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Assessment of groundwater potential over the Haryana region: GIS-AHP v/s field data

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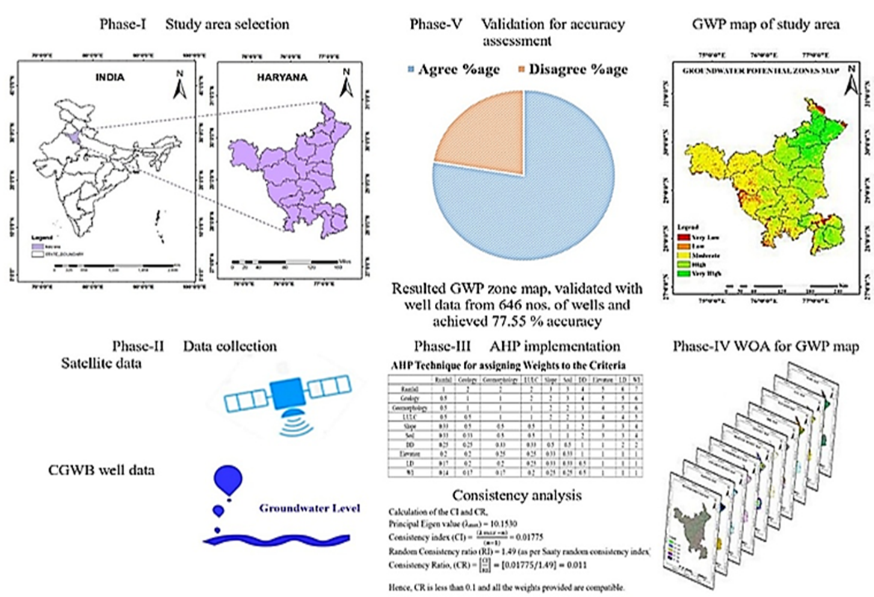
Abstract

This study delineates groundwater potential (GWP) zones across Haryana, India, for the year 2023 using geospatial techniques integrated with the analytical hierarchy process (AHP). Multiple thematic layers, including slope, land use/land cover (LULC), soil, geology, drainage density (DD), lineament density (LD), elevation, rainfall, and topographic wetness index (TWI), were generated using datasets from SRTM, Sentinel-2, food and agriculture organization (FAO), and the India meteorological department (IMD) and weighted through the AHP. These layers were integrated using weighted overlay analysis (WOA) to generate the final GWP map. The GWP map was validated against field groundwater level (GWL) data from 646 wells recorded in 2018 by the central ground water board (CGWB), resulting in an accuracy of 77.55 percent. This confirmed the reliability of the geographic information system (GIS) and AHP technique. The study reveals that moderate GWP zones dominate (43.71%) the region, followed by high (33.24%) and very high (11.96%) zones, whereas low and very low GWP zones cover 7.59% and 3.51% of the area, respectively. The findings indicate that Haryana's groundwater distribution is largely stable, with minor variation observed between 2018 and 2023. This shows stable aquifer behaviour and relatively unchanged recharge and extraction patterns over the five-year period. The outcomes of this study are valuable for strategic groundwater management, especially in arid and semiarid regions of Haryana state.



Graphical abstract

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1. Introduction

Groundwater is a crucial natural resource that sustains agricultural, industrial, urban, and rural development across India [1]. It is the primary water source for meeting the needs of the drinking, irrigation, and industrial sectors, especially in regions where surface water is either limited or unavailable. In Haryana, approximately 90% of the extracted groundwater is utilized for irrigation purposes, primarily through the use of tube wells [2]. Its demand has also increased many-fold due to population growth and the expansion of the industrial sector [3]. Haryana state plays a vital role in India's economy, especially in the agricultural and industrial sectors. As part of the water-rich Indo-Gangetic basin, it is on the verge of a severe water crisis due to the over-extraction of groundwater. These unique hydrological and socioeconomic characteristics make groundwater management a pressing challenge. Therefore, the importance of groundwater becomes particularly critical in arid and semiarid areas and where seasonal rainfall and surface water sources are limited [4]. This unsustainable use poses serious environmental and socioeconomic challenges, highlighting the urgent need for groundwater management.

Geospatial technology plays a crucial role in groundwater analysis by enabling accurate mapping, monitoring, prediction and management of subsurface water resources [5-7]. Geographic information system (GIS) facilitates the integration of multiple spatial datasets, allowing detailed analysis of parameters such as soil texture, land use/land cover (LULC), and topographical features that influence groundwater dynamics [8-9]. One particularly effective decision-making technique is the analytical hierarchy process (AHP), a multicriteria decision analysis (MCDA) method introduced by Saaty [7]. The AHP enables the systematic evaluation of various factors influencing the groundwater potential (GWP) by assigning weights on the basis of expert judgment and comparative importance. The assessment of GWP zones using GIS-based AHP techniques encompasses several essential phases. This includes data collection from diverse sources, processing these data to generate thematic layers, and assigning relative weights to these factors according to their impact on the GWP. This also includes the use of spatial analysis tools to integrate the thematic layers, ultimately resulting in a map of GWP zones. The changes in groundwater storage (GWS) in any region can also be evaluated by utilizing advanced geospatial techniques [8]. Vertical electrical sounding (VES) and GIS have been used to assess aquifer potential and vulnerability for groundwater management [9]. By employing fuzzy logic, it is possible to estimate groundwater inflow in tunnels accurately with simplified data and rule-based modelling [10]. Groundwater quality also becomes a significant concern in recent years and is influenced by various anthropogenic and natural factors. Mining activities impact groundwater quality, with high arsenic and iron levels posing health risks [11]. An IoT-based wireless sensor system can also be implemented for real-time monitoring of pH and TDS levels [12].

In this study, multiple thematic layers, such as slope, LULC, soil, geology, geomorphology, drainage density (DD), elevation, lineament density (LD), rainfall, and topographic wetness index (TWI) were used. The thematic layers were then reclassified and assigned weights using the AHP approach and finally integrated using a weighted overlay analysis (WOA) technique to produce the final GWP map. This map was validated using field-based groundwater level (GWL) data from 646 wells collected in 2018 from the central ground water board (CGWB). The temporal comparison of GWP (2023) and GWL (2018) also enables the evaluation of potential shifts in groundwater zones over a five-year period. This study aims not only to provide a scientifically grounded map of the GWP in Haryana but also emphasizes for long-term water resource planning, recharge zone identification, and extraction regulation, especially in the face of increasing water demand and climatic uncertainty.

2. Study area

The state of Haryana was selected as the study area for this research. Most of the regions in the state are characterized by semiarid to arid climatic conditions and increasing pressure on groundwater resources. Geographically, it spans from latitudes 27°39' to 30°35' North and longitudes 74°28' to 77°36' East, covering an area of approximately 44,212 km² (Figure 1). Haryana is bordered by Punjab to the north, Himachal Pradesh to the northeast, Uttarakhand and Uttar Pradesh to the east, Rajasthan to the south and southwest, and the national capital territory (NCT) of Delhi to the southeast. The state is home to approximately 7356 villages, many of which are experiencing acute water scarcity. The predominant reliance on groundwater for drinking, irrigation, and domestic needs, especially in rural and peri-urban areas, highlights the urgent need for groundwater assessment.

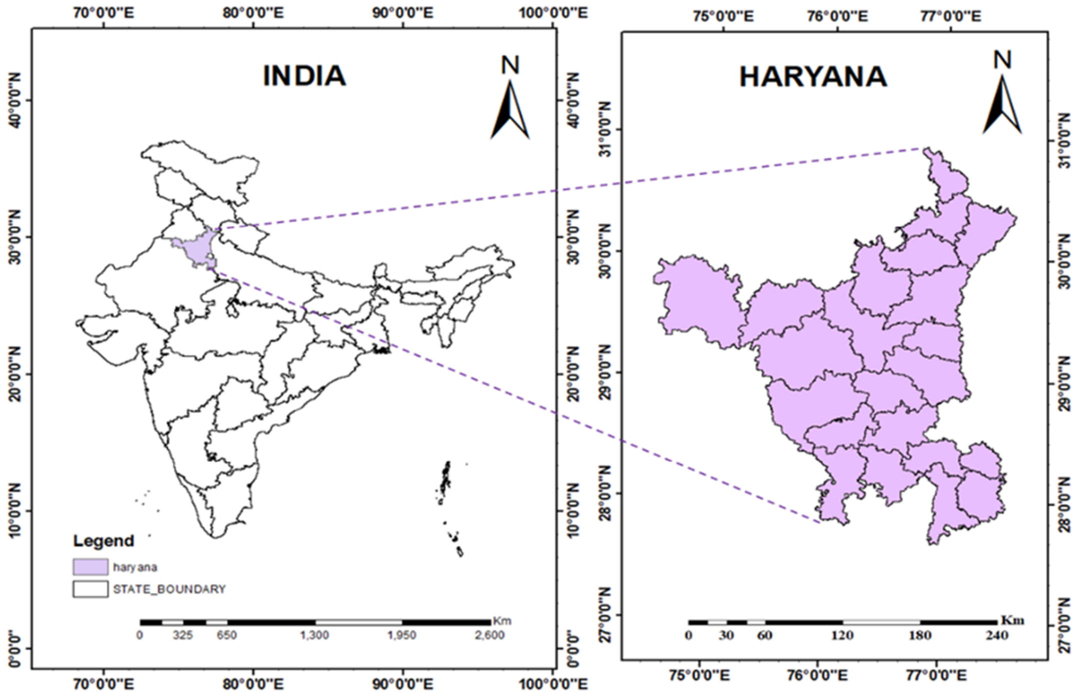

Figure 1. Study area map

Haryana's agriculture-centric economy, with intensive cultivation of water-demanding crops, including rice and wheat, has significantly contributed to the over-extraction of groundwater. Moreover, several blocks in the state have already been classified as "overexploited" by the CGWB, which means that the annual extraction exceeds the annual recharge. This situation is worsened by limited natural recharge, inadequate rainfall in certain zones, and the absence of effective groundwater management practices. These conditions make Haryana a critical case for applying geospatial techniques to monitor and manage groundwater resources.

3. Data and methodology

3.1. Data collection

The data used in this study were sourced from a combination of conventional field data and advanced remote sensing platforms, ensuring comprehensive spatial and thematic coverage for GWP mapping. A shuttle radar topographic mission (SRTM) digital elevation model (DEM) with a 30-meter spatial resolution was used to derive the slope map, TWI, and DD. These layers provide insights into the terrain structure and water flow behaviour. The relatively fine resolution of 30m enables reliable terrain analysis over a large area. The geomorphology and LD maps were obtained from the national remote sensing centre (NRSC) bhuvan platform, which provides standardized and verified datasets. The lineament layer is crucial for identifying subsurface fractures and potential recharge paths. The LULC map was derived using Sentinel-2 satellite imagery, which offers a 10-meter spatial resolution, making it suitable for identifying detailed land use classes. This high resolution improves the accuracy of the LULC layer, especially in distinguishing between agricultural fields, built-up zones, forests, and water bodies.

The geological map was prepared using datasets from the survey of India (SOI) and validated with field-level geological information to ensure consistency and relevance to aquifer properties. Similarly, the soil map was generated using the FAO soil dataset, which classifies soils on the basis of texture and drainage properties, which are important variables for infiltration and recharge assessment. Rainfall data were sourced from the India meteorological department (IMD), with long-term average precipitation values used to represent spatial rainfall variability across the state. Rainfall directly contributes to recharge and is one of the most heavily weighted factors in the AHP.

For validation purposes, GWL data from 646 well stations were obtained from the CGWB, India. These well measurements recorded in 2018 were taken as reference points for comparison with the

2023 GWP model outputs, allowing for spatiotemporal validation of the predicted zones. A summary of all the data sources is provided in Table 1.

Table 1. Data sources for the creation of different maps

Parameter	Dataset source
Slope	SRTM
LULC	Sentinel-2
Elevation	SRTM
Soil texture	FAO
Geology	SOI
DD	SRTM
Geomorphology	NRSC bhuvan
LD	NRSC bhuvan
Rainfall map	IMD
TWI	SRTM
GWL data	CGWB

3.2. Methodology

To delineate GWP zones, this study followed a systematic multistep approach that integrated geospatial analysis and decision-making techniques. Multiple thematic layers were created on the basis of hydrogeological and environmental variables that influence groundwater occurrence. These include slope, DD, elevation, LULC, soil, geology, geomorphology, LD, TWI, and rainfall maps. Each thematic layer was first reclassified into standardized classes on the basis of its hydrogeological influence on groundwater recharge (GWR). For example, gentle slopes and forested LULC types were ranked higher due to their increased infiltration potential. These reclassified layers were then assigned weights using the AHP. The pairwise comparison method was employed to quantify the relative importance of each factor, supported by expert judgment and literature review.

To ensure logical consistency in the weighting process, a consistency ratio (CR) was calculated. The resulting CR value of 0.011 (should be less than 0.1) indicates an acceptable level of consistency in the judgments. This step minimizes the impact of subjective bias in weight allocation. Once the layers were weighted, they were integrated using the WOA technique in GIS. This method allows the combination of multiple layers on the basis of their assigned influence, producing a composite GWP index map that classifies the region into five zones: very low, low, moderate, high, and very high potential. The final GWP map was then validated using GWL data from 2018 from the CGWB, which were obtained from 646 well locations across Haryana. The region wise comparison of well data with the derived GWP zones enabled a quantitative accuracy assessment. This reveals a validation accuracy of 77.55%, which supports the robustness of the approach. Figure 2 illustrates the complete workflow used in the study, including thematic layer preparation, AHP-based weighting, consistency testing, spatial integration, and final validation.

4. Results and discussion

4.1. Thematic layers

4.1.1. Slope

Slope is a critical topographic parameter that directly influences surface runoff and GWR. It represents the rate of change in elevation and thereby affects the time at which water remains on the surface before infiltrating into the subsurface [13-15]. Steep slopes promote rapid runoff and hinder water infiltration, thereby reducing the possibility of GWR. In contrast, gentle slopes favour slower runoff and allow more time for infiltration, which enhances the GWR and improves the GWP [17-18]. The slope variation in the Haryana region was derived from the 30-meter resolution SRTM DEM. The slope values were reclassified into ten distinct categories on the basis of the degree of inclination, as illustrated in Figure 3. A majority of the districts, including Sirsa, Fatehabad, Hisar, Jind, Kaithal, Rohtak, Jhajjar, Panipat, Karnal, Kurukshetra, Sonipat, and Palwal, are dominated by very gentle slopes ranging from 0 to 1.44 degrees. These districts indicate predominantly flat terrain ideal for agriculture and infrastructure development. Districts, including Bhiwani, Charkhi Dadri, Rewari, and Faridabad, show slightly more variation, with slopes mostly between 1.45 and 5.16 degrees, suggesting mildly undulating landforms.

Mahendragarh, Gurugram, and parts of Yamunanagar have moderate slopes ranging from 5.17 to 16.2 degrees, indicating rolling terrain and some elevated features. Panchkula and southern parts of Nuh (Mewat) show the steepest slopes, ranging from 16.3 to over 30 degrees, reflecting the presence of hilly terrain, particularly in the Shivalik foothills and Aravalli ranges. In these hilly regions, maximum slope values reaching 66.9 degrees also exist in small isolated pockets, representing the sharpest terrain variations in the state. This spatial slope distribution highlights the geomorphological diversity of Haryana, which ranges from expansive plains to high-relief zones. Flat terrain causes maximum infiltration and is responsible for very high GWP. Slightly gentle slopes support significant infiltration with minor runoff, and moderate slopes exhibit balanced infiltration-runoff conditions, leading to a moderate GWP. Steeper and very steeper slopes result in high surface runoff and minimal infiltration. The slope layer was assigned a moderate weight in the AHP framework, given its important but indirect role in GWR compared with more dominant factors such as rainfall and geology.

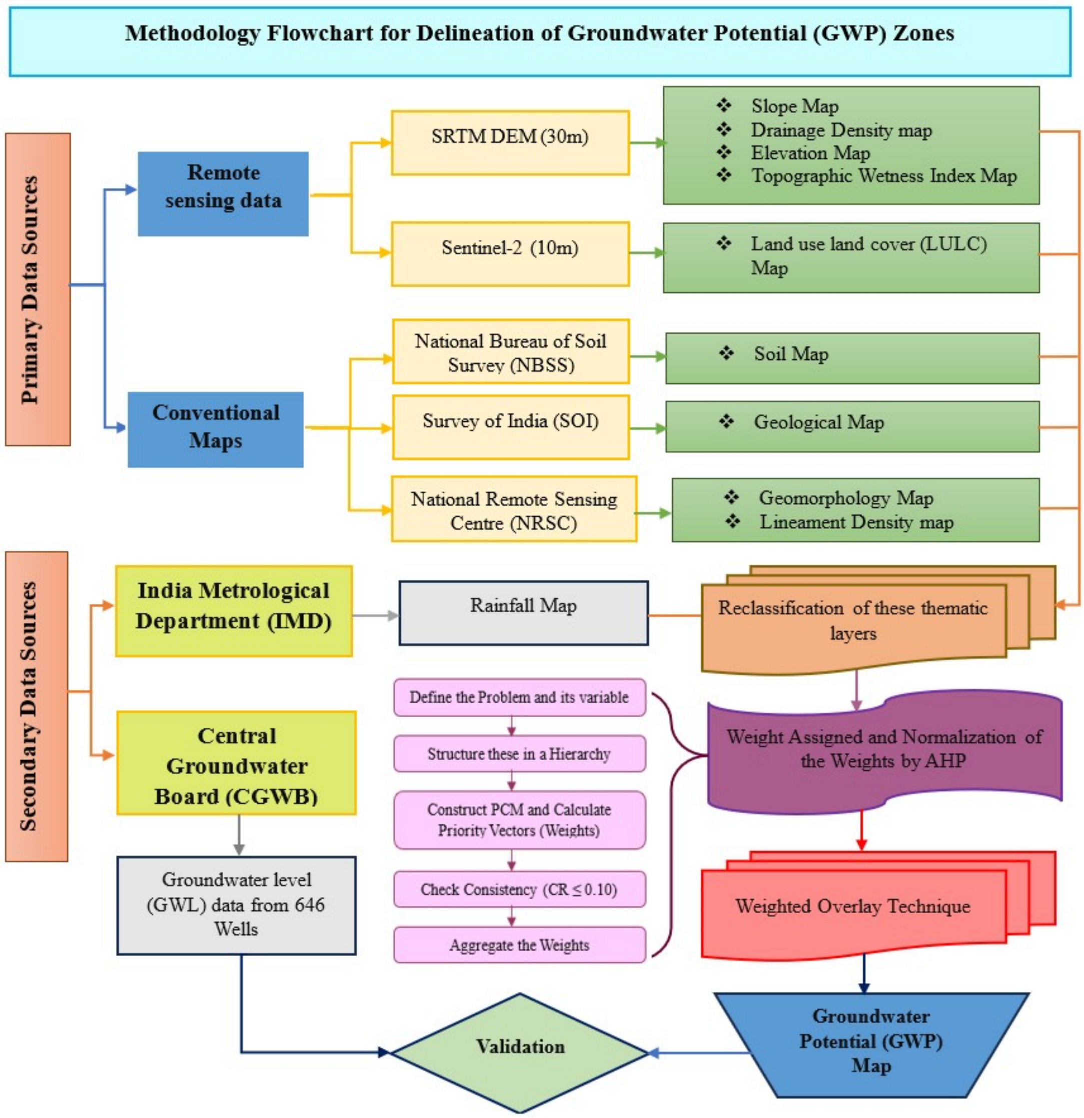

Figure 2. Methodology flowchart

4.1.2. LULC

LULC also plays a crucial role in the delineation of GWP zones, as it directly influences surface permeability, runoff, and GWR. Different LULC classes, such as agriculture, forests, urban areas, and water bodies, affect GWR rates differently [16]. Forested and wetland areas enhance GWR because of their high permeability and reduced surface runoff. Water bodies contribute through direct seepage. In contrast, urban and built-up areas reduce infiltration due to impervious surfaces, leading to decreased GWR. Forested and wetland areas enhance GWR because of their high permeability and reduced surface runoff. Water bodies contribute through direct seepage. In contrast, urban and built-up areas reduce infiltration due to impervious surfaces, leading to decreased GWR. Agricultural land impacts vary on the basis of crop type and irrigation intensity, whereas rangeland and bare land recharge depend on vegetation and soil characteristics [17].

Haryana has experienced rapid changes in LULC over recent decades, with significant transformations in various land categories. For example, forest cover declined by 56.3%, from 2.11 million hectares in 1966-67 to 0.92 million hectares in 2016-17, whereas barren land increased by 14.8%, reflecting increasing urban expansion and land degradation [18]. The LULC map (Figure 4), derived from 10-meter resolution Sentinel-2 imagery, captures fine-scale land use patterns and helps delineate areas with greater recharge potential. Additionally, LULC changes over time, such as urban expansion and agricultural intensification, can alter recharge dynamics. In the AHP model, LULC was given moderate weight on the basis of its spatial variability and direct influence on infiltration and storage.

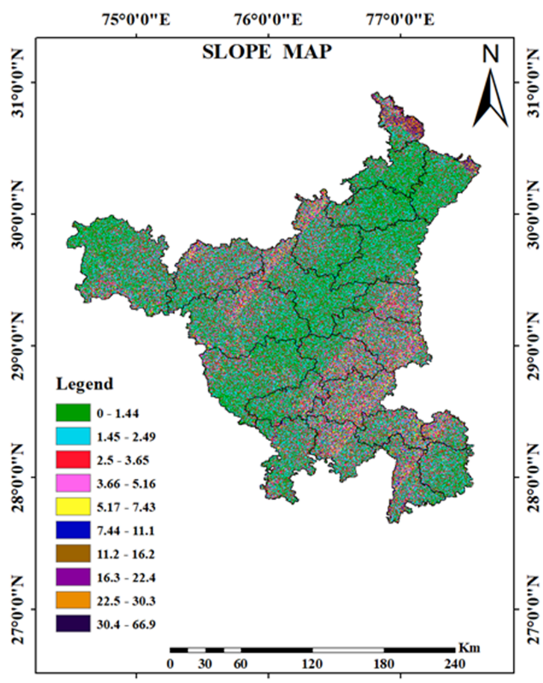

Figure 3. Slope map

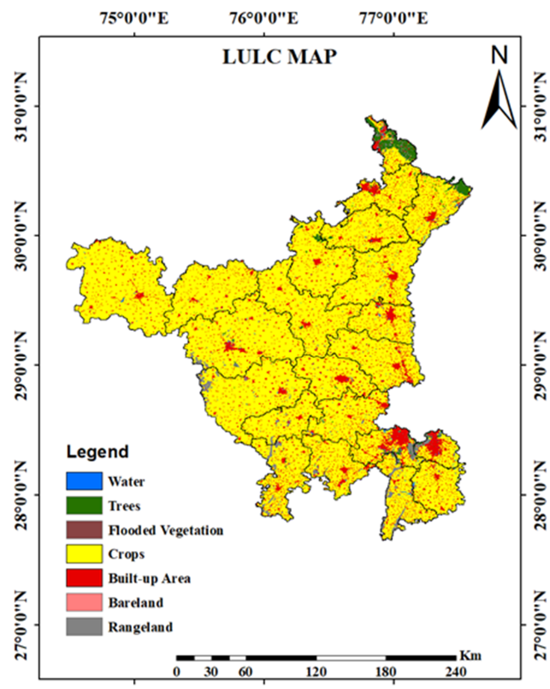

Figure 4. LULC map

4.1.3. Elevation

Elevation plays a crucial role in GWP assessment, as it influences both surface runoff and the spatial distribution of infiltration zones. Higher elevation areas generally experience greater runoff and reduced infiltration due to steeper gradients. However, lower elevation zones such as valleys and basins tend to accumulate water, promoting better GWR [19]. In addition to influencing recharge, elevation gradients affect the direction and velocity of groundwater flow. Steep terrains cause faster surface water movement, leaving little time for percolation, whereas gentler slopes support slower flow, increasing the chance of infiltration [20].

In this study, elevation data were extracted from the 30 m resolution SRTM DEM, ensuring adequate detail for regional analysis. The elevation range across Haryana spans from 130 m to 1540 m, as shown in Figure 5. Lower elevation classes, such as 130-210 m and 211-234 m, are favourable for GWR because of the gentle terrain that allows water accumulation and percolation. The mid-elevation zones (235-302 m) have moderate infiltration potential, but some runoff begins to occur because of the slightly increased slope. In contrast, higher elevations, including 303-461 m, are associated with steeper slopes that promote runoff and hinder infiltration. The highest elevation class (999-1540 m), although limited in spatial extent, represents the regions having rapid water movement results in minimal recharge potential. In the AHP model, elevation was assigned a relatively lower weight than dominant factors such as rainfall or geology. This is because elevation impacts the GWP indirectly, often in combination with slope and drainage patterns.

4.1.4. Soil

Soil characteristics such as texture, structure, permeability, and moisture retention play vital roles in determining GWP, as they directly influence water infiltration and storage capacity [21]. Owing to their coarse texture and high porosity, sandy soils allow for greater water infiltration, thereby enhancing GWR. In contrast, clay-rich soils, with finer particles and lower permeability, tend to impede water movement, resulting in limited recharge capacity [22].

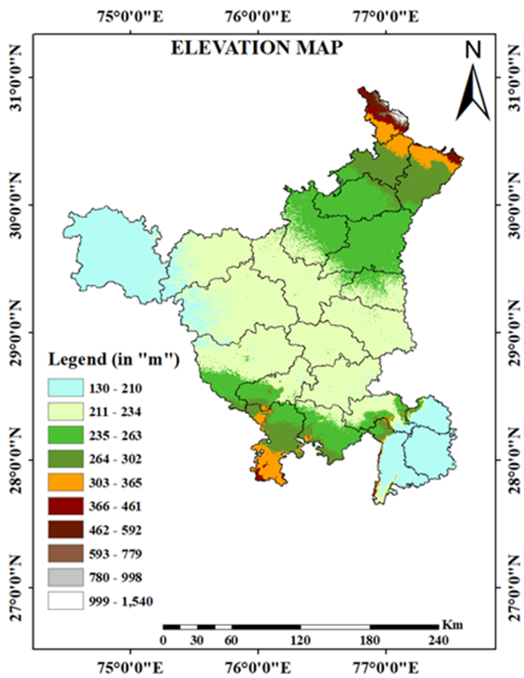

Figure 5. Elevation map

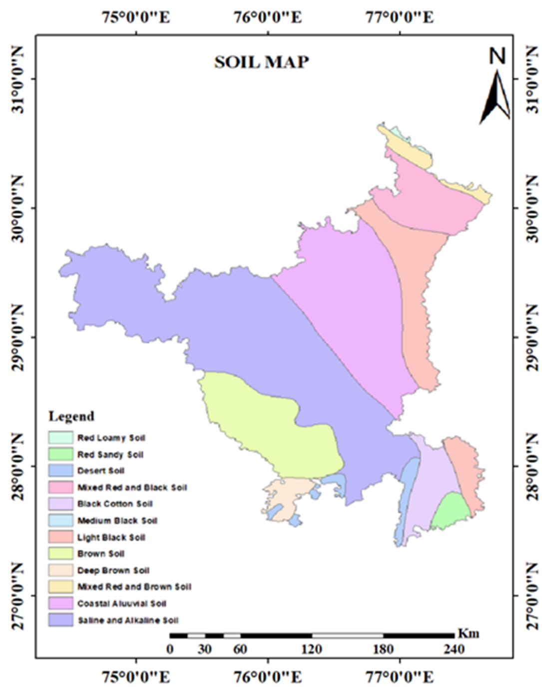

Figure 6. Soil map

In this study, soil classification was based on the FAO global soil dataset, which categorizes soils by type and texture (Figure 6). Red loamy and sandy soils exhibit moderate to high permeability, facilitating infiltration but varying in their ability to retain moisture. Conversely, black cotton and medium black soils, known for their clay content, exhibit strong moisture retention but slow infiltration, limiting GWR despite their water-holding capacity. The mixed red and black soils provide a balance between drainage and retention, contributing to moderate recharge levels. Coastal alluvial soils, typically found near water bodies, offer high porosity and excellent recharge potential because of their loose, unconsolidated nature. Moreover, desert and saline soils are less favourable for recharge because of their low permeability and high salinity, which limits both infiltration and water usability. In the AHP framework, soil was assigned a moderate weight, reflecting its significant but secondary influence compared with dominant factors such as rainfall and geology.

4.1.5. Geology

Geology is a critical factor in GWP assessment, as the composition, age, and structure of geological formations directly impact aquifer permeability and storage capacity [23]. Porous and fractured rock types, such as sandstone and limestone, allow groundwater to move easily through subsurface layers, supporting higher GWR. In contrast, impermeable formations, including clay and dense igneous rocks, hinder infiltration and reduce aquifer recharge [17]. Additionally, structural features such as faults and fractures serve as natural conduits for groundwater flow, enhancing the connectivity between recharge zones and storage zones. Therefore, accurate geological mapping is essential for identifying favourable conditions for GWS and extraction.

The study area encompasses several geological formations with distinct hydrogeological characteristics, as shown in Figure 7. The Eocene-Miocene formations, consisting of relatively porous sedimentary rocks, exhibit moderate to good recharge potential. The Miocene and Miocene-Pliocene formations, which are rich in sandy and gravelly deposits, offer high permeability and storage capacity, making them favourable for the GWP. In contrast, Palaeoproterozoic-Mesoproterozoic rocks, which are older and more consolidated, exhibit low permeability and reduced recharge potential. The Pliocene-Pleistocene formations, composed of mixed sediments, provided moderate to high recharge conditions. The Quaternary deposits, which are relatively recent have high potential because of their high porosity. In the AHP model, geology was given a high weight because of its fundamental role in governing the subsurface flow and storage and unconsolidated, have excellent aquifer of groundwater, second only to rainfall.

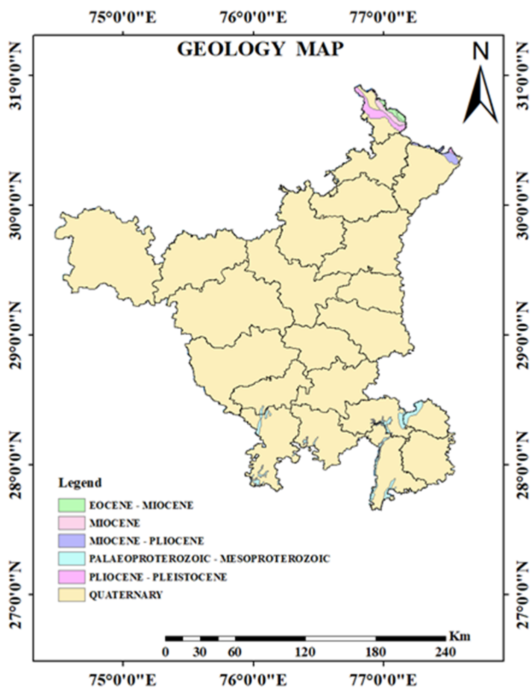

Figure 7. Geology map

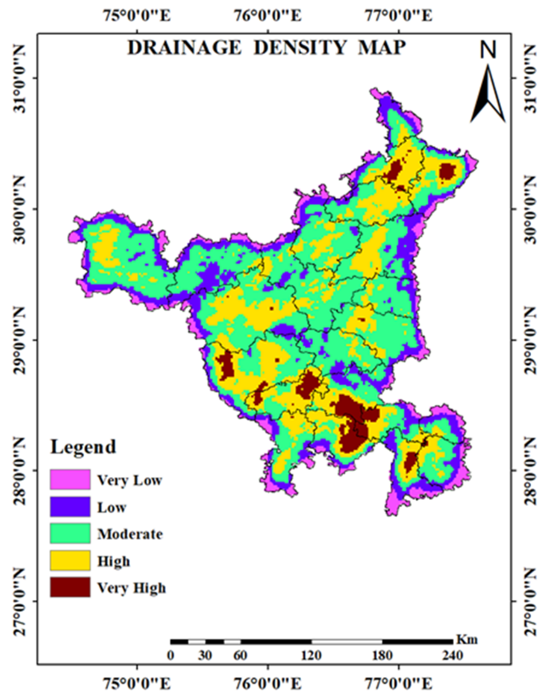

Figure 8. Drainage density map

4.1.6. Drainage density

Drainage density (DD), defined as the total length of streams and rivers per unit area, serves as an important indicator for assessing GWP. In any area, a high DD signifies a well-developed surface drainage network, which often results in increased surface runoff and reduced water infiltration, thereby lowering the GWR. In contrast, areas with low DD generally experience greater infiltration because surface water is retained for longer periods, increasing the potential for aquifer recharge [23]. This parameter is also valuable in hydrological modelling, as it reflects the combined effects of land use, slope, lithology, and rainfall on surface water dynamics. Changes in drainage patterns caused by urbanization, deforestation, or land degradation can significantly alter local GWP conditions [24].

In the study area, DD was classified into five categories: very low, low, moderate, high, and very high, as shown in Figure 8. Regions with high and very high DD typically correspond to steeper slopes and less permeable soils, leading to increased runoff and diminished recharge. On the other hand, zones with low to very low DD, often associated with flat terrain and permeable substrates, are more conducive to infiltration and have higher GWP. The moderate DD zones demonstrate a balance between runoff and recharge, making them moderately suitable for groundwater replenishment. In the AHP model, DD was assigned a moderate weight, as it plays a supportive but indirect role in controlling GWP through its influence on runoff and infiltration.

4.1.7. Geomorphology

Geomorphology, the study of Earth's surface features and their relationships with geological structures, is a significant factor in GWP mapping [22]. Landforms such as plains, valleys, hills, and plateaus influence both runoff and infiltration processes, which directly affect GWR. For example, alluvial plains, owing to their unconsolidated and porous sediments, generally exhibit high GWP, whereas rocky hills and plateaus, with limited soil cover and high surface runoff, tend to have low recharge potential [17]. In the study area, various geomorphological units were identified and classified, as shown in Figure 9. Aeolian interdunal depressions (AIDs) and aeolian plains support localized water accumulation and infiltration due to their flat topography and sediment composition. Aeolian sand dunes and sand sheets, shaped by wind activity, affect recharge differently on the basis of slope and compaction. The aeolian dune complex, a mixture of multiple dunes, plays a variable role in water retention.

Alluvial plains and flood plains, which are formed by river deposition, are particularly significant for the GWP because of their high porosity and infiltration potential. Additionally, man-made features such as dams and reservoirs directly enhance local GWR by acting as recharge structures. On the other hand, highly dissected structural hills and valleys (HDHVs), low-dissected denudational hills and valleys (LDHVs), and moderately dissected structural hills and valleys (MDHVs) have poor recharge potential because of steep slopes and limited permeability. The Pediment Pediplain Complex (PPC), characterized by gently sloping bedrock surfaces, has a moderate GWP depending on lithology and surface porosity. On the basis of its direct impact on surface water retention and infiltration, geomorphology was assigned a high weight in the AHP model, especially for its role in identifying recharge-prone areas.

4.1.8. Lineament density

Lineament density (LD) refers to the total length of linear geological features such as faults, fractures, and joints per unit area. These features are typically mapped using satellite imagery and aerial photographs [25]. Lineaments act as pathways for groundwater movement, enhancing the permeability of rock formations and promoting GWR. Therefore, areas with high LD are generally associated with higher GWP due to increased subsurface water infiltration, whereas low LD regions tend to have fewer pathways for infiltration, resulting in limited recharge [26]. In the study area, LD was classified into multiple ranges, as shown in Figure 10. These include structural lineaments in southeastern and central Haryana, especially those trending NW-SE, are particularly important for GWR. These features, often associated with faults or fractures, increase subsurface permeability and serve as conduits for water flow, making them critical zones for identifying high-yield aquifers and improving the GWP. Regions with very low LD (0-0.026) contain fewer fractures and hence exhibit low GWP. Areas with low LD (0.027-0.073) have limited but slightly improved GWR potential. Moderate LD zones (0.074-0.126) demonstrate significant groundwater movement due to a relatively high concentration of fractures, which act as conduits for infiltration.

Furthermore, geomorphic lineaments and structural lineament features also exist. Geomorphic lineaments, shaped by surface processes such as erosion or sediment transport, reflect shallow structural controls that influence near-surface water movement. Structural lineaments, often formed by tectonic forces, represent deeper geological faults and fractures that serve as critical zones of groundwater flow and storage. Recognizing and mapping these lineament types enhances the understanding of subsurface hydrological connectivity. On the basis of its direct role in facilitating recharge through fractures, the LD was assigned a moderate weight in the AHP model. While not as dominant as rainfall or geology, LD significantly supports GWP assessment in fractured terrains. Structural lineaments are particularly important, as they are typically associated with deep-seated tectonic features. These features act as primary conduits for subsurface groundwater flow and play a vital role in facilitating recharge.

4.1.9. Rainfall

Rainfall is a primary and direct contributor to GWR and is thus a fundamental factor in determining GWP zones. The amount, intensity, and temporal distribution of rainfall influence how effectively precipitation infiltrates the soil to replenish aquifers. Regions with frequent, evenly distributed, and moderate-intensity rainfall are more conducive to recharge, provided that the underlying soil and geological conditions support infiltration [27]. In contrast, areas with low rainfall or intense short-duration storms often experience high surface runoff and limited percolation, leading to reduced GWR. This makes rainfall variability and seasonal patterns essential for understanding regional groundwater dynamics [23].

In the present study, rainfall data obtained from the India Meteorological Department (IMD) were used to classify the region into multiple rainfall zones (Figure 11). The rainfall across Haryana ranges from 313.4 mm to 1,426.6 mm annually, with notable spatial variability. Areas receiving 313.4-461.8 mm of rainfall represent zones of lowest recharge and minimal GWP, whereas those with 461.9-571 mm also show limited recharge potential. Zones receiving 571.1-662.6 mm sizes fall into the moderate GWP category, indicating modest infiltration. Regions experiencing 662.7-929 mm of rainfall exhibit good recharge capacity, whereas those receiving 929.1-1,426.6 mm demonstrate very high to excellent GWP, as the high volume of precipitation significantly enhances aquifer recharge. Given its dominant role in driving GWR, rainfall was assigned the highest weight in the AHP analysis, making it a critical determinant of GWP in the region.

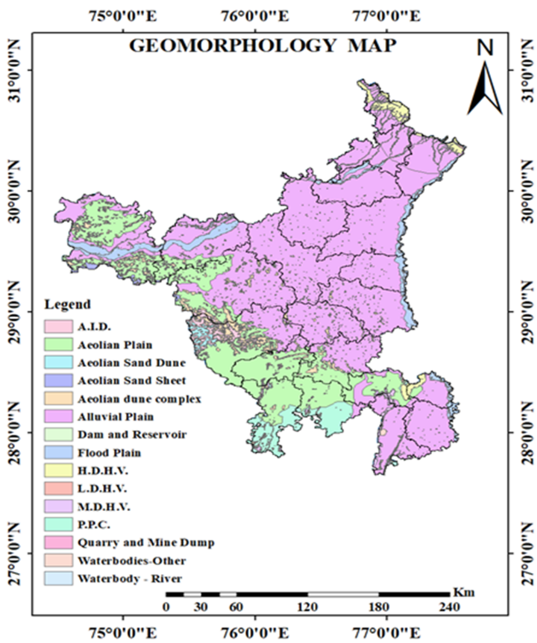

Figure 9. Geomorphology map

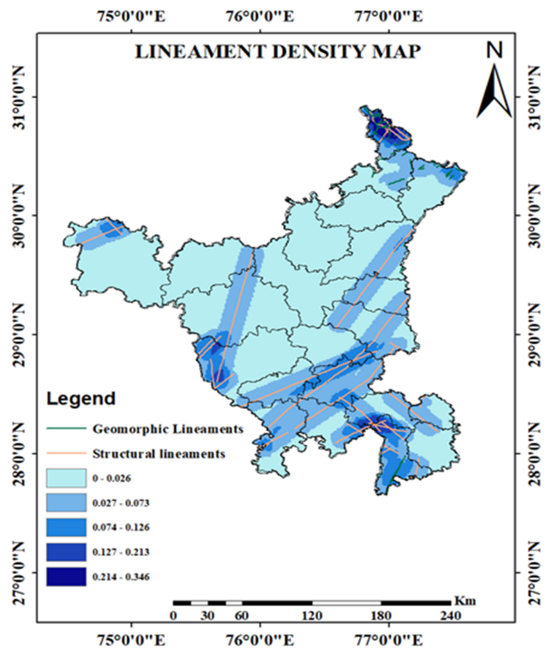

Figure 10. Lineament density map

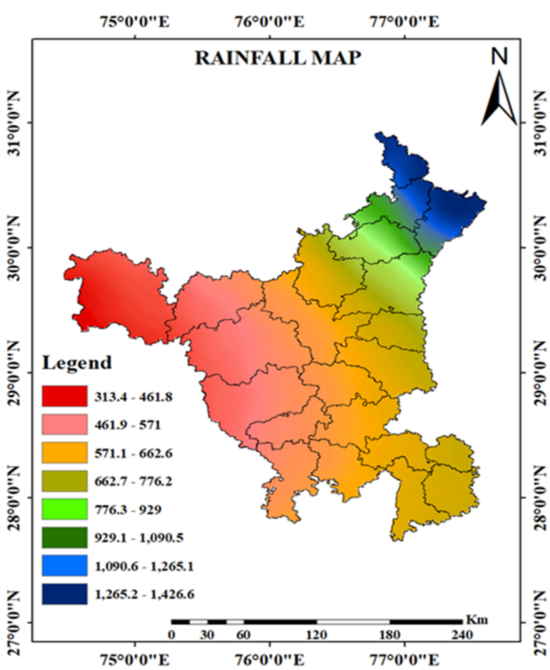

Figure 11. Rainfall map

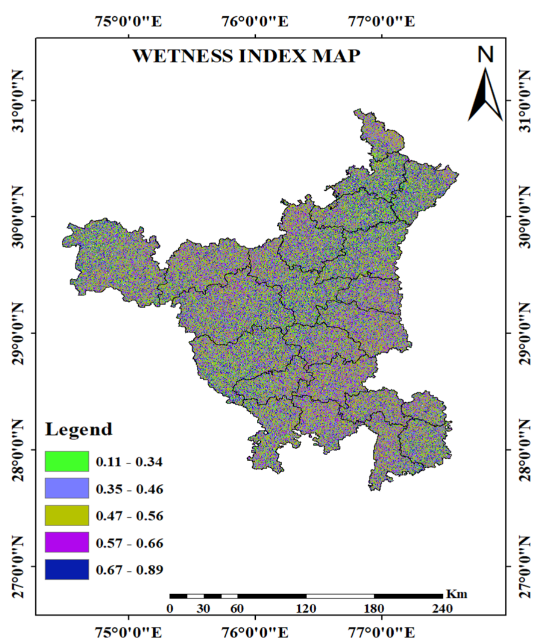

Figure 12. Topographic wetness index map

4.1.10. TWI

TWI map, derived from SRTM DEM, is a critical indicator in GWP analysis. It reflects the spatial distribution of soil moisture on the basis of terrain characteristics such as slope and drainage convergence [28]. High TWI values typically indicate areas with gentle slopes and convergent topography, where water tends to accumulate and remain for longer durations, facilitating deeper infiltration and aquifer recharge. Conversely, low TWI values are associated with steep or divergent slopes, which result in rapid runoff and limited moisture retention, reducing the GWR potential [27]. In the study area, TWI values were classified into five classes to understand their influence on GWP (Figure 12). Areas with TWI values between 0.11 and 0.34 represent low wetness zones, where minimal recharge occurs due to quick water runoff. Slightly improved conditions exist in the 0.35-0.46 range, indicating moderate water retention but still limited GWR. The moderate TWI class (0.47-0.56) has increased soil moisture and better recharge rates. Higher TWI ranges of 0.57-0.66 and 0.67-0.89 are characterized by favourable conditions for GWR due to prolonged water accumulation and enhanced infiltration. These zones are considered most suitable for GWP. The TWI was assigned a lower to moderate weight in the AHP model since, while it influences recharge through topographic control, its effect is complementary to factors such as slope and DD.

4.2. Weights assignment

MCDA is a structured approach used in complex decision-making scenarios where multiple interrelated factors must be considered to determine the most suitable option. The AHP is one of the most widely used techniques in geospatial modelling, especially for GWP assessment [7]. It enables the ranking of thematic layers on the basis of their relative importance, using a systematic process that combines both quantitative data and expert judgment. 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 seven professors and seven research scholars from the same expertise.

In the AHP methodology, each factor is compared pairwise against others to evaluate its relative influence on the objective, in this case, the GWR potential. A nine-point priority scale is used, where a value of 1 indicates equal importance, and 9 signifies that one factor is extremely more important than another (Table 2). These comparisons result in a PCM, which is later normalized to derive weights for each thematic layer. These weights reflect how strongly each factor contributes to the overall goal. This step-by-step approach ensures that the decision-making process is transparent, logical, and reproducible. This also makes AHP especially suitable for environmental and resource management applications.

Table. 2 Saaty's scale of relative importance [7]

Scale	**1**	**3**	**5**	**7**	**9**	**2, 4, 6 & 8**
Intensity of Importance	Equally Importance	Moderate Importance	Strong Importance	Very Strong Importance	Extreme powerful	Intermediate values between the two advancement judgements

4.3. Influence of different thematic layers

The process of mapping GWP begins with problem definition and identification of relevant thematic layers that influence GWR. These layers are then **evaluated** for their relative importance using the AHP, which employs Saaty's 1-9 scale to perform pairwise comparisons among all factors. The comparisons are organized into a PCM (Table 3), which quantifies expert judgment on how much more one layer contributes to GWP than another. To ensure consistency and comparability, this matrix is then normalized, resulting in a matrix where values are scaled proportionally across rows and columns (Table 4). The normalized PCM is then used to calculate the final weights assigned to each thematic layer, reflecting the relative priority of each factor in influencing the GWR potential. These weights are integral to the WOA, which combines the spatial layers into the final GWP map.

Table 3. Pairwise comparison matrix (PCM)

	Rainfall	Geology	Geomorphology	LULC	Slope	Soil	DD	Elevation	LD	TWI
Rainfall	1	2	2	2	3	3	4	5	6	7
Geology	0.5	1	1	2	2	3	4	5	5	6
Geomorphology	0.5	1	1	1	2	2	3	4	5	6
LULC	0.5	0.5	1	1	2	2	3	4	4	5
Slope	0.33	0.5	0.5	0.5	1	1	2	3	3	4
Soil	0.33	0.33	0.5	0.5	1	1	2	3	3	4
DD	0.25	0.25	0.33	0.33	0.5	0.5	1	1	2	2
Elevation	0.2	0.2	0.25	0.25	0.33	0.33	1	1	1	1
LD	0.17	0.2	0.2	0.25	0.33	0.33	0.5	1	1	1
TWI	0.14	0.17	0.17	0.2	0.25	0.25	0.5	1	1	1

Table 4. Normalization matrix

	Rainfall	Geology	Geomorphology	LULC	Slope	Soil	DD	Elevation	LD	TWI
Rainfall	0.255	0.325	0.288	0.249	0.242	0.224	0.190	0.179	0.194	0.189
Geology	0.128	0.163	0.144	0.249	0.161	0.224	0.190	0.179	0.161	0.162
Geomorphology	0.128	0.163	0.144	0.125	0.161	0.149	0.143	0.143	0.161	0.162
LULC	0.128	0.081	0.144	0.125	0.161	0.149	0.143	0.143	0.129	0.135
Slope	0.084	0.081	0.072	0.062	0.081	0.075	0.095	0.107	0.097	0.108
Soil	0.084	0.054	0.072	0.062	0.081	0.075	0.095	0.107	0.097	0.108
DD	0.064	0.041	0.047	0.041	0.040	0.037	0.048	0.036	0.065	0.054
Elevation	0.051	0.033	0.036	0.031	0.027	0.025	0.048	0.036	0.032	0.027
LD	0.043	0.033	0.029	0.031	0.027	0.025	0.024	0.036	0.032	0.027
TWI	0.036	0.028	0.024	0.025	0.020	0.019	0.024	0.036	0.032	0.027

Table 5. Relative weight of different thematic layers

Thematic Layer	Original Weight (%)	Relative Weight
Rainfall	23	0.23
Geology	18	0.18
Geomorphology	15	0.15
LULC	13	0.13
Slope	9	0.09
Soil Type	8	0.08
DD	5	0.05
Elevation	3	0.03
LD	3	0.03
TWI	3	0.03

4.4. Consistency analysis and WOA

The AHP also helps address uncertainty in these judgments through the use of the principal eigenvalue and consistency index. In the AHP, consistency analysis serves to evaluate the reliability of the judgements and assesses the consistency of the pairwise comparisons between criteria in relation to each other.

The procedure involves the computation of the consistency ratio (CR), which compares the consistency index (CI) of the evaluations against a random consistency index (RI). A CR value less than 0.1 is acceptable, indicating logical and consistent evaluations.

Calculation of the CI and CR,
Principal eigenvalue (λ_{max}) = 10.1530
Consistency index (CI) = $\frac{(\lambda\, max - n)}{(n-1)}$ = 0.01775
Random consistency ratio (RI) = 1.49 (as per the Saaty random consistency index)
Random consistency ratio (RI) = 1.49 (as per the Saaty random consistency index)

Hence, the CR is less than 0.1, and all the weights provided are compatible. The WOA is a method used for GWP analysis, in which we provide weighted thematic layers using AHP as input data. This approach involves reclassifying these thematic layers and then systematically evaluating multiple criteria affecting groundwater availability to obtain a final GWP map of the study area. The resulting GWP map has five classes: very low, low, moderate, high, and very high, as shown in Figure 13.

4.5. Validation of results

The final GWP map for the year 2023 was validated using GWL data from 646 wells obtained from the CGWB for the year 2018 (Figure 14). The validation involved comparing the spatial match between the GWP zones predicted through the GIS-AHP model and the actual GWL observations at the well locations. Each well point was assessed to determine whether it agreed or disagreed with the GWP zone classification of that region. The analysis yielded an overall accuracy of 77.55%, indicating a strong correlation between the model's predictions and real-world groundwater conditions. This high degree of agreement demonstrates the effectiveness and reliability of the GIS-AHP approach in delineating potential recharge zones and supports its use in sustainable water resource management (SWRM) across the state. Moreover, the comparison between the 2018 GWL and 2023 GWP data revealed only marginal variations, suggesting that the region's groundwater dynamics have remained relatively stable over this five-year period. This stability implies limited changes in recharge, extraction, or aquifer depletion during the interval. However, the results also underscore the importance of ongoing monitoring and integrated groundwater management practices, especially considering the growing demand for water and climate variability.

5. Conclusions

This study effectively delineated groundwater potential (GWP) zones across the Haryana region of India using an integrated approach that combines a geographic information system (GIS) and the analytical hierarchy process (AHP). Different thematic layers, such as slope, land use/land cover (LULC), geology, soil, geomorphology, lineament density (LD), elevation, wetness index (WI), drainage density (DD) and rainfall, have different effects on the GWP. By generating and analysing these thematic layers, the spatial variability in groundwater recharge (GWR) conditions was systematically assessed. The resulting GWP map was validated using groundwater level (GWL) data from 646 observation wells provided by the central ground water board (CGWB). The model achieved an accuracy of 77.55%, confirming the reliability of the GIS-AHP approach in representing actual groundwater conditions.

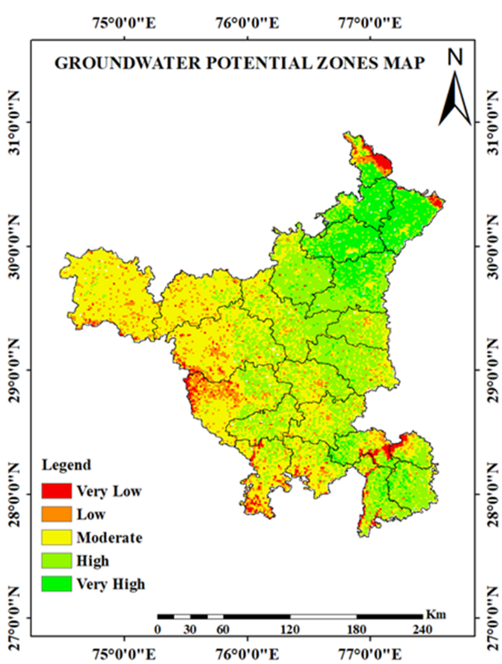

Figure 13. GWP map

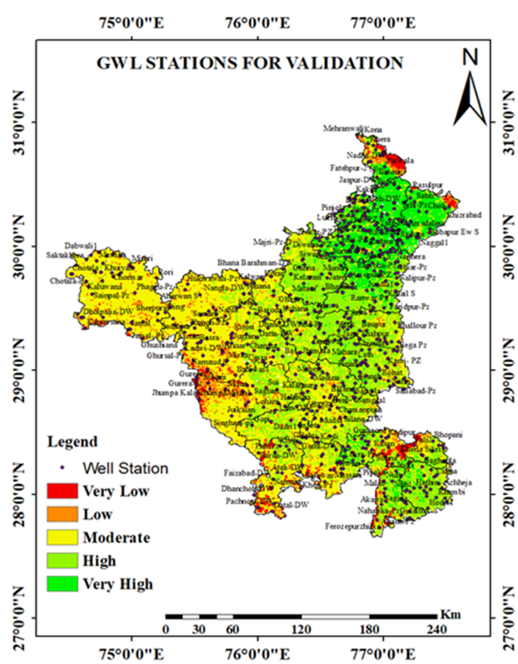

Figure 14. GWL station map

Among the influencing factors, rainfall, geology, and geomorphology were identified as the most dominant in controlling GWP, while LULC, slope, and soil had moderate influences, and DD, elevation, LD, and TWI had relatively lower impacts. The spatial distribution revealed that the moderate GWP zone covered the largest area (43.71%), followed by the high (33.24%) and very high (11.96%) zones. In contrast, the low and very low GWP zones accounted for 7.59% and 3.51% of the total area, respectively. This indicates that the majority of Haryana has moderate to high GWR potential, with only a limited portion facing low recharge prospects. A comparison between the current GWP (2023) and historic GWL data (2018) revealed minimal changes in groundwater conditions over the five-year period. This shows stable aquifer behaviour with limited variation in recharge and extraction dynamics. However, to maintain this equilibrium, this study emphasized the urgent need for continuous monitoring, demand-side regulation, and region-specific groundwater management strategies.

Uncertainty in GWP assessment

Despite the use of a robust GIS-AHP framework, this study involves inherent uncertainties due to limitations in data resolution, thematic layer classification, and expert judgment in weight assignment. Variability in field conditions, seasonal groundwater fluctuations, and the generalization of thematic data may also impact the accuracy of the results. To reduce these uncertainties, future studies should incorporate time series data, high-resolution inputs, and sensitivity analysis of AHP weights to better validate the model against observed field data.

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ارزیابی پتانسیل آب‌های زیرزمینی در منطقه هاریانا: داده‌های میدانی GIS-AHP در مقابل داده‌های میدانی

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کلمات کلیدی

فرآیند تحلیل سلسله مراتبی
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چکیده

این مطالعه، مناطق پتانسیل آب زیرزمینی (GWP) را در سراسر هاریانا، هند، برای سال ۲۰۲۳ با استفاده از تکنیک‌های مکانی-مکانی تلفیق‌شده با فرآیند تحلیل سلسله مراتبی (AHP) ترسیم می‌کند. لایه‌های موضوعی متعدد، شامل شیب، کاربری/پوشش زمین (LULC)، خاک، زمین‌شناسی، تراکم زهکشی (DD)، تراکم خطواره‌ها (LD)، ارتفاع، بارندگی و شاخص رطوبت توپوگرافی (TWI)، با استفاده از مجموعه داده‌های SRTM، Sentinel-2، سازمان غذا و کشاورزی (FAO) و اداره هواشناسی هند (IMD) تولید و از طریق AHP وزن‌دهی شدند. این لایه‌ها با استفاده از تحلیل همپوشانی وزنی (WOA) برای تولید نقشه نهایی GWP ادغام شدند. نقشه GWP با داده‌های سطح آب زیرزمینی میدانی (GWL) از ۶۴۶ چاه ثبت‌شده در سال ۲۰۱۸ توسط هیئت مرکزی آب‌های زیرزمینی (CGWB) اعتبارسنجی شد که منجر به دقت ۷۷.۵۵ درصد شد. این امر، قابلیت اطمینان سیستم اطلاعات جغرافیایی (GIS) و تکنیک AHP را تأیید کرد. این مطالعه نشان می‌دهد که مناطق با GWP متوسط (۴۳.۷۱٪) بر منطقه تسلط دارند و پس از آن مناطق با GWP بالا (۳۳.۲۴٪) و بسیار بالا (۱۱.۹۶٪) قرار دارند، در حالی که مناطق با GWP کم و بسیار کم به ترتیب ۷.۵۹٪ و ۳.۵۱٪ از منطقه را پوشش می‌دهند. یافته‌ها نشان می‌دهد که توزیع آب‌های زیرزمینی هاریانا تا حد زیادی پایدار است و تغییرات جزئی بین سال‌های ۲۰۱۸ تا ۲۰۲۳ مشاهده شده است. این نشان دهنده رفتار پایدار آبخوان و الگوهای تغذیه و استخراج نسبتاً بدون تغییر در طول دوره پنج ساله است. نتایج این مطالعه برای مدیریت استراتژیک آب‌های زیرزمینی، به ویژه در مناطق خشک و نیمه‌خشک ایالت هاریانا، ارزشمند است.

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