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Identification of Groundwater Potential Zones using a Data-driven Model and GIS Technique: A Case of Papumpare District, Arunachal Pradesh, India

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ABSTRACT: The increasing demand for clean water due to urbanisation and population growth has intensified the need to explore alternative water resources, particularly groundwater. This study focuses on Papumpare district in Arunachal Pradesh, India, where groundwater resources are limited because of the predominantly hilly terrain. Utilising Geographic Information System (GIS) technologies and Multi-Criteria Decision-Making Analysis (MCDMA), specifically the Analytical Hierarchy Process (AHP), this research aims to delineate potential groundwater zones within the district. Eight thematic layers, including geology, slope, geomorphology, land use and cover, lineament density, rainfall, and drainage density, were integrated to assess groundwater potential. This study focuses on the overlay weighted analysis and delineation of groundwater potential zonation (GWPZ) based on the influence of key environmental parameters within a specified region. The findings provide a detailed map of high- and low-potential groundwater areas and support sustainable water resource management efforts. This research advances understanding of groundwater resources and offers valuable insights for sustainable management in the study area.

1. INTRODUCTION

Groundwater is a vital element of the natural water cycle and for human growth[1]. Its accessibility makes it a vital resource for domestic, agricultural, and socio-economic needs. Urbanisation, deforestation, and industrialisation significantly affect both groundwater quantity and quality[2-4]. Public water supply systems are not efficient enough to fulfil the current water demand due to growth in domestic and commercial activities[5, 6]. Groundwater is the next resource people are looking for to fill this gap. Therefore, groundwater demand is increasing exponentially worldwide due to population growth, urbanisation, and uneven rainfall patterns[7-9]. Global estimates show groundwater extraction at 36% for domestic use, 42% for agriculture, and 27% for industrial applications[10, 11]. Identifying, mapping, and protecting potential groundwater zones are necessary in the current scenario because natural and anthropogenic activities can be damaging. Both the activities directly and indirectly influence the accessibility, availability and quality of groundwater sources over time and across space[12-15].

To determine groundwater potential zones, researchers use parameters such as geomorphology, slope, lineament density (LD), geology, soil types, drainage density (DD), land use and land cover (LULC), and rainfall[16, 17]. Investigators have found that integrating Geographic Information System (GIS), remote sensing (RS), and MCDMA (Multi-Criteria Decision-Making Analysis) effectively delineates Groundwater Potential Zones (GWPZ)[18, 19]. A frequently employed technique in MCDMA is the Analytical Hierarchy Process (AHP), recognised for its straightforwardness, effectiveness, and dependability[20, 21]. In the AHP methodology, weights for various thematic layers and their subclasses were assigned based on local field expertise and groundwater-related assessments[18, 21, 22]. This approach significantly improves oversight and is cost-effective, enabling rapid decision-making for environmental and water resources conservation. A recent study on the Papumpare groundwater spring potential zone used AHP and Fuzzy-AHP to determine its spatial distribution and found them to be very effective tools. They found that groundwater springs should be preserved by using sustainable long-term management practices[23]. A similar past study used AHP, remote sensing and GIS methods with different parameters to identify the groundwater potential area of Papumpare district. They found that very high groundwater potential zones are limited and need government intervention for sustainable use in future[24].

Himalayan regions are very sensitive to climate change and global warming[25]. Arunachal Pradesh has many regions that fall within the Himalayan region where groundwater potential is very low. Therefore, by default, Arunachal Pradesh is also not rich in groundwater resources, as the region is mostly hilly terrain. The western foothills districts are significantly more deficient in groundwater resources than the eastern foothills districts. Papumpare district, which has Arunachal Pradesh's capital, Itanagar, is also a twin capital city[26]. As a smart city, the demand for clean water will increase in the future[27]. The district is largely hilly and mountainous, with only a few plain areas. Many small streams and rivers have dried up in recent decades due to urbanisation and industrial development in the district, increasing pressure on groundwater resources. This study uses AHP alongside GIS technologies to delineate and map potential groundwater areas. The resulting map will support sustainable groundwater management by predicting high- and low-potential zones.

The investigation clearly identifies regions with high and low groundwater potential. This helps future generations use it sustainably.

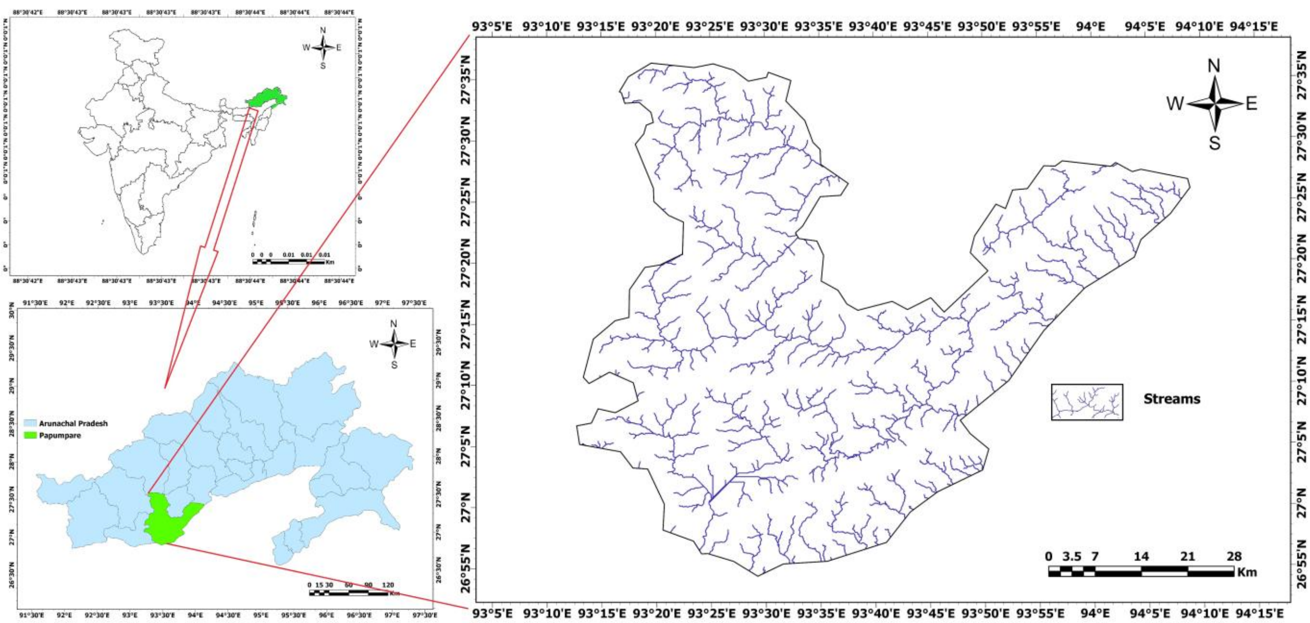

Figure 1. Location map of the study area.

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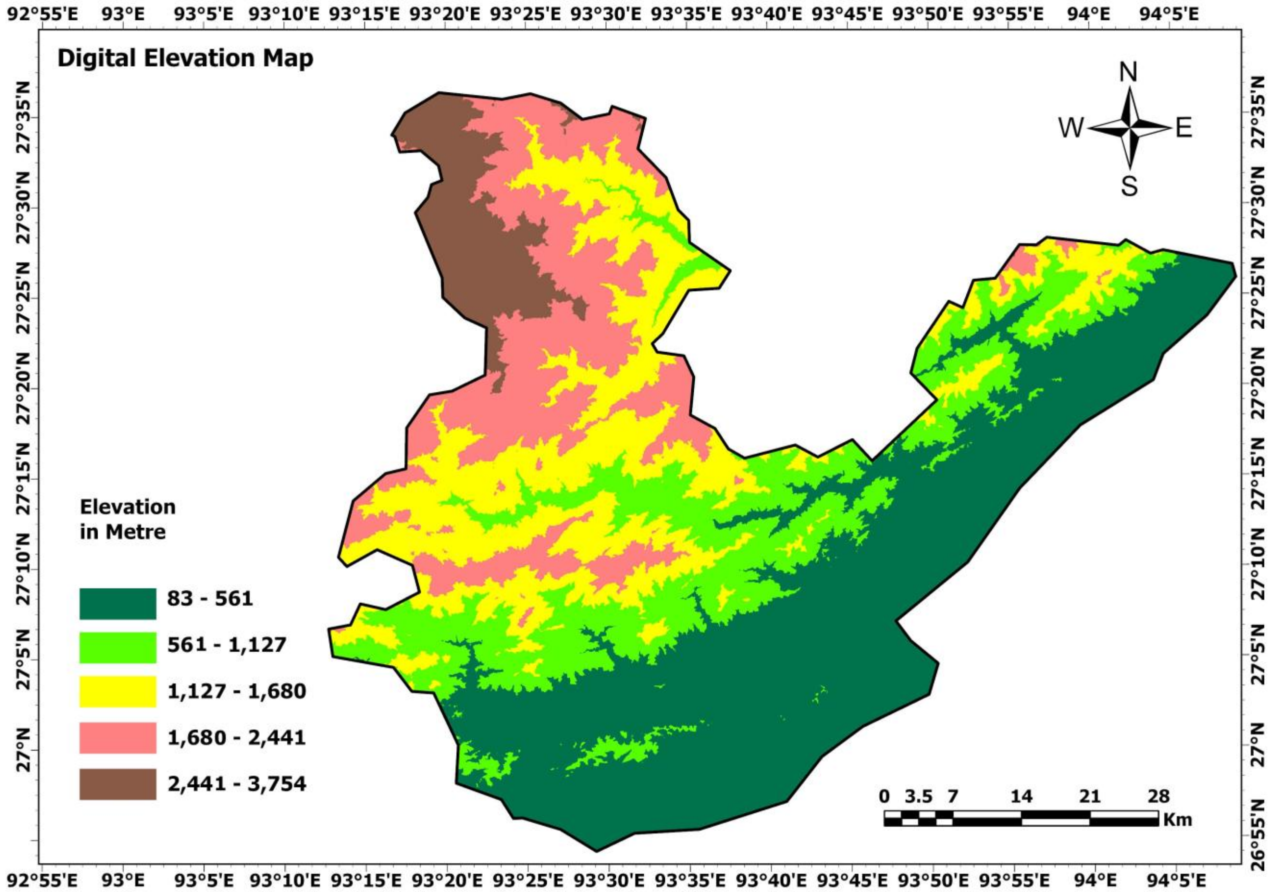

Figure 2. Digital elevation map of the study area.

2. MATERIALS AND METHODS

2.1. Study area

The Papumpare district is located in Arunachal Pradesh, India (**Figure 1**). The district's headquarters is Yupia, while its most prominent urban centre is Itanagar, which has been developed as a Smart City under the Government of India's mission[27]. It is situated between 26°56'17" N and 27°38'32" N and 93°12'43" E and 94°12'36" E (Fig. 1)[24]. The district also contains the state capital and covers approximately 3529.9 square kilometres. According to the 2011 Census, Papum Pare district has a population of approximately 176,573 people[28]. The Nyshi tribe is the district's main tribe, while other tribes also settle in the capital region. The area falls under heavy rainfall zones due to the southwestern monsoon. Most of the area is hilly, with varying elevations and forest cover, and hill slopes limit human settlement and activity (**Figure 2**). Several significant rivers and streams traverse the district, including the Dikrong River, Pare River, and Poma River, which contribute to its rich biodiversity and scenic landscapes. These water bodies play a vital role in the region's ecology, agriculture, and daily life.

2.2. Data and methodology

Primary and secondary data have been gathered from multiple sources (**Table 1**). Eight thematic layers, including geology, slope, geomorphology, land use and land cover (LULC), lineament density, rainfall, and drainage density, were selected for the overlay. Geological information was obtained from the Geological Survey of India website (https:// bhukosh.gsi.gov.in/). The Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), with a spatial resolution of 30 meters, was acquired from the US Geological Survey website (https://earthexplorer.usgs.gov/) to analyse the region's drainage density, slope, and lineament density map. The Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) from the US Geological Survey website (https://earthexplorer.usgs.gov/) for the purpose of land use/land cover (LULC) in the region. Rainfall data were obtained from the CRU TS v. 4.04 website (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.06/). We obtained soil information from the FAO/UNESCO Soil Map.

Table 1. Data sources of thematic layers.

Map layer	Data source
Rainfall	https://www.imdpu. gov. in/
Land use/land cover	https://earthexplorer.usgs.gov/
DEM	https://earthexplorer.usgs.gov/
Lineament density	Extracted from DEM
Slope	Extracted from DEM
Geology	https:// bhukosh.gsi.gov.in/
Geomorphology	https:// bhukosh.gsi.gov.in/
Soil	FAO/UNESCO Soil Map Page
Drainage density	Extracted from DEM

2.3. Allocation of weights and normalisation by AHP process

The Analytic Hierarchy Process (AHP), developed by Saaty, is frequently used for complex decision-making, particularly in scenarios requiring paired evaluations[29]. The AHP framework comprises four phases: weight assignment, pairwise comparison matrix formulation, weight normalisation, and consistency verification. In AHP, elements are organised in a matrix, with weight values assigned between 1 and 9 based on pairwise comparisons. **Table 2** describes the conventional scale for establishing pairwise comparisons. Expert evaluations were utilised to produce pairwise comparisons among the parameters.

Table 2. The relative importance of the parameters.

Intensity of importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

The AHP identifies the probability of uncertainty arising in evaluations using the primary Eigenvalue and the consistency index[29, 30]. The Consistency Index (CI) is obtained using the following equation.

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

Here, λ_{max} is the significant eigenvalue of the pairwise comparison matrix, and n is the number of classes.
To evaluate consistency and scale, the Consistency Ratio (CR), which quantifies the consistency of the pairwise comparison matrix, is computed[29].

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad (2)$$

Here, RI is the Ratio Index or Random Index.
Table 3 shows the calculated weight values for the consistency checks using Equation (2). The AHP approach was employed to normalise the weights assigned to each thematic layer and its respective classes, with ranks shown in **Table 4. Table 5** shows the Pairwise comparison matrix of thematic layers of various parameters.

Table 3. RI used for consistency checks.

N	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41

Table 4. Pairwise comparison matrix of thematic layers.

Parameters	**Rainfall**	**Geology**	**Geomorphology**	**Slope**	**Drainage Density**	**Lineament Density**	**LULC**	**Soil**
Rainfall	1							
Geology	1/3	1						
Geomorphology	1/3	1	1					
Slope	1/3	1	1	1				
Drainage Density	1/3	1	1	1	1			
Lineament Density	1/5	1/3	1/3	1	1/3	1		
LULC	1/5	1/3	1/3	1/5	1/5	1/3	1	
Soil	1/7	1/5	1/7	1/7	1/7	/3	1	1

Table 5. Normalised weighted values of the parameters and their percentage by AHP.

Parameters	**Weight**	**Weight Percentage**
Rainfall	0.321	32.1
Geology	0.132	13.2
Geomorphology	0.138	13.8
Slope	0.130	13.0
Drainage Density	0.147	14.7
Lineament Density	0.705	7.1
LULC	0.353	3.5
Soil	0.260	2.6

2.4. Overlay weighted analysis

Based on the influence of parameters and their corresponding classes in regulating potential groundwater recharge over a region, the distinct layers are reclassified, and ranks are allocated with consideration of their influence.

Each parameter and its corresponding classes are assigned ranks and weights according to their relative potential impact (**Table 6**). This is based on a review of contemporary literature, the geographical context, and other regional characteristics (LULC, precipitation, soil composition, geology, geomorphology, etc.). The equation below is a raster computation of these parameters integrated in ArcGIS Pro, producing the resulting map.

$$GWPZ = (GW \times GW_i) + (GM_w \times GM_{wi}) + (SL_w \times SL_{wi}) + (S_w \times S_{wi}) + (LD_w \times LD_{Wi}) + (LU_w \times LU_{Wi}) + (DD_w \times DD_{wi}) + (RF_w \times RF_{wi}) \quad (3)$$

Here, GWPZ means groundwater potential zone. G, GM, SL, S, LD, LU, DD, and RF represent geology, geomorphology, slope, soil, lineament density, Land use, drainage density, and rainfall, respectively. w represents the weight of a layer, and wi represents the weight of a particular layer class.

Table 6. Ratings assigned to sub-classes of each parameter.

Parameters	Sub-classes	Rank
Rainfall	1374-1488 mm	1
	1488-1563 mm	2
	1563-1628 mm	3
	1628-1684 mm	4
	1684-1776 mm	5
Geology	Mesozoic & Palaeozoic intrusive & metamorphic rocks	1
	Neogene sedimentary rocks	5
	Undivided Paleozoic rocks	2
	Quaternary sediments	3
Geomorphology	Strori - Highly Dissected Hills and Valleys	4
	Fluori Piedmont Alluvial Plain	5
	Fluori Active Floodplain	5
	Channel Bar	1
	Channel Island	1
	Scarp	1
	Terrace	1
	Landslide	1
	DenOri - Piedmont Slope	2
	WatBod River	3
	Valley	1
	Point Bar	1
	Hill	1
	Fluori Older Flood plain	3
	Strori - Low Dissected Hills and Valleys	4
	Palaeochannel	1
	Braid Bar	1
	Fluori - Younger Alluvial plain	3
	Strori Moderately Dissected Hills and Valleys	2
	Intermontane Valley	1

	Cuesta	1
	Ridge	1
	WatBod Others	2
	Inselberg	1
	WatBod Pond	2
	Fluori Older Alluvial Plain	3
	Alluvial Fan	3
	WatBod Lake	2
Slope	Flat (0º-9º)	5
	Gentle (9º-19º)	4
	Moderate (19º-28º)	3
	Steep (28º-38º)	2
	Very Steep (38º-84º)	1
Drainage density	Very Low (0.001-0.244) km/km^2	5
	Low (0.245-0.414) km/km^2	4
	Moderate (0.415-0.585) km/km^2	3
	High (0.586-0.785) km/km^2	2
	Very High (0.786-1.243) km/km^2	1
Lineament density	Very Low (0.001-0.066) km/km^2	5
	Low (0.067-0.179) km/km^2	4
	Moderate (0.18-0.286) km/km^2	3
	High (0.287-0.398) km/km^2	2
	Very High (0.399-0.65) km/km^2	1
LULC	Water Bodies	5
	Forest Cover	4
	Agriculture land	3
	Human Settlement	2
	Barren Land	1
Soil	Orthic Acrisols	1
	Eutric Cambisols	4
	Dystric Nitosols	4

3. RESULT AND DISCUSSIONS

3.1. Rainfall

Precipitation has a crucial role in the hydrological cycle and greatly influences groundwater availability and replenishment[31, 32]. It is the principal source of groundwater and drives its variations. The magnitude of precipitation directly influences groundwater replenishment, with higher intensity resulting in enhanced recharge and vice versa. Precipitation of the study area varies from 1488 to 1684 mm, as shown in **Figure 3**. The entire watershed experienced the highest annual precipitation.

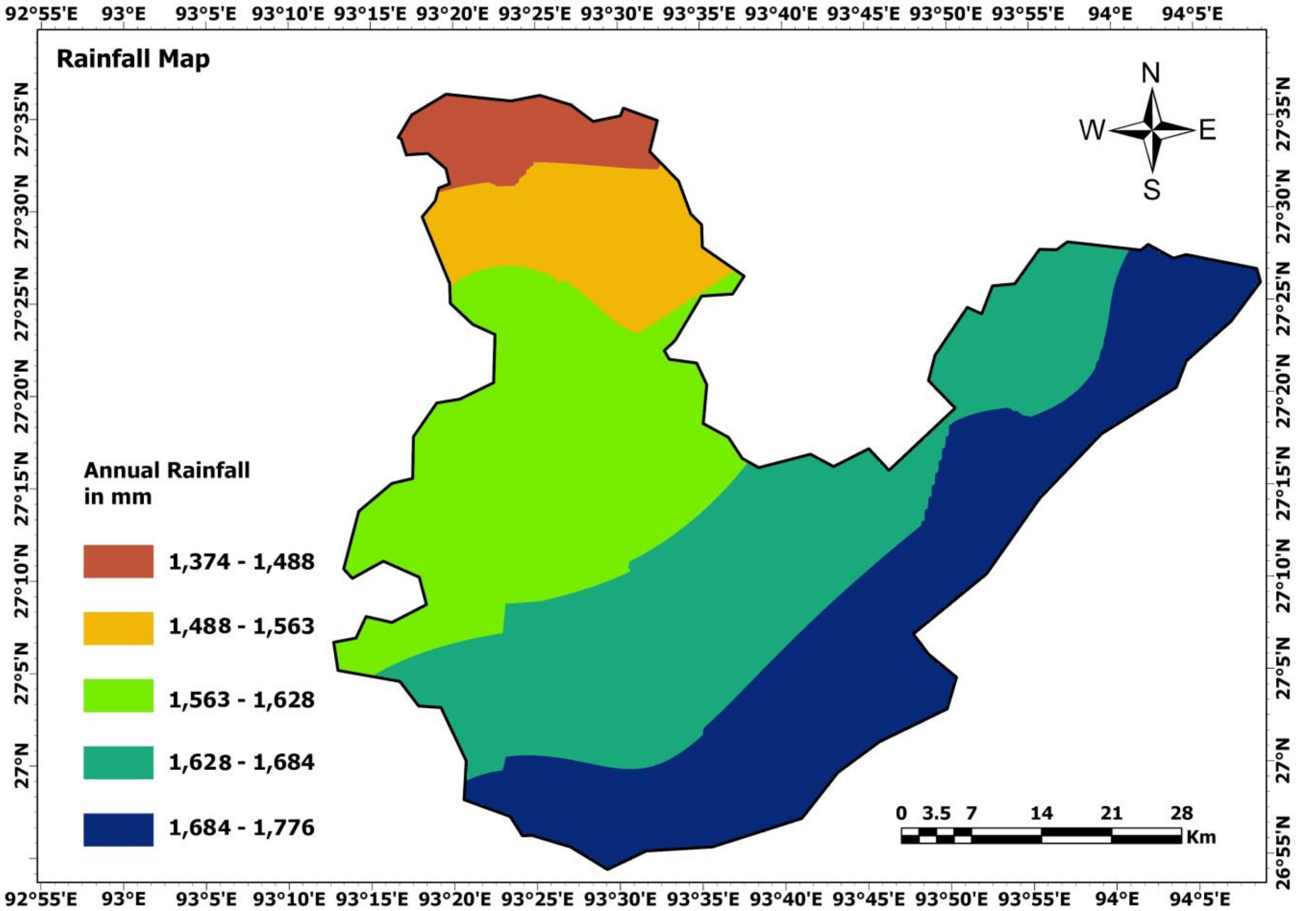

Figure 3. Annual average rainfall map of the study area.

3.2. Land use and cover

Land use and land cover directly and indirectly contribute to groundwater replenishment. It provides crucial data on soil moisture, infiltration, groundwater, and surface water, and offers insights into groundwater needs[33, 34]. Urbanisation is increasing in the watershed, and groundwater replenishment capacity is increasing relative to previous non-urbanised regions. **Figure 4** shows the thematic LULC maps. Human settlements are concentrated in areas with lowlands and along water sources. Agricultural land is concentrated in certain foothill plains, and most areas are covered by forest.

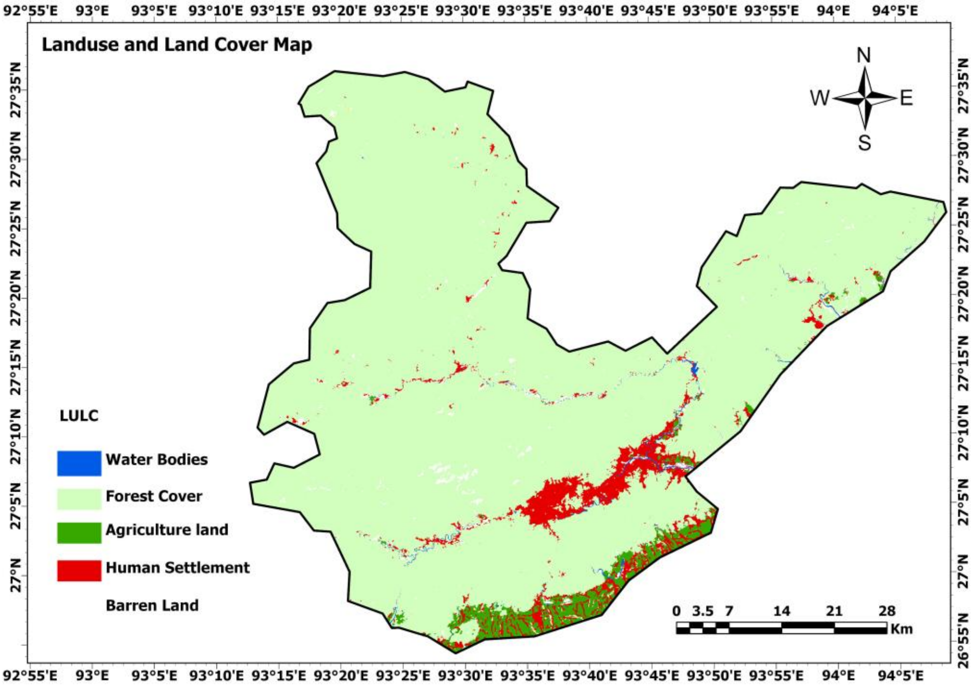

Figure 4. Land use and cover of the study area.

3.3. Lineament density

Lineament density is crucial for recognising groundwater resources, as it indicates significant groundwater productivity. It is defined by either curved or straight linear arrangements in structural, drainage, lithological, and topographical irregularities[8, 16, 35]. In this region, lineament density varies from 0 to 0.65 km/km² (**Figure 5**). Groundwater dynamics and presence are positively correlated with lineament density. Consequently, the region's lineament density has been classified into five distinct categories.

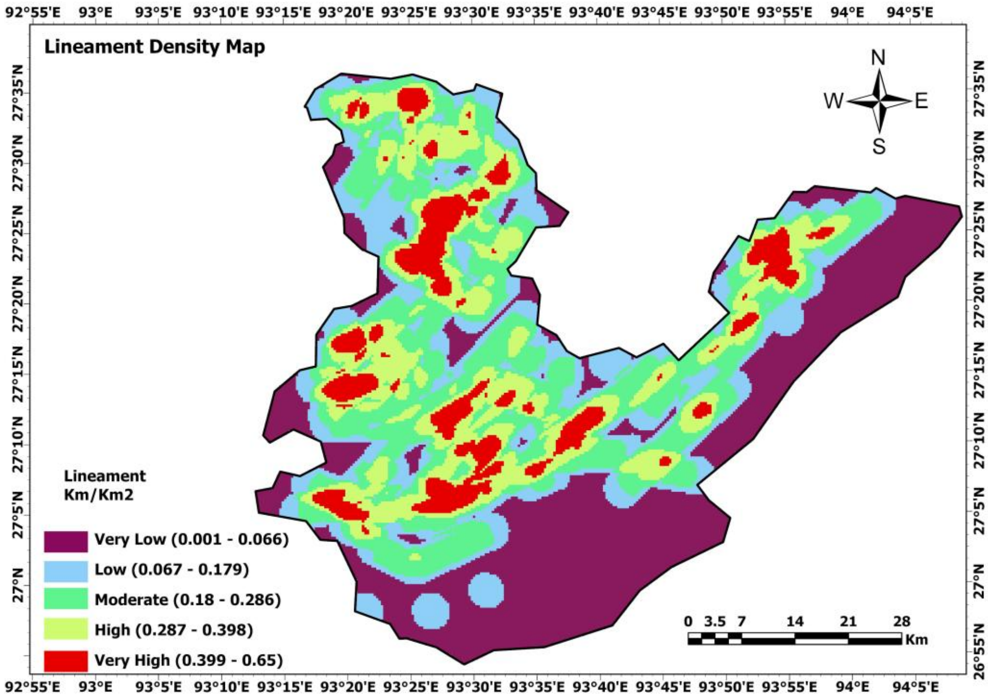

Figure 5. Lineament density of the study area.

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3.4. Drainage density

Drainage density controls the permeability and percolation rate of precipitation in particular regions. Stream networks and the associated land surface they drain over the channel's length can signify potential groundwater areas[8, 35]. Drainage density is affected by the topographical features and the permeability of geological formations. An aquifer is promising when drainage density within the watershed facilitates groundwater replenishment. Hydrogeological characteristics and soil moisture retention capabilities determine drainage density, which in turn facilitates groundwater recharge[36, 37]. If the incline is level, permeability is very high while drainage density remains very low. Drainage density was categorised into five categories, i.e., very low, low, moderate, high, and very high (**Figure 6**).

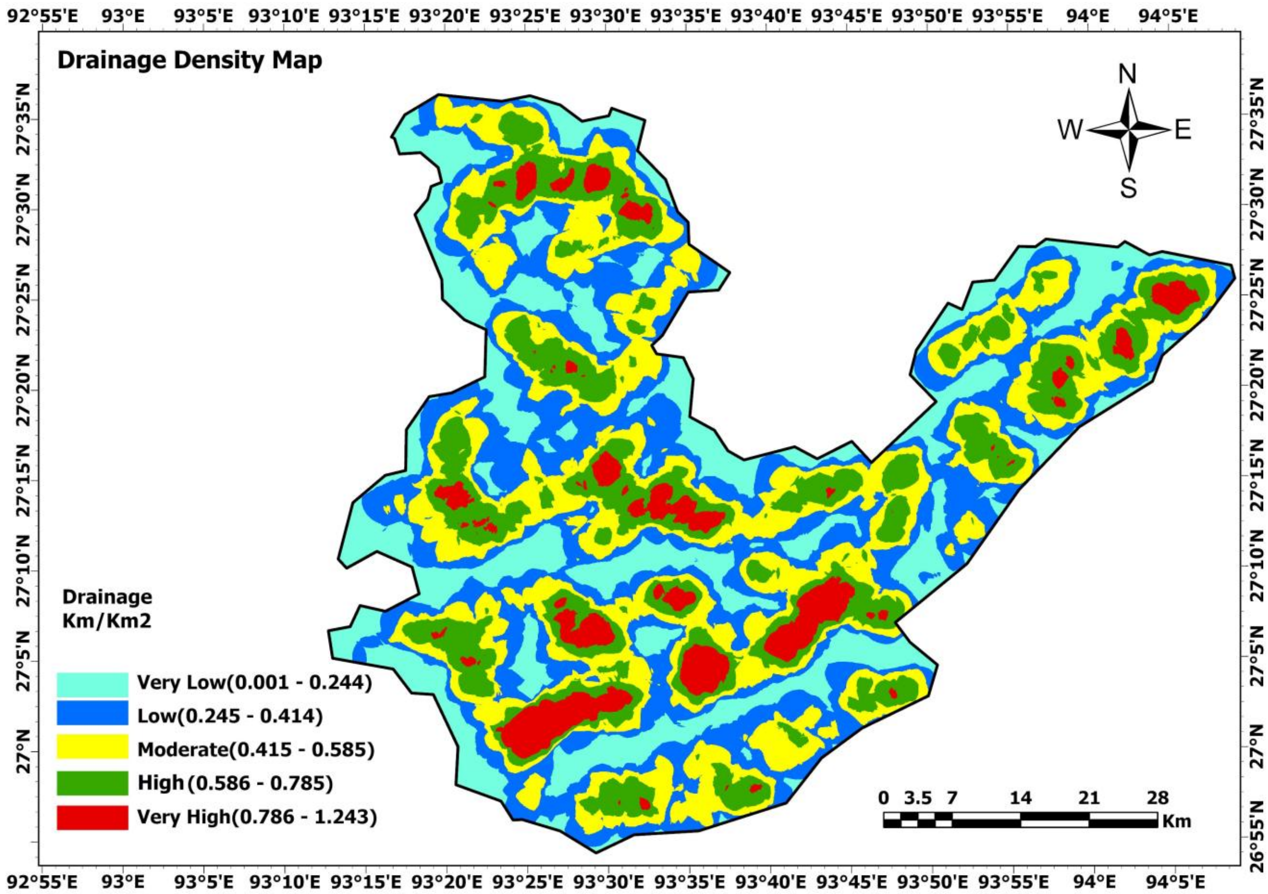

Figure 6. Drainage density of the study area.

3.5. Slope

Slope is a crucial determinant for recognising groundwater recharge areas within a basin. The fundamental principle behind slope's significance in groundwater replenishment is retention time. Gradient affects the velocity and duration of surface runoff, as well as the infiltration potential of geological formations. Level areas within the watershed serve as reliable indicators of groundwater potential zones because of their longer retention time and infiltration rate. Surface runoff velocity is very rapid, and retention time is minimal because of the terrain's steepness[38-40]. When the incline is sufficiently gentle, the surface runoff has ample opportunity to infiltrate into the subsurface. In this research, the slopes were categorised into five categories: flat, gentle, moderate, steep, and very steep (**Figure 7**).

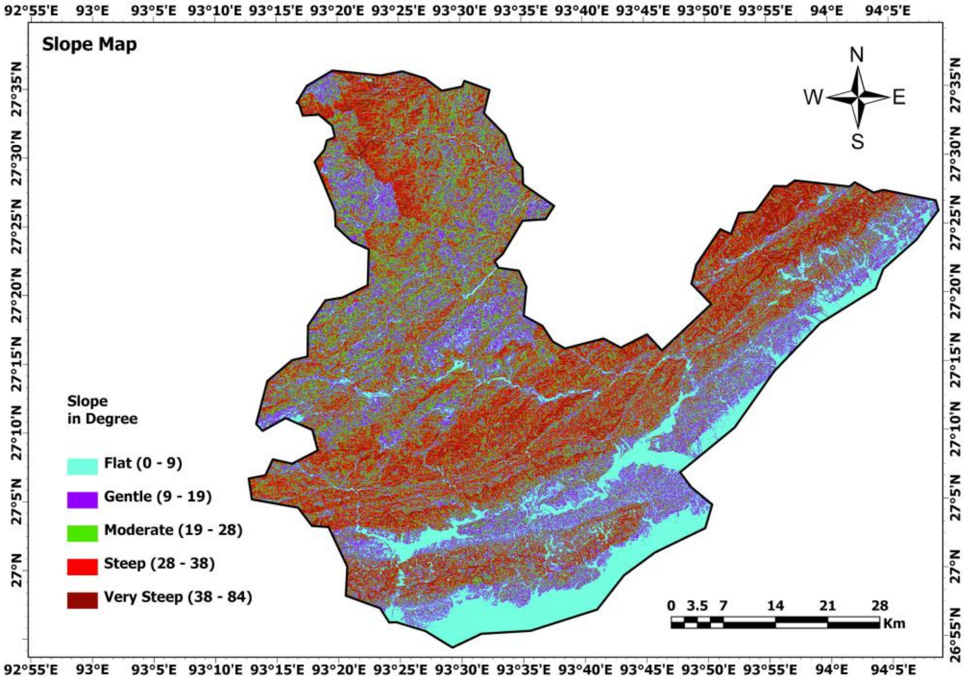

Figure 7. Slope of the study area.

3.6. Geomorphology

Geographic Information System (GIS) tools were employed to categorise landforms according to their importance in groundwater contribution. The topographical features of a geomorphological unit differ in their attributes and spatial arrangement. The presence and flow of subterranean water depend on the region's geomorphological features. Low mountains and flat plains indicate potential for groundwater if hydrogeological conditions facilitate water transmission[19, 24]. **Figure 8** shows the study area, which is mostly covered by dissected hills and valleys.

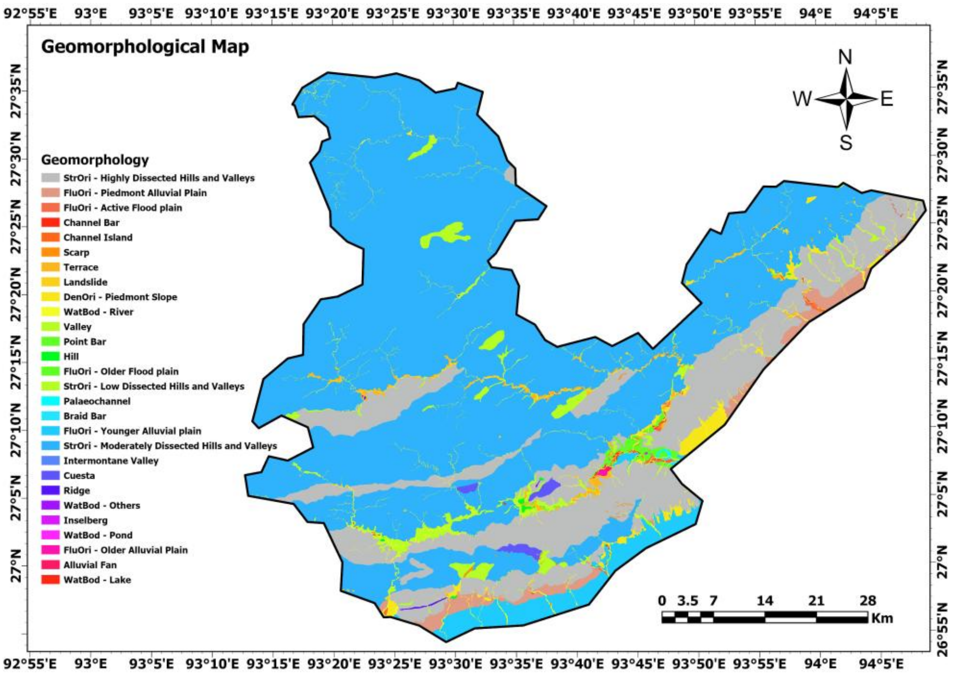

Figure 8. Geomorphological map of the study area.

3.7. Geology

The presence of groundwater within an aquifer depends on the geological characteristics and permeability of the geological formations[41, 42]. Water is retained in the aquifer when the geological structure contains and transmits the infiltrating water. The quantity and capacity of water retained in the geological formations depend on the region's hydrogeologic conditions[43]. Water can be retained only if adequate void spaces exist within the geological formations. The aquifer is considered promising when sufficient voids exist within the hydrogeologic framework. Geological formations with consistent grain size typically have adequate porosity and elevated permeability. Aquifer replenishment transpires when rainwater infiltrates the subsurface from surface runoff, lakes, and streams[24, 44]. Foothill regions of the study area are composed of sedimentary rocks and a small area of metamorphic rocks, as shown in **Figure 9**.

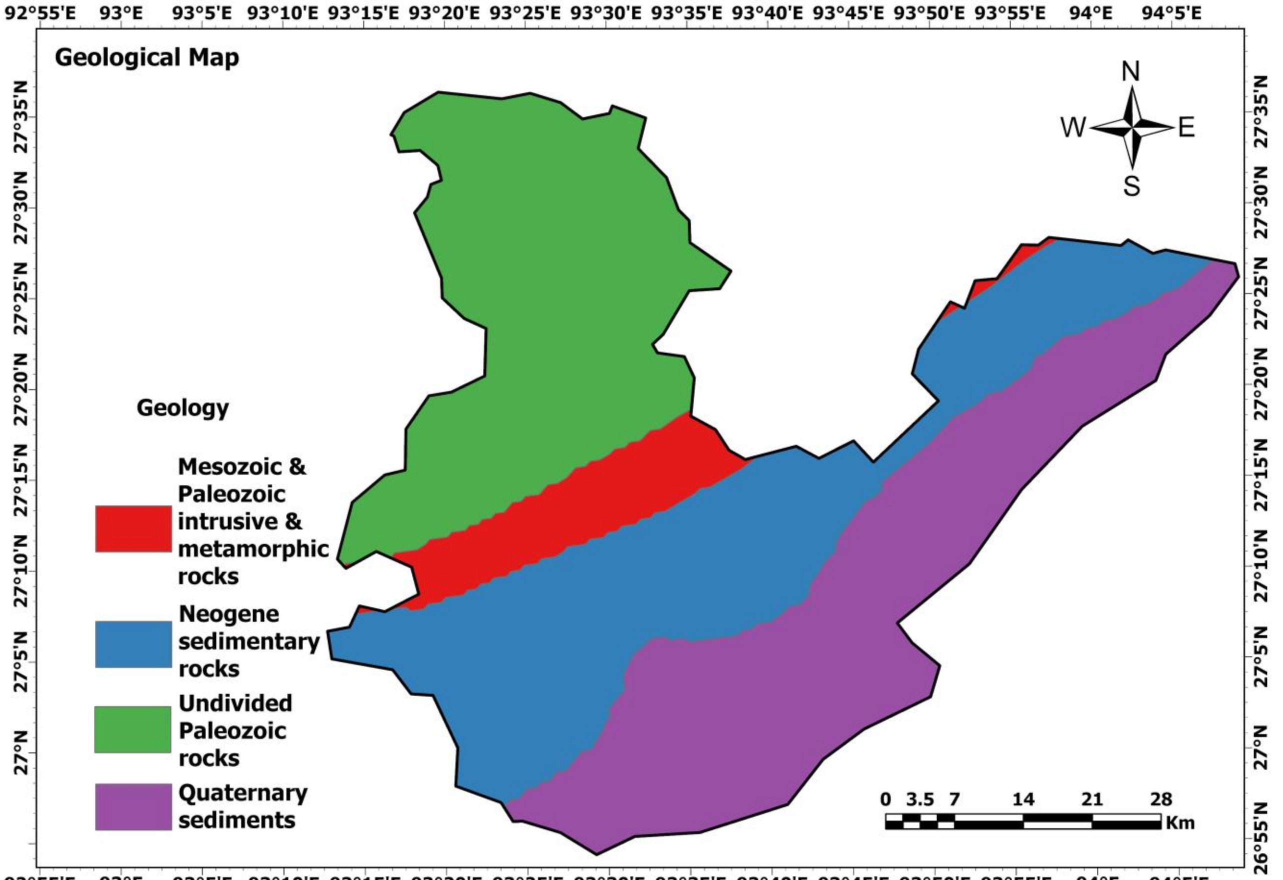

Figure 9. Geology map of the study area.

3.8. Soil

Subsurface water is retained in the interstitial gaps among soil granules. The quantity of water retained in the specified hydrologic units is contingent upon the texture and dimensions of the soil particles[45, 46]. Nevertheless, based on data from productive wells, the depths are considerable, and in such instances, soil influence is relatively small. Infiltration of precipitation via soil is a notable characteristic that subsequently facilitates access to water[47]. If there exists a significant likelihood of water percolating through the soil, it is evident that a substantial volume of water is retained in the aquifer. **Figure 10** shows the soil type of the study area; the whole region is divided into three soil types.

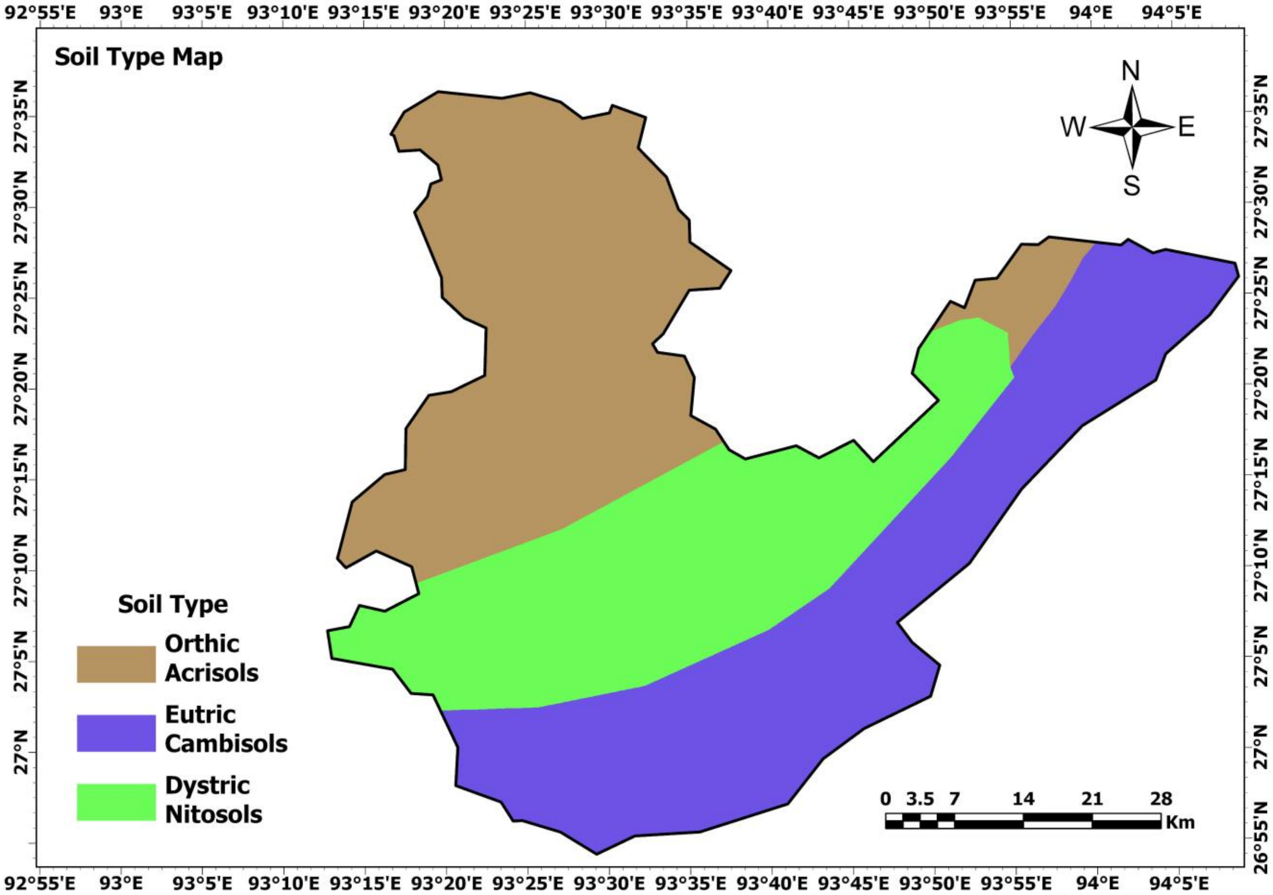

Figure 10. Soil map of the study area.

3.9. Delineation of Groundwater Potential Zones (GWPZ)

The established AHP weights were used to categorise groundwater potential areas. The established weights were allocated to the relevant key elements (drainage density, lineament density, geology, slope, soil, geomorphology, and LULC) to produce the groundwater potential zones. The investigation used the weighted overlay analysis tool within the GIS platform (Fig. 10). As shown in **Figure 11**, the detected potential zones were categorised into five qualitative classes: Very good, Good, Moderate, Poor, and Very poor, as shown in **Table 7**.

Table 7. Groundwater potential zone categories of the study area.

Category		Area in Sq Km	Area in percentage
Very poor		27	0.80
Poor		802	23.84
Moderate		1437	42.72
Good		874	25.98
Very good		224	6.66

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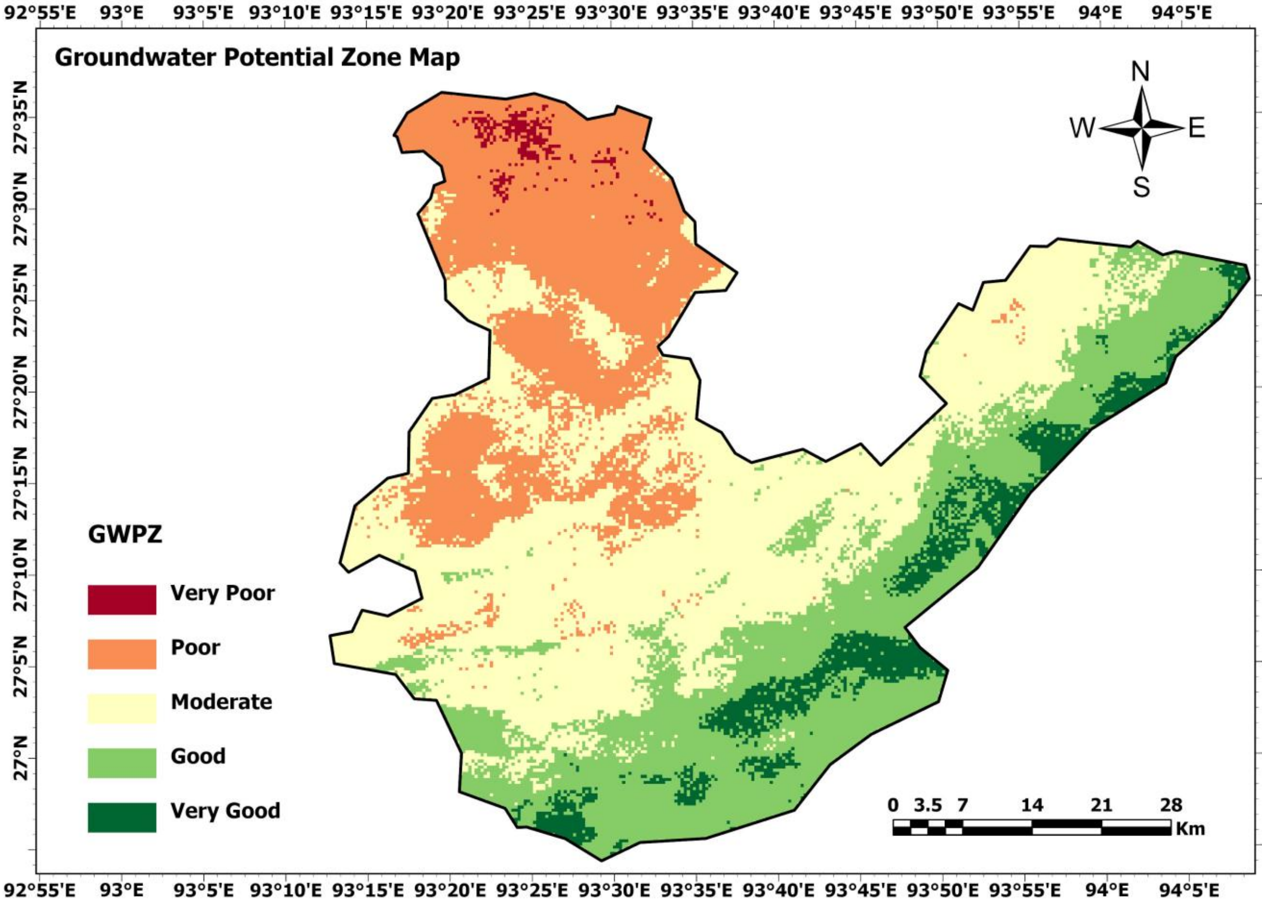

Figure 11. Groundwater potential zone map of the study area.

4. CONCLUSION

The research uses AHP and GIS platforms to identify groundwater potential areas within the Papumpare district of Arunachal Pradesh, India. The data-driven GIS techniques effectively identified groundwater potential zones by using critical factors such as rainfall, drainage density, lineament density, slope, land use/land cover, geomorphology, soil, and geology as criteria for groundwater assessment. The findings indicate that 42.72% of the region has moderate potential, 6.6% has very good potential, and 0.8% has very poor groundwater potential. The northern area consists of hills and mountains and relies less on groundwater resources because of several permanent rivers and streams. Nevertheless, the southern foothills and plains predominantly rely on groundwater supplies. That means 6.6% of the area with very good potential will have to bear the pressure in the coming future. The state and district administration must formulate suitable plans based on the study's findings to tackle the impending water scarcity challenges. The advantage is that water replenishment occurs naturally due to substantial rainfall throughout the year.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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