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Identification of Groundwater Potential Zones Utilizing GIS, RS and AHP: A Case Study of Rupandehi District in Nepal

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Abstract

Groundwater is a vital natural resource currently under immense pressure due to overexploitation and a lack of systematic planning. This study aims to identify and map groundwater potential zones (GWPZ) in the Rupandehi district of Nepal using an integration of Geographic Information System (GIS), Remote Sensing (RS), and the Analytic Hierarchy Process (AHP). Seven thematic layers—rainfall, geology, slope, land use/land cover (LULC), soil, drainage density, and lineament density—were integrated within a GIS platform. Multi-Criteria Decision Analysis (MCDA) via AHP was employed to weigh these layers based on their relative importance. The resulting GWPZ map categorizes the district into High, Moderate, and Low potential zones. Findings indicate that 34% of the area possesses high potential, 45% moderate, and 21% low potential. High-potential zones are primarily in the southern Terai plains, while northern mountainous regions exhibit lower potential. This study provides a data-driven guide for water resource managers to ensure sustainable groundwater.

Keywords: *AHP, GIS, Groundwater Potential Zone, MCDA, Remote Sensing.*

1. Introduction

The proliferation of environmental challenges and the surging demand for natural resources have necessitated a more systematic approach to water management. Groundwater, a fundamental and essential natural asset, is stored in the subsurface geological formations within the critical zone of the Earth's crust (Fan, 2015). As a primary water form, it fills the empty spaces within a geological layer, acting as a hidden but vital reservoir (McWhorter & Sunada, 1977). These geological structures, composed of soil, sand, and rocks are known as aquifers, which serve both as channels for transport and as repositories for long-term storage (Hay et al., 1990; McWhorter & Sunada, 1977). The presence of groundwater in a geological structure and the potential for its exploration predominantly rely on the porosity formation (Waikar & Nilawar, 2007).

Despite its importance, groundwater is a precious resource that is shrinking day by day (Halder et al., 2020). There is a growing sense of urgency regarding access to clean drinking water, especially in the context of impending global water scarcity (Halder et al., 2020). Rapid modernization, industrialization, and population growth have led to a significant lack of quality water supply in both rural and urban areas (Gnanachandrasamy et al., 2018). Furthermore, recent progress across diverse sectors like agriculture, industry, and urbanization has resulted in a heightened demand for water supply, primarily fulfilled through the utilization of groundwater resources (Dawoud, 2005).

The current management of these resources faces significant hurdles; a lack of proper plans for groundwater exploration and the random selection of points for bore wells result in failure most of the time (Barcelona, 1985). Indiscriminate misuse has led to a decrease in the potential of groundwater and a dangerous reduction in groundwater levels (Prasad et al., 2008). Excessive utilization and significant alterations over time have placed immense pressure on groundwater resources globally (Arulbalaji et al., 2019). Consequently, establishing a sustainable groundwater management plan to effectively utilize this vital resource through the delineation of groundwater potential zones (GWPZ) is no longer optional but a necessity.

In response to these challenges, Remote Sensing (RS) and Geographic Information Systems (GIS) have emerged as a powerful set of tools for collecting, storing, retrieving, managing, analyzing, and displaying spatial data in a simplified way (Cooperative & Collins, 1988). These tools offer a cost-efficient and time-saving approach to map groundwater potential (Jha & Peiffer, 2006). Over the past decade, many researchers have found Multi-Criteria Decision Analysis (MCDA) to be an effective tool for assessing the management of groundwater (Pietersen, 2007; Madrucci et al., 2008). Specifically, the Analytic Hierarchy Process (AHP) stands out as one of the most commonly employed techniques in MCDA (Saaty, 1990). The assessment of groundwater potential has extensively employed these integrated GIS and AHP techniques in various global contexts (Rahmati et al., 2015; Shekhar & Pandey, 2015; Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Ajay Kumar et al., 2020).

This study summarizes the groundwater potential zone mapping of the Rupandehi district in Nepal. While previous literature, such as Pathak (2017), has presented methods to delineate shallow groundwater potential in the Terai plain using GIS applications, there is a distinct gap in the application of multi-criteria decision models for this region. Since no such studies utilizing the AHP method have been reported for this specific study area to date, the current study serves as a pioneer work that is crucial for the rapid assessment of groundwater potential in a region facing increasing agricultural and domestic water demands. The primary objective of this study is to delineate groundwater potential zones within the Rupandehi district and create a comprehensive guide map for groundwater exploration and exploitation. This study aims to ensure optimal and sustainable development and management of vital water resources, identify suitable locations for water extraction to support effective development planning, and provide data-driven services for agricultural purposes within the district. By implementing a fast and cost-effective methodology, this study aims to mitigate the adverse effects of unplanned water resource development and contribute to the limited body of geospatial hydrogeological study in the Nepalese context.

2. Materials and Methods

2.1 Study Area

The study area for this investigation is the Rupandehi District, a strategically significant region situated within the Lumbini Province of western Nepal. Administratively, the district is comprised of 16 local levels, including one sub-metropolitan city, five municipalities, and ten rural municipalities. Geographically, Rupandehi presents a diverse and complex topographical profile, characterized by the rugged mountainous terrain of the Churia Hills in the northern part and the expansive, fertile flatlands of the Terai Plain to the south.

The hydrological framework of the district is dominated by the Tinau River, which serves as the primary watercourse. This system is complemented by the Bhaluhi/Danda River to the east and the Danav River to the west, both of which are notable fluvial systems that influence the region's hydrogeological characteristics (Pathak, 2017). While various research initiatives have previously targeted the identification of groundwater resources in this district, a significant methodological gap remains; specifically, the Analytic Hierarchy Process (AHP) has not been utilized in prior studies for this specific area.The selection of Rupandehi as the study location is further reinforced by its status as the home district, which allowed us for a more nuanced understanding of local environmental challenges, land use patterns, and water demand. By focusing on this geographically varied landscape, the study provides a robust geospatial assessment that aligns with the overarching goal of the project: to delineate precise groundwater potential zones through the integration of Remote Sensing, GIS, and Multi-Criteria Decision Analysis. The location map and spatial orientation of the study area are illustrated in Figure 1.

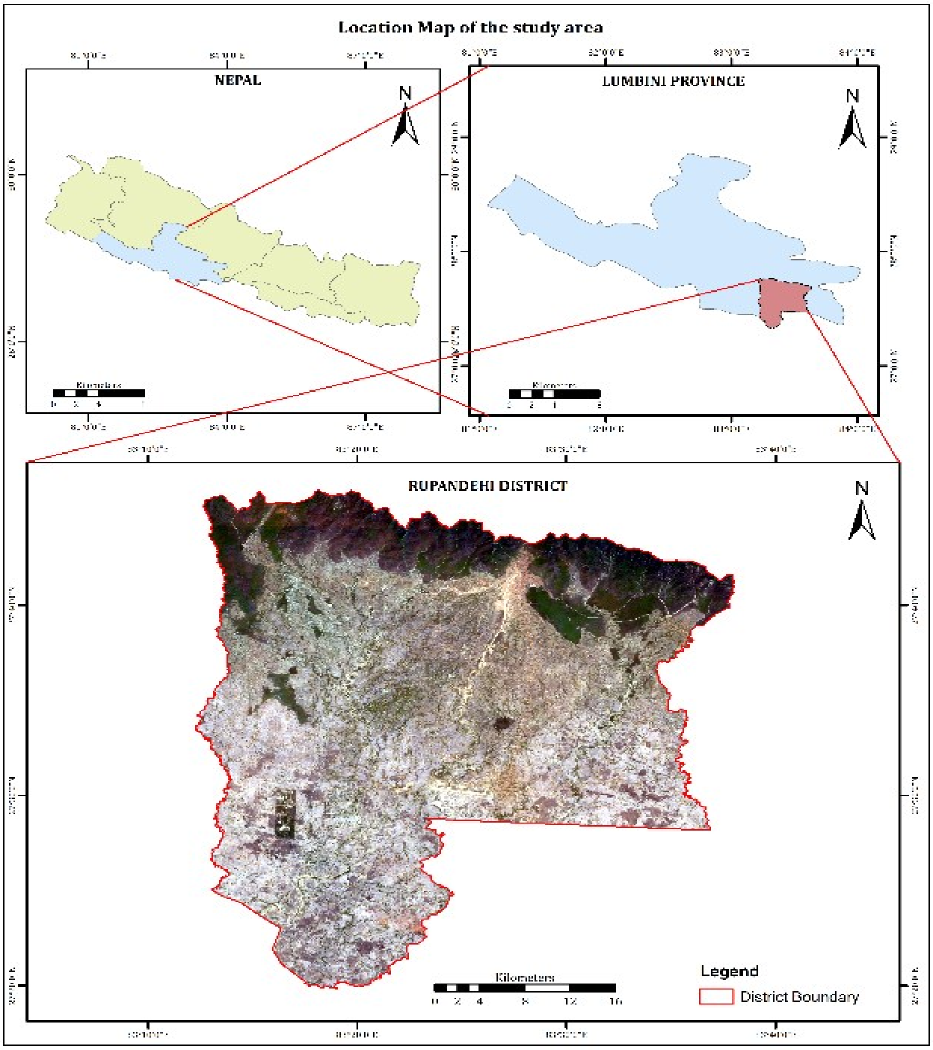

Figure 1: This figure illustrates the geographical location of Rupandehi District within Lumbini Province, Nepal, highlighting the 16 local administrative units and the distinct transition from the northern Churia Hills to the southern Terai Plain.

2.2 Data and Software used

The spatial datasets integrated into this study were meticulously selected to represent the physical and environmental variables that govern groundwater occurrence in the Rupandehi District. Each thematic layer serves a specific hydrogeological purpose, bridging the gap between surface observations and subsurface potential to ensure a comprehensive multi-criteria analysis.

Table 1:Tables shows the data used in this study.

SN	Thematic Layer	Data Type	Source	Resolution / Scale	Rationale for Selection
1	Geology	Vector	USGS / DMG Nepal	1:50,000	Defines the lithological framework and primary porosity of aquifers.
2	Rainfall	Raster	Dept. of Hydrology & Meteorology	30-year Mean	Represents the principal source of natural recharge to the system.
3	Slope	Raster	SRTM DEM	30m	Controls the duration of water contact and infiltration rates.
4	LULC	Raster	ESRI / Sentinel-2	10m	Reflects surface permeability and anthropogenic impact on recharge.
5	Soil	Vector	FAO-UNESCO / NARC	1:250,000	Dictates texture-based infiltration capacity and water retention.
6	Drainage Density	Derived Raster	SRTM DEM	30m	Indicates the efficiency of surface runoff; inversely related to potential.
7	Lineament Density	Derived Raster	Landsat 8 OLI/TIRS	30m	Highlights structural fractures that facilitate deep percolation.

The integration of these parameters allows for a holistic understanding of the hydrogeological environment. Geology and Soil layers provide the foundational data for subsurface storage. In the northern Churia Hills, the geology consists of harder formations that inherently limit infiltration, whereas the southern Terai Plain features deep alluvial deposits, primarily sand and gravel characterized by high primary porosity. The soil layer complements this by defining the vertical hydraulic conductivity; for instance, the coarse-textured sandy soils found in the district allow for rapid recharge compared to clay-heavy soils.

Topographic factors, specifically Slope and Drainage Density, are critical in determining the runoff-infiltration ratio. The steep slopes of the Churia region promote high-velocity surface runoff, leaving insufficient time for water to seep into the ground. Similarly, a high drainage density suggests a robust network of streams that quickly channel surface water away, typically indicating lower groundwater potential zones.

Furthermore, Land Use/Land Cover (LULC) and Rainfall act as the primary input and filter variables for the system. Rainfall is the essential source of recharge; without adequate precipitation, even the most porous aquifers remain depleted. The LULC layer determines the effective recharge by indicating surface permeability. Urban (built-up) areas act as impermeable barriers, while the forested and agricultural lands prevalent in Rupandehi facilitate healthy recharge. Finally, Lineament Density, derived from Landsat 8 imagery, identifies secondary porosity. These linear features, such as faults and fractures, serve as crucial conduits for groundwater movement and are frequently associated with high-yielding wells in complex terrains.

The execution of this study utilized a suite of specialized software environments to process the diverse spatial datasets required for the Analytic Hierarchy Process (AHP) and multi-criteria analysis. ArcMap 10.8 served as the foundational platform, facilitating spatial database management, the generation of all thematic layers, and the execution of the final weighted overlay analysis to delineate the potential zones. To enhance the accuracy of structural features, ERDAS IMAGINE 5.2 was employed for the advanced pre-processing of satellite imagery, specifically for calculating band ratios essential in the extraction of lineaments from Landsat 8 OLI/TIRS data.

The quantitative component of the study, specifically the AHP calculations, involved the development of a pairwise comparison matrix and rigorous consistency ratio checks, which were performed using a specialized Multi-Criteria Decision Analysis (MCDA) spreadsheet tool. Furthermore, Google Earth Engine (GEE) was leveraged for its high-performance cloud computing capabilities to conduct the Land Use Land Cover (LULC) classification. This integration of GEE ensured a high-accuracy surface analysis across the geographically varied landscape of the Rupandehi district, bridging the gap between raw satellite data and actionable hydrogeological information. The interoperability of these tools allowed for a seamless transition from raw data acquisition to the final production of the Groundwater Potential Zone (GWPZ) map.

2.3 Thematic Layer Preparation and Reclassification

The study methodology follows a systematic workflow of Multi-Criteria Decision Analysis (MCDA) integrated with Geospatial Science (Figure 2). The process began with the collection of multi-source spatial data, followed by the generation and standardization of seven thematic layers in a GIS environment (Figure 2).

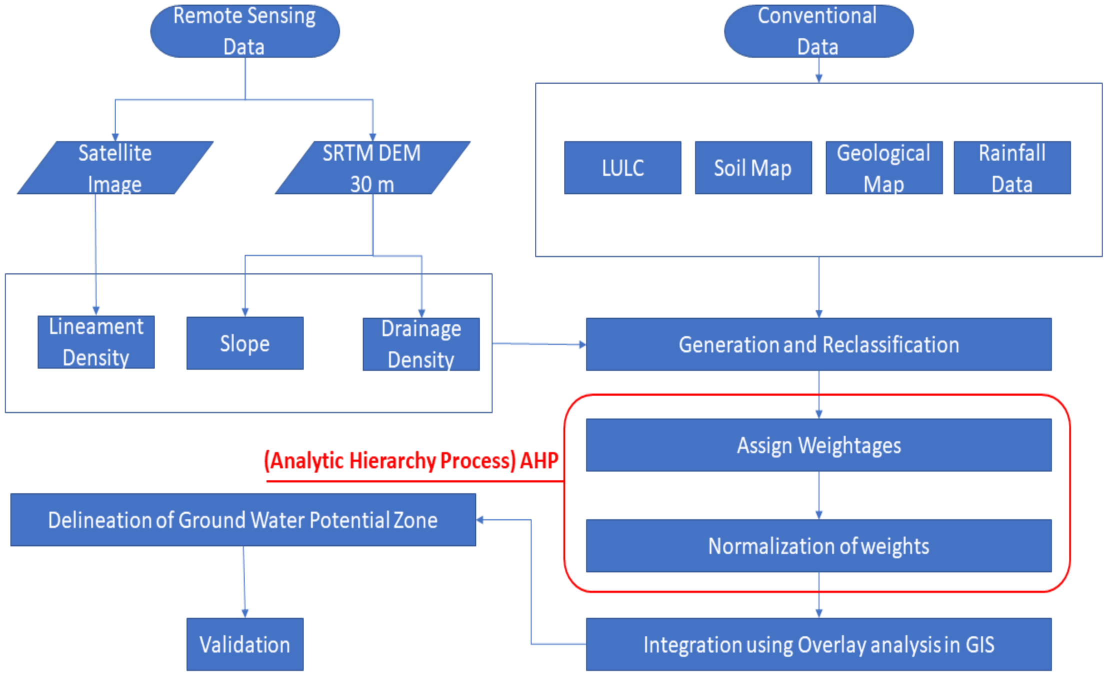

Figure 2: A comprehensive flowchart depicting the systematic integration of spatial data acquisition, thematic layer generation, Multi-Criteria Decision Analysis (MCDA) via AHP, and the final validation process.

The raw data for Rainfall, Geology, Slope, LULC, Soil, Drainage Density, and Lineament Density were processed to create individual thematic maps. To perform a mathematical comparison, each layer was reclassified into five categories, ranging from 'Very Low' to 'Very High' potential using the Spatial Analyst extension in ArcMap 10.8. This standardization ensures that diverse units (e.g., millimeters of rain vs. degrees of slope) are comparable on a common scale.

Rainfall is a vital factor in determining groundwater potential; since the Rupandehi district is located in a tropical bio-climatic zone, the Inverse Distance Weight (IDW) method was used to interpolate data from 13 stations within the study area and neighboring districts. As shown in Figure 3a, rainfall is maximum in the north-east and decreases toward the western part. Geology also plays a vital role in the distribution and movement of water; the study area comprises Undivided Precambrian rocks, Neogene Sedimentary rocks, and Quaternary sediments (Figure 3b). Terrain features like slope, generated from SRTM DEM, express ground steepness; flat areas are prioritized for groundwater recharge, whereas steep slopes, reaching up to 57.4 degrees in this study, promote runoff (Figure 3c).

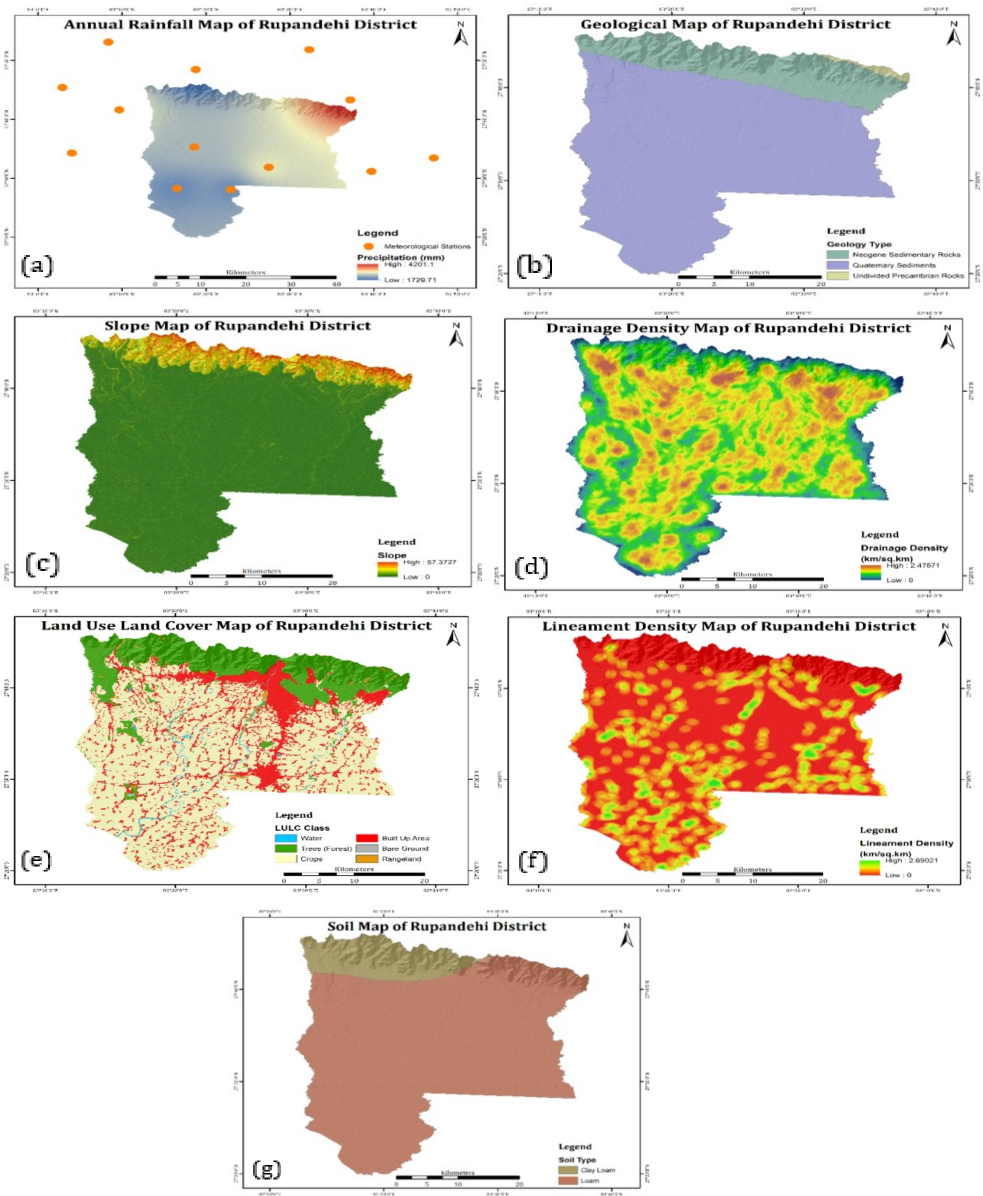

Figure 3: Thematic maps of the study area: (a) Annual Rainfall: Spatial patterns highlighting high-recharge zones in the northeast; (b) Geology: Distribution of lithological units and aquifer storage capacity; (c) Topographic Slope: Terrain steepness showing infiltration vs. runoff zones; (d) Drainage Density: Surface water network intensity affecting groundwater recharge; (e) LULC: Land utilization classes identifying permeable and impermeable surfaces; (f) Lineament Density: Structural conduits indicating secondary porosity; (g) Soil Texture: Spatial classification of soil permeability and water retention.

This is complemented by drainage density (Figure 3d), which shows an inverse correlation with groundwater potential as density increases, potential decreases (Nair et al., 2017). Furthermore, LULC significantly influences resources by altering recharge conditions; the Sentinel 2A-derived map identifies water, forest, crops, built-up areas, bare ground, and rangeland (Figure 3e). Lineament density (Figure 3f), identified via PCI Geomatica and manual digitization of hill shades, highlights structural fractures that serve as pathways for groundwater movement (Magesh et al., 2012). Finally, soil characteristics determine water retention based on permeability; the district is predominantly covered by Clay Loam and Loam, with Loam being more favorable for potential due to its higher permeability (Arshad et al., 2020), as depicted in the soil map (Figure 3g).

2.4 Assignment of Weights and Normalization

The Analytical Hierarchy Process (AHP) is a robust and widely recognized GIS-based method for delineating groundwater potential zones through multi-criteria decision analysis (Arulbalaji et al., 2019). This method allows for the systematic integration of diverse thematic layers by assigning relative importance through expert-informed pairwise comparisons. For this study, seven thematic layers were selected based on their hydrogeological significance in the Rupandehi district (Table 2).

The weights for these layers were assigned using the fundamental scale developed by Saaty (1990), which ranges from 1 (equal importance) to 9 (extreme importance) (Table 2). In the GIS environment, each thematic layers sub-classes were reclassified and assigned a rank (R_j) from 1 to 5, where 1 indicates "Very Low" and 5 indicates "Very High" influence on groundwater potential (Table 4).

Table 2: Fundamental scale for pairwise comparison judgements (Saaty, 1990)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

To ensure the logical reliability of the weight assignments, the Consistency Ratio (CR) was evaluated. The Consistency Index (CI) was first calculated using the principle eigenvalue (λ_{max}) and the number of factors (n). Then, the consistency index (CI) is calculated as;

$$CI = \frac{\lambda max - n}{n-1} \quad \text{Eq 1}$$

Where n is the number of factors used in the analysis.Now, the Consistency Ratio defined as

$$CR = \frac{CI}{RCI} \quad \text{Eq 2}$$

where RCI = Random consistency Index value, whose values were obtained from Saaty's standard (Table 3).

$$CR = \frac{0}{1.32} = 0 \quad \text{Eq 3}$$

According to (Saaty, 1990), CR of 0.10 or less is acceptable to continue the analysis. If the consistency ratio is greater than 0.10, then there is the need to revise for locating causes of inconsistency and correct it. If the CR value equals 0 then there is perfect level of consistency in pairwise comparison (Table 3). The CR value is not greater than 0.1, that means the judgement matrix is reasonably consistent.

Table 3: Standard Random Consistency Index (RCI) Values (Saaty, 1990)

The consistency index of randomly generated reciprocal matrices							
			Order of matrix				
N	1	2	3	4	5	6	7
RCI value	0.00	0.00	0.58	0.9	1.12	1.24	1.32

Table 4: Integrated AHP Pairwise Comparison Matrix, Normalization, and Thematic Ranking

Thematic Layer	**Rainfall**	**Geology**	**Slope**	**Drainage Density**	**LULC**	**Lineament Density**	**Soil**	**Normalized Weight (Wj)**	**Sub-class Rank (Rj)**
Rainfall (Rf)	1	1.09	1.35	1	1.65	1.16	1.57	17.25%	1 - 5
Geology (Ge)	0.92	1	1.12	0.86	1.06	1.2	1.2	14.71%	1, 3, 2005
Slope (Sl)	0.74	0.89	1	0.61	1.44	0.69	1	12.30%	5 - 1
Drainage Density (DD)	1	1.16	1.65	1	1.65	1.2	1.65	18.14%	5 - 1
LULC	0.61	0.95	0.69	0.61	1	0.6	0.83	10.42%	1 - 5
Lineament Density (LD)	0.86	0.83	1.44	0.83	1.66	1	1.57	15.75%	1 - 5
Soil (Soil)	0.64	0.83	1	0.61	1.2	0.64	1	11.44%	2 - 3

2.5 Delineation of Groundwater Potential Zones

The final stage of the spatial modeling process involves the calculation of the Groundwater Potential Index (GWPI) to comparatively assess and delineate potential zones within the study area. This integration considers all pertinent environmental and physical factors related to the occurrence and movement of groundwater resources (Subba Rao, 2006). The GWPI was computed using the weighted linear combination method proposed by Malczewski (1999), which aggregates the relative contribution of each thematic layer.

The index for each spatial grid cell was calculated according to the following equation:

$$\text{GWPI} = \sum_{j=1}^{n} (W_j \times R_j) \quad \text{Eq 4}$$

Where:

a. W_j represents the normalized weight of the jth parameter.

b. R_j signifies the rating or rank of the individual class within that parameter.

c. n represents the total number of thematic parameters used in the analysis.

In the context of this study, the equation is expanded to include all seven hydrogeological drivers:

$$GWPI = (Rf_w . Rf_r) + (Ge_w . Ge_r) + (Sl_w . Sl_r) + (DD_w . DD_r) + (LULC_w . LULC_r) + (LD_w . LD_r) + (Soil_w . Soil_r) \quad \text{Eq 5}$$

where Rf is Rainfall, Ge is Geology, Sl is Slope, DD is Drainage Density, LULC is Land Use Land Cover, LD is Lineament Density, and Soil is Soil Texture. The subscripts w and r denote the thematic weight and the subclass rank, respectively.

As detailed in Table 5, each parameter was categorized into specific factors and assigned ranks ranging from 1 (Very Low potential) to 5 (Very High potential) based on their influence on the hydrological cycle. By overlaying these ranked layers within the ArcMap 10.8 environment, the continuous GWPI values were generated and subsequently classified into distinct zones to produce the final Groundwater Potential Zone (GWPZ) map for the Rupandehi district. Raditional herbal remedies have played a significant role in healthcare systems worldwide, including Ayurveda, Traditional Chinese Medicine (TCM), and other ethnopharmacological practices(Sen et al., 2011). While herbal compounds are often assumed to be safe due to their natural origins, many lack extensive toxicity studies, particularly through modern scientific methods(Woo et al., 2012). This can lead to safety concerns, especially in long-term use or high doses(Moreira et al., 2014).

As drug discovery and toxicology studies progress, computational approaches have gained prominence(Cherkasov et al., 2014). Specifically, Quantitative Structure-Activity Relationship (QSAR) models have become a popular tool for predicting the biological activity of chemical compounds based on their molecular structures(Varsou et al., 2024). QSAR models can predict potential toxic effects without the need for large-scale clinical testing or experimental setups, making them efficient for early-stage screening(EBSCOhost, 2023).

Table 5: Comprehensive Categorization and Ranking of Parameters Influencing GWPZ

Parameters	**Sub-classes/Factors**	**Normalized Weight (Wj)**	**Assigned Rank (Rj)**
Rainfall	Very Low to Very High	17.25	1 - 5
Geology	pC (Precambrian), N (Neogene), Q (Quaternary)	14.71	3, 1, 2005
Slope	0-1°, 1-2°, 2-3°, 3-5°, >5°	12.3	5, 4, 3, 2, 1

Drainage Density	Very Low to Very High	18.14	5, 4, 3, 2, 1
LULC	Water, Forest, Crops, Rangeland, Bare, Built-up	10.42	5, 5, 5, 3, 1, 1
Lineament Density	Very Low to Very High	15.74	1, 2, 3, 4, 5
Soil	Loam, Clay Loam	11.44	3, 2

While QSAR models have been applied extensively in the pharmaceutical and industrial sectors, little attention has been given to herbal medicines(Xu et al., 2024). The lack of data about traditional medicines creates a barrier to ensuring the safe use of those compounds in modern healthcare.

There is a growing need for computational models that can predict the toxicity of herbal compounds, thus bridging the gap between traditional medicine and modern toxicological evaluation(Machhar et al., 2019).

This study aims to develop a machine learning – based QSAR model to predict toxicity of herbal and synthetic organic compounds, using RDKit-calculated molecular descriptors. The model will be trained and validated with known toxicity data from herbal and plant derived compounds.

The outcomes could benefit both the scientific community and the herbal medicine industry by offering a tool for early-stage screening, potentially reducing the need for extensive in vivo and in vitro testing(Krewski et al., 2010).

3. Results and Discussion

The integration of multi-criteria decision analysis (MCDA) and geospatial techniques has resulted in the identification of varying groundwater potential zones (GWPZ) across the Rupandehi district. The following sections detail the outcomes of the thematic overlay and the subsequent interpretation of these findings in the context of regional hydrogeology.

3.1 Delineation of Groundwater Potential Zones (GWPZ)

Taking into account the topography and local knowledge of the study area, regions with varying levels of groundwater availability have been identified, ranging from high-yielding to dry zones. Due to the specific resolution of the spatial data used, the classification was refined into three primary zones to ensure a robust and practical assessment. The resulting Groundwater Potential Zone (GWPZ) map of the Rupandehi district (Figure 4) categorizes the landscape into High, Moderate, and Low recharge potentiality, covering areas of 438.06 km2, 588.83 km2, and 277.01 km2respectively Statistical analysis reveals that 45% of the district falls under the moderate potential zone, while the high potential zone accounts for 34%, and the low potential zone covers the remaining 21% (Figure 5).

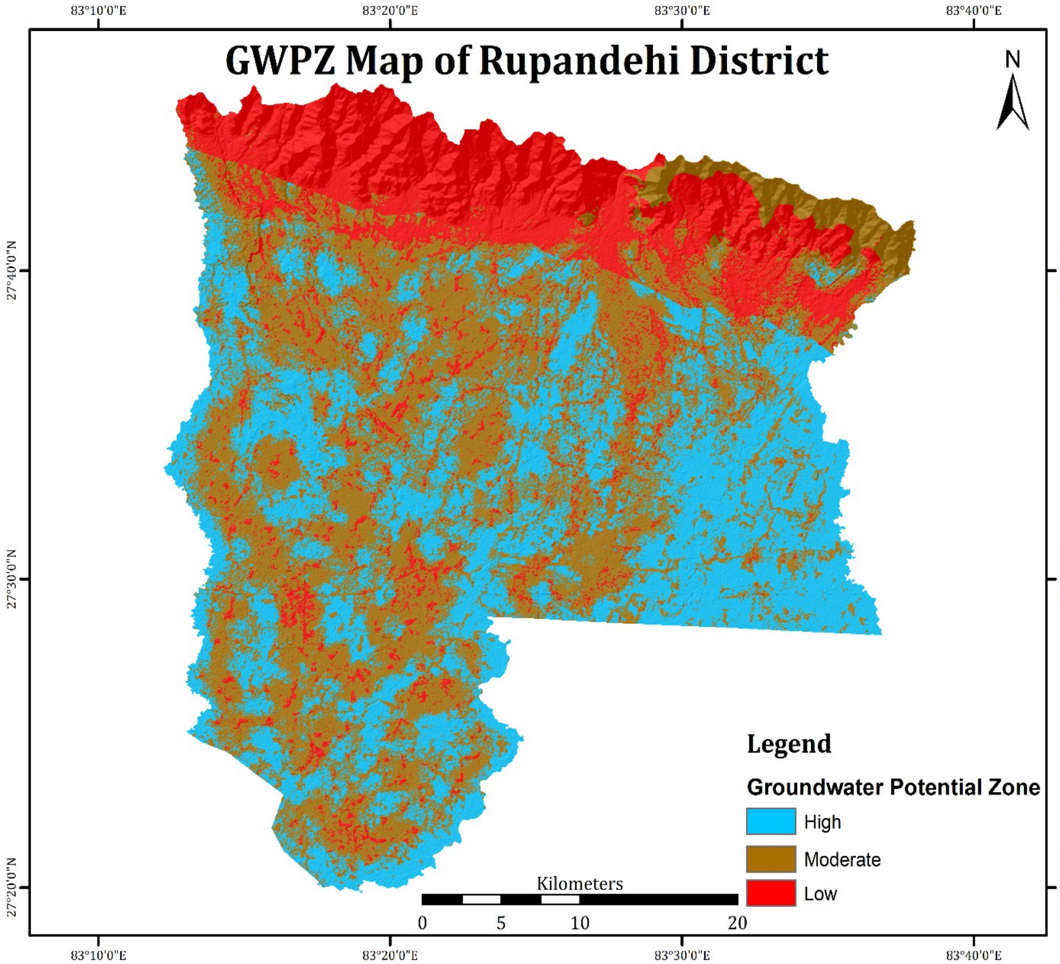

Figure 4: The resulting predictive GWPZ map produced through Weighted Overlay Analysis, categorizing the district into High (34%), Moderate (45%), and Low (21%) potential zones based on the integrated GIS and AHP model.

Geographically, the High and Moderate potential zones are predominantly situated in the southern part of the district. This concentration is attributed to the presence of permeable loamy soil, gentle slopes, and flat terrain, combined with high lineament density which facilitates deep percolation. In contrast, Low potential zones are primarily confined to the northern hilly regions. In these areas, the steep slopes of the Churia range promote rapid surface runoff over infiltration, while the consolidated Neogene sedimenta ry rocks offer limited primary porosity for aquifer storage, as discussed by Subba Rao (2006).

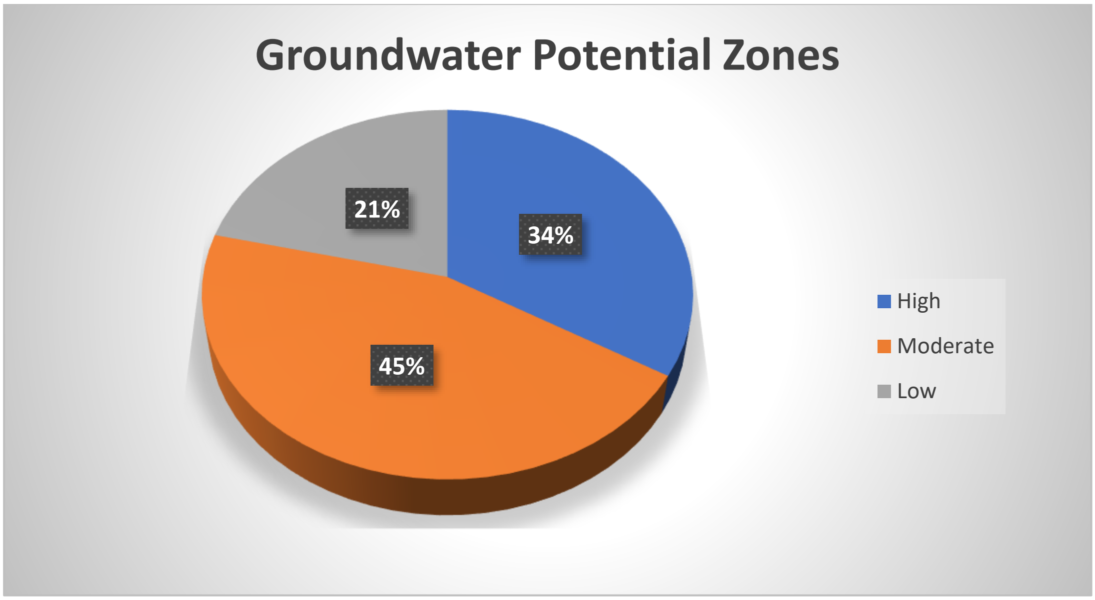

Figure 5: A pie chart illustrating the percentage distribution of delineated groundwater potential areas within the district, where the Moderate potential zone occupies the largest portion at 45%, followed by High potential at 34%, and Low potential at 21%.)

3.2. Model Validation and Accuracy Assessment

The reliability of the delineated groundwater potential zones was further validated using historical well-yield data from the Groundwater Resource Development Board (GWRDB), Nepal, recorded in 2019. A total of 43 wells were utilized for this cross-verification (Figure 12) (Figure 6). The validation process involved comparing the discharge values of these wells measured in liters per second (lps), against the predicted GWPI categories.

The results indicate that wells located in the Low and Moderate potential zones typically exhibit yielding capacities in the range of 0.4 to 30 lps. Conversely, the wells situated within the High potential zones consistently show higher water-yielding capacities, exceeding 30 lps (figure 6). Out of the 43 wells analyzed, 35 wells (approximately 81.4%) demonstrated a high level of agreement with the model-predicted potential categories. However, eight wells showed discrepancies: four low-yielding wells (Nos. 6, 7, 15, and 20) and two moderate-yielding wells (Nos. 28 and 30) were found in predicted high-potential areas, while two high-yielding wells (Nos. 39 and 42) were located in moderate-potential zones (Figure 6). These variations are likely due to localized factors such as concentrated urban settlements or intensive agricultural extraction, which can locally depress or enhance the water table beyond the resolution of surface-based GIS parameters.

Ultimately, the high rate of correlation between the predicted zones and actual field measurements confirms that the integrated GIS, RS, and AHP-based techniques are highly effective for groundwater resource assessment. This methodology provides a reliable framework that can be adapted to other geographically similar regions for sustainable water management (Arulbalaji et al., 2019).

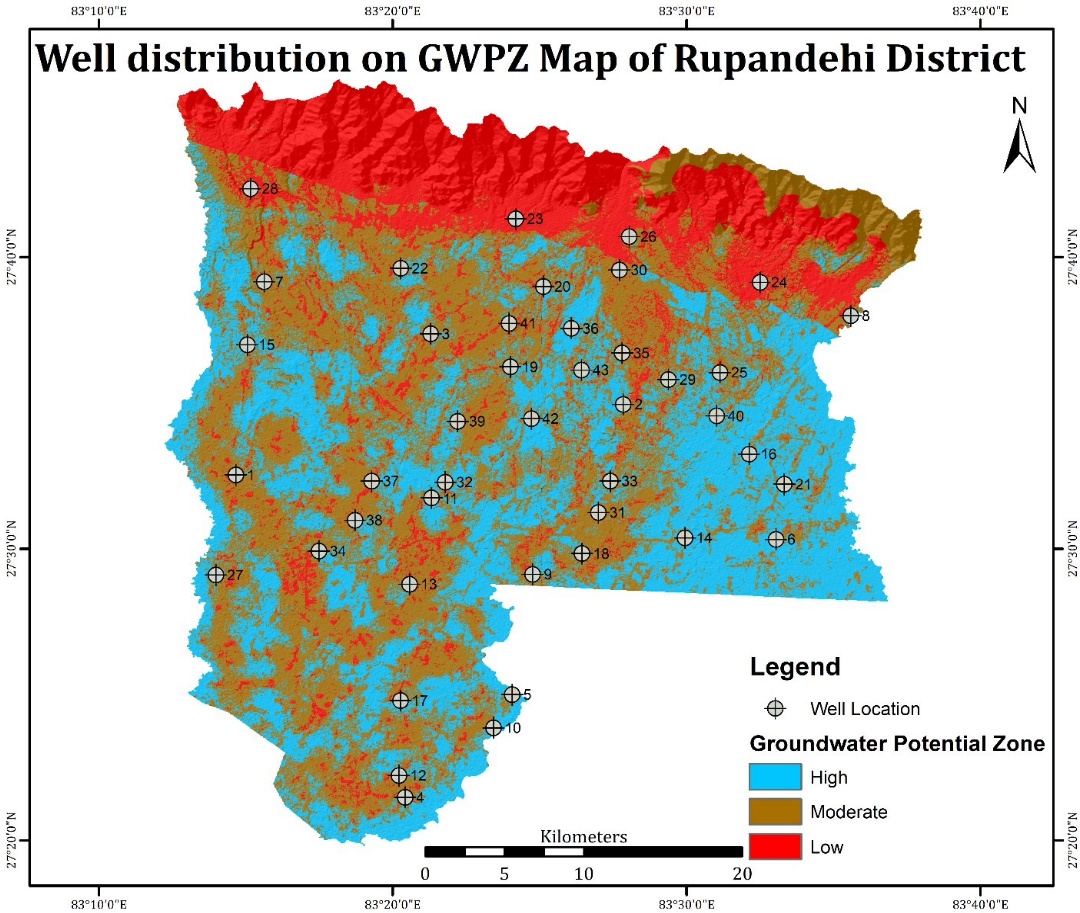

Figure 6: A spatial validation map showing the locations of 43 observation wells overlaid on the predicted groundwater potential zones. The map displays the correlation between field-recorded well discharge data and the model-generated high, moderate, and low potential zones across the district.

3.3. Discussion

The spatial distribution of groundwater potential in Rupandehi district reveals a clear hydrogeological dichotomy between the northern and southern regions. The High and Moderate potential zones, which collectively cover 79% of the study area, are primarily concentrated in the southern and central Terai plains. This dominance is largely attributed to the presence of Quaternary alluvial sediments characterized by high primary porosity and a predominantly flat topography with slopes less than 1°. These factors facilitate maximum infiltration by increasing the "contact time" between surface water and the soil. As noted by Subba Rao (2006), lithological composition and topographic flatness are the primary drivers for subsurface water storage in such alluvial terrains.

In contrast, the Low potential zones (21% of the area) are predominantly found in the northern hilly regions. The steep slopes, which reach up to 57.4°, and the presence of consolidated Neogene sedimentary rocks promote rapid surface runoff over infiltration. This reflects an inverse correlation between drainage density and groundwater potential; as the drainage network becomes denser in these hilly terrains, the likelihood of groundwater recharge decreases because water is efficiently exported as surface discharge. This observation aligns with the findings of Nair et al. (2017) regarding the efficiency of drainage systems in reducing water residence time on the surface.

The integration of lineament Density proved to be a critical indicator of secondary porosity. High lineament density in specific zones signifies the presence of faults and fractures that act as pathways for groundwater movement, which is particularly vital for locating permeable zones in otherwise consolidated geological formations. Furthermore, the study highlights the impact of Land Use Land Cover (LULC), where forested areas and crop lands are assigned high ranks due to their recharge-facilitating properties. Conversely, built-up areas and bare ground are identified as impediments to recharge, creating what Aykut (2021) describes as a recharge deficit due to increased surface impermeability.

The validation of the GWPZ model against 43 wells recorded in 2019 by the Groundwater Resource Development Board (GWRDB) confirms the high reliability of the AHP-based approach. The fact that 35 out of 43 wells (81.4%) matched the predicted potential categories provides strong evidence for the model's accuracy. Specifically, wells in high potential zones yielded capacity greater than 30 liters per second (lps), while those in lower potential zones ranged between 0.4 and 30 lps. The slight discrepancies (8 unmatched wells) are likely due to localized anthropogenic factors, such as high-density settlements or intensive agricultural extraction, which can locally alter the groundwater table.

Overall, the successful delineation of these zones demonstrates that the integration of GIS, Remote Sensing, and AHP is a robust and useful method for groundwater assessment. This approach provides a scientific basis for sustainable water resource planning in Rupandehi and can be readily applied to other geographically similar regions.

4. Conclusion

In this study, groundwater potential zones (GWPZ) in the Rupandehi district of Nepal were identified through the integrated application of Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP). Seven critical thematic layers geology, land use land cover (LULC), slope, drainage density, lineament density, precipitation, and soil were generated using a combination of conventional data and satellite imagery to assess the region's hydrogeological characteristics. Weights were systematically assigned to each individual theme and its respective sub-classes based on the AHP technique to quantify their influence on groundwater occurrence. The resulting analysis classified the study area into three distinct potential zones: high, moderate, and low. The Moderate potential zone represents the largest area at 45%, while the High and Low potential zones cover 34% and 21%, respectively. Geographically, the high and moderate potential areas are situated in the southern plain lands characterized by gentle slopes, whereas the low potential zones are primarily confined to the northern hilly regions.

The effectiveness of this methodology was verified by validating the predicted zones against 43 existing wells, where 35 wells (81.4%) showed a positive agreement with the model. Discrepancies in the remaining eight wells are attributed to localized factors such as proximity to dense urban settlements, intensive agricultural activity, or the increasing trend of dryness since the 2018 validation data was recorded. This study underscores the value of RS and GIS as instrumental tools for water resource planners in undertaking groundwater development initiatives for irrigation and domestic supply. Furthermore, the study identifies promising future research directions, including the exploration of advanced machine learning techniques like deep learning and support vector machines to improve predictive accuracy for complex datasets. Ultimately, this study provides a scientific basis for sustainable water management that can be replicated across different geological and hydrological settings in other parts of Nepal.

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Supplementary Materials

a. *Data Availability Statement*: The primary spatial data, thematic layers, and the AHP decision matrix that support the findings of this study are available from the corresponding author upon reasonable request. This includes the processed GIS shapefiles, reclassified raster layers for Rupandehi district, and the weighted overlay calculation sheets generated during the analysis.

b. *Data Sources*: This study integrates multiple data sources, including Remote Sensing products (Sentinel-2A imagery and SRTM DEM), conventional meteorological records from the Department of Hydrology and Meteorology (DHM), and hydrogeological maps. Validation was performed using historical well-discharge data (2019) provided by the Groundwater Resource Development Board (GWRDB), Nepal.
c. *Generative AI Statement*: During the preparation of this manuscript, the authors utilized generative artificial intelligence (AI) tools for the specific purposes of refining technical descriptions, structuring the AHP methodology, paraphrasing complex hydrogeological discussions, and improving the overall academic tone of the manuscript. While AI was used to assist in the synthesis of literature and linguistic clarity, all core scientific contributions, including the selection of thematic parameters, the determination of AHP weightages, the GIS-based spatial analysis, and the final interpretation of groundwater potential zones are the original work of the authors. All content has been rigorously reviewed and validated by the authors to ensure scientific integrity and technical accuracy.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflict of interest.

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Here is the detailed reference list for the sources cited within the manuscript, including their respective DOI links as provided in your documentation:

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