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Application of Poisson Regression to identify probable groundwater potential zones in hilly region: a case study from Doramba Rural Municipality, Ramechhap

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ABSTRACT

This study applies a Poisson regression model combined with geospatial techniques to identify probable groundwater potential zones in the hilly region of Doramba Rural Municipality, Ramechhap, Nepal. Given the crucial reliance of mountain communities on natural springs for domestic and agricultural needs and the recent depletion of these resources due to anthropogenic activities and climate change, a robust assessment methodology is essential. Using a digital elevation model (DEM) and other thematic layers including slope, curvature, topographic position index (TPI), drainage density, topographic wetness index (TWI), geology, and lineament density, a comprehensive database was created. The Poisson regression model was then used to analyze the relationship between these factors and the occurrence of 74 observed springs. The results, validated through 10-fold cross-validation with a mean AUC of 0.74, demonstrated good predictive ability. The final groundwater potential map classified the area into very low, low, moderate, and high-potential zones, providing a vital tool for sustainable water resource management and spring source conservation in the region.

Keywords: *Groundwater potential; validation; thematic layers; spring inventory*

INTRODUCTION

Numerous mountain communities upstream rely on natural springs to fulfill their household and agricultural needs (Chapagain et al., 2019). Groundwater resources including spring sources play a crucial role in securing human requirements, improving livelihood, and maintaining balance in the ecosystem. Most of the drinking water supply schemes in the hill and mountain areas are through gravity flow systems from natural springs, which represent the groundwater storage within the catchment, and form an important component of the Himalayan water budget (Andermann et al., 2012). Local residents have been using these groundwater springs since time immemorial to meet their basic domestic, irrigation, and livestock needs (Ghimire et al., 2019). Spring sources form the backbone of Nepal's domestic water supply in the middle mountain watersheds. However, in recent years, the water resource in the aquifers is depleting as a result of multiple anthropogenic activities and climate change factors (Tambe et al., 2012).

Anthropogenic activities like degradation of the catchments, land use change, and development of infrastructures such as road networks have disrupted the hillslope hydrology in the middle mountains of Nepal (Ghimire et al., 2019), which has led to drying up of spring sources and the reduction of regular flow regimes, especially during the dry season (Chapagain et al., 2019; Ghimire et al., 2019). Due to the reduction in surface water availability but an increase in water demand, the use of groundwater resources including spring resources is essential in coming years, especially in mountainous and hilly regions.

Groundwater potential assessment is a difficul process since it requires an accurate evaluation of all recharge and discharge characteristics. Furthermore, effective groundwater assessment demands long-term data, which is not readily available in many regions of the world, particularly in developing countries (Mekonnen & Hoekstra, 2016). With the emergence of modern techniques such as geospatial modeling, which includes geographical information system (GIS) and remote sensing (RS) technology, the assessment of groundwater resources has been eased to some extent. RS and GIS form a powerful set of tools used for the collection, storage, and management of spatial data in a simplified manner. Pathak et al. (2021) and Pradhan et al.(2021) reported that GIS is a promising tool for groundwater exploration. The natural slope, drainage density, geomorphology, physiography of an area, the rock type, and its alignment play significant roles on the availability of groundwater.

Several studies across the world have been carried out combining GIS and RS technologies with multi-criteria decision-making methods; and have provided very good results on groundwater potential assessment in several studies (Aneesh & Deka, 2015; Pathak & Shrestha, 2016; Upadhyaya et al., 2024).

In this regard, this study aims to prepare a digital database and thematic maps considering the key factors including slope, lineament density, lithology, geomorphology, hydro-geomorphology, drainage density and lineament density which affect groundwater potential and poisson regression method to delineate groundwater potential zones in the Doramba Rural Municipality of Ramechhap district.

THE STUDY AREA

The study area covers Doramba Rural Municipality located in the northern part of Ramechhap district in Bagmati Province of Nepal (Fig. 1). It lies between 85˚ 49’ 327” E to 86˚ 01’ 30” E latitude and 27˚28’ 41” N to 27˚ 36’ 52” N longitude. The Doramba rural municipality covers an area of 140.9 square kilometers and has a population of approximately 17,686 people (CBS, 2021).

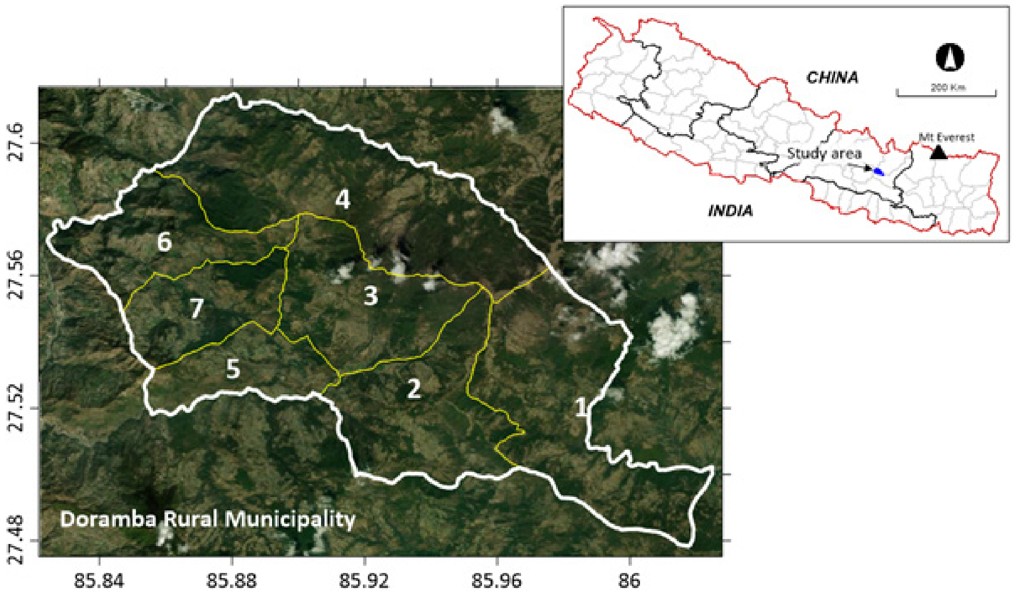

Fig. 1: Location map of the study area (Doramba rural municipality with ward number).

Most of the population in the area is engaged in agriculture and livestock farming. The rural municipality is rich in natural resources such as forests, rivers, and hills. The Sailung Hill, located at an altitude of 3146 m, is a popular destination for tourists and trekkers. The altitude ranges from 715 to 3,138 meters above mean sea level (amsl).

Data collected during the desk study and from field work were compiled, analyzed, and interpreted in GIS environment. A total of 74 springs were observed in the study area. The spring inventory map of the study area is shown in Fig. 2.

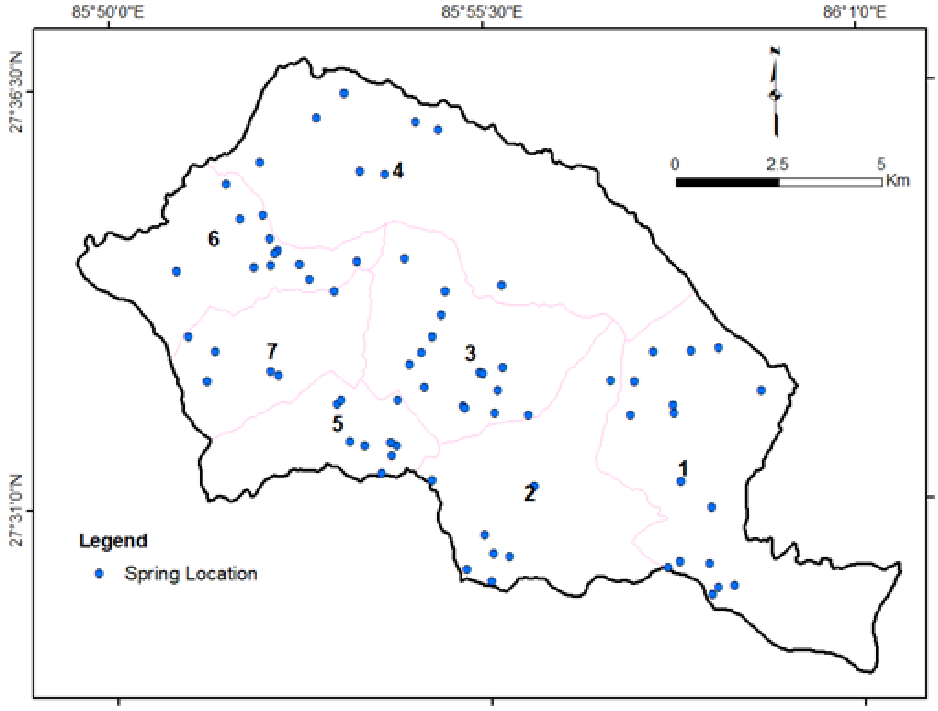

Fig. 2: Spring distribution.

DATA COLLECTION

The study was attempted by considering eight different thematic layers' including elevation, slope, curvature, topographic position index (TPI), drainage density, topographic wetness index (TWI), geology and lineament density. These data were collected from different sources and processed in the GIS environment to create the database. Geological map was obtained from Department of Mines and Geology, Government of Nepal (DMG, 2020), Digital elevation model (DEM) was extracted from interpolated version of Shuttle Radar Topography Mission (SRTM) (version4) (EROS, 2015) with resolution 30 m.

Elevation

Topography plays a key role in shaping groundwater conditions in rocky terrains (Davis & De Wiest, 1966). There is not a direct relationship between groundwater seepage and elevation, but in the area where the rainfall is ample, a highly elevated region can act as a recharge zone through the cracks and joints available in the rock and can create pressure head (Condon & Maxwell, 2015). The elevation range in the study area lies between 790 m to 3150 meter above sea level (masl) (Fig. 3a).

Slope

The slope is one of the most important groundwater recharge regulating factors, especially in mountainous watersheds (Magesh et al., 2012). The steep slopes will lead to rapid runoff and greater soil erosion rates with a little groundwater recharge. Generally, the slope is usually known as a description of the steepness of the area. It influences the amount and rate of water infiltration into the ground, which in turn affects the recharge of groundwater. Generally, the slope is known as a description of the steepness of the area. A varying slope range from 0 to 75° can be observed in the study area (Fig. 3b).

Curvature

The directional derivative, or total curvature, describes the rate of change in the inclination angle of the tangential plane along a profile line (Schwartz, 1974). In simple terms, curvature reflects the shape of the terrain's slope. It influences how water moves across the surface, affecting flow accumulation, deceleration, and the convergence or divergence of runoff. Positive curvature indicates a convex slope, zero curvature represents flat terrain, and negative curvature corresponds to a concave slope. In the study area, curvature values range from –12 to 15.3 (Fig. 3c). Concave slopes (negative curvature) tend to retain water for longer periods, which supports groundwater recharge, while convex slopes (positive curvature) promote faster runoff, reducing recha ge potential.

Topographic position index

The Topographic Position Index (TPI) describes whether a location is situated higher or lower than its surrounding terrain. Positive TPI values indicate ridge tops and elevated slopes where runoff dominates, reducing the likelihood of groundwater recharge. Negative values, on the other hand, mark valleys and depressions where water naturally accumulates, creating favorable conditions for infiltration and storage (Fig. 3d). Areas with values close to zero represent relatively flat or mid-slope positions, which may allow moderate recharge depending on soil and geological conditions. In this way, TPI serves as an important topographic factor for assessing groundwater potential, as low-lying concave areas generally support recharge while ridge zones are less favorable.

Drainage density

The drainage density, the ratio of the total length of all streams in a basin to the basin area, of a region is important because it affects surface-runoff processes such as the intensity of torrential floods, concentration, sediment load, and even water balance in a drainage basin area. Higher values of drainage density represent larger streams or rivers, while lower values indicate smaller tributaries as shown in Fig. 4a.

Topographic wetness index (TWI)

The study area is relatively limited in size, and the nearest rain gauge station is located at a considerable distance, which necessitated the use of the Topographic Wetness Index (TWI) as a proxy for hydrological conditions in this analysis. The TWI has been used extensively to describe the effect of topography on the location and size of saturated source areas of runoff generation. Moore et al. (1991) proposed Eq (1) for the calculation of TWI under the assumption of steady-state conditions and uniform soil properties.

$$TWI = log(\frac{\alpha}{tan\beta}) \qquad 1$$

where α is the cumulative upslope area draining through a point (per unit contour length), and tan β is the slope angle at that point. TWI is an indicator of the spatial distribution of soil moisture because groundwater flow often follows the surface topography. Higher value of TWI zone indicates possibility for groundwater in the rock flowing through the factures. The distribution of TWI in the study area varies from 3 to 22.3 as shown in Fig. 4b.

Geology

Geology is an important factor that can affect groundwater potential zone mapping. The type of geology in an area can impact groundwater potential in several ways such as the properties of the underlying aquifer are primarily determined by the geology of the area. The type of rock or sediment that makes up the aquifer can impact its porosity, permeability, and storage capacity. Geology can also affect the rate at which water infiltrates into the ground and recharges the groundwater system. Areas with highly fractured or karstic geology, such as limestone or volcanic rocks, can have faster and more efficien recharge, leading to higher groundwater potential. The type of geology in an area can also impact groundwater quality. Certain types of rocks and sediments can contain minerals or other substances that may affect the quality of the groundwater.

For the preparation of geological map, data prepared by department of Mines and Geology of Nepal was digitized and reclassified into 30 m resolution raster data. Basically, Ulleri Formation (Ul): Augen gneisses, muscovite biotite gneisses, feldpathic schists. Chour carbonates (Cr): white to grey compact dolomite and dolomitic limestones interbedded with shales beds. Ghan Pokhara Formation (Gp): Black to grey carbonaceous slates and green shales. Ranimatta Formation

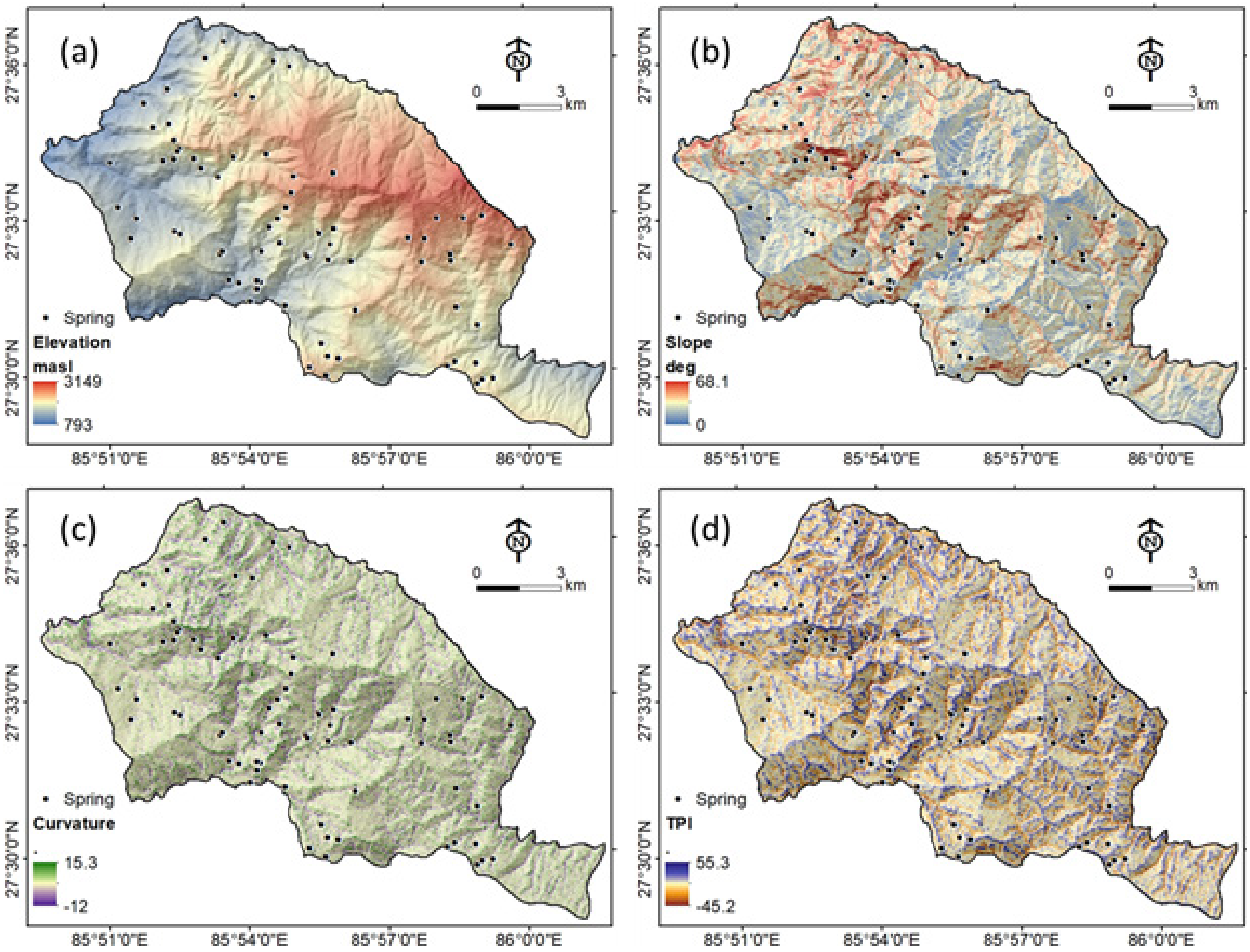

Fig. 3: Topographic factors: a) elevation, b) slope, c) curvature and d) TPI.

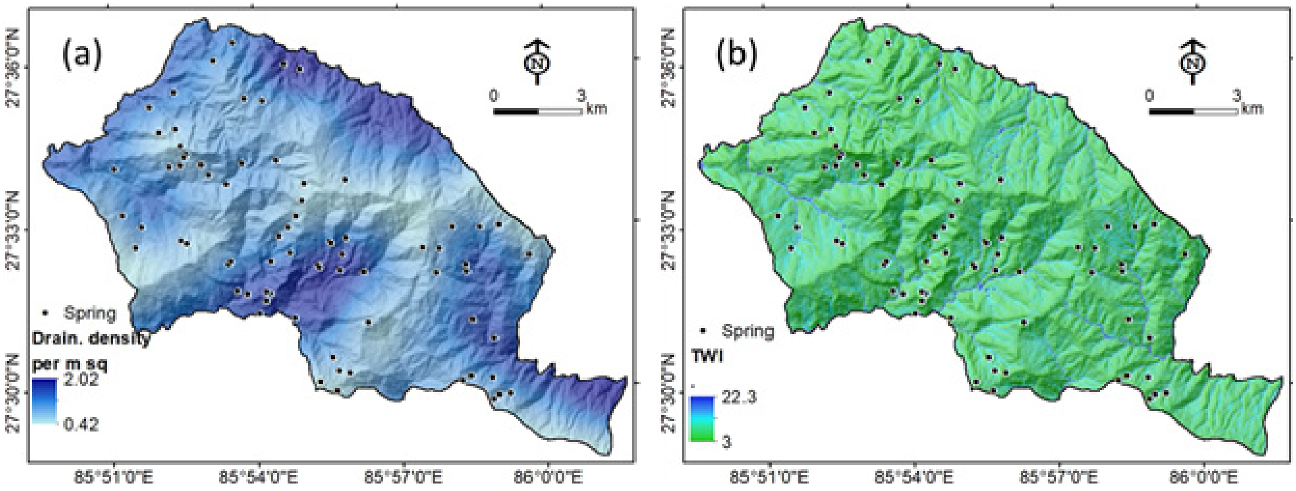

Fig. 4: Hydrologic factors: a) drainage density and b) TWI.

(Rm): Grey to greenish grey shales shaly phyllites, slates garnetiferous phyllites greyish white quartzites with carbonate beds and amphibolites. Naudanda Formation (Nd): White, massive, fine to medium grained quartzites with ripple marks interbedded with green phyllities and Basic intrusions are found in study area. Most of area is covered by Quartzite types (Fig. 5a).

Lineament density

A lineament is a geographical structure that reflects an underlying geological feature, such as a fault, fracture, or joint. These structures contribute in the penetration of runoff water into the subsurface and are essential for groundwater storage and flow. Higher lineament density leads to higher recharge and, as a result, improved groundwater prospects. The fault map was extracted from the geological map and minor lineaments were delineated from satellite imageries and hillshade map of the area. Hillshade maps help in visualizing the topographic features and identifying potential lineaments. Lineaments are often characterized by pronounced linear shadows or variations in shading. After the lineament features were digitized, lineament density was calculated. This involves determining the total length of the lineaments within the study area and dividing it by the area of the study area. The resulting value represents the lineament density (Fig. 5b).

METHODOLOGICAL FRAMEWORK

The methodology for assessing groundwater potential in this study integrates spatial data analysis with statistical modeling using Poisson regression (Consul & Famoye, 1992), which is suitable for modeling count-based data such as spring occurrences. The process began with the data collection from various sources and the generation of thematic maps. To quantify the relationship between these factors and groundwater occurrence, a Poisson regression model was applied, using observed spring counts as the response variable. The model estimated how each factor influences groundwater potential and was used to calculate a suitability index across the study area. Finally, the groundwater potential zones were mapped, and the resulting map was validated against the locations of observed springs to assess its predictive accuracy.

To quantify the relationship between groundwater occurrence and the conditioning factors, Poisson regression was employed, using the number of springs in each spatial unit (e.g., grid cell or slope unit) as the response variable. The model relates the expected count of springs λ_i to the predictor variables X_{ij} through a log link function as given in Eq (2):

$$\ln(\lambda_i) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots\ldots + \beta_p X_{ip}, \qquad (2)$$

where λ_i is the expected number of springs in the i^{th} spatial unit, X_{ij} is the value of the j^{th} criterion, and β_j are the regression coefficient estimated using maximum likelihood methods. The significance of each factor was evaluated to determine its contribution to groundwater occurrence. Based on the regression outputs, a groundwater potential suitability index was calculated for each spatial unit, with higher predicted counts indicating zones of greater groundwater potential. This index was then visualized in a GIS environment to generate a groundwater potential map, classified into categories such as very high, high, moderate, and low potential. Finally, the map was validated by comparing predicted high-potential zones with observed spring locations, and accuracy was assessed using statistical measures such as the correlation between observed and predicted spring counts.

RESULTS AND DISCUSSION

The dataset was randomly split into ten subsets for 10-fold

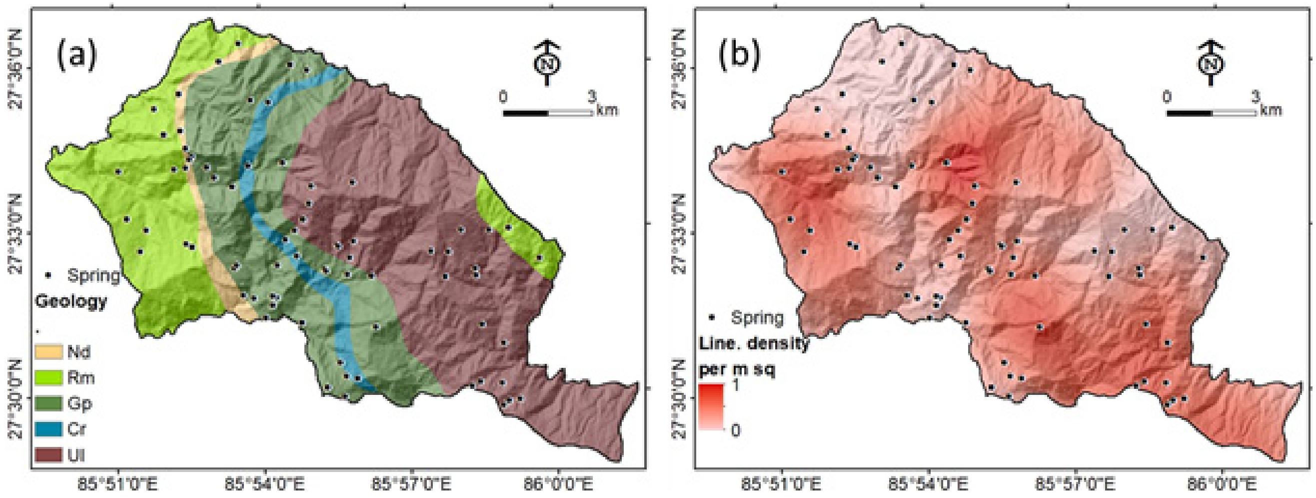

Fig. 5: Geologic factors: a) geology of the study area and b) lineament density.

cross-validation. In each round, one subset was used as a test set while the remaining nine were used to train the model. The trained model then predicted spring occurrence for the test set. This process was repeated ten times so that every subset served as the test set once. In this analysis, spring locations were coded as 1 and non-spring locations as 0, while the independent variables included all the factors thought to influence groundwater potential. One of the strengths of logistic regression is that it can directly estimate the probability of occurrence for each location, regardless of how the factors are analyzed.

The predicted probabilities from all iterations were combined in a GIS and converted into raster format for mapping. Groundwater potential maps were classified into four categories—low, medium, high, and very high—based on these probabilities. The natural breaks classification method was used to define the class boundaries, grouping values so that each class boundary corresponds to a significant jump in the data (Jenks, 1967; Mahalingam & Olsen, 2016). Using this method, the final groundwater potential map was divided into four probability zones, ranging from very low to high, as shown in Fig. 6.

Validating a groundwater potential model is essential to ensure its reliability and technical significance. In this study, the AUC-ROC metric was used as the primary benchmark, as it is widely recognized for evaluating models in groundwater potential mapping. Model accuracy was assessed by comparing predicted results with observed spring locations. Receiver operating characteristic (ROC) curves provide a visual representation of this accuracy, showing the tradeoff between sensitivity (correctly predicted spring locations) and 1− specificity (correctly predicted non-spring locations). The area under the ROC curve (AUC) quantifies the model's performance: an AUC of 0.5 indicates no better than random prediction, while values approaching 1 indicate near-perfect accuracy. As the ROC curve rises above the line of equality and moves toward the upper left corner, the AUC increases, reflecting improved model performance. Results from 10-fold cross-validation showed a high mean AUC of 0.74 for the poisson regression model, indicating good predictive ability (Fig. 7).

Based on the Poisson regression model, the provided table outlines the relationship between various environmental factors and groundwater potential. The coefficient represent the weight or importance of each variable in predicting the likelihood of finding groundwater. A positive coefficient indicates a favorable relationship, meaning that as the value of the variable increases, the potential for groundwater also increases. Conversely, a negative coefficient suggests an inverse relationship, where an increase in the variable's value corresponds to a decrease in groundwater potential (Table 1).

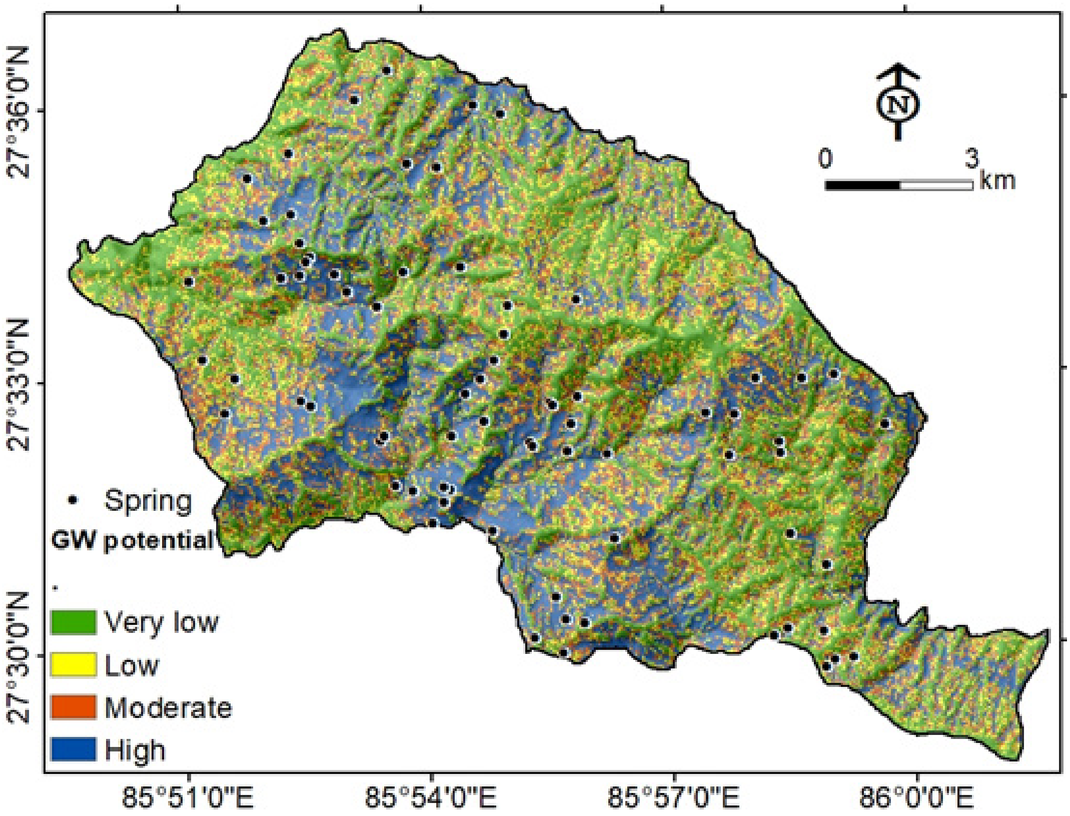

Fig. 6: Groundwater potential map of Doramba Rural Municipality.

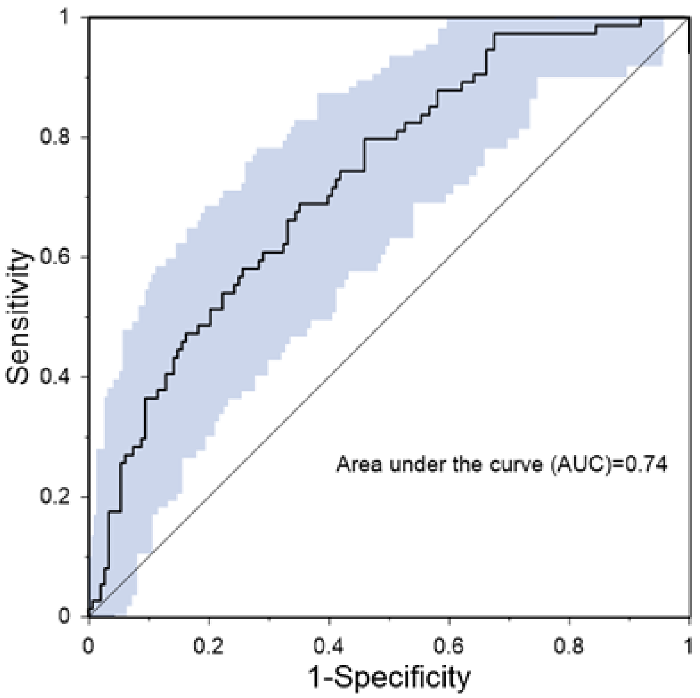

Fig. 7: Model accuracy assessment using AUC of ROC.

Table 1: Model parameters for the components.

Source		Value
Intercept		-0.942
Elevation		0
Slope		0.011
Curvature		-0.016
TPI		-0.023
Drain density		-0.133
TWI		0.117
Line. density		-0.718
Geology	Nd	0
	Rm	-0.410
	Gp	0.032
	Cr	0.312
	Ul	-0.024

Variables with the strongest influence, whether positive or negative, are those with coefficient furthest from zero. For example, lineament density (-0.718) and drainage density (-0.133) have significant negative impacts, suggesting that areas with higher lineament and drainage density are less likely to have groundwater. This could be due to rapid runoff and a lack of water infiltration. In contrast, TWI (0.117) has a positive coefficient which is expected as the TWI measures the accumulation of water. The geology variables also show a strong influence, with Cr (0.312) being the most favorable type for groundwater accumulation, while Rm (-0.410) is the least. The variables with coefficient close to zero, such as elevation (0) and Nd (0), have a negligible effect on the model's predictions. This suggests that in the studied area, elevation itself does not significantly influence groundwater potential, likely because other variables like slope and TWI already capture the relevant topographic effects. In summary, the model identifies specific geological types, low lineament density, and high TWI as the key factors for predicting high groundwater potential in this region.

CONCLUSIONS

The study successfully delineated groundwater potential zones in the Doramba Rural Municipality by integrating Poisson regression and GIS technologies. The model accurately identified key factors influencing spring occurrence. The findings indicate that certain geological formations, high topographic wetness index (TWI), and areas with low lineament density are the most favorable for groundwater potential. Conversely, zones with high drainage density and specific geological types were found to be less conducive to groundwater accumulation. The final groundwater potential map serves as a valuable resource for local policymakers and water resource managers. It can be used to guide future water exploration and conservation efforts, ensuring the sustainability of spring sources that are the backbone of domestic water supply in the middle mountain watersheds of Nepal. Further research could focus on validating these findings in other similar regions and exploring additional variables that might influence groundwater potential

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