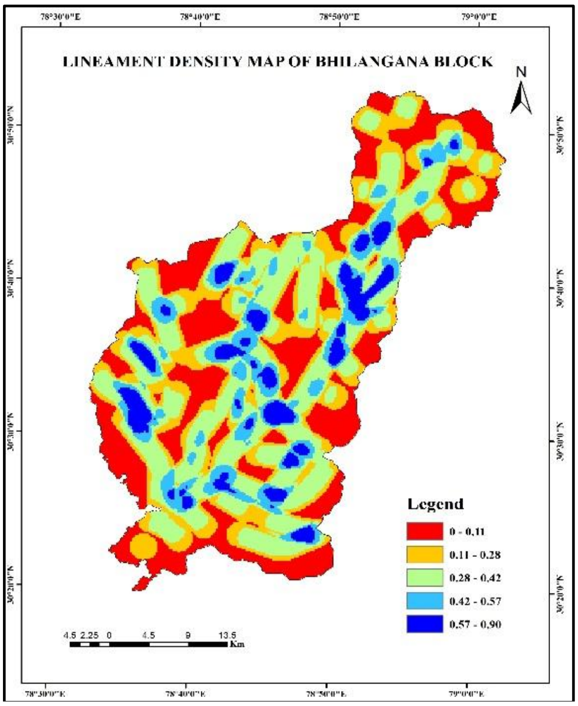

Figure 6. Lineament density

Drainage density

Drainage density is a measure of the total length of all stream orders in a unit area; it is an indicator of the infiltration and permeability characteristics of a drainage basin [33]. A higher drainage density indicates less groundwater infiltration, while a lower drainage density indicates less surface runoff, resulting in greater groundwater recharge [34]. Bhilangana Block is home to various perennial streams, including the Bhilangana, Balganga, and Dharam Ganga rivers. The drainage density was classified into five categories, representing the following percentages of the total area: very low (21.37 %), low (25.53 %), moderate (24.50 %), high (20.91 %), and very high (7.67 %) (Figure 7).

Soil

The type, texture, and composition of the soil affect groundwater recharge [35]. Geology, relief, and geomorphology all influence the characteristics and distribution of soil, whether directly or indirectly. The groundwater potential of soil is determined by its infiltration and runoff characteristics. The primary soils of the Bhilangana Block are sandy and loamy. Sandy soil was assigned a higher weight than loamy soil due to its superior permeability (Figure 8).

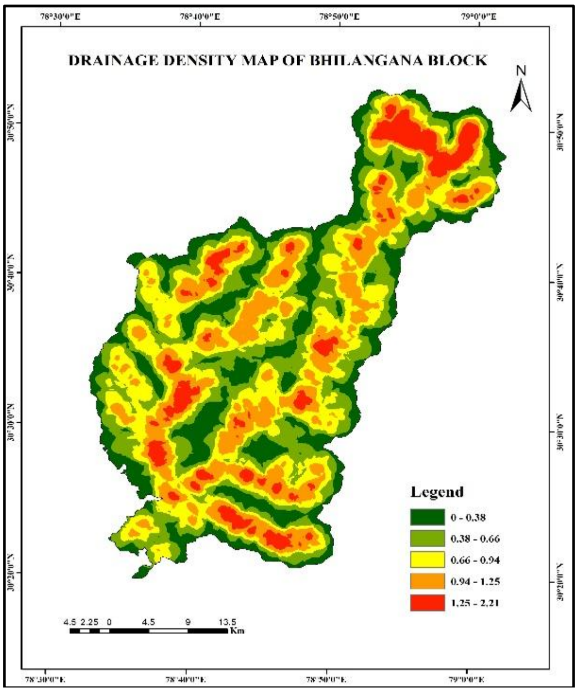

Figure 7. Drainage density

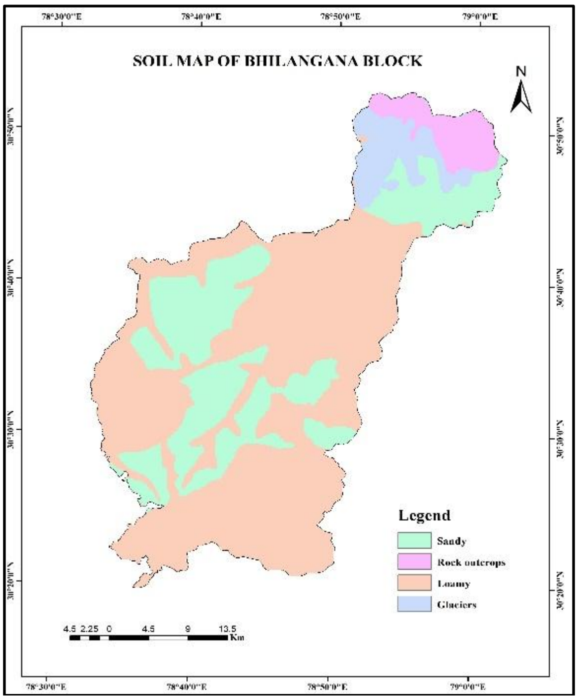

Figure 8. Soil

Rainfall

Rainfall directly controls the hydrological cycle, and groundwater recharge primarily depends on it [36]. In the Bhilangana Block, annual rainfall ranges from 1,316 to 1,677 mm. The amount and timing of rainfall determine the rate of infiltration. In recent years, climate change has affected rainfall patterns, with greater amounts of precipitation occurring over shorter periods. Such rainfall patterns, increase the likelihood of surface runoff, resulting in less water infiltration into the ground. Higher rainfall levels were assigned greater weights, whereas lower rainfall received lower weights (Figure 9).

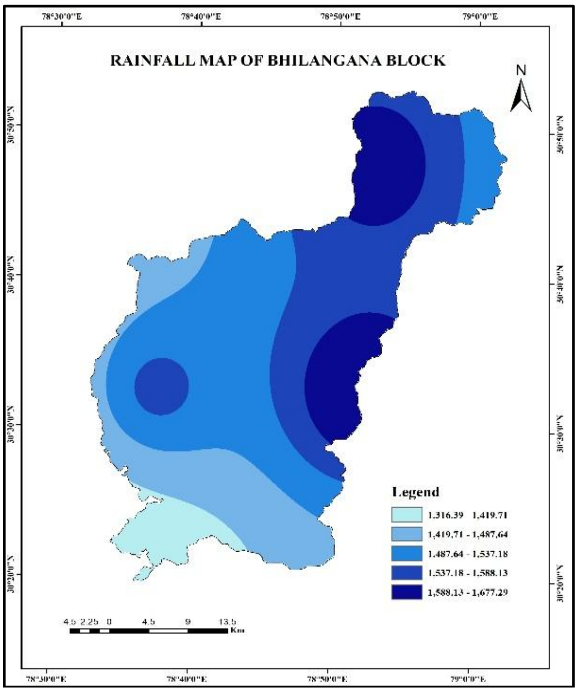

Figure 9. Rainfall

LULC

LULC has a direct impact on water availability, which could be used as an indicator of potential groundwater zones [37]. It controls how water infiltrates, percolates, and permeates in a specific location. The study area includes LULC classes such as water, crops, trees, rangeland, built-up areas, and bare ground. A weight of 4 was assigned to cropland, as water can easily infiltrate through the loose soil to the subsurface. Rangeland received a score of 3, while bare ground was assigned a score of 1 because of its limited ability to absorb water (Figure 10).

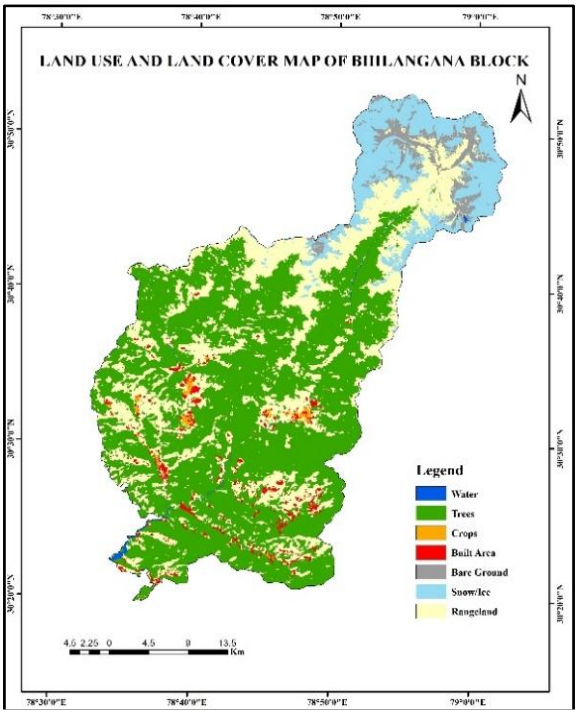

Figure 10. Land use and land cover (LULC)

DELINEATION OF GROUNDWATER POTENTIAL ZONES

Based on the weighted evaluation of multiple groundwater-controlling criteria, a series of thematic maps was generated and subsequently integrated to delineate zones of groundwater potential. Each thematic layer was assigned a relative weight and rank according to its influence on groundwater occurrence, storage, and movement. These interpreted layers were then systematically overlaid using weighted overlay analysis within a GIS environment to assess the cumulative effect of the influencing factors on groundwater potential [38].

The overlay analysis classified the study area into five groundwater potential zones: very high, high, moderate, low, and very low. The "very high" groundwater potential zone (51.70 km²) covers approximately 3.81 % of the total study area. Areas categorised under the "high" groundwater potential zone (225.66 km²) account for about 16.66 % of the region. The "moderate" groundwater potential zone (474.64 km²) constitutes approximately 35.05 % of the total area. In contrast, over 45 % of the Bhilangana Block falls within the "low" and "very low" groundwater potential zones (507.67 km² and 104.50 km², respectively). The spatial distribution of groundwater potential zones is shown in Figure 11, providing critical insights for groundwater exploration, resource planning, and sustainable water management in the study area.

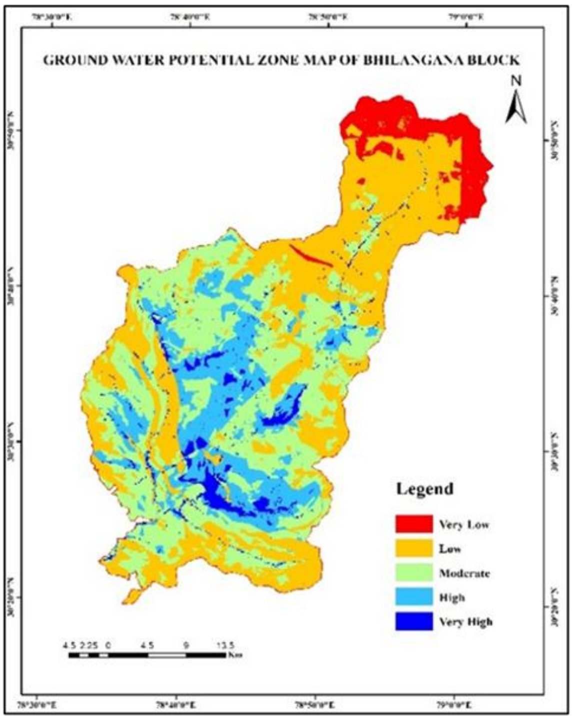

Figure 11. Map of groundwater potential zones of the Bhilangana Block

CONCLUSION

The findings of this study indicated that integrating modern techniques, such as the Analytic Hierarchy Process (AHP), with the existing Geographical Information System (GIS) and Remote Sensing (RS) data could provide a highly effective approach for delineating groundwater potential zones. This combined methodology not only enhances the precision of spatial analysis but also significantly reduces the time, effort, and financial resources required for large-scale groundwater assessment. By systematically evaluating multiple thematic layers, the GIS–RS–AHP framework provides a comprehensive understanding of the factors influencing groundwater occurrence. Overall, the study demonstrates that this integrated technique is a valuable decision-support tool for sustainable water resources management. The delineated potential zones can be useful for identifying and prioritising suitable sites for groundwater recharge structures, thereby supporting long-term planning and management of water resources in the study area [39].

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