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Comparative Analysis of Different Factors Affecting Groundwater Potential Using Geospatial Techniques

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Abstract

Groundwater is an essential natural resource for supporting biological existence on Earth. It is also helpful in promoting socioeconomic development. The management of this resource is of utmost importance, particularly when there is over depletion for fulfilling the demand. In this study, an investigation was conducted to evaluate the role of the factors responsible for groundwater potential (GWP) in the Ratmau Rao basin (Uttarakhand). GWP is controlled by various parameters, such as geological formations, slopes, soil types, drainage networks, and surface runoff, for which a thorough study is needed. Geographic information system (GIS) and remote sensing technologies are suitable platforms for spatiotemporal monitoring of groundwater storage (GWS). This further helps in the sustainable use and effective management of groundwater. The analytical hierarchy process (AHP) was implemented in this study within a GIS environment to assess the elements that affect the GWP. The quality and accuracy of hydrogeological inputs can be improved by satellite imagery. Geospatial technologies offer valuable insights into complex hydrogeological systems, which are extremely important for places in Himalayan foothills that are confronted with the issue of groundwater depletion. The study covers an area of 323 km2, utilizing remote sensing technology with field surveys to provide maps related to hydrogeomorphology (HG), drainage density (DD), soil, land use land cover (LULC), lineament density (LD), and slope. Different parameters were analysed using multicriteria decision analysis (MCDA) to evaluate the effects of each criterion on the GWP using the AHP. In this research, among all six factors affecting the GWP, HG affects the GWP the most, with an influencing weight of 0.425, followed by DD (0.227). Furthermore, soil type and LULC had impacts, with weights of 0.127 and 0.108, respectively. LD and slope have the least impact on GWP, as their influence weights are only 0.074 and 0.038, respectively. Overall, HG has the greatest influence on the GWP, followed by DD, soil type, LULC, LD, and slope.

Keywords: Groundwater, thematic maps, GIS, and analytical hierarchy process.

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1. Introduction

Water is a natural resource and has an essential role in every field for living beings. This resource is present in both surface water and groundwater. It plays a vital role in supporting all forms of life on our planet. Groundwater has its utmost importance owing to its crucial contribution to human well-being, ecological equilibrium, and socioeconomic progress [1]. The regulation of groundwater availability and replenishment is influenced by various factors, such as formations in the Earth's crust, slopes, and runoff from the surface [2]. Recently, there has been a noticeable rise in the reliance on groundwater for many purposes, including domestic, agricultural, and industrial use. The excessive consumption of this specific resource is leading to its gradual depletion, thus necessitating the deployment of effective management techniques [3].

This study highlights the various factors that influence groundwater potential (GWP) and provides a comprehensive understanding to monitor groundwater resources appropriately. The utilization of geographic information system (GIS) and remote sensing technology has led to significant progress in the spatial and temporal monitoring of groundwater [4]. These technological advancements facilitate the evaluation of hydrogeological and geomorphic attributes, hence helping in the delineation of GWP across different geographical areas [5]. In this study, an approach of multicriteria decision analysis (MCDA), i.e., the analytical hierarchy process (AHP) in conjunction with GIS was used to evaluate several factors influencing GWP. This study aims to help implement sustainable groundwater management in the Ratmau Rao Basin. This objective will be accomplished by conducting a comparative analysis of the influence of different factors on the GWP. The predicted outcomes of this study are expected to serve as a foundation for strategic planning and conservation efforts aimed at mitigating the accelerated depletion of water resources.

The concept of groundwater zonation refers to the division of underground water resources into distinct zones on the basis of various hydrogeological characteristics [6]. This study focuses on the identification of regions exhibiting substantial GWP by employing modern mapping methodologies. Initially, satellite images and aerial photographs were used to enhance and improve preexisting hydrogeological maps [7]. However, recent technological inventions have facilitated the creation of highly accurate maps with limited dependence on traditional fieldwork methods [8]. Remote sensing is a commonly employed technique because of its extensive and quick coverage, facilitating the understanding of variations in hydrogeological systems, particularly in geographically

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isolated regions [9-10]. To increase precision, the system is integrated with GIS, field measurements, and modelling methodologies. Spatial analysis tools refer to a set of techniques and methodologies used to analyse and interpret spatial data. These tools are able to examine a wide range of areas, such as land-use planning and environmental management, by providing significant value and benefits [11]. This approach offers a cost-effective and time-efficient solution for managing complicated spatial data.

2. Study area

The Ratmau Rao Basin is located in the Haridwar district of Uttarakhand state (India) and has an area of ~323 sq. km. This area is occupied by latitudes 29°56'14.62" N to 30°10'37.74" N and longitudes 77°53'53.02" E to 78°04'14.15" E. This region is surrounded by the Pathri Rao River on the eastern side and the Solani River on the western side. It encompasses different topographies, including mountains, bazadas, alluvial plains and approximately 42 villages located in this area. This study area is located in the Himalayan region, which may be ideal for GWP due to its geological diversity, but most of the villages in this basin are facing water scarcity. This basin also plays a crucial role in regional hydrology, supporting agricultural and local populations that rely on groundwater.

3. Data and techniques

Various data sources were precisely integrated in this study. These include satellite data, in the form of Landsat-8 imagery, as well as topographic maps from the Survey of India. Additionally, for soil information, a soil map was obtained from the National Bureau of Soil Survey and Land Use Planning (Nagpur, Maharashtra). Ancillary data, which are essential for comprehensive analysis, were gathered to support this research. Furthermore, hydrogeological data were obtained from the Irrigation Research Institute (IRI) and the Water and Land Management Institute (WALMI) Lucknow. This extensive dataset provides a strong foundation for the subsequent analyses and assessments conducted in this study.

MCDA facilitates the integration of various spatial data layers to enhance the decision-making process. The process involves the decomposition of complicated problems into smaller components, which are subsequently assessed to achieve full resolution. In the domain of MCDA, several approaches are available to address situations of different levels of complexity [12]. The AHP is a decision-making methodology under consideration that was created by Thomas Saaty during the 1980s [13]. The AHP is a technique utilized for the purpose of evaluating and comparing different alternatives while considering multiple criteria. This framework offers a systematic methodology for decision-making, taking into account several aspects and their respective levels of significance [14-15]. The utilization of this particular tool is prevalent across various disciplines, including business and engineering. This study employs the AHP as a technique within the broader framework of MCDA for assigning weights to various criteria. However, the AHP presents several difficulties, particularly when challenged with an extensive collection of criteria, hence requiring the execution of multiple iterations of pairwise comparison analysis [16]. The methodology employed for allocating weights to thematic layers in the evaluation of GWP includes many essential phases.

4. Model construction

The initial phase involves a comprehensive examination of the literature to identify and analyse the various models utilized. The present problem is clearly defined and systematically examined with respect to numerous thematic factors that affect the GWP. Each thematic layer has the potential to include many feature classes, which in turn might impact groundwater dynamics [12], [2], [17]. The pairwise comparison matrix (PCM) is used to assign relative weights to the thematic layers using Saaty's scale. The number 1 signifies that there is an equal level of importance between two levels; however, a value of 9 represents a significant degree of importance of one layer over the other, as shown in Table 1 [13], [6].

Table 1. Saaty's 1-9 Scale for pairwise comparison method [13]

Level of Importance	Definition	Significance
1	Equal	Both criteria contribute equally to the objective.
3	Moderate	Slight preference for one criterion based on judgment and experience.
5	Strong	Strong preference for one criterion, heavily guided by judgment and experience.
7	Very Strong	Very strong preference for one criterion, extremely guided by judgment and experience.
9	Extreme	Overwhelming evidence supports one criterion over the other.
2, 4, 6, 8	Intermediate	Utilized when a compromise between criteria is necessary.
Reciprocals	Inverse	If "i" is compared to "j" with a certain number, "j" has the reciprocal number when compared to "i".

Assigning the weights for many criteria is crucial when the AHP is used. Weights offer valuable insights into the relative significance of chosen criteria. These perspectives, which come from decision-makers, are extremely important for determining how effective each criterion is. PCMs encompass all conceivable pairings of criteria to determine those that possess a greater level of importance [14].

The AHP method employs a systematic approach to break down the problem into smaller components, assigns relative weights to different thematic layers and associated feature classes, and determines these weights on the basis of expert opinions [13]. This methodology facilitates more precise results and reveals the relationships among various factors affecting GWP. In this study, on the basis of previous literature and expert opinions, weights were assigned to the criterion. To collect the opinions of the experts, a team was formed that included six professors and seven research scholars from the same expertise. Conducting an evaluation of consistency using paired comparisons is necessary to determine the consistency ratio (CR). To ensure a decision of excellent quality, it is suggested that the CR be maintained at a value of 0.1 or below. A consistency ratio value of 0.1 indicates that the relationships between criteria in the AHP are consistent and that the assigned weights are appropriate. If the CR is above the threshold of 0.1, it is advisable for experts to re-evaluate and make appropriate modifications to the weights inside the PCM [13].

5. Methodology and results

This research employs a multifaceted methodology including advanced software tools, e.g., ArcGIS (version 10.8.2), ERDAS IMAGINE (version 14.0), Q-GIS (version 3.32), and SURFER (version 18.3.3), for data analysis. An investigation of physical characteristics, including geographical setting, soil texture, LULC, agricultural practices, and climate conditions, was carried out to provide a comprehensive understanding of the study area. Overall, the GWP is influenced by various thematic layers, including the soil, slope, land use and land cover (LULC), DD, geology, geomorphology, lineament density (LD), rainfall, roughness index, and wetness index. In this study, only six thematic layers were considered because these layers have a major impact on the GWP. The procedure of developing these thematic layers is shown in Fig. 1.

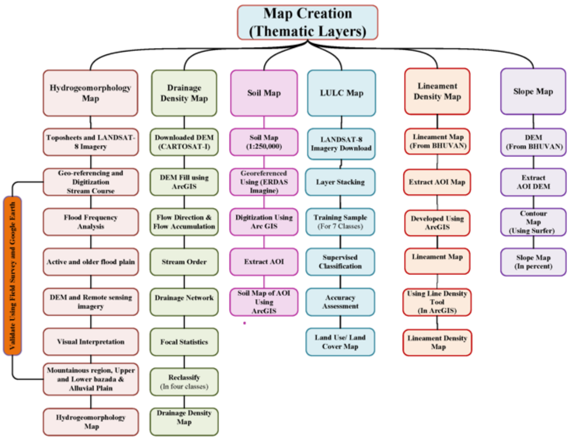

Fig. 1. Procedures of different maps Creation

5.1 Hydrogeomorphology map

The scientific study of landforms on the Earth's surface and the forces that shape them is known as geomorphology [4]. GWP is affected mainly by long-term geomorphological changes [18]. By digitizing stream courses from toposheets and confirming them with Google Earth and LANDSAT-8 data, a hydrogeomorphology (HG) map was produced for this study. The mapped landforms include active and older flood plains, upper and lower bazadas, alluvial plains, and stream courses, as shown in Fig. 2. The research area is dominated by alluvial plains and mountainous terrain, with alluvial plains in the southern region and hilly terrain in the northern region. Owing to water availability and rapid flood return, active flood plains and stream courses are responsible for higher GWP. The topographical features of the research area include a hilly region that exists at a higher elevation than the surrounding environment. The northern portion of the research area is a topographically diverse region characterized by a range of forested areas and shrublands. Importantly, the presence of mountains in the region facilitates effective drainage, leading to a restricted capacity for groundwater. As a result, this particular region was allocated comparatively less weighting in the assessment.

The upper bazada and lower bazada formations consist of a heterogeneous combination of rocks, pebbles, sand, and clay. In the Upper Bazada region, the presence of sand and clay is relatively diminished, while there is a notable abundance of boulders and pebbles. In contrast, the lower bazada region has a lower quantity of boulders and pebbles, revealing a significant abundance of sand and clay components. The categorization of the bazada regions was established by considering their influence on the GWP and subsequently assigning suitable weights to each category. The alluvial plain, located south of the Bazada plains, includes a large area with approximately fifteen villages located nearby. From a geological perspective, these alluvial plains are composed of deposits that range from unconsolidated to semiconsolidated. These deposits mostly consist of sand, silt, clay, and kankar.

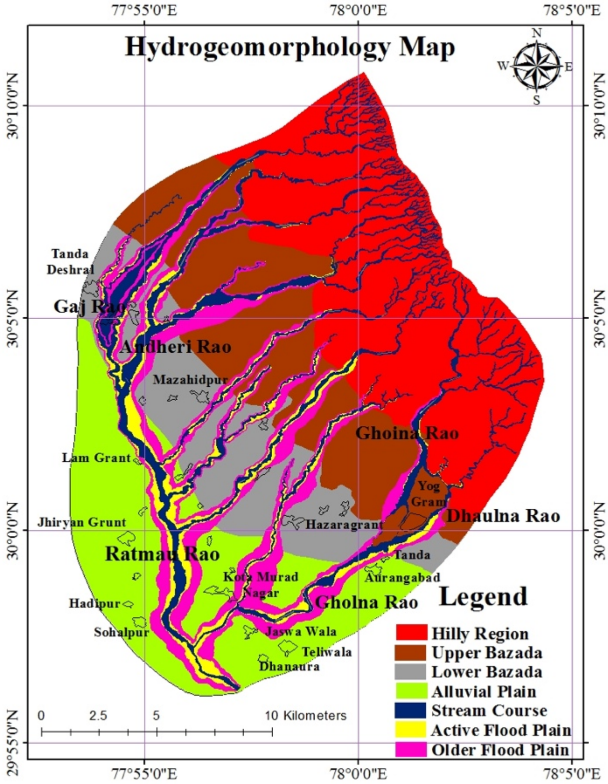

Fig. 2. Hydrogeomorphology Map

To determine the regions that are susceptible to flooding on the basis of the frequency of flood events in the region, a flood frequency analysis was carried out using Gumbel's method. In particular, regions that experienced flooding at a recurring interval of 5 years were categorized as active flood plains, whereas those with a flood recurrence period of 100 years were designated as older flood plains. Importantly, both active and older flood plains play significant roles as efficient infiltration zones, hence contributing to a favourable GWP. As a result, these areas receive more weight in the assessment process.

5.2 Drainage density map

The present study reveals that there is a significant variation in the number of drainages across different regions. In this research area, higher DD was observed in the northern region, and a gradual reduction was observed in the southern region. The presence of a significant quantity of drainages indicates a limited capacity for groundwater. A significant amount of rainfall water is lost by surface runoff, resulting in less infiltration to replenish the groundwater. On the other hand, regions characterized by a limited number of drainages exhibit reduced run-off and increased infiltration, hence facilitating the replenishment of groundwater resources [19], [3].

A DD map was created by applying the focal statistics tool to the drainage map, followed by reclassification in ArcGIS. The research area features a variety of DD values, ranging from 0-4.52 km/km^2. To facilitate analysis, the range of DD is further divided into four distinct classes: (i) high (3.39-4.52), (ii) medium (2.26-3.39), (iii) low (1.13-2.26), and (iv) very low (0.0-1.13) DD, measured in km/km^2 (shown in Fig. 3).

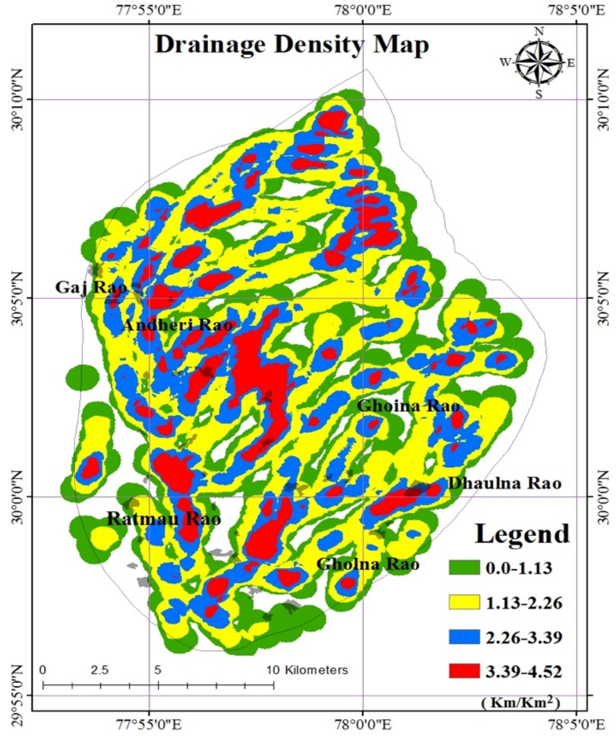

Fig. 3. Drainage Density Map

The calculation of DD involves determining the ratio between the length of the drainage system, measured in kilometres, and the entire area of the region, measured in square kilometres. The GWP is influenced mostly by DD, which is regarded as the most significant factor. The relationship between the permeability of the soil and infiltration rate is inversely proportional [20]. The existence of high DD in any area indicates a correspondingly high probability of surface runoff. Therefore, the chances for infiltration decreased, resulting in a reduced probability of GWP. Similarly, a location with a low DD is more likely to have a high GWP because of reduced surface run-off and increased infiltration [21]. On the basis of this analysis, greater weight was assigned to regions with lower DD, whereas regions with higher DD were assigned relatively lower weights.

5.3 Soil map

Different soil types also play important roles in determining infiltration capacity, which in turn directly influences GWP. Factors such as soil texture, thickness, clay content, and permeability are key determinants of infiltration [22]. In areas with sandy soil textures, which are characterized by low porosity and high permeability, favourable conditions exist for the GWP. On the other hand, soil that is composed of clay and has a high degree of porosity and a low level of permeability leads to reduced infiltration rates and a lower capacity for GWP [23]. Two prominent classifications of soil exist in the study area: sandy soil (S) and loamy sandy soil (LS). The categorization of these soil types is further refined by considering many parameters, including soil depth, erosion, and slope range. The categorization of soil depth consists of five distinct groups: D1 (soil depth less than or equal to 7.5 cm), D2 (soil depth ranging from 7.5 cm to 30 cm), D3 (soil depth ranging from 30 cm to 60 cm), D4 (soil depth ranging from 60 cm to 90 cm), and D5 (soil depth beyond 90 cm). The classification system based on slope range comprises six distinct categories: A (0–1% slope range), B (1–3% slope range), C (3–5% slope range), D (5–10% slope range), E (10–15% slope range), and F (15–25% slope range). Furthermore, the soil in the study area has been classified into four distinct groups on the basis of the extent of erosion observed. These groups are categorized as follows: slight erosion (e1), moderate erosion (e2), severe erosion (e3), and very severe erosion (e4) (shown in Fig. 4).

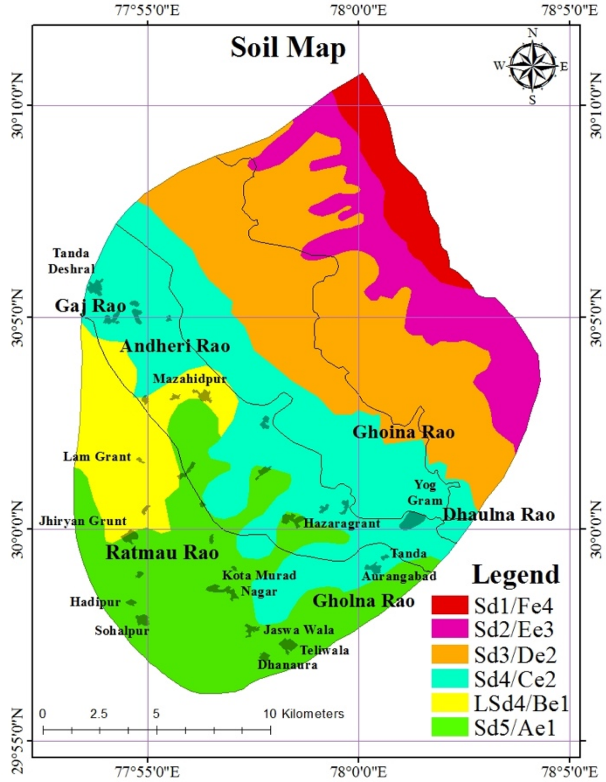

Fig. 4. Soil Map

This classification system offers a full and extensive analysis of the soil characteristics in the study area. This system provides useful insights that may be utilized in a range of environmental and agricultural assessments. There will be a greater infiltration rate in sandy soils with minor erosion and low slope ranges that have greater depths. Therefore, there is a greater probability of a good GWP, so it has been assigned more weight. Soils with a loamy texture are susceptible to erosion and have a high slope range with a very shallow depth and contain rock particles. As a result, there may be a low rate of infiltration, resulting in a lower probability of GWP, and a low weight has been assigned comparatively.

5.4 Land use/land cover map

LULC has a significant role in affecting GWP zones, as it encompasses human activities that utilize the Earth's surface. These include natural elements such as vegetation, soil, rocks, water bodies, and artificial structures [6]. Man-made features such as buildings, roads, and concrete structures also affect the GWP. The LULC map for the area was created using LANDSAT-8 (USGS) satellite data. This map was classified through supervised classification using the maximum likelihood algorithm, achieving an accuracy rate of 86%. LULC includes various categories, e.g., forest, social forest, built-up areas, water bodies, dry rivers, agricultural land, and eroded land, as shown in Fig. 5. Each LULC class was assigned a weight on the basis of its influence on GWP. Water bodies receive the highest weight because of their continuous groundwater recharge capacity.

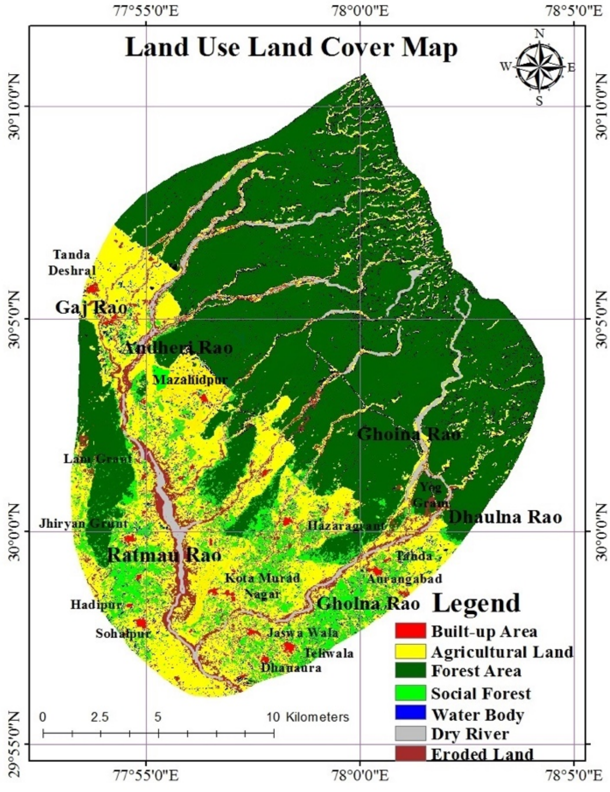

Fig. 5. Land use land cover map

Because agricultural regions help maintain the integrity of soil and prevent erosion during water runoff, a large weight has been assigned to these regions. Vegetation cover also reduces direct water evaporation and is assigned a weight lower than that of water bodies but higher than that of other categories. Social forests hold a greater weight than regular forests but less than agricultural areas. The lowest weight is assigned to waste land due to its lack of vegetation cover, and other factors are also weighted according to their influence on groundwater.

5.5 Lineament density map

Lineaments refer to the linear characteristics observed on the Earth's surface. These are typically associated with underlying geological structures such as faults, joints, and areas of weakness. A lineament encompasses various geological features, such as a fault-aligned valley, a sequence of faults, a linear coastline, or a combination thereof; [24]. The examination of groundwater lineaments is highly important in the field of hydrogeology since these lineaments control the flow of groundwater and significantly affect the GWP [25]. Lineaments are predominantly observed in the North–West and North–East directions. There is minimal existence of lineaments in the southeast and northeast directions. The presence of lineaments in hard rock regions is a significant factor in enhancing the infiltration rate for groundwater recharge.

Lineaments also have a significant effect on the determination of the GWP, resulting in increased GWP in nearby areas of lineament regions [26]. The lineament map was obtained from Bhuvan, and then, the LD map was generated by the line density tool within ArcGIS software. The resulting map is categorized into five distinct classes, with values ranging from 0.0 to 1.78 km/km^2. The LD classes exhibit a range of values, namely, very low (0.0-0.15), low (0.15-0.44), moderate (0.44-0.72), good (0.72-1.01), and very good (1.01-1.78) km/km^{2,} as shown in Fig. 6.

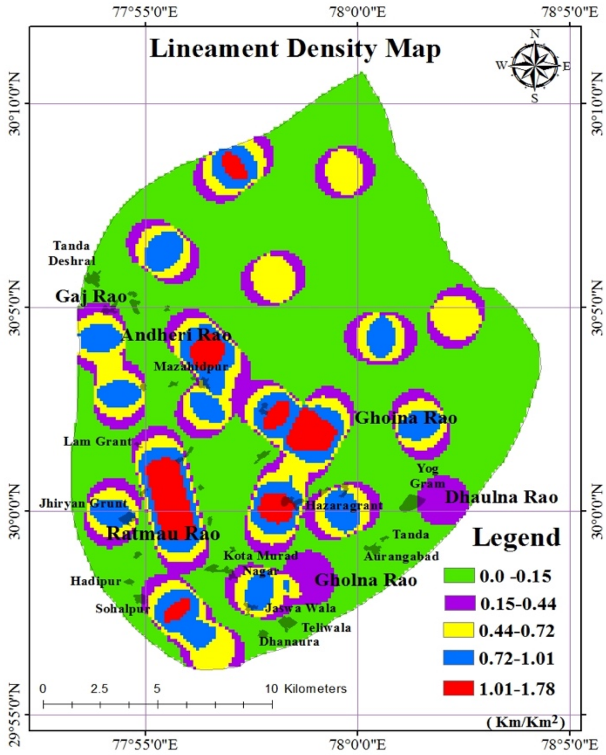

Fig. 6. Lineament density map

Areas with a higher density of lineaments exhibit more capacity for infiltration and groundwater recharge, leading to a rise in GWP. Consequently, a higher LD is indicative of a greater likelihood of a good GWP, whereas a lower LD suggests inadequate groundwater conditions. The class ranging from 1.01–1.78 km/km^2 was assigned a higher weight, whereas the class ranging from 0.0–0.15 km/km^2 was assigned a lower weight**.**

5.6 Slope map

The slope of land has a crucial role in affecting the GWP of any area. In this study area, the southeastern and southwestern regions have gentle slopes, indicating favourable conditions for groundwater with minimal runoff. On the other hand, the northern and northeastern parts have steeper slopes, leading to increased runoff and a reduced GWP. The slope map, created using Cartosat-I DEM data from BHUVAN, categorizes slopes into five classes ranging from 0–7% to 41–100%, as shown in Fig. 7. Weightage is assigned accordingly, with greater emphasis on areas with gentle slopes due to the high GWP, and less weight is assigned to areas with steep slopes, indicating a lower GWP.

6. Assigning weights to the criteria

An essential stage in determining GWP zones is to provide weights to the criterion. In this analysis, the significance of each criterion is calculated using AHP. The weights assigned to thematic layers affect the GWP zones. The weights for the site selection criterion in GWP assessment are determined using expert opinions and a thorough literature review. The assessment of consistency in the AHP approach is conducted through the utilization of the value of the consistency ratio (CR), which must be equal to or less than 0.1. The AHP assigns weights to each criterion on a scale of 1–9 according to Saaty [13]. The final weights were assigned to thematic layers after normalization (Tab. 2) of the pairwise comparison matrix (Tab. 3).

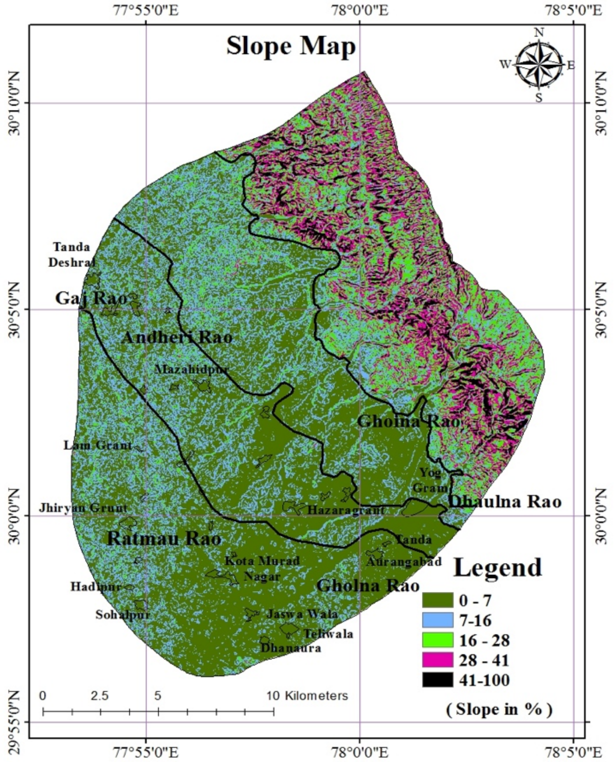

Fig 7. Slope map

6.1 Consistency analysis

To assess the compatibility of the initial preference ratings, it is necessary to calculate the consistency index (CI) and the consistency ratio (CR). This may be achieved by utilizing the principal eigenvalue (λ_{max}) value of 6.55 and a random consistency ratio (RI) of 1.24.

The calculation of the consistency index (CI) is performed in the following manner:

The CI can be calculated using the formula (λ_{max} - n)/(n - 1), where λ_{max} represents the maximum value and n represents the sample size. In this case, the CI is calculated as (6.55 - 6)/(6 - 1) = 0.55/5 = 0.11.

The calculation of the CR obtained by dividing the CI by the RI results in a value of approximately 0.089.

6.2 Comparative analysis of factors influencing GWP

The factors influencing GWP within the research area exhibit a measurable hierarchy in terms of relative importance. These factors are presented in distinct descending order: HG, DD, soil, LULC, LD, and slope. A definite hierarchy becomes evident when evaluating the impacts of several characteristics on the GWP. HG holds a prominent position in the analysis, carrying a significant weight of 0.425. This is mostly due to its comprehensive coverage of several categories, such as mountainous (hilly) regions, upper bazada, lower bazada, stream courses, active flood plains, older flood plains, and alluvial plains. Various topographical factors have the most significant impact on GWP resources. The DD is assigned a weight of 0.227, which denotes the measure of drainage network density and its influence on groundwater. Different soil types, which are classified into categories, i.e., Sd1/Fe4, Sd2/Ee3, Sd3/De2, Sd4/Ce2, LSd4/Be1, and Sd5/Ae1, are organized in a hierarchical manner with a weight of 0.127. The various soil types present distinct characteristics that together influence the GWP. The fourth-ranked category in terms of LULC comprises various components, including built-up areas, agricultural lands, forests, social forests, waterlogged areas, sandy lands, and eroded lands. This category has a weight of 0.108, indicating the significance of human activities and the different forms of land cover. The LD, although having a relatively low weight of 0.074, indicates the existence of geological characteristics that influence the movement and retention of groundwater. Despite its function in water transportation, the slope percentage, which has the lowest weight of 0.038, exerts the least influence. The study area is characterized primarily by the primary role of HG in influencing the GWP.

Table 2. Pairwise Comparison matrix

	HG	DD	LD	LULC	Slope	Soil
HG	1	2	3	8	9	5
DD	0.5	1	3	4	5	2
LD	0.33	0.33	1	0.5	2	0.25
LULC	0.125	0.25	2	1	3	2
Slope	0.111	0.2	0.5	0.33	1	0.33
Soil	0.2	0.5	4	0.5	3	1

Table 3. Normalize matrix

	HG	DD	LD	LULC	Slope	Soil
HG	0.441	0.467	0.222	0.558	0.391	0.472
DD	0.22	0.233	0.222	0.279	0.217	0.189
LD	0.147	0.078	0.074	0.035	0.087	0.024
LULC	0.055	0.058	0.148	0.07	0.13	0.189
Slope	0.049	0.047	0.037	0.023	0.043	0.031
Soil	0.088	0.117	0.296	0.035	0.13	0.094

7. Conclusion

The assessment of groundwater resources plays a crucial role in the management of groundwater for domestic and agricultural purposes, particularly in the region adjacent to the foothills of the Himalayas. In this region, groundwater is depleted at an accelerated rate, increasing the costs associated with groundwater exploration. However, this procedure largely depends on the availability of spatial and temporal data, which are sometimes not easily accessible. In this particular investigation, an evaluation was conducted to determine the zones with groundwater potential (GWP) across a geographical expanse of 323 square kilometres in Haridwar district, Uttarakhand. The assessment included the production of maps of HG, DD, soil, LULC, LD and slope. In this research, factors influencing GWP show a hierarchy of importance: hydrogeomorphology (42.5%), drainage density (22.7%), soil (12.7%), LULC (10.8%), lineament density (7.4%) and slope (3.8%). Hydrogeomorphology, including mountainous (hilly) regions and upper/lower bazada regions, plays a crucial role in influencing the GWP. Drainage density reflects network patterns and significantly affects GWP. Soil types and LULC, including built-up, agricultural, forest, etc., also contribute significantly. Lineament density indicates the influence of geological features, whereas slope has the least impact. The development of these maps involved the integration of remote sensing data, supplementary information, and in-person field surveys. All the data were processed within the environment of a GIS framework. The accurate evaluation and comparative analysis of the factors affecting groundwater resources help to precisely identify the locations of groundwater sources. These results are verified and refined through extensive field surveys to obtain a thorough understanding of GWP resources.

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