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Groundwater potential assessment in part of Kavrepalanchowk district using cosine amplitude method

***Bala Ram Upadhyaya, Santosh Silwal, Ananta Man Singh Pradhan and Sanjeeb Baral**

Water Resources and Energy Research Centre, Water and Energy Commission Secretariat, Government of Nepal
**Corresponding author's email: brupadhyaya1@gmail.com*

ABSTRACT

Groundwater plays a vital role in sustaining agriculture, domestic supply, and ecological balance in Nepal's mid-hill regions, where surface water availability is highly seasonal. This study assesses groundwater potential in part of Kavrepalanchowk District using the Cosine Amplitude Method (CAM), a statistical approach that integrates multiple thematic layers to delineate potential zones.

In this study, multiple thematic layers such as elevation, slope, aspect, curvature, topographic position index (TPI), topographic wetness index (TWI), drainage density, geology and lineament density, were weighted and combined within a GIS framework to delineate groundwater potential map. The resulting map classified the area into five distinct groundwater potential zones: very low, low, moderate, high, and very high. Among the controlling parameters, lineament density (15.8%) and the Topographic Wetness Index (14.4%) were the most influential parameters, underscoring the critical role of structural features and surface saturation in groundwater occurrence. Other factors such as aspect, drainage density, and elevation contributed significantly, while geology and curvature exhibited comparatively lower influence. These findings demonstrate that geomorphological and hydrological factors exert greater control over groundwater potential than lithological characteristics in the study area. The outcomes provide a scientific basis for prioritizing recharge interventions and developing effective groundwater management strategies.

Keywords: Groundwater potential; Cosine amplitude method; GIS; Spring inventory

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INTRODUCTION

Groundwater is one of Nepal's most valuable natural resources, shaped by the country's diverse geology, geomorphology, and physiography. In intra-mountain valleys such as Kathmandu and Dang, aquifers are confined within isolated basins, while in the Terai plains south of the Himalayas, groundwater systems are more extensive and continuous. The Terai region has long relied on groundwater as the primary source of drinking water and, since the introduction of tube well technology in the early 1970s, as a critical input for agriculture.

Despite this reliance, water availability in Nepal's mountainous regions remains highly seasonal. Flat hill terrains with high agricultural potential are often restricted to seasonal cropping cycles due to limited irrigation options. Surface irrigation is frequently impractical in these areas, underscoring the need for alternative approaches. Groundwater is becoming a very important source of fresh water, especially as other water sources dry up (Upadhyaya et al. 2024). Expanding groundwater use in the mid-hills could therefore play a transformative role in enhancing agricultural productivity and food security.

Groundwater potential mapping is an essential tool for identifying areas favorable for groundwater occurrence and recharge (Rahmati et al. 2016). In recent years, Geographic Information System (GIS) and Remote Sensing (RS) techniques have become widely used because they allow integration of multiple thematic layers into a composite analysis. Globally, researchers have employed a wide spectrum of methods to assess groundwater resources, ranging from traditional hydrogeological surveys and geophysical investigations to modern approaches that integrate Geographic Information Systems (GIS) and Remote Sensing (RS) (Rodriguez and Ferolin, 2024). Traditional techniques, such as pumping tests, well inventories, and electrical resistivity surveys, provided valuable insights into aquifer characteristics but were often limited in spatial coverage and accuracy (Kumar et al. 2020).

A wide range of statistical and machine learning techniques have been employed to delineate groundwater potential (GWP) zones. Among the most widely used are the frequency ratio method (Guru et al. 2017; Manap et al. 2014), the logistic regression model (Chen et al. 2018; Nguyen et al. 2020), and multicriteria decision evaluation approaches (Masoud et al. 2022; Singh et al. 2018). More advanced ensemble and machine learning methods, including the random forest algorithm (Naghibi et al. 2017; Nguyen et al. 2020), maximum entropy model (Golkarian and Rahmati, 2018; Rahmati et al. 2016)and boosted regression trees (Chen et al. 2018; Naghibi et al. 2017) have demonstrated strong predictive capabilities. Recently, deep learning frameworks such as convolutional neural networks and deep neural networks have been introduced, offering promising results in capturing complex nonlinear relationships between hydrogeological parameters and groundwater occurrence (Lee et al. 2012, 2018; Pradhan et al. 2021).

Traditional approaches such as the Analytic Hierarchy Process

(AHP) have been widely applied in Nepal to assign weights to thematic layers including lithology, slope, rainfall, and land use. AHP, developed by (Saaty, 1980), relies on expert-based pairwise comparisons and consistency checks to derive factor weights, and has proven effective in delineating groundwater potential zones in diverse hydrogeological settings (Pathak et al. 2021; Sapkota et al. 2021; Timalsina et al. 2024). However, AHP is inherently subjective, as it depends on expert judgment. (Pradhan et al. 2019) applied a spatial multi-criteria evaluation (SMCE) approach to delineate groundwater potential zones in Dolakha District, highlighting the importance of integrating geomorphological and hydrological parameters in mountainous terrains.

This study employs the Cosine Amplitude Method (CAM) to quantitatively evaluate the influence of groundwater-controlling factors on groundwater occurrence. CAM determines objective weights by measuring the similarity between groundwater inventory vectors and thematic factor vectors. Although CAM has previously been applied in landslide susceptibility mapping (Kim and Park, 2017), its use in groundwater potential assessment is introduced here for the first time.

The primary objective of this study is to delineate groundwater potential zones in part of the Kavrepalanchowk District by applying the CAM, a relatively new approach in groundwater potential mapping. This objective is accomplished through the preparation and overlay of thematic layers representing the most critical parameters that influence groundwater recharge and flow within the study area. The results of this study are anticipated to contribute significantly to irrigation planning and the sustainable management of water resources within the study area.

STUDY AREA

The study was conducted in the middle hill region of Kavrepalanchowk District, located within Bagmati Province, Nepal. This area is characterized by rugged topography, hard-rock geological formations, and diverse hydrological features that play a critical role in supporting agriculture and rural livelihoods. The region lies within the subtropical climatic zone, experiencing distinct wet and dry seasons, with monsoon rainfall contributing significantly to surface and groundwater recharge.

Hydrologically, the study area is drained by several perennial streams that form an interconnected network of surface water flow. The major drainage systems include the Roshi Khola, Sailandhu Khola, Sundi Khola, Sisne Khola, Dapcha Khola, Andheri Khola, Dhital Khola, and Okhar Khola. These streams not only sustain local ecosystems but also provide potential sources for irrigation development in the middle hills. The location map of the study area is shown in Fig. 1.

METHODOLOGY

The methodology adopted for groundwater potential (GWP) assessment in this study is the CAM. This statistical technique evaluates the relationship between groundwater spring occurrences, considered as the dependent variable, and a set of conditioning factors serving as independent variables. These factors include elevation, slope, aspect, curvature, topographic wetness index (TWI), drainage density, lineament density, and geology. By systematically analyzing these parameters, CAM generates objective weights that reflect their relative influence on groundwater occurrence. The different thematic layers were generated in ArcGIS and stored in geodatabase. CAM provides valuable insights into the relative significance and predictive capacity of each factor, thereby enhancing the understanding of groundwater potential across the study area.

After the identification of GWP, the validation was carried out by area under curve (AUC) of receiver operating characteristics curve (ROC) method considering cumulative percentage of springs and percent of groundwater potentiality probability value.

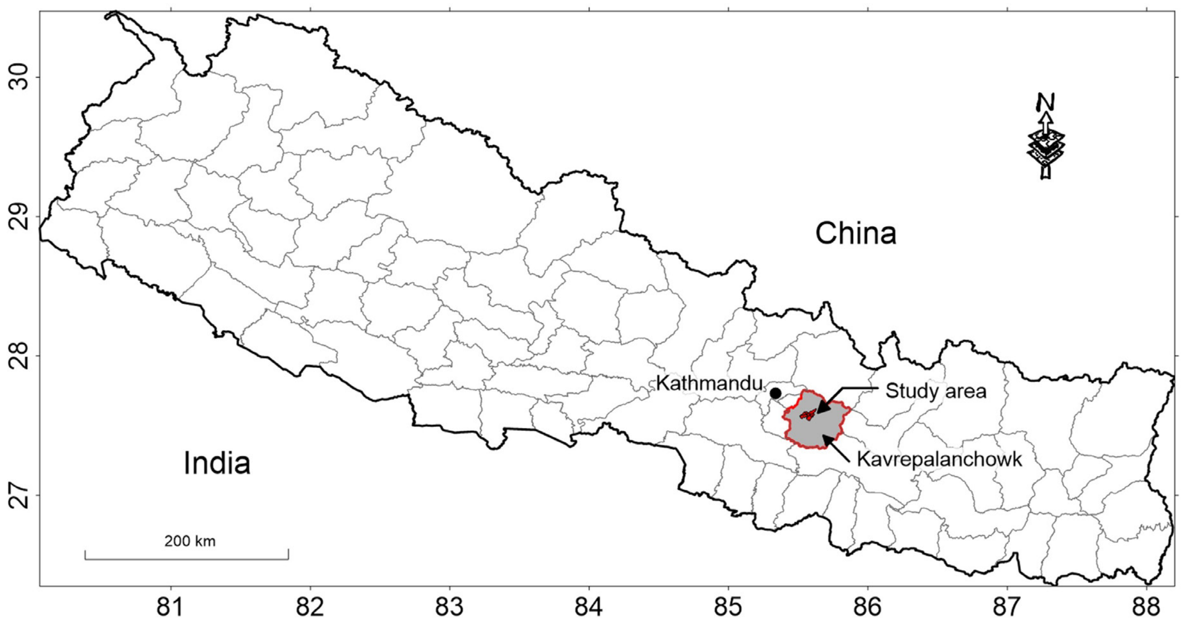

Fig. 1: Location Map of the Study area.

Cosine Amplitude Method (CAM)

The CAM was employed to determine the degree of association between the inventory data and each controlling factor. Each factor and the dependent variable were represented as vectors in multidimensional space, and the cosine of the angle between vectors was calculated using:

$$CAM_i = \frac{\sum_{j=1}^{n} L_j . F_{ij}}{\sqrt{\sum_{k=1}^{n} L_j^2} . \sqrt{\sum_{j=1}^{n} F_{ij}^2}} \qquad (1)$$

Where L_j Spring presence or absence (often 1 or 0) at pixel or mapping unit j, F_{ij} is the value or class code of factor i at unit j, n is the total number of pixels. The resulting CAM values, ranging from 0 to 1, were interpreted as weights, with higher values indicating stronger influence on groundwater occurrence.

DATA COLLECTION

Accurate and reliable data are fundamental to groundwater potential assessment. This section outlines the procedures adopted for collecting, organizing, and preparing datasets used in the analysis. Both primary and secondary sources were utilized to ensure comprehensive coverage of hydrogeological, topographical, and environmental parameters.

Primary data collection

Spring inventory

To understand groundwater conditions, a comprehensive inventory of springs was conducted across the study area. The inventory revealed that fracture-controlled springs are the most dominant type, reflecting the influence of structural discontinuities on groundwater flow. In addition to these, other spring types were documented, including depression springs, dug wells, seepage springs, and contact springs. Representative photographs of the observed springs are presented in Fig. 2. The occurrence of these springs is strongly linked to specific geological environments such as colluvial deposits, residual soils, and rock–soil interfaces, highlighting the strong control of local lithology and geomorphology on groundwater distribution and discharge. . The springs inventory map is presented in Fig. 3.

Fig. 2: Representative Example of springs observed during field visit.

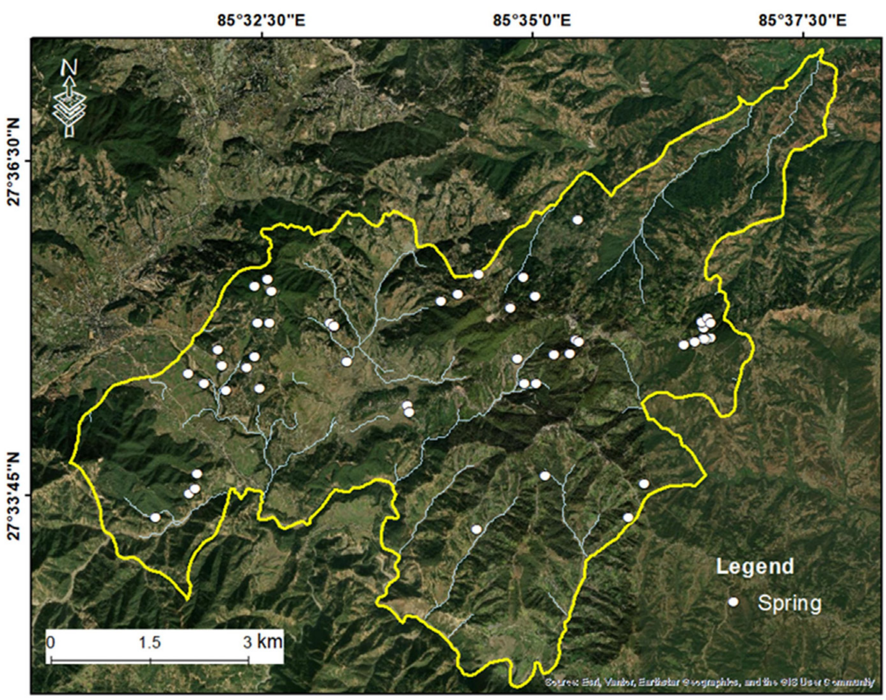

Fig. 3: Spring inventory map of the study area.

Secondary data

Thematic maps

Nine thematic layers were compiled from multiple sources to support the analysis. The geological map was obtained from the Department of Mines and Geology (DMG, 2020), while the remaining thematic maps were derived from the Digital Elevation Model (DEM) provided by the Department of Survey, Government of Nepal.

Topographic data

Topographic data refers to information that describes the surface features of the Earth, including elevation, slope, aspect, Curvature and Topographic Position Index (TPI). It is essential in groundwater potential studies because terrain strongly influences recharge, runoff, and subsurface flow.

Elevation

The DEM was processed in ArcGIS to generate an elevation layer, which was stored in the geodatabase along with other thematic maps. This layer was subsequently integrated into the CAM analysis to evaluate its contribution to groundwater potential zones.

Research has shown that favorable slope and elevation conditions strongly influence groundwater potential, particularly in regions with complex terrain, were elevation controls recharge and discharge dynamics. The elevation within the study area ranges from 856 to 1823 meters above sea level (masl), as illustrated in Fig. 4a.

Slope

The slope map of the study area was generated using a DEM, which itself was derived from contour data available on the digital topographic maps provided by the Department of Survey. Analysis of the DEM indicates that slopes in the region range from flat terrain to gradients as steep as 62° (Fig. 4b). The southern part of the study area is predominantly characterized by steeper slopes. In contrast, the majority of the watershed is covered by gentle slopes, particularly within the 0–10° and 10–20° ranges. Areas with lower slope gradients are of greater significance for groundwater potential compared to steeper terrains, as flatter landforms provide more favorable conditions for infiltration and storage of groundwater (Kamali Maskooni et al. 2020).

Aspect

The Aspect Map of the study area was generated using the DEM described earlier. Figure 4c illustrates the aspect map of the study area. This map illustrates the orientation of slopes, which plays a significant role in groundwater potential. Slopes facing north generally exhibit higher groundwater potential compared to other orientations, owing to their favorable conditions for moisture retention and reduced evapotranspiration. The spatial distribution of aspects further influences the variability of groundwater potential across the region. Given the presence of multiple hills and diverse geomorphological settings, aspect distribution in the study area is highly heterogeneous, resulting in considerable variation in groundwater availability.

Curvature

Curvature map of the study area derived from the DEM, expresses the concavity or convexity of terrain (Fig. 4d). Concave surfaces favor water accumulation and infiltration, enhancing recharge, while convex surfaces promote runoff and reduce groundwater potential.

Topographic Position Index (TPI)

TPI, derived from the DEM, measures the relative elevation of a point compared to its surrounding terrain (Fig. 4e). Negative values indicate valleys and depressions that often act as groundwater discharge zones, while positive values represent ridges that function as recharge areas. Values near zero correspond to mid-slope or flat terrain.

Hydrologic data

Hydrologic data represents the movement and distribution of water across a landscape. In the present study, drainage density and the Topographic Wetness Index (TWI) are employed as key hydrological controlling factors for assessing groundwater.

Drainage Density

The drainage system of the study area is primarily influenced by slope, bedrock characteristics and orientation, as well as regional and local fracture patterns. The drainage network was delineated from digital topographic maps provided by the Department of Survey. Figure 5a presents the drainage density map, which reveals that the majority of the watershed is characterized by low drainage density, while areas of both high and very low drainage density occupy comparatively smaller portions. High drainage density indicates greater overland flow, which limits subsurface percolation. In contrast, low drainage density enhances infiltration capacity, thereby offering more favorable conditions for groundwater recharge(Bagyaraj et al. 2013). Consequently, zones with lower drainage density are considered more suitable for delineating groundwater potential areas.

Topographic wetness index (TWI)

The Topographic Wetness Index (TWI) is a terrain-based parameter derived from the DEM that quantifies the spatial distribution of soil moisture (Fig. 5b). It is calculated from the upslope contributing area and local slope, with higher TWI values indicating zones of greater water accumulation and potential recharge, while lower values correspond to drier areas with limited infiltration.

Geologic data

Geologic data refers to information about the lithology, structure, and subsurface characteristics of a study area. It is critical in groundwater potential assessment because the type of rock, soil, and structural features directly influence infiltration.

Geological map

The geological map of the study area (Fig. 6a) was prepared using data published by the Department of Mines and Geology. The dominant lithological unit is the Tistung Formation (Ti), followed sequentially by the Markhu Formation (Mr) and the Sarung Khola Formation (so). In the northeastern part of the study area, rocks belonging to the Siprin Khola Formation (sk) and Augen Gneiss are present. Additionally, recent alluvial deposits (Q) are observed in the western sector of the watershed.

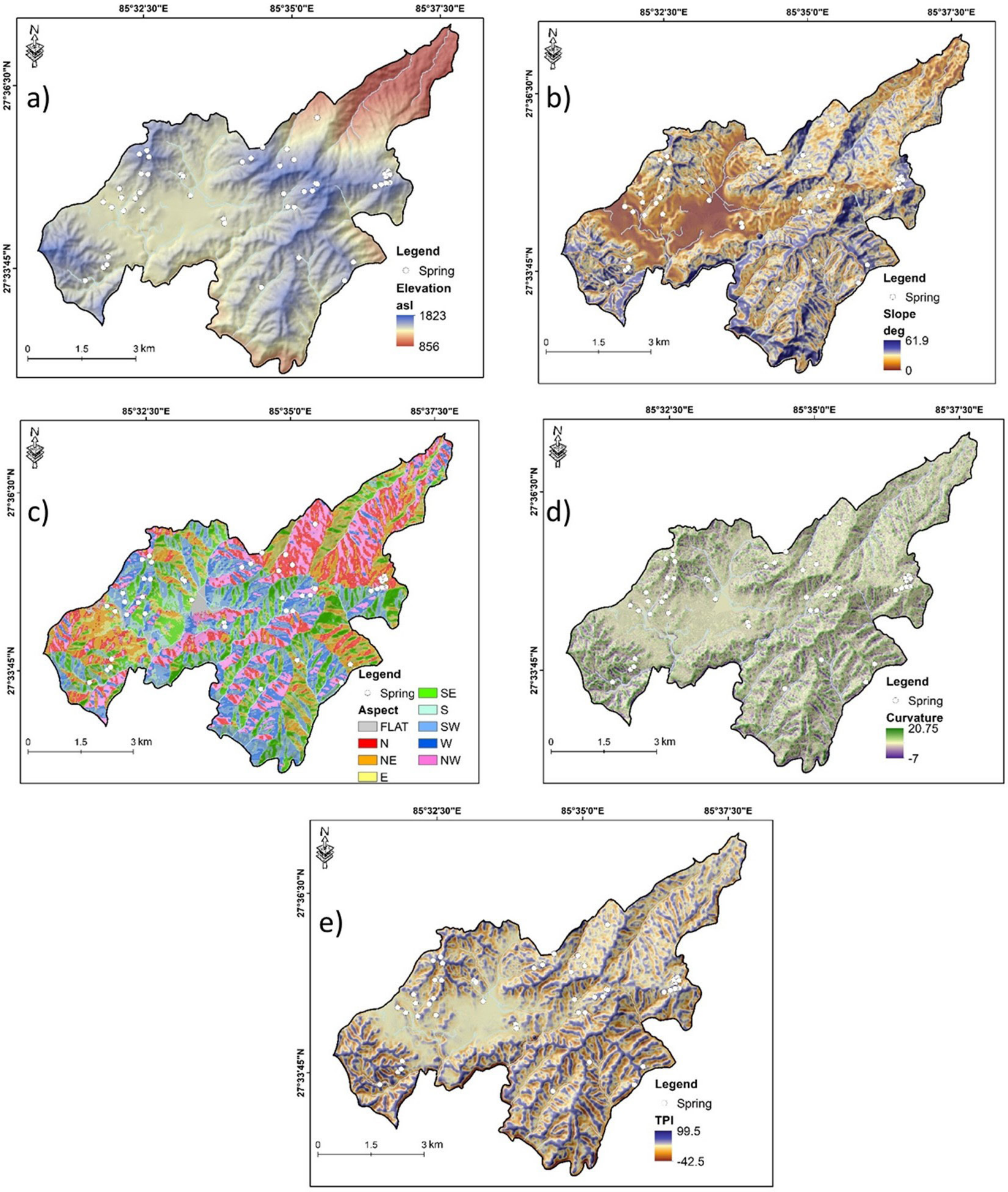

Fig. 4: Topographic conditioning factor of groundwater potential a) Elevation b) Slope c) Aspect d) Curvature e) TPI.

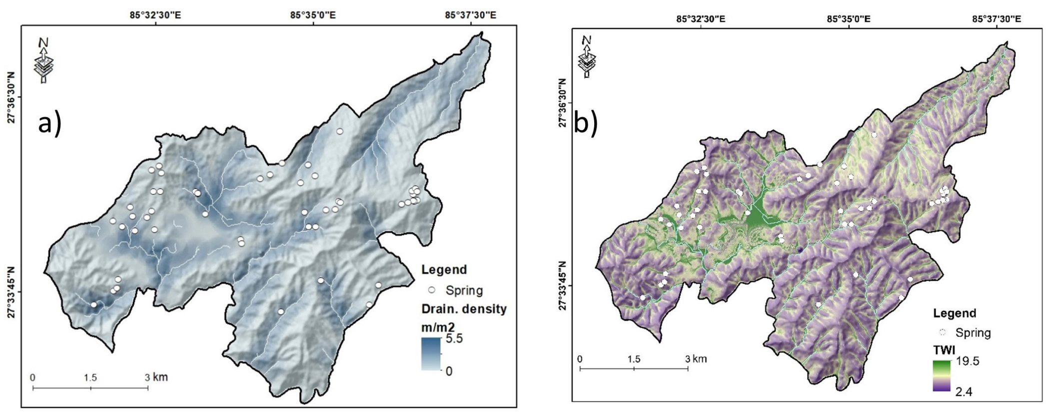

Fig. 5: Hydrologic conditioning factor of groundwater potential a) Drainage Density b) TWI.

Lineament density

Lineaments are linear geological features formed as a result of mechanical deformation in rocks, including faults, thrusts, fold axes, and joints. These structures play a critical role in the occurrence and movement of groundwater within hard-rock aquifers, as they enhance secondary porosity and act as conduits for subsurface flow. The lineament map was developed by analyzing high-resolution Landsat satellite imagery to identify lineaments, with verification conducted through careful examination of the satellite images. In addition, structural information was incorporated from the geological map to ensure accuracy and completeness (Fig. 6b). Areas with higher lineament density are considered more favorable for groundwater availability, as the increased presence of fractures and discontinuities facilitates infiltration and storage within the hard-rock system (Rajaveni et al. 2017).

RESULTS AND DISCUSSION

The groundwater potential map was developed by overlaying nine different thematic layers, including slope, aspect, land cover, drainage density, and geology. To captures spatial variations across the study area, the output values were classified into five categories by using the natural breaks classification method (Jenks, 1967) i.e. very low, low, moderate, high, and very high (Fig.7) and each class is occupied in the study area 9.28%, 22.22%, 27.01%, 27.15% and 14.35% of total study area respectively (Fig.8).

The resulting analysis indicates that the groundwater potential of the study area predominantly falls under the "High" category. However, the findings are specific to the current study area, where extensive flat terrain and valley floors provide abundant water resources.

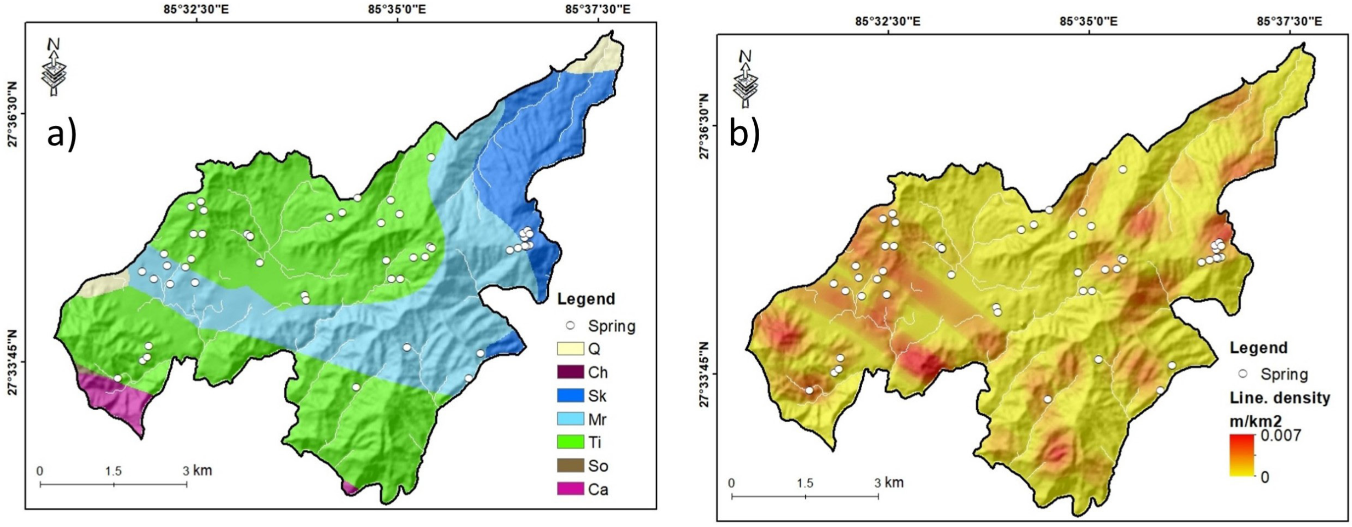

Fig. 6: Geologic conditioning factor of groundwater potential a) Geological map, and b) lineament density map

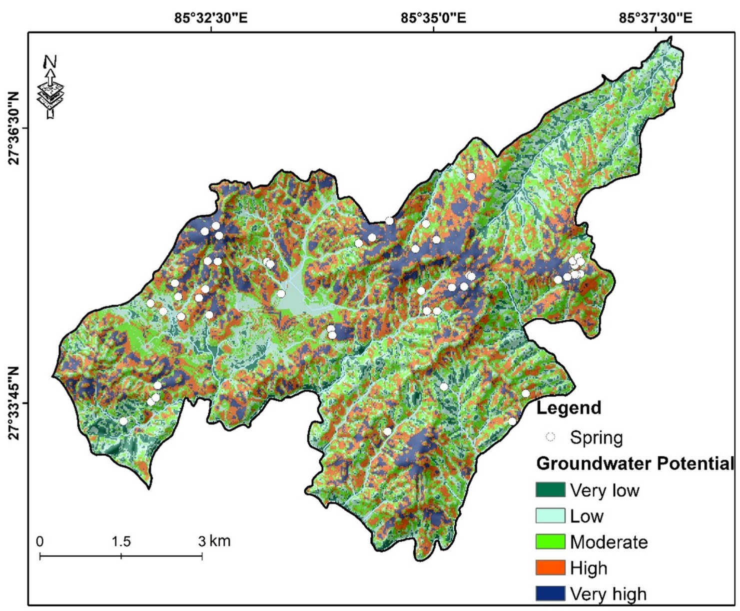

Fig.7: Groundwater potential map

The relative contribution of each thematic factor to groundwater potential modeling was assessed using a variable importance analysis. As illustrated in the chart, lineament density emerged as the most influential parameter, accounting for 15.8% of the model's predictive strength. This underscores

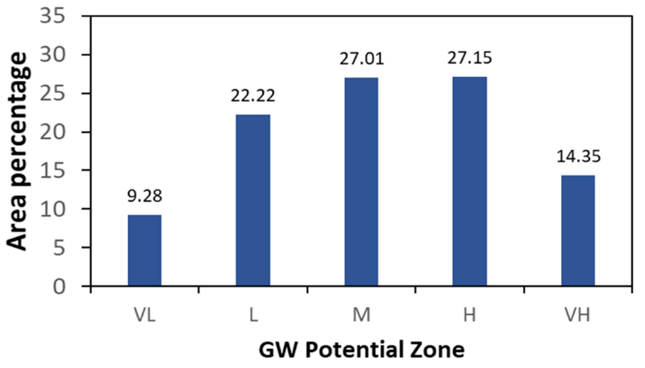

Fig. 8: Area percentage of different GWP zones.

the role of structural discontinuities in facilitating groundwater movement and storage. The Topographic Wetness Index (TWI) followed closely at 14.4%, reflecting the significance of surface saturation and runoff accumulation in recharge dynamics.

Other topographic and hydrological variables such as aspect (13.4%), drainage density (13.1%), and elevation (12.9%) also contributed substantially, indicating that slope orientation, stream concentration, and terrain elevation are critical in controlling infiltration and subsurface flow. Slope (10.2%) and Topographic Position Index (TPI, 9.5%) provided moderate influence, while geology (7.6%)—though traditionally considered a key factor—ranked lower, suggesting that surface features may exert greater control in the study area's hydrogeological context. Curvature, with the lowest importance at 2.9%, had minimal impact on groundwater potential prediction. These results highlight the dominance of geomorphological and hydrological parameters over lithological ones in the model, reinforcing the utility of integrated geospatial analysis for groundwater assessment in complex terrains.

Validation of Result

The Receiver Operating Characteristic (ROC) validation curve provides a meaningful assessment of the model's predictive performance in delineating groundwater potential zones. The training dataset achieved an AUC of 82.3% (Fig.10), reflecting the model's strong ability to capture the underlying relationships between hydrogeological conditioning factors and groundwater occurrence. The test dataset yielded an AUC of 73.1%, which, although lower, demonstrates that the model generalizes reasonably well to unseen data. This balance between training and test performance confirms the reliability of the groundwater potential map for practical applications, while also revealing areas where further refinement could enhance its robustness across diverse spatial contexts.

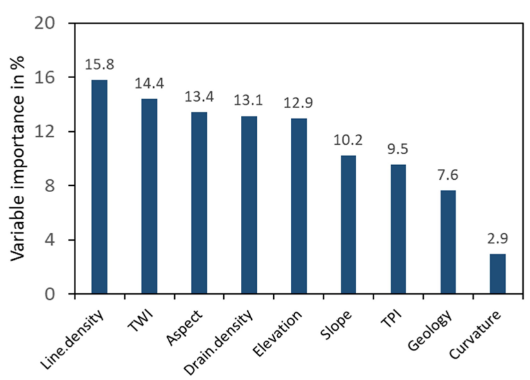

Fig. 9: Importance of conditioning factors.

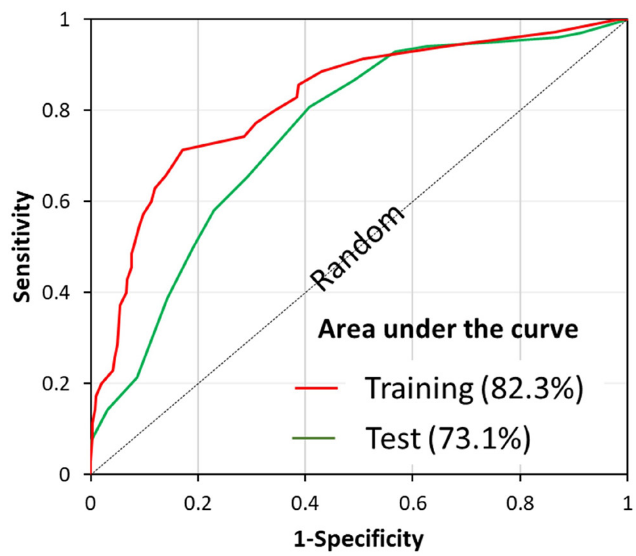

Fig. 10: Validation based on AUC analysis.

CONCLUSIONS

The groundwater potential map was constructed by integrating nine thematic layers and classified into five categories using the natural breaks (Jenks) method, revealing that very low, low, moderate, high, and very high potential zones occupy 9.28%, 22.22%, 27.01%, 27.15%, and 14.35% of the study area, respectively. Variable importance analysis highlighted the dominance of geomorphological and hydrological factors, with lineament density (15.8%) and Topographic Wetness Index (14.4%) emerging as the most influential parameters, followed by aspect, drainage density, and elevation. Validation through ROC curve analysis yielded AUC values of 82.3% for the training dataset and 73.1% for the test dataset, confirming that the model effectively captured groundwater occurrence patterns while generalizing satisfactorily to unseen data.

This study demonstrates that the Cosine Amplitude method provides a robust framework for delineating groundwater potential zones, with results underscoring the critical role of structural discontinuities, surface saturation, and terrain characteristics in groundwater movement and storage. The validated map offers a reliable tool for groundwater resource assessment and sustainable management, providing valuable guidance for policymakers and planners in prioritizing exploration and development.

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