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Groundwater Potential Zone Mapping in the Ghaggar River Basin, North-West India, Using Integrated Remote Sensing and GIS Techniques

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Abstract: The immense dependence of the growing population on groundwater has resulted in depletion at a fast pace can be seen nowadays. Identifying a groundwater potential zone can be proved as an aid to provide insight to the decision-makers and local authorities for planning purposes. This study evaluated the delineation of groundwater potential zones using integrated remote sensing and GIS approach. Various thematic layers such as geology, geomorphology, lineament, slope, drainage, soil, land use/land cover, and rainfall were considered in this study as these have influence on the occurrence of groundwater and its cycle, and maps have been prepared in GIS domain. Afterward, appropriate weights were assigned to these layers based on multi-criteria decision analysis, i.e., Analytical Hierarchy Process (AHP). Groundwater potentiality has been delineated in different zones (low, moderate, high, and very high) in the study region based on weighted overlay analysis. The study reveals zones with different groundwater prospects viz. low (1.27%), moderate (15.65%), high (75.54%), and very high (7.29%). The ground survey data provided by CGWB (Central Ground Water Board) of nearly 100 wells/dug wells/borewells/piezometers have been used for validation purposes, showing comparable results with the groundwater prospects zones. It also confirms that the majority of these wells fall under very high or high groundwater potential zones. They were also found to be thereby indicating that there is the existence of a permeable reservoir with considerable water storage in the subsurface. One of the most important issues for users and governments is groundwater depletion. Planning for the available groundwater resource is made easier by identifying the potential for groundwater (low to high).

Keywords: groundwater potential; GIS; remote sensing; analytic hierarchy process; overlay analysis

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1. Introduction

Groundwater is one of the significant natural resources that are vital for life and ecological diversity, especially in regions that are devoid of major surfaces of water bodies in the vicinity. The importance of groundwater can be well imagined from the fact that approximately one-third of the world's population is dependent on it for drinking, irrigation, and domestic and industrial purposes [1,2]. In fact, it has been estimated that nearly 80% of the rural population and approximately 50% of the urban regions use groundwater for domestic purposes. This over-dependence on the usage of groundwater for domestic, agricultural, or industrial purposes has led to the over-exploitation of this resource. Thus, groundwater conservation demands protection from contamination and judicious use.

Groundwater shows dynamism and is replenishable, but seepage of effluents from the industries leads to its contamination. Porosity and permeability are two primary factors that control the rate of groundwater flow. When rainwater or water from nearby surface bodies infiltrates the Earth's surface it is available as groundwater [2,3]. The groundwater table registers depletion when the rate of withdrawal is more than the rate of recharge. Thus, the regions with high groundwater depletion or reduction and that have high withdrawal rates must be identified. To alleviate the water crisis, proper awareness regarding groundwater conservation, maintenance, and adequate implementation of several government schemes is highly needed. For a better understanding of the groundwater resources and their behavior, there is an urgent need for intensive study of the geology, geomorphology, soil, drainage, rainfall, lineament, slope, and land use/land cover pattern in the region [1].

Groundwater-oriented research has taken up new directions while combining with remote sensing technology and geographic information systems (GIS) [4–7]. Re-mote sensing, with its advantages of spectral, spatial, and temporal availability of data covering large and inaccessible areas in a short amount of time, has become a very useful tool in collecting, storing, transforming, retrieving, displaying, and analyzing spatial data. It is used for a variety of purposes, including determining the feasibility of recharge sites, evaluating ground and surface water resources, and identifying co-occurrences. Satellite imagery provides immediate and relevant baseline data on characteristics such as lineaments, geology, geomorphology, drainage, land use/cover, and so on [7–9]. Groundwater prospecting and recharge sites identification have been effectively implemented using remote sensing and GIS techniques [10,11], and groundwater potential zones have been delineated using combined remote sensing and GIS approaches [12]. Various thematic maps have been created using remote sensing and GIS techniques to calculate groundwater resources on a river basis. Groundwater availability is limited in a hard rock landscape. Groundwater is almost exclusively found in fractured and worn horizons in such rocks. Measurement of groundwater levels, pump test analysis, and groundwater quality analysis, geological and climatological studies and groundwater potential zone mapping have been carried out by many researchers [13]. Reduced time and expense demonstrate that integrated GIS and RS with AHP is a useful tool for identifying possible groundwater zones. Because groundwater is dynamic, it is practical to identify possible groundwater zones by integrating RS data into the GIS [14,15]. Researchers used a variety of methods to identify prospective groundwater zones, including quantitative methodology, influence factor (IMF) approaches, groundwater simulation, GIS-based deep learning, and a combination of RS and AHP [2,16].

Since these techniques have been proven to be dependable and efficient, many researchers have started using them. Additionally, a number of aspects are frequently taken into account in the integrated method to lessen inaccuracy and human error [16]. When there are multiple options for a set of pairwise comparisons and insufficient data for validation, analysis using the AHP technique is suggested as the best one. AHP techniques have been identified as one of the standard methodologies now-adays for delineating suitable sites for artificial recharge and potential groundwater zones in semi-arid areas as well [17]. In the Kilinochchi district, multi-criteria decision-making (MCDM) technology such as AHP is used with the combination of RS-GIS methods to identify potential groundwater zones by assigning weight to different thematic layers [15]. These methods can successfully include organization, appropriateness, and precision in the decisions. AHP has been widely used by various researchers in solid waste management and environmental impact analyses [2,14,15,17,18]. Groundwater potential zone mapping using remote sensing and GIS is a technique that allows the identification and delineation of areas with high potential for ground-water availability based on a range of geospatial data. This approach integrates satellite images, digital elevation models, land use/land cover data, and hydrogeological parameters to create a spatial model that predicts the presence of groundwater.

Similarly, because groundwater is constantly being mined for drinking and irrigation in the Ghaggar River basin, it is critical as well as essential to demarcate ground-water potential zones in the Ghaggar river basin. Therefore, after considering these factors, some of the research objectives were formulated as follows; (a) to better understand the geology and hydrogeological environment of the Ghaggar River basin and (b) to map groundwater potential zones in Ghaggar River Basin, North-West India in line with several topographic, hydrographic, and climatic factors, using the GIS-based MCDM technique, i.e., AHP.

2. Materials and Methods

2.1. Study Area

The study area lies in the north-western part of India comprising parts of Punjab and Haryana and forms part of the Ghaggar River Basin originating from the Shivalik hills of Himachal Pradesh traverses through Chandigarh, Haryana, Punjab, and Rajasthan (Figure 1) and covers an area of 20,490 sq. km. It lies between north latitudes 30°45′5.93″ to 29°11′49.29″ and east longitudes 77°54′36.79″ to 73°13′26.88″. Figure 1 [18] shows the study area which falls in the Ghaggar River Basin with a drainage network delineated using SRTM DEM of 30 m resolution.

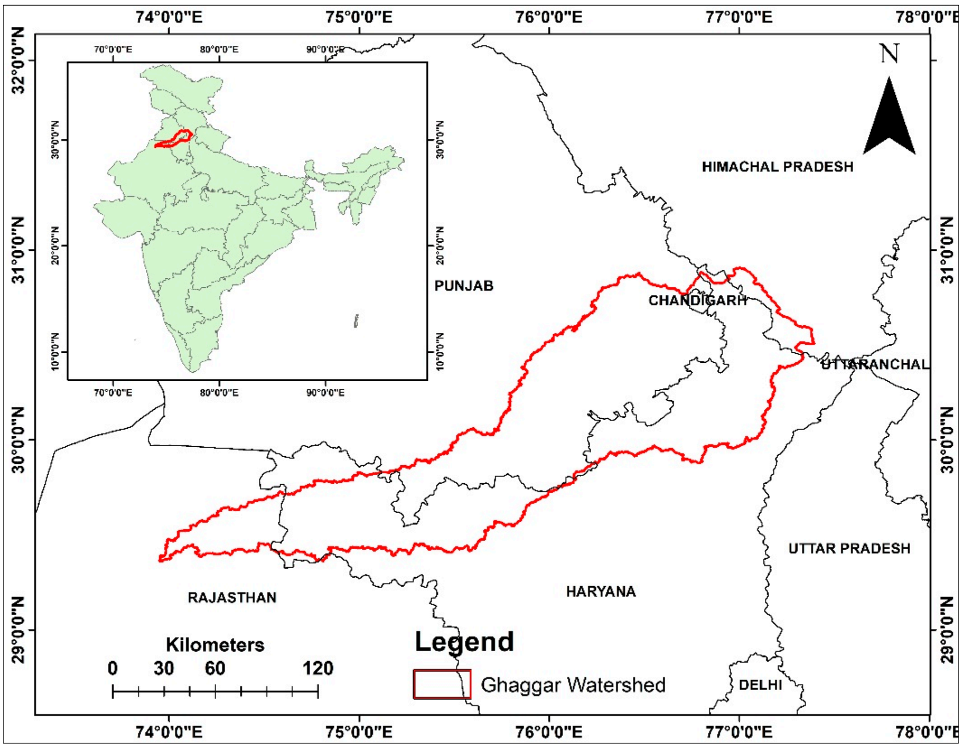

Figure 1. Location Map of the Study Area.

2.2. Materials

In this study, several thematic layers, i.e., geology, geomorphology, lineament, slope, drainage, soil, land use/land cover, and rainfall have been used to demarcate groundwater potential zones in Ghaggar River Basin, North-West India, using Integrated Remote Sensing and GIS Approach. A detailed description of the data is provided in Table 1.

2.2.1. Thematic Layers

Geology plays an important part in groundwater availability. In the Punjab and Haryana plains, as we follow the east-to-west trend, the hard rock exposures are completely absent in the study area. The entire area has the presence of sedimentary and metamorphic rocks (Figure 2) [18]. Primarily, it is alluvium in the majority of the area. The sub-surface lithological sections are predominantly from the quaternary and composed of clay and sand, and their compositions are layered in a horizontal manner with thicknesses ranging between 230 and 340 m. At various horizons, secondary kankar deposits in clay and sand are found. Fine-grained sediments represent the entire sequence in the flood plain. The older alluvium formation varies from clay to sandy. Along the Ghaggar River, younger alluvial deposits with terraces and flood plain are observed. The sediments comprise of loose grey, silt, clay, and very fine angular sand with a thickness of about 1 to 1.5 m. The younger aeolian deposits are comprised of positively skewed, loose, non-carbonated, very fine-grained sediments of quartz grains, and feldspar.

Table 1. Showing primary and secondary data used in this study.

Name of Dataset	Temporal Resolution	Spatial Resolution	Acquisition Date	Source
Landsat-8 (OLI)	16 days	30 m	28 April 2017	USGS
SRTM DEM	-	1 arc second (30 m)	-	USGS
PERSIANN-CCS	24 Hrs.	$0.04 \times 0.04°$	August and September 2017	CHRS
Geological Map	-	-	-	GSI
Geomorphology Map	-	-	-	SOI
Soil Texture	-	-	-	National Soil Conservation and Salinization Board
Soil Type	-	-	-	National Soil Conservation and Salinization Board
Water Level data	-	-	-	CGWB

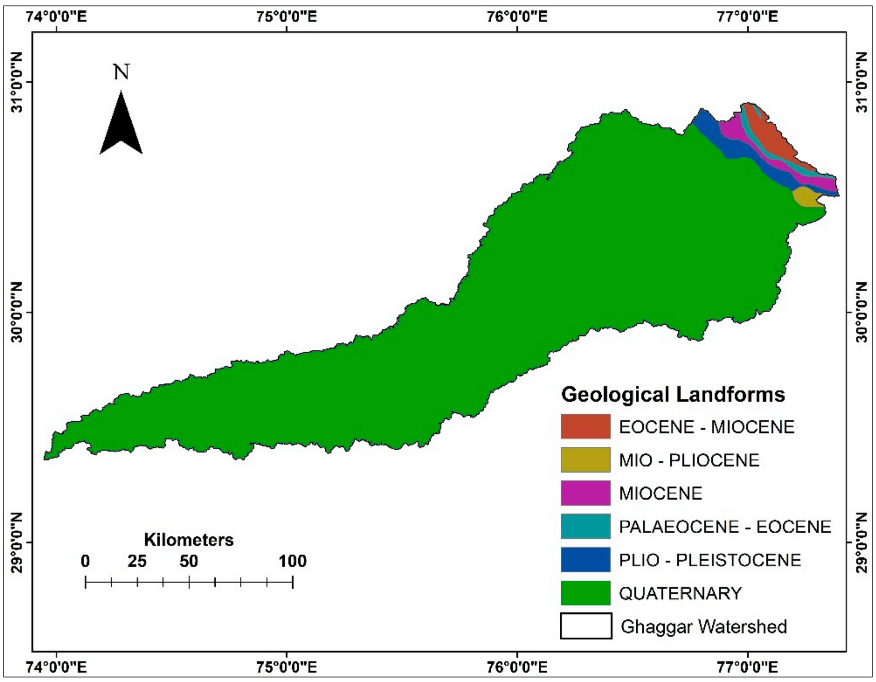

Figure 2. Geological map of the study area (stratigraphic formations included) (Source: Geological Survey of India).

2.2.2. Geomorphology

The hydro geomorphological investigation reveals a strong link between hydro-geomorphic units and groundwater resources. A comprehensive examination of diverse landforms and geomorphic units' aids in the identification of probable ground-water zones in the research area. Groundwater potential zones and artificial recharge sites can both benefit from geomorphological units [19]. Denudational hills, residual hills, piedmonts, Pedi plain, and younger alluvial plain are the dominant geomorphic units found in the research region using satellite image interpretation (Figure 3) [18].

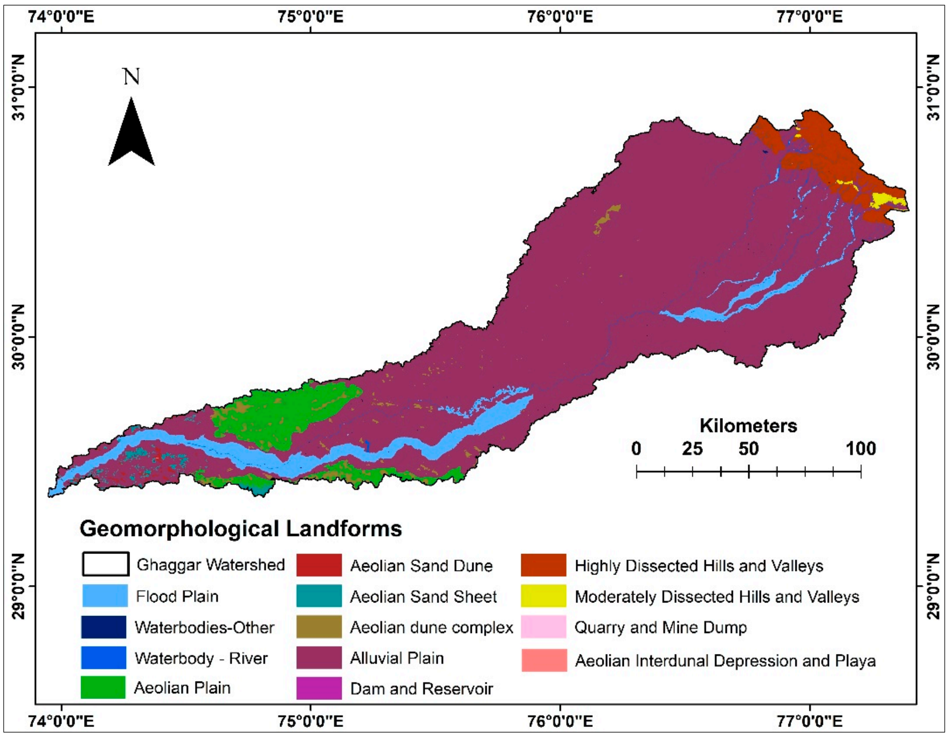

Figure 3. Geomorphological map (Source: Geological Survey of India).

These landforms serve as groundwater storage reservoirs as well as recharge and runoff zones in some cases. The groundwater occurrence and movement in the research area are limited to alluvial deposits.

2.2.3. Soil

Soil type influences the groundwater quality and quantity. Geological processes, such as weathering and erosion by the action of rivers, wind, and rains, depend on the environment, and this process over millions of years is necessary for the formation of a few centimeters of the soil layer. The Punjab and Haryana plains of the Ghaggar basin are low to gently sloping and covered with loamy sand, clay, sand, loamy clay, sandy clay, sandy clay loam, and silty clay loam in the majority of the area covering 96 per-cent (more than 18,500 sq. km) of the area (Table 2).

The soil has an essential role in defining the quality and quantity zones of groundwater. Coarse and fine texture soil types have good groundwater potential. The soil map also shows the geographical spread of certain soil types (Figure 4) [19]. Soil texture in the study region varies from fine to coarse to rocky texture. The majority of the region, more than 96 percent, has a fine to coarse texture (Figure 5) [19]. Soil texture has a major role to play in water infiltration. The fine and coarse textured alluvium present in the study region facilitates infiltration capacity and thus accounts for the high potential zone for groundwater availability.

Table 2. Soil texture and types of the study area.

S. No.	Texture	Types of Soil	Hydrologic Soil Group	Area (km^2)	Area (%)
1	Coarse Texture	Loamy sand, sand	A	8473.72	43.76
2	Fine texture	Clay, loamy clay, sandy clay, salty clay, sandy clay loam, silty clay loam	D	10,113.06	52.23
3	Others	Rocky, other non-soil categories (built-up, water bodies)	Others	774.23	4.01
		Total area in km^2		19,361.01	100

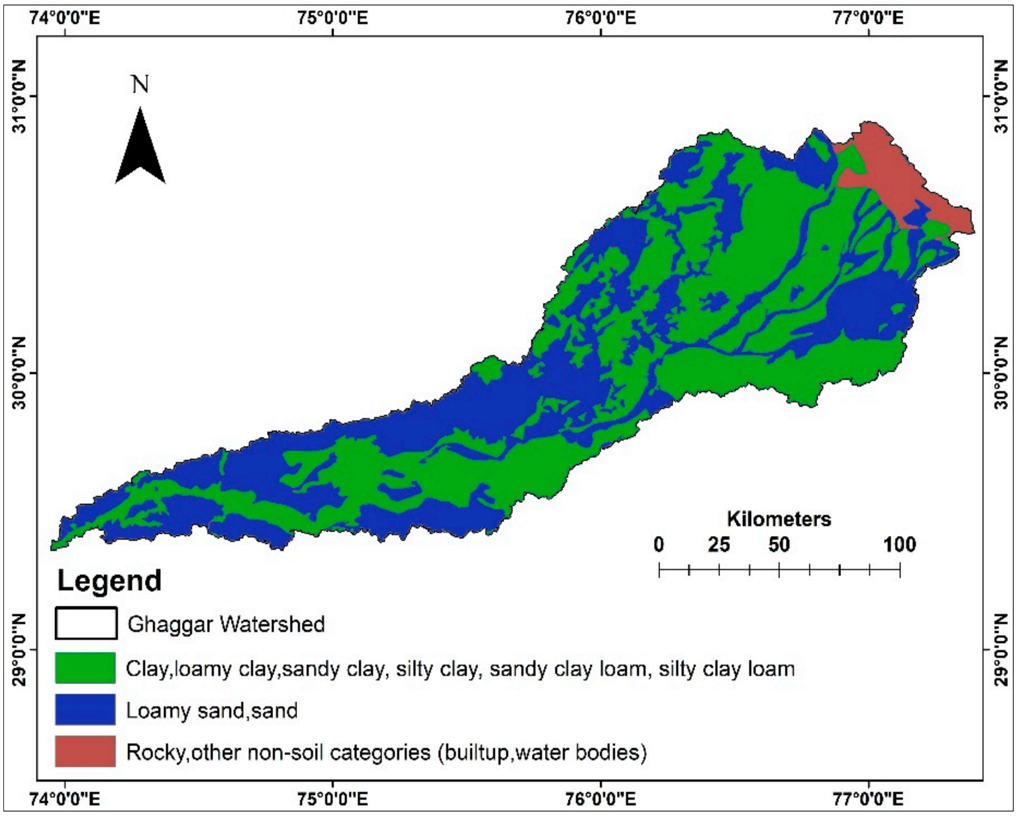

Figure 4. Soil types of study area (Source: National Soil Conservation and Salinization Board).

2.2.4. Land Use/Land Cover

Land use refers to man's actions on land, including numerous purposes, whereas land cover refers to features that have come from land transformation. Remote sensing data primarily records information on the land surface, from which land use information must be extrapolated. The Landsat 8 data were subjected to supervised classification (maximum likelihood method) and broadly into five classes viz. vegetation or forest cover, agriculture or cropland, water bodies settlement or built-up area, and others (scrubland, wasteland, fallow land, etc.) (Figure 6) [19]. Nearly 80–100 training samples were collected and verified for each LULC class through field surveys, google earth, and existing ground truth data which were further used as signature files in the supervised classification technique.

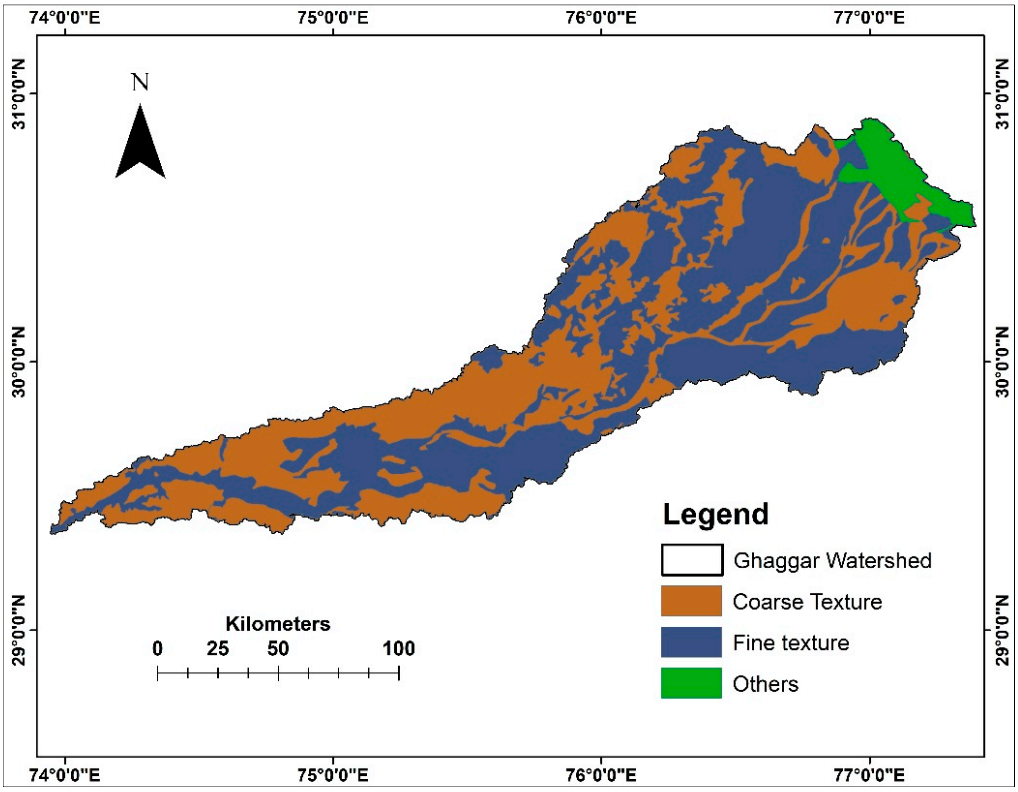

Figure 5. Soil texture map of the study area (Source: National Soil Conservation and Salinization Board).

We can infer the soil moisture, surface water, groundwater, and infiltration status through the land use/land cover analysis as they play a pivotal role in the groundwater recharge process. Regions covered with vegetation/forest cover and agriculture have cracks that help in loosening the soil and eventually increasing the infiltration rate in the soil [20]. Dense forest cover can actually be beneficial for groundwater recharge in certain circumstances. When it rains, the water is absorbed by the soil and vegetation, which helps to recharge the groundwater. Trees and other plants also help to slow down the flow of water over the land, which can reduce erosion and increase the amount of water that soaks into the ground [17]. Surface characteristics control the rate of runoff or infiltration. Urban regions with concrete pavements and roads leave little space for infiltration and groundwater recharge.

2.2.5. Drainage

Owing to its relationship with surface runoff and permeability, drainage density might indirectly suggest an area's groundwater potential. The drainage map of the re-search area, including several tributaries, was created using 1: 50,000 scale SOI topography maps and updated using satellite imagery. The studied region is characterized by a dendritic pattern (Figure 7) [19]. The basin's morphological history, beginning slope, variances in rock resistance, structural controls, and structural controls influence the drainage pattern [21]. The drainage pattern is extremely useful in analyzing geomorphic characteristics and following landform change. In the study area, the highest drainage of the sixth order has been recorded (Table 3).

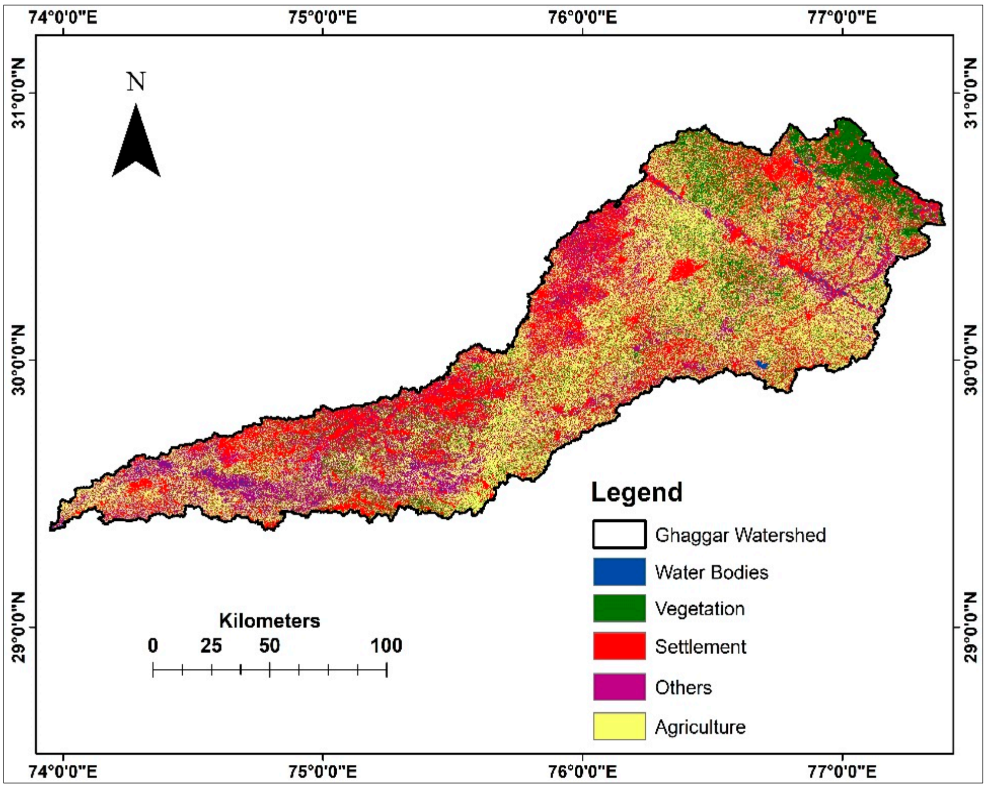

Figure 6. LULC of the study area.

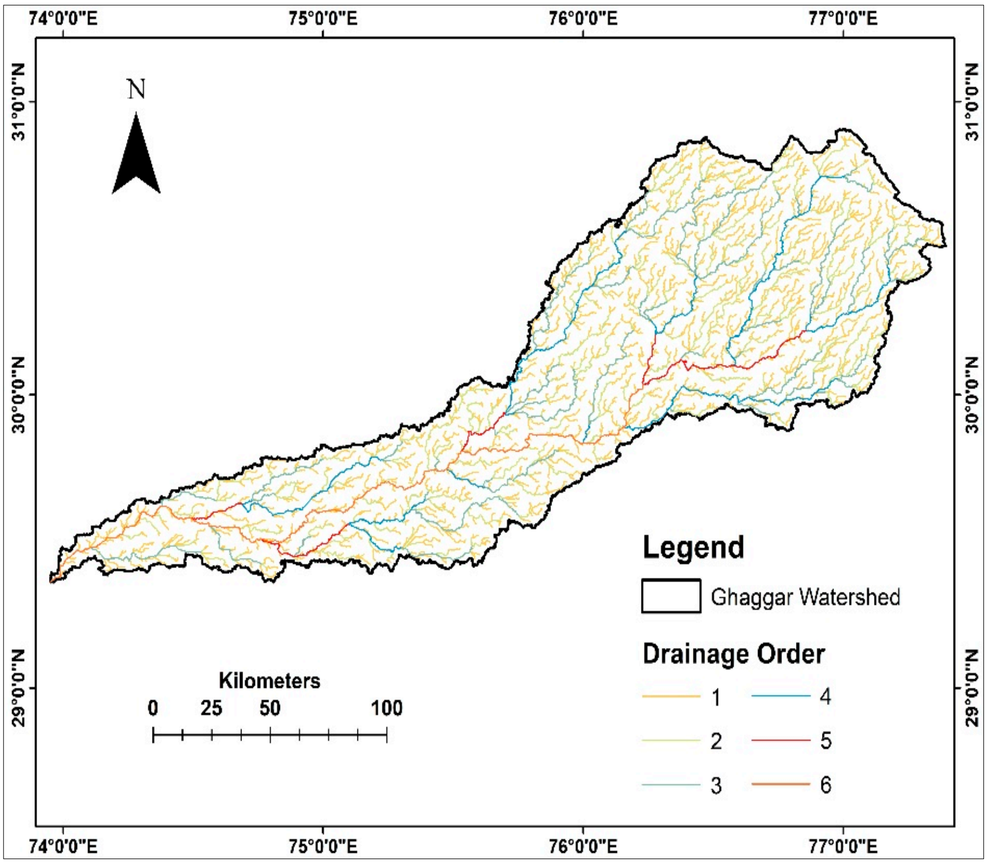

Figure 7. Drainage order map of the study area.

Table 3. Drainage density and stream number.

S. No.	Stream Orders	No. of Streams	Stream Length (km)	Drainage Density (Dd) km per km^2
1	1	845	3610.7	0.181
2	2	397	1859.04	0.093
3	3	263	408.18	0.020
4	4	87	351.15	0.017
5	5	81	1265.3	0.063
6	6	1	7494.37	0.37

2.2.6. Drainage Density

The drainage density can be deciphered from Figure 8 [19] and Table 3.

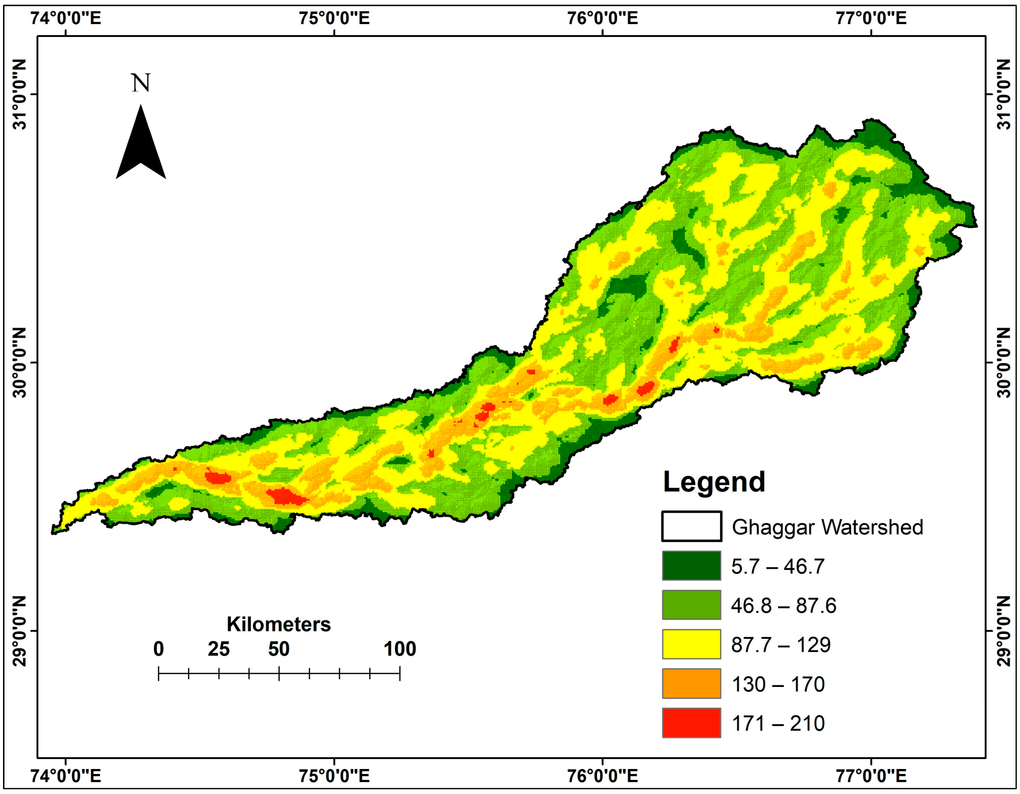

Figure 8. Drainage density of study region (no. of stream in per sq. km).

The average drainage density in the Ghaggar basin has been calculated to be 0.124 per sq. km. The lowest drainage density in the region was found to be 0.017 per sq. km for the fourth-order stream, whereas the highest was recorded for the sixth-order stream, which is 0.37 per sq. km. The drainage density for the first-order, second-order, third-order, fourth-order, fifth order, and sixth-order streams has been recorded to be 0.181 per sq. km, 0.093 per sq. km, 0.020 per sq. km, 0.017 per sq. km, 0.063 per sq. km, and 0.37 per sq. km, respectively.

The drainage classes ranging from very low, low, moderate, and high to very high in the area of coverage is also shown on the map (Figure 8). High drainage density zones have poor groundwater prospects, while zones with lower and lower drainage density zones gradually improve their groundwater prospects. When compared to a low drainage density area, a high drainage density area increases surface runoff [22]. The lower drainage density zones in the area imply that the rock is more fractured and has a higher permeability.

2.2.7. Lineament Density

Lineaments are weaker zones of bedrock that form as a result of the Earth's movement. The junction of lineaments has good groundwater potential zones [23]. In satellite images, lines appear as linear, curvilinear, and rectilinear lines. The Main Boundary Thrust and the Yamuna Tear Fault are major lineaments in the region with numerous south-west trending micro-lineaments. Figure 9 depicts a number of lineaments discovered in the research area using satellite images. As shown in Table 4, the lineament density in the region ranges from less than 0.06 km to 0.31 km per sq. km. The majority of the lineaments are NNE-SSW to ENE-WSW, with modest to steep reversals of dips from NE to SW.

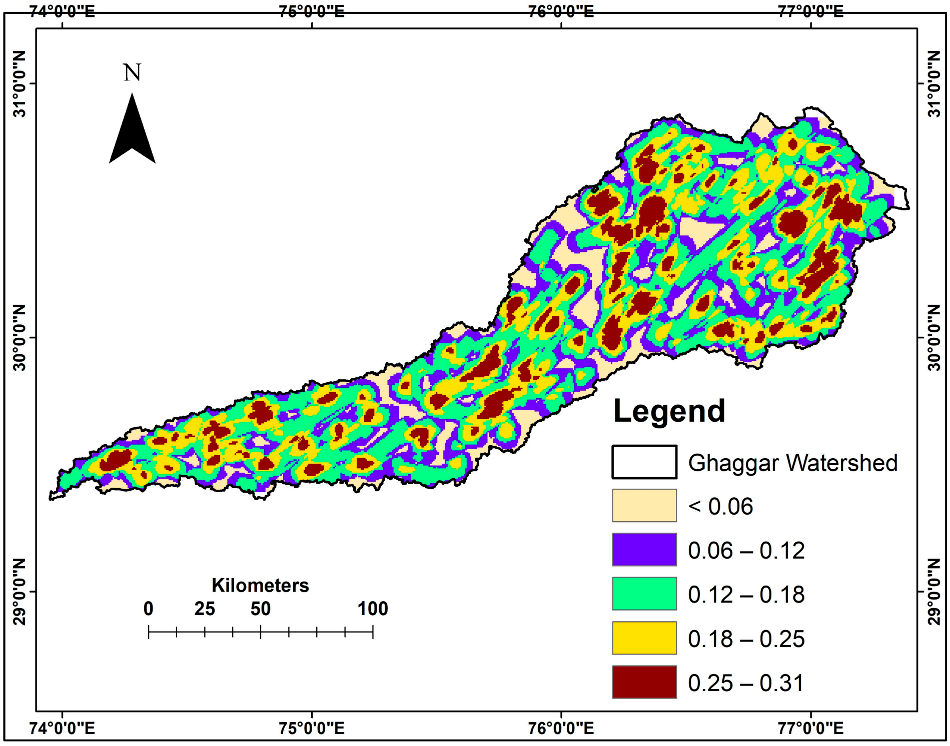

Figure 9. Lineament Density Map of the Study Area.

Table 4. Lineament distribution in the study area.

S. No.	Lineament Density (km/km^2)	Area (km^2)	Area (%)
1	0 to 0.06	2611	13
2	0.06 to 0.1	8280	41
3	0.1 to 0.18	6905	35
4	0.18 to 0.25	2016	10
5	0.25 to 0.31	194	1
	Total	20,006	100

The majority, almost 76 percent, of the lineament density ranges between less than 0.06 km per sq. km to 0.18 km per sq. km and covers an area of more than 15,185 sq. km. The lowest lineament density ranging between 0 and 0.06 km per sq. km, has been recorded over 2611 sq. km, covering almost 13 percent of the study area. Lineament density ranging between 0.06 and 0.1 km per sq. km has been recorded over 8280 sq. km covering 41 percent of the study region. Lineament density ranging from 0.1 to 0.18 has been found to cover an area of 6905 sq. km spanning over 35 percent of the area under study. Depending on their character and aerial extent, these lineaments have been classified as major and minor lineaments. Using GIS, a lineament density map (Figure 9) was created using the lineament map as the base map. Water level variations have been found to be inversely proportional to lineament density which means the water level is lower in areas having higher lineament density.

2.2.8. Slope

The slope angle is regarded as one of the most important inputs for determining potential groundwater zones because it has a significant impact on the study area. The slope map was created using the SRTM DEM data of the study area. Slope classification is an important part of soil mechanics and geotechnical engineering as it provides a means to predict the stability and strength of slopes. Slope classification is based on the degree of soil saturation, the amount of slope, the presence of water, and the characteristics of the materials present. The slope map was created using the commonly used Wentworth's average slope approach. Figure 10 depicts the various slope classes and their spatial distribution. The slope in the study area has been divided into eight categories, viz. slope zone 0 to 0.3 degrees as surface level or very low slope, slope zone 0.4 to 0.8 degrees as low slope, and slope zone 0.8 to 1.4 degrees as a very gentle slope, 1.4 to 2.2 degrees as a gentle slope, 2.2 to 9.2 degrees as gentle to moderate slope, 9.2–16.1 degrees as moderate to a steep slope, 16.2–24.4 as steep slope, and 24.5–48 degrees as a very steep slope. Based on the possibilities for groundwater availabilities, they were given weightage of 8, 7, 6, 5, 4, 3, 2, and 1 accordingly. Since runoff is directly proportional to slope, more weightage have been assigned to shallow slopes and lesser weightage to steeper ones. The majority of the research area (more than 52 percent covering approximately 10, 500 sq. km) falls in the very gentle slope (0.8 to 1.4 degrees) to gentle to moderate slope (2.2 to 9.2 degrees) category, as seen in Table 5. The northernmost part of the study area, which operates as a runoff zone, has a very steep slope of nearly 48 degrees, and it forms roughly 0.58 percent of the study area covering just 113 sq. km. In addition, a steep slope ranging between 16.2 to 24.4 percent is observed in approximately 216 sq. km forming 1.08 percent of the study region, whereas a moderate slope to steep slope is observed in only 2.6 percent of the study area covering nearly 506 sq. km. Very low to low slope is observed in nearly 43 percent of the study region spanning over 8736 sq. km.

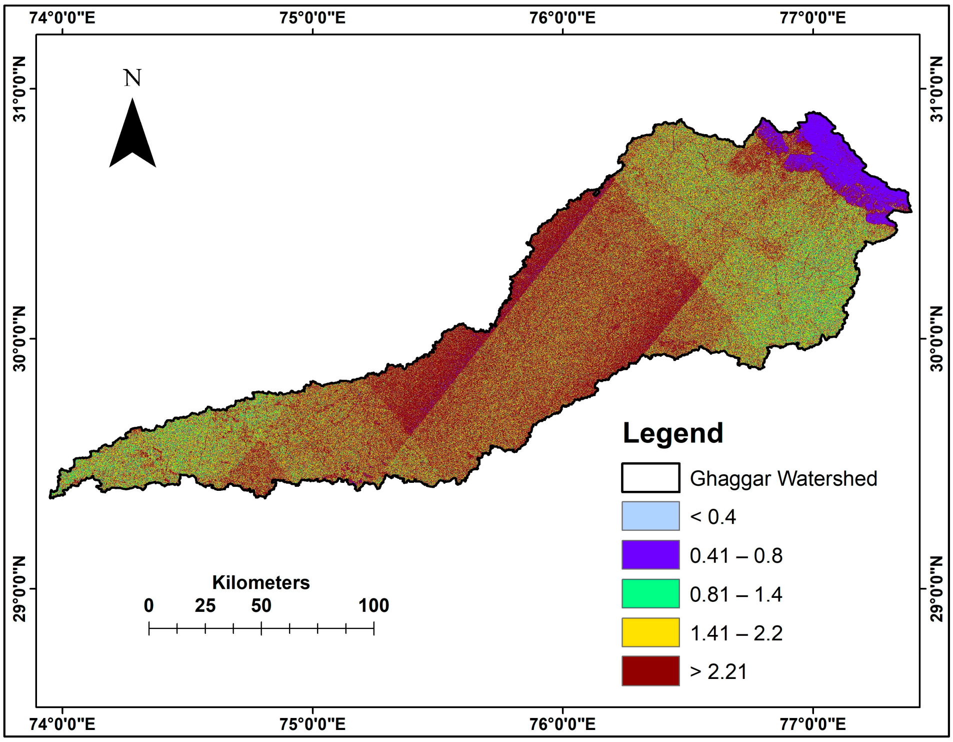

Figure 10. Slope classification of the study area.

Table 5. Slope area statics of study area and its classification.

S. No	Slope	Slope Types	Area (km^2)	Area (%)
1	0–0.3	Very Low	4099	20.54
2	0.4–0.8	Low	4637	23.22
3	0.8–1.4	Very Gentle	5111	25.6
4	1.4–2.2	Gentle	5001	25.05
5	2.2–9.2	Gentle to moderate	497	2.48
6	9.2–16.1	Moderate to steep	290	1.45
7	16.2–24.4	Steep	216	1.08
8	24.5–48	Very steep	113	0.58
			19,964	100

2.2.9. Rainfall

India is a tropical country, and rainfall is the main source of water here. Rainfall or precipitation also has a major role to play in groundwater recharge and other hydrological processes. The satellite precipitation data for the amount of rainfall in the Ghaggar basin in ArcGrid format has been downloaded from UCI-CHRS's Data Portal (chrsdata.eng.uci.edu) (Figures 11 and 12).

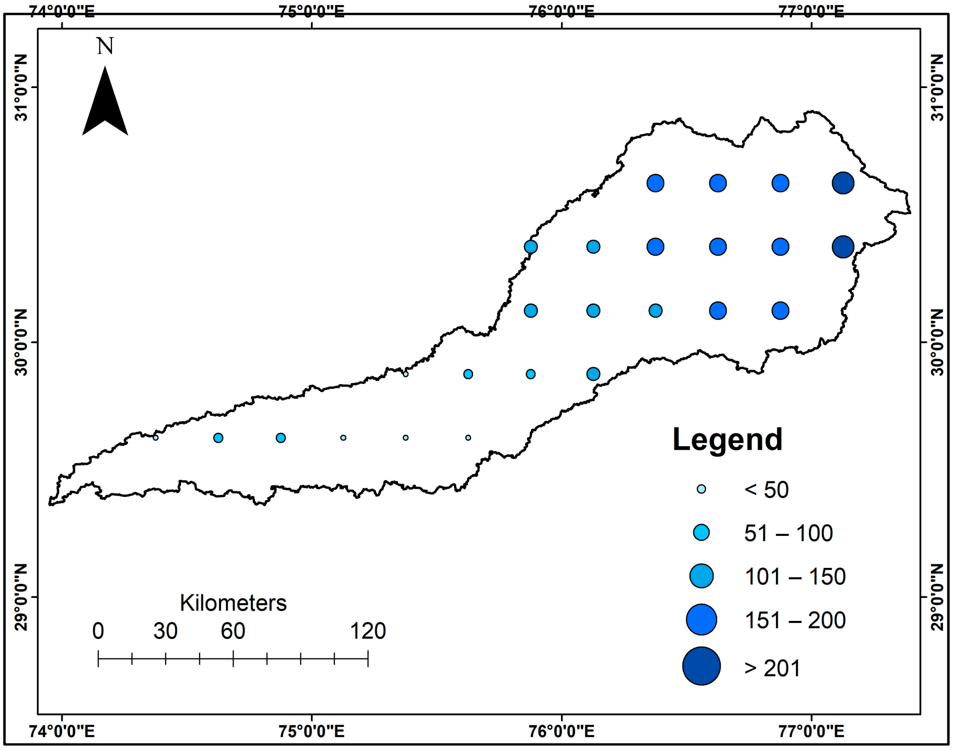

Figure 11. Average rainfall distribution in the study area (Source: chrsdata.eng.uci.edu).

Data domain: ncols 119; nrows 173; xllcorner 68.000; yllcorner −7.500; cell size 0.25; NODATA_value −99; and Unit: mm. Groundwater recharge and availability greatly dependent on the amount of rainfall in the region, especially in regions that do not have the availability of surface water in the form of rivers, lakes, and ponds, and groundwater potential is higher in regions with more rainfall and vice versa [24,25]. There is variation in the amount of precipitation received from region to region. It has been observed that the region at higher elevations receives more rainfall, and the availability of groundwater will decrease with decreased rainfall [3,26,27]. The classification into zones has been done by assigning weights to the various parameters that influence groundwater availability (Table 6).

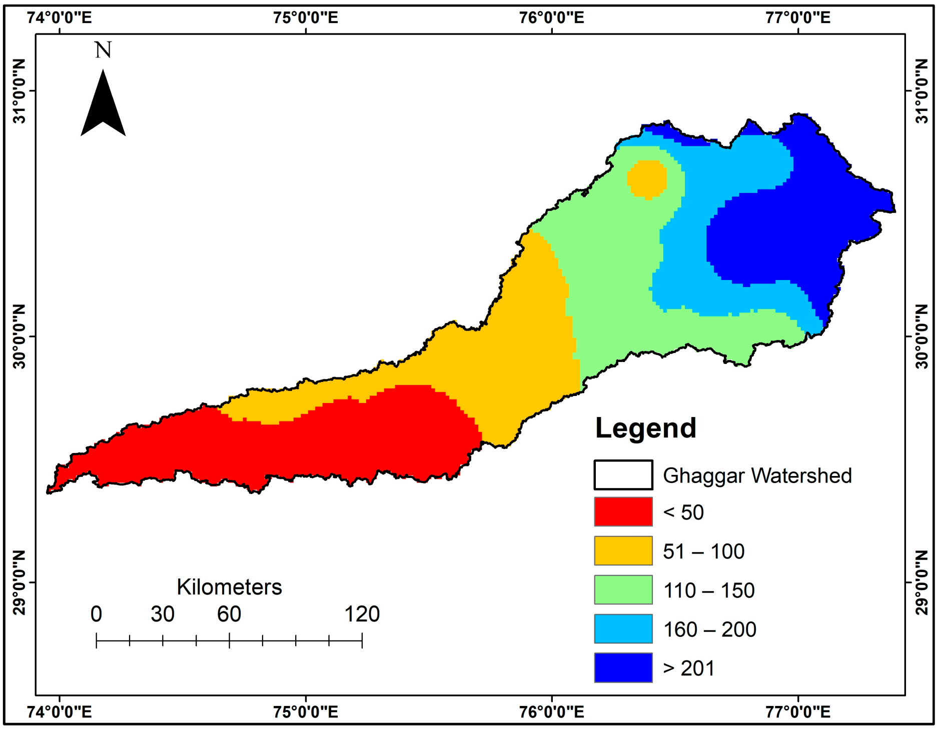

Figure 12. Interpolated rainfall distribution in the study region (Source: chrsdata.eng.uci.edu).

Table 6. Analytic Hierarchy Process (AHP) based weights assigned to each criterion for groundwater potential zone mapping.

Parameters	Hydro-Geomorphology/ Geology/Soil	Rainfall	Slope	Lineament	Drainage	LU/LC	Weight
Hydro-geomorphology/ Geology/Soil	6	5	4	3	2	1	0.41
Rainfall	6/2	5/2	4/2	3/2	2/2	1/2	0.20
Slope	6/3	5/3	4/3	3/3	2/3	1/3	0.14
Lineament	6/4	5/4	4/4	3/4	2/4	1/4	0.10
Drainage	6/5	5/5	4/5	3/5	2/5	1/5	0.08
Land use/Land Cover	6/6	5/6	4/6	3/6	2/6	1/6	0.07

2.3. Methods

The Geological Quadrangle Map issued by the Geological Survey of India was used to create a geological map of the area (GSI). Other thematic maps were created using GIS from satellite images and included drainage density, geomorphology, lineament density, land use/land cover, slope, and soil. A groundwater potential zonation map was created by combining all of the theme layers. The following three steps were used to integrate various themed maps using GIS: (i) creating a spatial database, (ii) analysing spatial data, and (iii) Data Integration [28].

Arc GIS software was used to construct all of the thematic maps, which included digitization of scanned maps, error correction, topology building, attribute assignment, and projection [27,28]

The drainage pattern, lineament, soil, hydrogeomorphology, geology, slope, and rainfall determine the groundwater prospect map of the area [29]. Each theme was evaluated, and a weighting was assigned based on its impact on groundwater recharge and storage. A groundwater prospect map was created by integrating all of these themed maps and incorporating limited data on groundwater levels. Different geological formations that give rise to a variety of landforms, such as structural hills, pediments, buried pediments, and valley fills, have varying water-holding capacities, indicating a range of aquifer characteristics.

Each thematic map, such as geomorphology, geology, drainage, drainage density, lineament, lineament density, soil, slope, and land use/land cover, offers information on groundwater occurrence. To discover the crossing polygons, each theme was superimposed on another theme. By combining two thematic maps in this way a new map was created. This composite map was then superimposed on a third thematic map, and so forth. As a result, a final composite map was created. The groundwater potential zones were delineated and grouped into four zones, namely (i) low, (ii) moderate, (iii) high, and (iv) very nigh, in the final map, using a simple mathematical model to assign weightage to each polygon. The methodology adopted in this study is represented in the figure below (Figure 13).

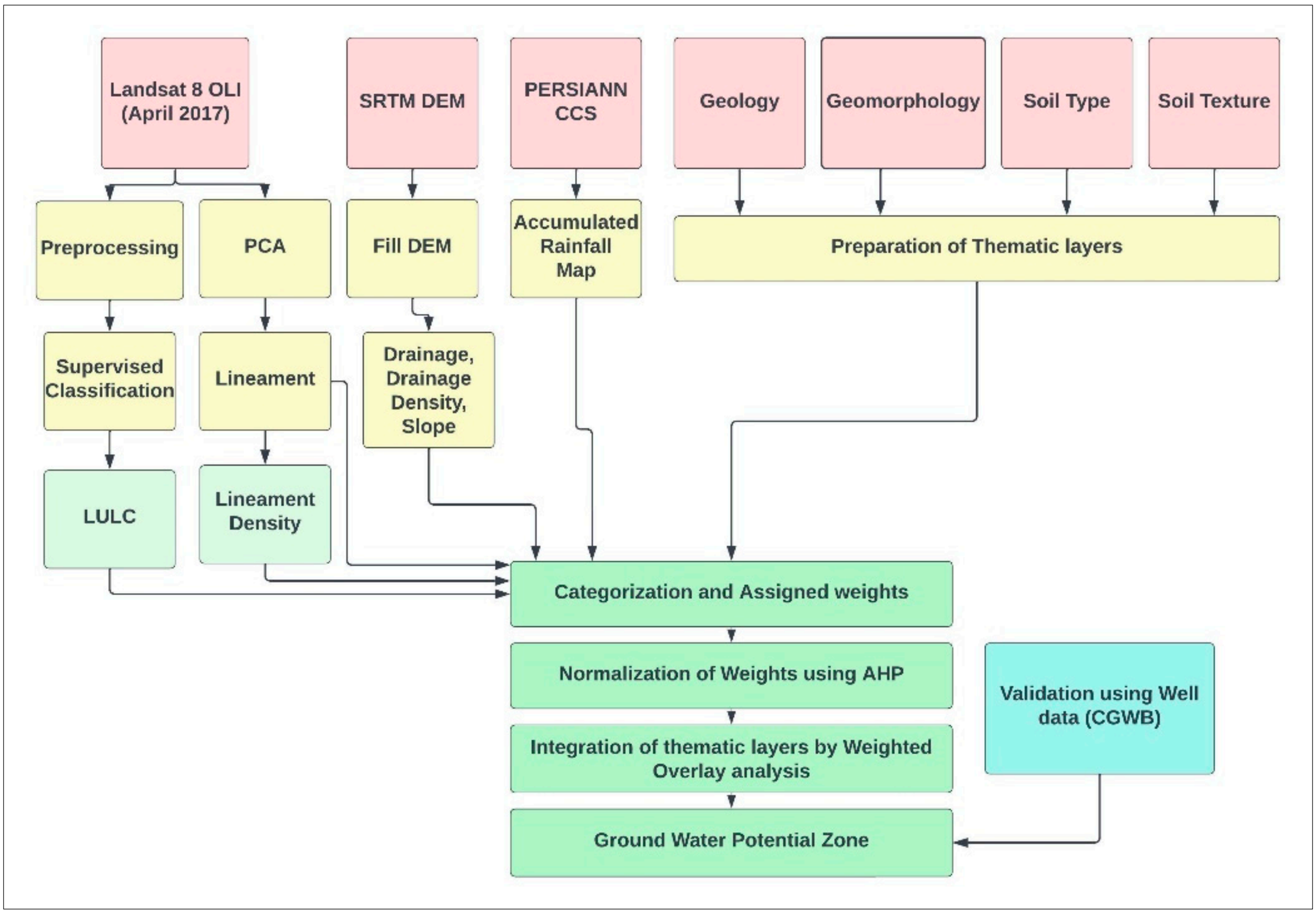

Figure 13. Methodology adopted.

Assigning Rank and Weight to Thematic Layers

For the evaluation of the groundwater potential zones, the spatial thematic layers have been integrated using a weighted overlay approach.

Before overlaying could be performed, all the individual spatial layers had to be reclassified into a uniform rank ranging from 1 to 4, where 1 was allocated poor groundwater potential, whereas 4 was allotted excellent groundwater potential. Matrix-based pairwise comparisons on Analytical Hierarchy Process (AHP) have been used for assigning weights (Table 6). The assigning of the weights has been carried out based on experiences gained through field surveys and existing literature on research work carried out in the field [4,15,27,30–32]. Hydrogeomorphology, soil, and geology have been assigned the highest weight. Moderate weight has been assigned to drainage density, lineament density, and slope. The lowest weights have been assigned to land use/land cover (Table 7).

Once the weights were assigned to the various spatial thematic layers or parameters, the ranking was done for sub-variables in each theme [15,23,33–37] (Table 7). The highest value characterized the region with maximum groundwater potential, whereas the lowest value characterized the region with the lowest groundwater potential.

Table 7. Weights assigned for different parameters controlling/influencing groundwater in the study area.

Parameter	Classes	Weight	Rank
Geomorphology/Geology/Soil	Alluvial Plains	0.41	4
	Older Flood Plains		4
	Highly Dissected Structural Hills and Valleys		1
	Piedmont Alluvial Plain		3
	Coarse Texture Soil		4
	Fine Texture Soil		4
	Rocky Soil		1
	Sedimentary		4
	Metamorphic		1
Rainfall (mm)	250–350	0.20	1
	350–450		2
	450–550		3
	550–650		4
Slope (Degrees)	0–10	0.14	4
	10–20		3
	20–30		2
	30–40		1
	40–50		1
Lineament Density (km/km^2)	0–0.05	0.10	1
	0.05–0.10		1
	0.10–0.15		2
	0.15–0.25		3
	0.25–0.35		4
Drainage Density (km/km^2)	0.01–0.05	0.08	4
	0.05–0.10		3
	0.10–0.15		2
	0.15–0.20		1
Land Use/Land Cover (LU/LC)	Water Bodies	0.07	3
	Vegetation		4
	Agriculture		4
	Settlement		1
	Others		2

3. Results and Discussion

3.1. Delineation of Groundwater Potential Zones

The assimilation of all the spatial thematic layers has been performed in the ArcGIS software to get a single map portraying the groundwater potential zone (Figure 14). On a scale of 1–4, four different classes have been taken viz. low, moderate, high, and very high (Table 8 & Figure 15). As evident from the map (Figure 15), moderate, high, and very high zones are uniformly distributed in the region where alluvium is dominant, whereas low zones fall in the lower Shivalik belt or the hilly region in the study area. The study area has good groundwater potential as the majority of the region falls (76.69% of the area) and lies in the zone with high groundwater potential. Approximately 7.29% of the region falls in the zone with very high groundwater potential, whereas 15.65% and 1.27% of the area fall in the zone with moderate and low potential, respectively, as is evident from the pixel-based analysis (Table 8) and pie chart (Figure 15). As is evident from the pixel-based calculations 14,912.9 sq. km of the area falls in the high groundwater potential zone; 3080.81

sq. km falls in the moderate groundwater potential zone; 1435.7 sq. km falls in the very high groundwater potential zone; and 251.94 sq. km falls in the low groundwater potential zone (Table 8).

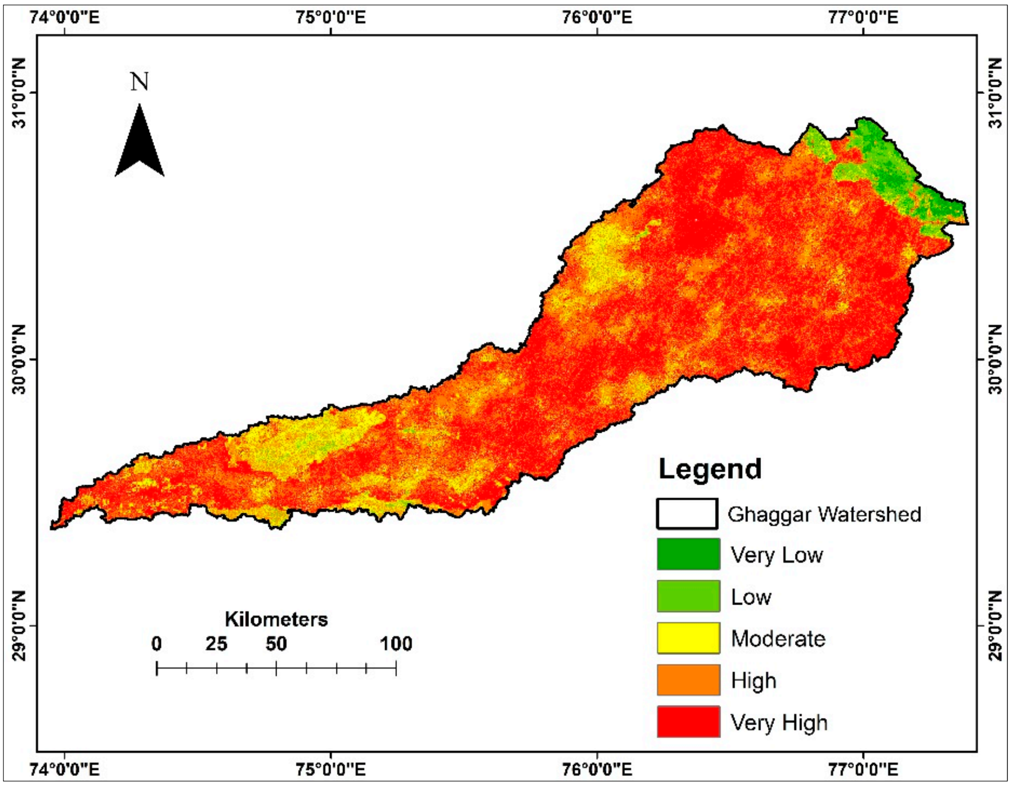

Figure 14. Groundwater potential zone map of the study area.

Table 8. Pixel-based analysis for ground water potential (30 m).

S. No.	Value	Count Pixel	Classes	Area (sq. km)	Area (%)
1	2	21,938	Low	19.74	0.10
2	3	258,013	Low	232.2	1.17
3	4	796,503	Moderate	716.8	3.64
4	5	2,626,677	Moderate	2364.01	12.01
5	6	7,998,471	High	7198.6	36.5
6	7	8,571,521	High	7714.3	39.19
7	8	1,595,224	Very High	1435.7	7.29
			Total	19,681.5	100

The regions with favorable geological, soil, and geomorphological form and high lineament density, very gentle slope, and low drainage density have very high and high groundwater potential. The zones with low groundwater potential are those that have a steep slope and unfavorable geological, soil, and geomorphological form. The recharge capacity of the zones with low groundwater potential is lower when com-pared with the very high, high, or moderate zones [16,32,38].

3.2. Validation of Groundwater Potential Zones Using CGWB Well Data

The results obtained from the remote sensing-based studies need to be validated with field studies or ground truthing. In the present study, well data (piezometer or dug well) provided by the CGWB has been taken as they are considered as a proxy for the availability of groundwater (Figure 16). Groundwater level data from 100 wells for the pre-monsoon season has been used for analysis. It is no wonder that the regions with high groundwater potential zones support perennial dug wells, whereas the zones with low groundwater potential tend to dry during summers or non-monsoon seasons. The data groundwater level from approximately one hundred dug wells, bore wells, and piezometers from CGWB have been used for validation purposes. Field surveys also confirmed that a majority of these dug wells, bore wells, or piezometers are in regions that show very high or high groundwater potential zones. They were also found to be thereby indicating that there is the existence of a permeable reservoir with considerable water storage in the subsurface.

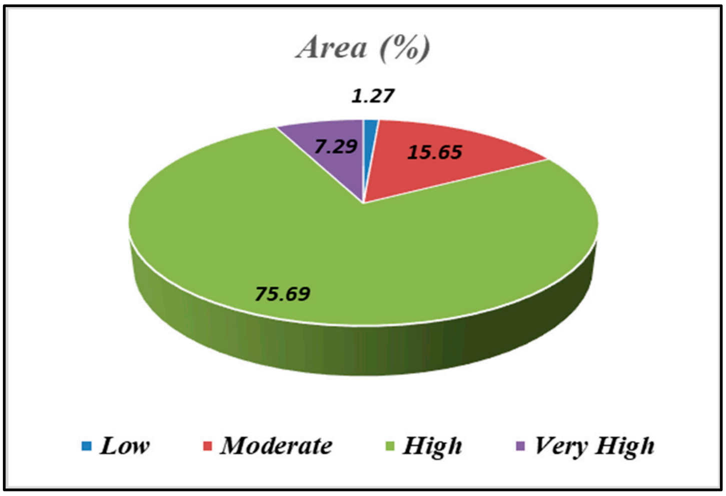

Figure 15. Pie chart showing groundwater potential in the study region.

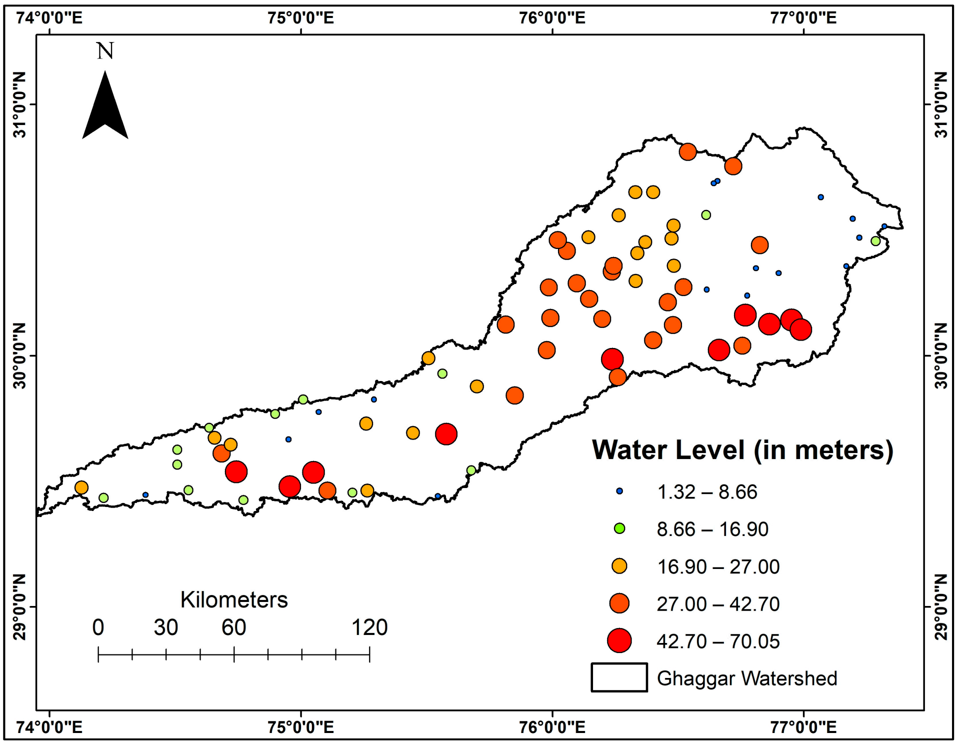

Figure 16. Groundwater level depth (Source: Central Ground Water Board).

Ref. [29] analyzed groundwater level fluctuations in Haryana, a part of the study area, from 2005–2014 using time-series data from the CGWB. The study found that groundwater levels have been declining at an alarming rate in the region due to over-exploitation for irrigation and domestic purposes. Ref. [39] analyzed groundwater level changes in the Ghaggar River Basin from 1998–2016 and found a significant decline in groundwater levels, especially in the southern parts of the basin. These studies high-light the issue of groundwater depletion in the study area and indicate that the groundwater level data used in the current study may have been affected by exploitation [40,41].

As can be clearly seen, the high groundwater potential zones, delineated as seen in Figure 17, coincide with the groundwater at shallow depths. Thus, these observations not only prove the high-level accuracy of the assessment using the geospatial approach for the characterization of the groundwater potential zones in the study region. In the current global scenario, where we have been extensively using natural resources, leading to the over-exploitation, and dwindling of these resources, we need to follow sustainable ways and means [3,42]. In this context, the sustainable use of groundwater resources cannot be ignored, keeping in view the necessity to promote socio-economic development and the long-term sustainability of agriculture, especially in regions that are based on agrarian economy and are devoid of significant river channels [43,44]. Agriculture largely depends on dug wells and rainfall in the study region, especially during the monsoon seasons.

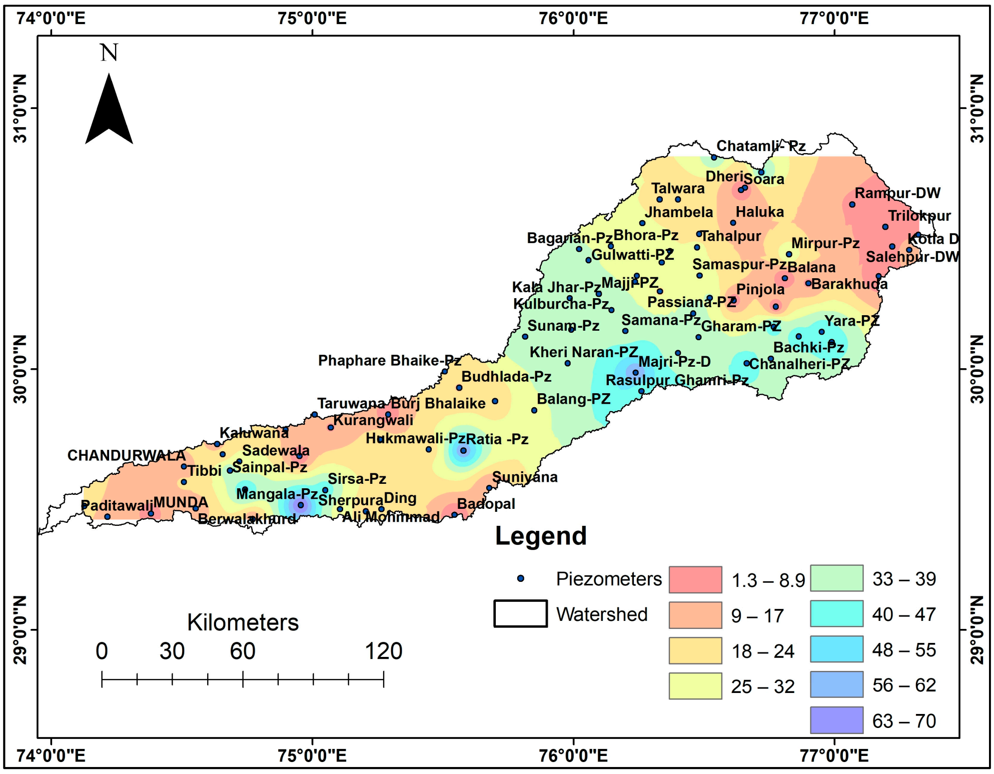

Figure 17. Interpolated groundwater level depth.

There is hardly any river lift irrigation in the region as there is no major perennial river. The rivers that flow through the region are only seasonal during the monsoons. All this has led to increased demand for groundwater extraction and amounts to a groundwater deficit.

The potential groundwater zones in the region have been delineated through RS and GIS-based AHP methodology, and the results revealed that more than 83 percent of the region falls in a high and very high groundwater potential zone. This zone has favorable rainfall, hydro-geomorphology, slope, land use/land cover, drainage density, and lineament density [45–48]. The recharge of the groundwater is mainly through rainfall. The moderate to steep areas are considered to be favorable for groundwater recharge and are ideal sites for rainwater recharge structures such as farm ponds, check dams, and water absorption trenches to harness stormwater and minimize runoff.

4. Conclusions

In the present study, an attempt has been made to delineate the groundwater potential zones in the Ghaggar River basin in the northwestern part of India using GIS and AHP techniques. A total of eight thematic layers, such as geomorphology, geology, soil, LULC, rainfall, lineament density, drainage density, and slope gradient have been used in the study for the delineation of the potential groundwater zones. The study area can be classified into four distinct groundwater potential zones such as low, moderate, high, and very high. A total of 75.69% and 7.29% of the area falls in high and very high groundwater potential zone, respectively. A total of 15.65% falls in the moderate groundwater potential zone, whereas 1.27% falls in the low groundwater potential zone. The region with high groundwater potential zones falls in the sedimentary beds. The validation of these delineated groundwater potential zones has been done using groundwater prospects or well data.

The potential groundwater zones in the present study can be instrumental in locating suitable sites for groundwater extraction, developing a sustainable approach for groundwater utilization, and the formulation of better land-use planning or urban planning and water resource management strategies in the already water-stressed region. The present study strongly affirms the application of remote sensing and GIS techniques in groundwater prospect mapping. The study area has high groundwater potential in the region despite the absence of a major river network in the region. This can be attributed to the presence of a strong network of paleochannels.

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