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Groundwater potential mapping in central hills of Nepal: A comparative study of conventional and modified frequency ratio methods

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ABSTRACT

Springs serve as lifelines for rural communities in the Himalayan region, providing essential domestic water supplies and irrigation purposes. The depletion of streams and spring sources poses a significant environmental menace, threatening water access for these communities. To ensure sustainable access to groundwater for local communities, a thorough assessment of Himalayan hydrogeology is essential. A map of groundwater potential has been prepared using Geographic Information Systems (GIS), employing the Conventional Frequency Ratio (FR) and Modified Frequency Ratio (MFR) methods and evaluated the predictive performance of these in the Shivapuri Rural Municipality, Central Nepal. The MFR method excels in classifying groundwater potential areas with an AUC of 0.80, indicating an 80% success rate, compared to the FR method's AUC of 0.65 (65% success). Both methods share an AUC of 0.60 for the prediction rate curve, implying similar performance in outlining potential spring zones. However, the MFR method better distinguishes between high and low potential zones. This study provides critical information that can be used to support decision-making processes for the effective management and utilization of groundwater resources in the region.

Keywords: Groundwater potential mapping; Modified frequency ratio; Springs; GIS

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INTRODUCTION

Springs serve as lifelines for rural communities in the Hindu Kush-Himalayan region, providing essential domestic water supplies. Groundwater resources could be used for multiple purposes like the surface water resources in the hills of Nepal (Kaini 2016). In mountainous and hilly areas, groundwater manifests through springs and seepage of varying discharge volumes. Groundwater springs emerge when underground water seeps out onto the earth's surface. This can happen through cracks and fissures in rocks, along fault lines, or via porous soil formations and extensive zones with fractures (Das and Pal 2019; Mondal et al. 2019). These springs and seepage ultimately contribute to the formation of streams. Finding locations where groundwater naturally comes to the surface is crucial to mapping areas with high spring potential (Chen et al. 2020). The availability of groundwater resources varies greatly across locations and is primarily influenced by many factors including landforms, rock formations and weather patterns. The Himalayan region benefits from a natural advantage with abundant monsoon rains that recharge aquifers, leading to a higher volume of spring discharge. However, the depletion of streams and spring sources poses a significant environmental threat, jeopardizing water access for these communities (Negi and Joshi 2002; Merz et al. 2003; Vaidya 2015).

Groundwater potential mapping has been recognized as an investigation practice, the outcomes of which provide useful data inputs concerning groundwater management projects (Moghaddam et al. 2015). Groundwater Potential (GWP) refers to the probability of finding groundwater in a specific location (Yousefi et al. 2020). Traditionally, engineers and hydrogeologists have depended on geological models, geophysical modeling and drilling test methods to identify areas with high groundwater potential (Chen et al. 2011). While these methods can be very accurate, they are time-consuming and expensive (Nampak et al. 2014; Rizeei et al. 2019).

Recent advancements in Geographic Information System (GIS) and computer modeling have empowered the combined use of remote sensing and GIS to effectively identify high groundwater potential areas, a crucial step in modern water resource management (Oh et al. 2011). Several statistical tools are used to create GWP maps, including the frequency ratio method (Ozdemir 2011; Moghaddam et al. 2015; Naghibi et al. 2015), logistic regression model (Ozdemir 2011), multi-criteria decision evaluation (Rahmati et al. 2015; Golkarian and Rahmati 2018; Yifru et al. 2020; Hasanuzzaman et al. 2022), random forest model (Naghibi et al. 2016; Rahmati et al. 2016; Thanh et al. 2022), maximum entropy model (Golkarian and Rahmati 2018), boosted regression tree (Naghibi et al. 2016) and deep neural network (Pradhan et al. 2021). These mapping techniques consider various factors that influence groundwater movement and accumulation, along with the interactions between these factors.

Decades of human activities like deforestation, poorly planned road construction, overgrazing, underground excavations, and excessive groundwater use have declined water availability. Unplanned infrastructural developments are exacerbating water availability in natural springs in Nepal's mid-hills of Nepal (Gurung et al. 2019). Disruption in the natural flow of springs on hilly slopes causes springs to dry up, mainly during the dry periods. The Gorkha earthquake (2015) further aggravated the situation, with the drying up of around 5,000 groundwater streams (Ghimire et al. 2019). Furthermore, it is anticipated that surface water availability for domestic and irrigation purposes could further be reduced due to climate change impacts on water resources (Kaini et al. 2021). On the other hand, it is likely that the irrigation water requirement in Nepal would be increased in the dry season in the coming decades (Kaini et al. 2022). The facts that a reduction in surface water availability and an increment in water demand for various purposes in future have highlighted the use of groundwater resources in coming years, including the use of spring resources, especially in mountainous and hilly regions. To ensure sustainable access to groundwater for local communities, a thorough assessment of Himalayan hydrogeology is essential.

The modified frequency Ratio (MFR) method was applied for the landslide susceptibility mapping and it has proven valuable for landslide susceptibility mapping (Li et al. 2017). By mapping areas with high potential for groundwater springs, a zone can be delineated for easier access to vital groundwater resources and it facilitates the discovery of new springs but also creates a valuable reserve in case of droughts (Corsini et al. 2009). The MFR method is highly effective because it integrates both statistical and geospatial analysis to assess the relationship between groundwater occurrences and various influencing factors, such as geology, land use, slope and rainfall. By modifying the conventional frequency ratio (FR) approach, the MFR method allows for a more refined weighting of these factors, improving the accuracy of groundwater potential predictions. The MRF model is particularly advantageous in regions with limited groundwater data, as it leverages existing environmental and geological information to identify areas with high groundwater potential, supporting sustainable water resource management and planning.

This study aims to prepare a groundwater potential map using both FR and MFR methods, and evaluate the effectiveness of these methods in accurately predicting groundwater potential with a focus on the Shivapuri Rural Municipality. By doing so, the study seeks to provide valuable insights and data to support sustainable groundwater resource management and planning in the region, aiding in decision-making processes for both current needs and future challenges, such as droughts.

STUDY AREA

The study area encompasses Shivapuri Rural Municipality in Nuwakot district, Bagmati province (Fig. 1). Characterized by a temperate climate, the region experiences hot and humid summers followed by dry and cold winters. Annual precipitation averages 1,400 mm, with 80% concentrated in the monsoon season (June to September). Temperatures range from 2°C to 17°C in winter and 19°C to 30°C in summer. The elevation varies significantly, from a high of 2,657 meters above sea level (masl) at the peak of Shivapuri Nagarjun National Park to a low of 612 masl at the Likhu Khola riverbed.

MATERIALS AND METHODS

Study overview

The methodological approach applied for investigating GWP using FR and MFR mehods is depicted in Fig. 2. These models analyze the relationships between existing groundwater spring data (dependent variable) and various factors influencing groundwater potential (independent variables). The combined results from these models were then used to create a map of GWP for the study area.

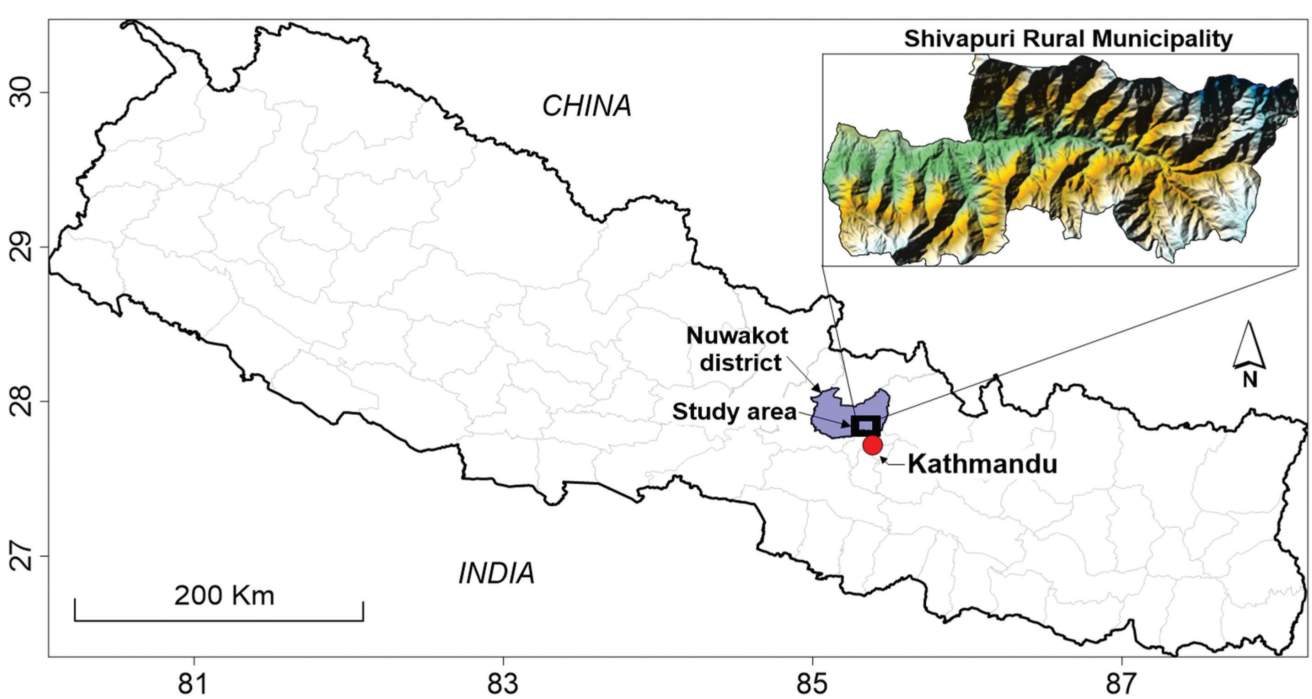

Fig. 1: Location map of the study area.

Conventional Frequency Ratio Method (FR)

The FR method denotes the likelihood of a specific attribute occurring which helps to assess the likelihood of a specific characteristic (attribute) existing in a particular location (Bonham-Carter 1994). It considers existing springs (the dependent variable) as a sign of groundwater and analyzes various factors (independent variables) that might influence where those springs appear (Oh et al. 2011; Naghibi et al. 2016; Pradhan and Kim 2016; Shrestha et al. 2017).

$$FR = \frac{N\left(C_{ij} \cap S\right)}{N\left(C_{ij}\right)}, \quad (1)$$

where, *FR* is frequency ratio of the class of factor, is the pixel of springs in class *i* of parameter *j* and is pixel of certain class *i* of parameter *j*. The greater the ratio exceeds one, the stronger the relationship between landslide occurrence and the specific factor attribute; conversely, a ratio below one indicates a weaker relationship.

Modified Frequency Ratio Method (MFR)

The MFR method initially follows the same steps as the FR method. However, it diverges in a crucial aspect: normalization. The modified method normalizes the calculated frequency ratios to a range between 0 and 1. This normalization allows for a more precise interpretation of the results and facilitates their integration with other statistical procedures that rely on similar value ranges (Li et al. 2017). The framework involves three key procedures as shown in Fig. 3.

The normalization step ensures all continuous factor values fall within a consistent range, typically between 0 and 1. This allows for direct comparison between different factors during subsequent stages like precision setting and frequency analysis. By having all factors on the same scale, the method avoids giving undue weight to factors with originally larger values. Similarly, precision setting is a technique used to balance computational efficiency with accuracy in the calculation of frequency ratios. It aims to reduce the computational burden without significantly impacting the final results.

Spring Inventory

The study mapped out 87 locations where groundwater springs exist within the study area as shown in Fig. 4. Out of them, 61 locations (70%) of spring were used for assessing groundwater potential areas as training dataset. The remaining 30% formed the validation dataset, which helps to assess the accuracy of the models. Figure 5 presents the observed springs in the study area. The field surveys encounters various types of sprins such as depression, contact and fracture springs.

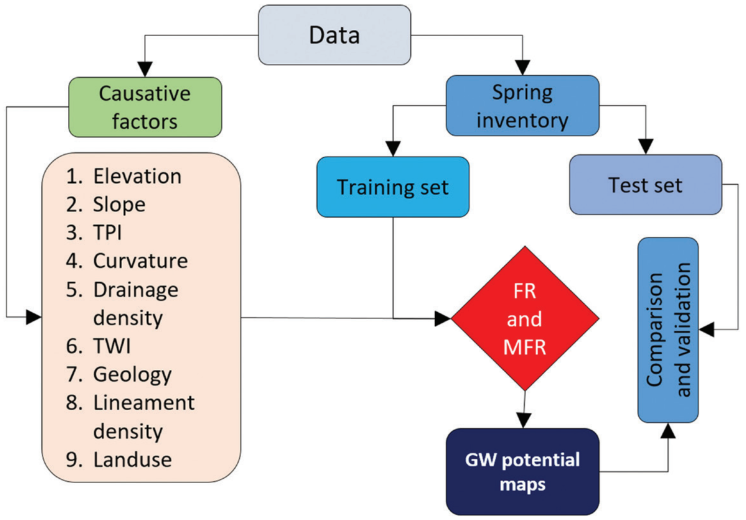

Fig. 2: Methodology for investigating groundwater potential mapping using Conventional and Modified Frequency Ratio Methods.

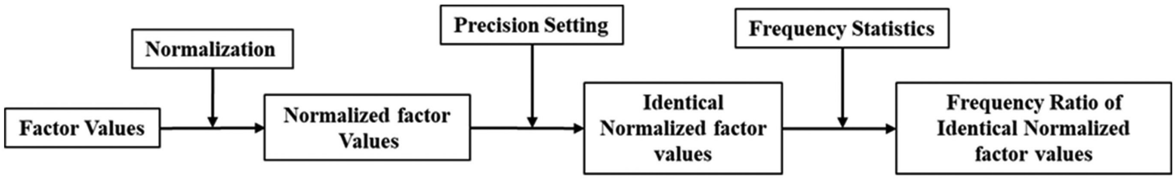

Fig. 3: Modified frequency method (Li et al. 2017).

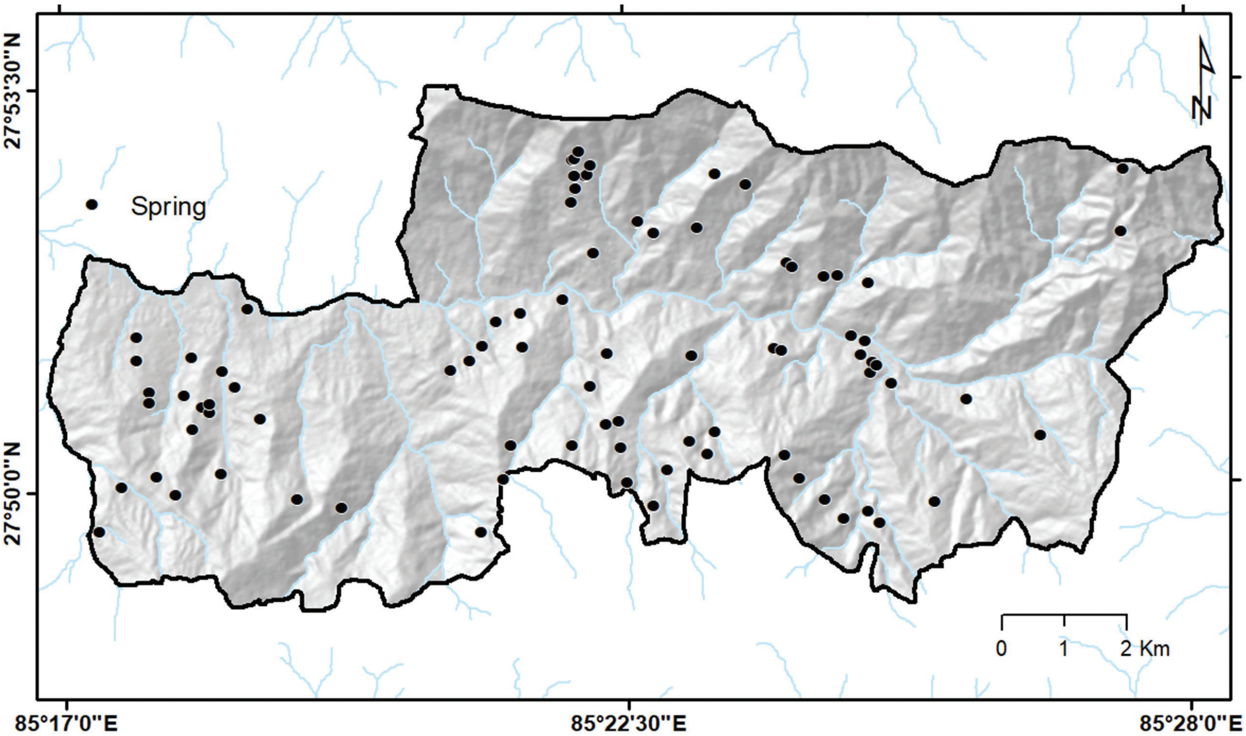

Fig. 4: Spring inventory map of the study area.

Fig. 5: Springs observed in Shivapuri municipality during field survey.

Causative factor preparation

This study selected various factors influencing the occurrence of spring phenomena, namely elevation, slope angle, topographic position index (TPI), curvature, topographic wetness index (TWI), drainage density, lineament density, landuse and geology. These thematic maps were created for subsequent analysis using GIS environment. Each thematic layer was resampled to a consistent grid size of 20×20 m. Digital elevation model (DEM) was used to produce the following topographic factors.

Elevation

The Elevation of the study area were extracted from the DEM. Elevation plays a significant role in groundwater spring distribution due to the downward movement of water along the elevation gradient (Chen et al. 2019). The range of elevation values in the study area (612 masl to 2519 masl) suggests a variation in topography that can influence groundwater movement and storage. The slope map of the study area is shown in Fig. 6a.

Slope

Slope, which describes how steep or flat an area is, plays a crucial role in how water runs off the land. Steeper slopes allow water to flow away more quickly, leading to higher runoff (Naghibi et al. 2016). Conversely, gentler slopes allow for greater infiltration and longer residence time, promoting groundwater recharge. Slope map of the study area was prepared by using the DEM. The slope angle in the study area ranges from 0 to 60^{O}. The slope map of the study area is shown in Fig. 6b.

Topographic Position Index (TPI)

The TPI is another important parameter in assessing GWP. TPI evaluates the relative position of a point in the landscape compared to its surroundings. Positive TPI values indicate locations that are higher than the average elevation of the surrounding area, while negative values signify depressions or lower areas. The TPI map of the study area is depicted in Fig. 6c.

Curvature

Curvature emerges as a crucial factor in GWP due to its influence on both surface water flow and subsurface aquifer systems (Regmi et al. 2015). Curvature plays a key role on how fluids like water behave (Ercanoglu and Gokceoglu 2002; Al-Abadi et al. 2016). It affects how the flow concentrates or spreads out (convergence and divergence) and how it speeds up or slows down (acceleration and deceleration). Curvature ranges of the study area varied from 10.9 to −7.9. The curvature map of the study area is shown in Fig. 6d.

Topographic wetness index (TWI) and drainage density, derived from a DEM, were employed as key hydrological factors influencing groundwater occurrence.

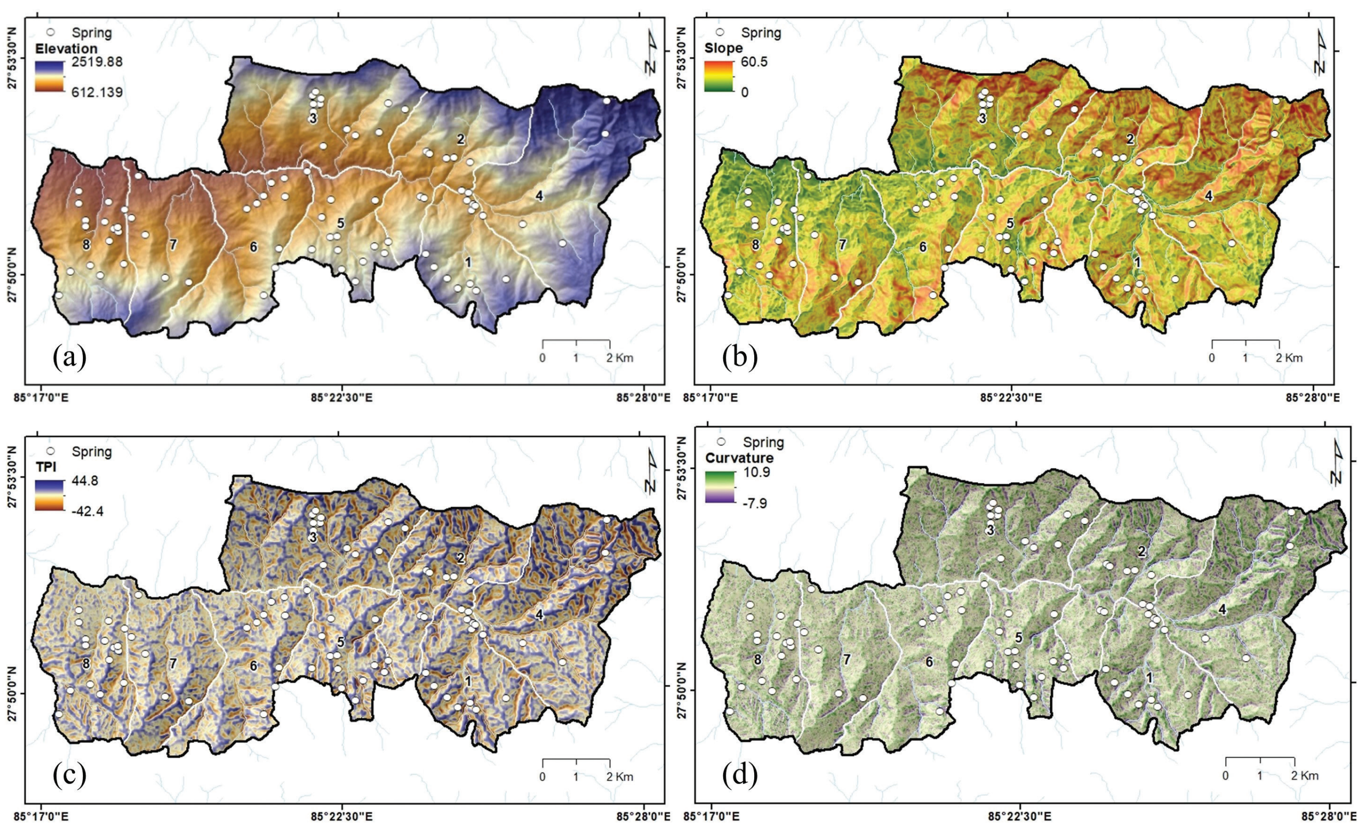

Fig. 6: Thematic maps of topographic factors a) Elevation, b) Slope c) TPI and d) Curvature.

Topographic wetness index (TWI)

TWI is a crucial factor in assessing the potential for groundwater spring occurrence. It reflects the wetness conditions of the terrain based on its topography, providing valuable insights into areas with elevated groundwater potential. It's computed as mentioned in Eq. (2) (Moore et al. 1991).

$$TWI = \ln\left(\frac{A_s}{\tan\beta}\right), \quad (2)$$

where A_s is the contributing area, often represented by flow accumulation and is the slope angle at a given point. Higher TWI values often correspond to regions where water tends to accumulate, indicating favorable conditions for groundwater discharge, including the emergence of springs. The TWI map of the study area is depicted in Fig. 7a.

Drainage Density

Drainage density refers to the closeness or spacing of streams and rivers within a specific area and it is calculated by dividing the total length of streams in an area by the total area itself. A high drainage density indicates a more intricate network of streams and rivers, while a low density suggests fewer waterways. The areas with a high concentration of streams and rivers tend to lose water quickly as runoff, making them less likely to have abundant groundwater (Yeh et al. 2016; Muhammad and Khalid 2017). On the other hand, areas with fewer streams and rivers allow more water to soak into the ground, which can significantly increase the potential for groundwater (Prasad et al. 2008; Thomas and Duraisamy 2018). Lineament map was prepared reviewing the image with the HD satellite image from Landsat image lineament and the verification were made by conserving the satellite image. The drainage density of the study area varies from 1.6 to 6.1 km/km^2. The drainage density map of the study area is shown in Fig. 7b.

Landuse

Land use plays a crucial role in mapping GWP because different land uses can influence the amount of water that infiltrates the ground and replenishes groundwater resources (Jothibasu and Anbazhagan 2017). The land use map of the study area was classified into eight categories such as Water body, Cultivation, Forest, Bush, Grass, Barren Land, Cliff and Sand. The landuse map of the study area is shown in Fig. 8.

Geology

Understanding the types of rock in an area is a key tool for groundwater potential mapping. This is because different rocks have varying abilities to store and transmit water, which are crucial factors for groundwater availability (Ayazi et al. 2010). The geology map of the study area was prepared using the map from the Nepalese Department of Mines and Geology with field verification. Five different types of formation namely; Himal Group (Hm), Augen Gness and Banded Gness (Gn), Pandrang Quartzite(Pa), Undiiffertiated schist,quartzite,gneiss and calcareous silicate rocks (Sh) and Chandragiri formation (Ca). Rock types found in the area include garnet/kyanite, biotite gneiss along with garnetiferous mica schist with some augen gneiss. In the upper part of the area, there are marbles and quartzites, whereas the lower part is characterized by predominantly banded gneiss with augen. Moving towards the middle section of the municipality, there is a distinct layer composed of schist and calcareous silicate rocks. The orientation of rock exposures is represented by N to NW dipping succession of grayish feldspathic schist and augen gneiss. The geological map of the study was obtained from Department of Mines and Geology (DMG 2020) as presented in Fig. 9a.

Lineament density

Lineaments are linear features on the Earth's surface that often represent zones of weakness in the rock, such as faults, fractures, or joints. Lineaments provide valuable clues for identifying areas with promising groundwater potential (Magesh et al. 2012). Their presence suggests pathways and zones of increased permeability that can influence groundwater flow and ultimately contribute to spring formation. Lineament map was prepared reviewing the image with the HD satellite image from Landsat image lineament and the verification were made by conserving the satellite image. The lineament density map of the study area was classified as five categories using natural breaks method. The lineament density map of the study area is shown in Fig. 9b.

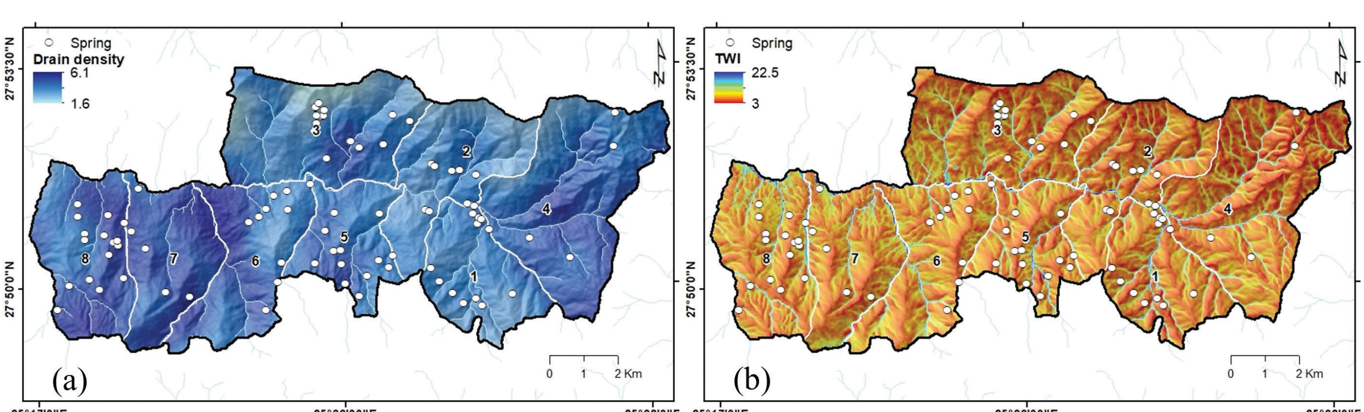

Fig.7: Thematic maps of hydrological factors a) TWI and b) Drainage Density.

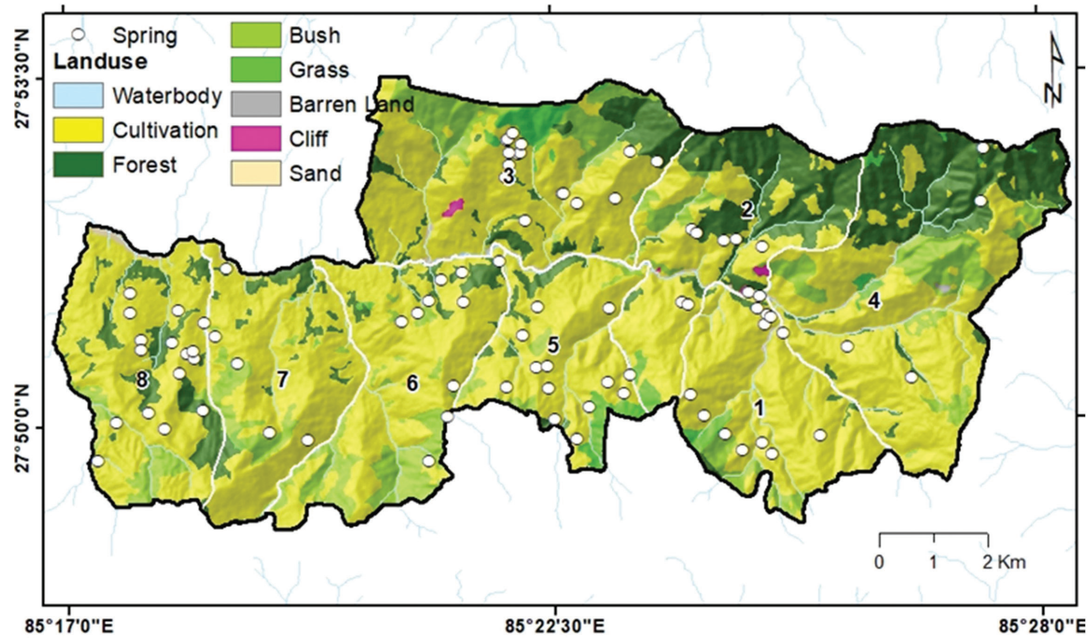

Fig. 8: Thematic maps of Landuse map.

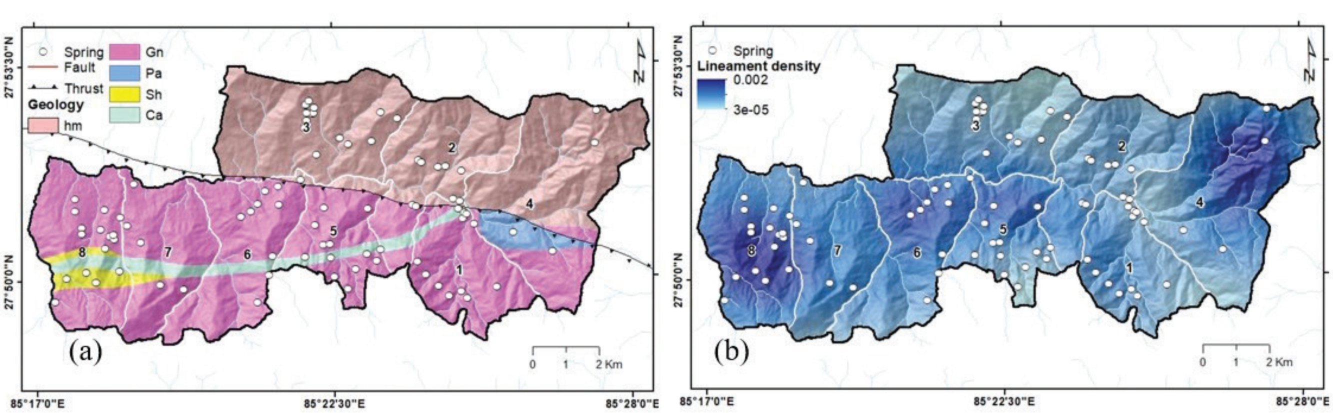

Fig. 9: Thematic maps a) Geology and b) Lineament Density.

RESULTS AND DISCUSSION

Response Curves

This analysis focuses on comparing the response curves generated by the FR vs MFR methods for mapping GWP. By comparing these curves, we can gain valuable insights into the potential differences in how each method identifies areas with high spring potential as collectively depicted in Fig. 10.

The analysis indicated that both the modified and conventional methods for calculating frequency ratios showed similar trends for various factors related to groundwater spring occurrence. However, the results from the modified method revealed more detailed variations in frequency ratios compared to those obtained from the conventional method. The frequency ratios for elevation, computed using the modified method, exhibit a peak around 1500 masl while from conventional method peak is observed around 1800 masl (Fig. 10a). The decline in frequency ratio observed when slope exceeds about 55° (Fig. 10b) in the results obtained from the modified method contrasts with the results obtained from the conventional method, where such a trend is not evident. The TPI also showed a higher FR value (1.8) with the modified method (Fig. 10c), potentially highlighting its improved ability to identify areas favorable for groundwater. Meanwhile, curvature (Fig. 10d) exhibits a high FR value of 1.8, indicating a greater likelihood of groundwater potential when using the MFR method. In contrast, the conventional frequency ratio method yielded a lower FR value of 1.2 for the same feature.

When looking at drainage density (Fig. 10e), the FR curves show peaks at around 3.5 km/km^2 for the modified method and 1.4 km/km^2 for the conventional method. In case of TWI, the trends of FR and MFR shows almost similar frequency pattern (Fig. 10f) showing high potential in between 10.5 to 15 TWI values.

Landuse analysis (Fig. 10g) also showed contrasting results. The modified method identified cultivated areas as having a high potential for groundwater occurrence (FR of 1.4), however, the conventional method suggested cliffs might be more favorable based on a higher FR value. High FR for certain groundwater spring occurrence factors might be surprising, but they don't necessarily mean those factors directly control spring formation. These high values could simply be statistical artifacts and other factors might play a more significant role in determining where springs appear.

The peak values of the frequency ratio curves for lineament density (Fig. 10h) shows the area with high densities are more favorable for probability of occurrence of the groundwater. The modified FR method showed distinct results for the different lithological layers. Geology type "Sh" within these layers had a significantly higher peak FR value of 2.5 compared to the conventional method which is 2 (Fig. 10i). Notably, the conventional method produced peak values less than 2 for other rock types.

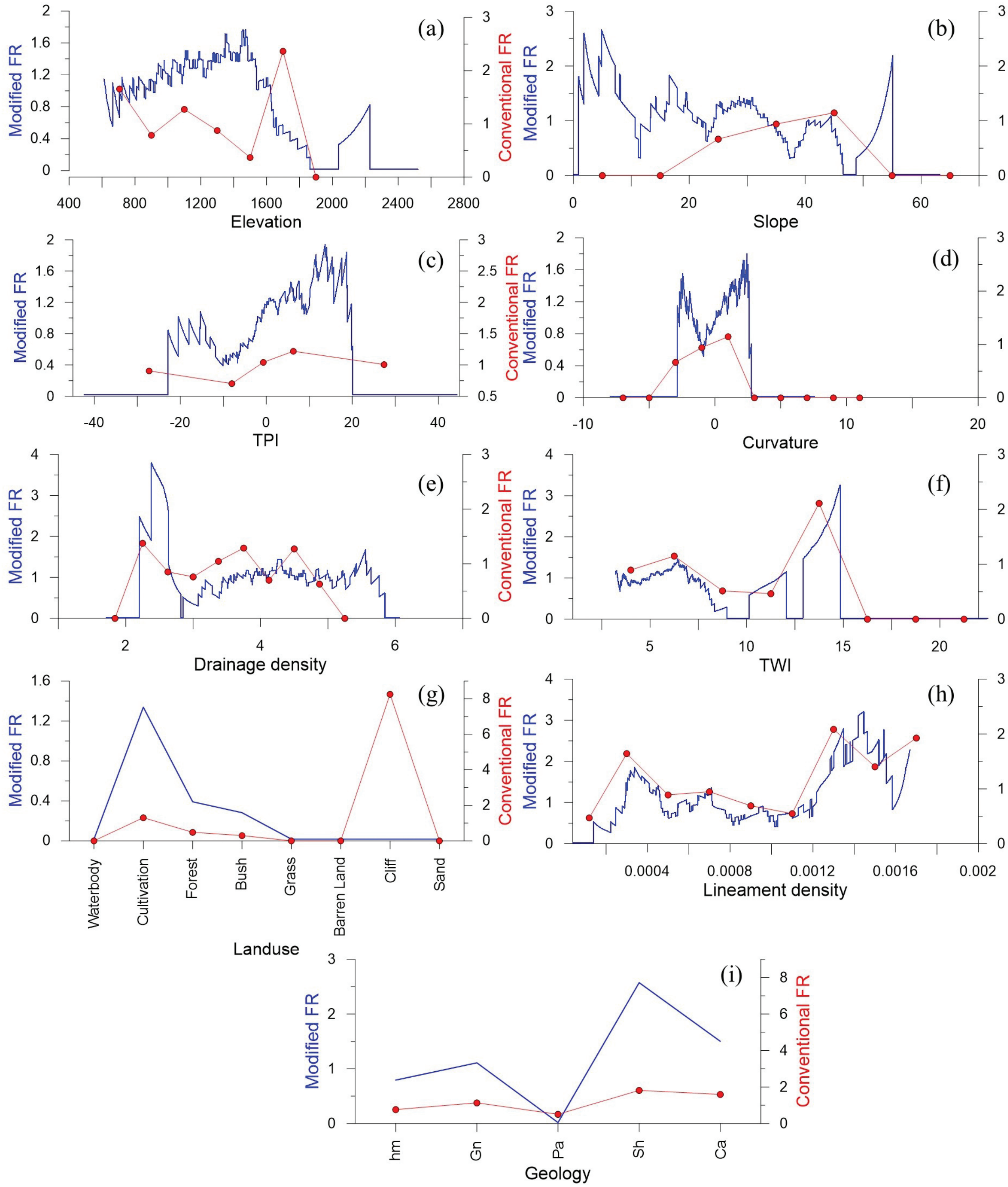

Fig. 10: The frequency ratios of different Groundwater causative factors.

Groundwater potential assessment

GWP maps of the study area was prepared using MFR and FR methods. To identify variations in GWP area across the entire study region, the output values of the two methods were reclassified into four levels: very low, low, moderate and high using the natural break classification system (Jenks 1967) as shown in Fig. 11. The analysis revealed significant differences in the distribution of potential groundwater zones between the MFR and the FR method. A higher frequency ratio value indicates high groundwater potential, while a lower value indicates less potential (Manap et al. 2014). The MFR method designated a larger portion of the area (28.57%) as having very low groundwater potential compared to the conventional method (21.09%). This suggests a more cautious approach by the MFR method in identifying areas with a high likelihood of groundwater. Conversely, the conventional method allocated a larger percentage of the area to the low (35.18%) and moderate (31.80%) potential zones compared to the MFR method (low: 30.66%, moderate: 26.63%). Interestingly, both methods agreed on a similar area (around 14%) having high potential for groundwater springs presented in Table 1.

Table 1: The distribution of the spring potential values and areas with respect to the groundwater spring occurrence potential zones

Class of GWP	MFR		FR	
	Range	Area %	Range	Area %
Very low	3.004-8.328	28.57	4.721-7.891	21.09
Low	8.328-9.417	30.66	7.891-9.116	35.18
Moderate	9.417-10.346	26.63	9.116-10.469	31.80
High	10.346-15.569	14.15	10.469-15.497	11.94

Figure 11 shows that eastern part of the Shivapuri Rural Municipality is highly potential for groundwater. The southern and central part of the region has medium to low groundwater potential. In contrast, the northern part of the study area has a very low potential for groundwater. The northern part is characterised by higher elevation and steep slopes, which is unfavourable for groundwater recharge resulting to low groundwater potential. The eastern and central part of the study area has lower elevation and mild slopes supporting to groundwater recharge, leading to higher groundwater potential.

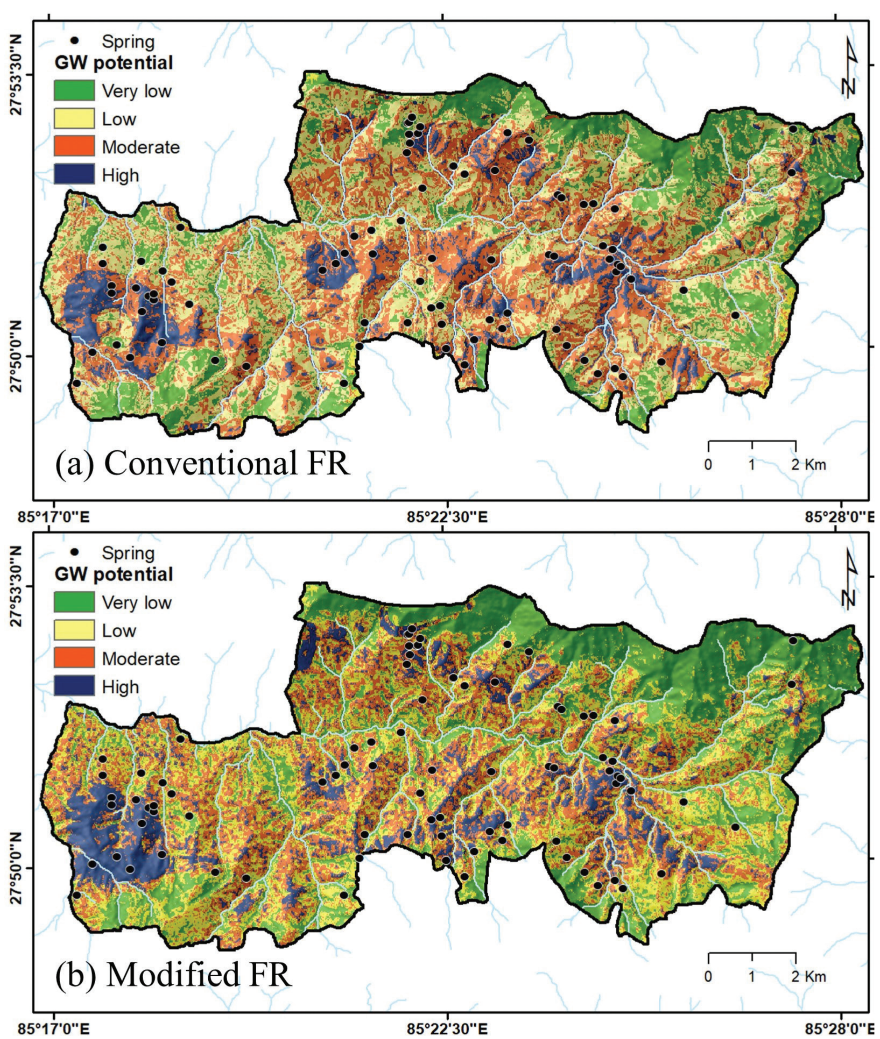

Fig. 11: Groundwater spring potential map using a) FR and b) MFR.

Additionally, the central and western regions vicinity to the rivers hold the highest potential for groundwater springs due to their proximity to recharge zones.

Overall, the gently sloping areas which are also located in the terrain consisting undiiffertiated schist, quartzite, gneiss and calcareous silicate rocks (Sh) and Chandragiri Formation (Ca), cultivation area and nearby rivers showed higher groundwater potentiality. On the other hand, the steep-sloping areas consisting of Himal Group (Hm) classes and forest area showed the lowest potentiality values.

Validation of the results

The Area Under the Curve (AUC) of Receiver Operating Characteristic curve (ROC) method was employed to assess the performance of both the MFR and FR methods in groundwater potential zones (Hanley and McNeil 1982; Narkhede 2018). The performance of the methods was quantitatively evaluated using the success rate curve utilizing training dataset and prediction rate curve using test dataset (Chung and Fabbri 2003). Evaluating a model's prediction success rate is crucial for the accuracy of the model, as reliable predictions are essential for the success of any groundwater exploration scheme. The cumulative occurrence of GWP (Fig. 12) was determined by overlaying the groundwater potential map with the locations of training springs. The MFR method demonstrated a stronger performance compared to the conventional FR method for predicting groundwater potential area. The MFR method achieved an AUC value of 0.80, indicating an 80% success rate in accurately classifying areas with spring potential (Fig. 12a). In contrast, the conventional FR method obtained an AUC of 0.65, translating to a 65% success rate (Fig. 12b). It is important to note that both methods share an AUC value of 0.60 for the prediction rate curve, suggesting similar performance in terms of predicting the overall distribution of groundwater potential zones across the study area.

The analysis revealed a trade-off models with a higher AUC for the success rate curve often have a lower AUC for the prediction rate curve. This suggests potential overfitting, where the model memorizes training data specifics and might not perform well on new data (Li et al. 2017). The model demonstrates promising results based on the AUC values for both the success rate and prediction rate curves. The high AUC for the success rate curve indicates good training performance, while the high AUC for the prediction rate curve suggests the model can effectively generalize these learnings to predict spring potential in unseen data. This makes it a valuable tool for future groundwater exploration projects.

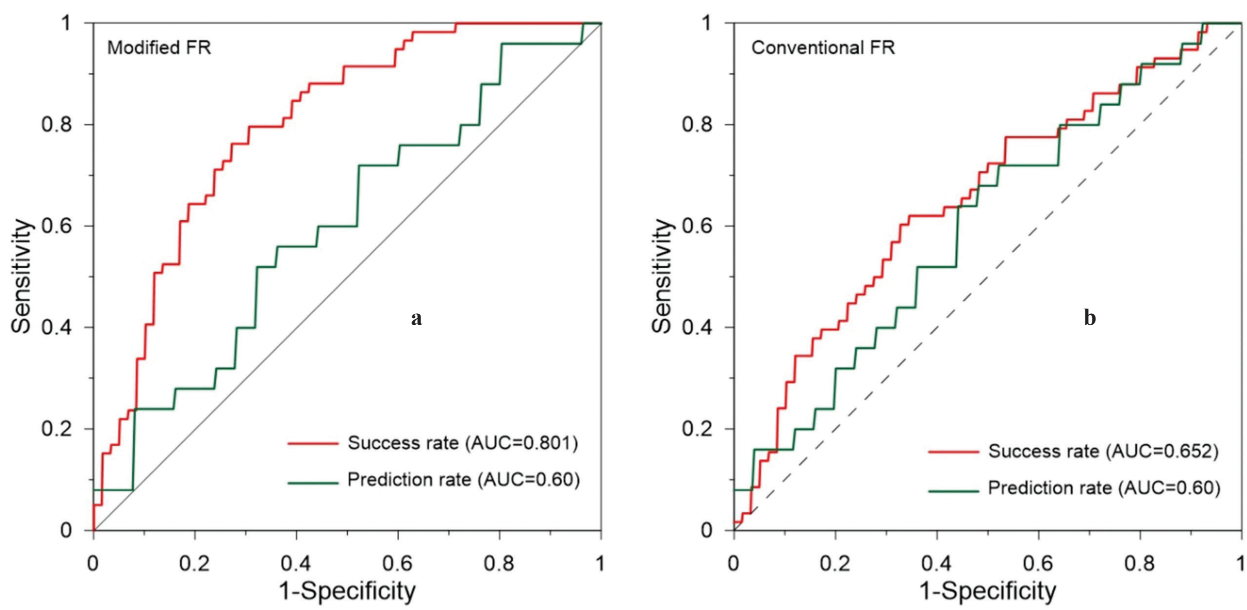

Fig. 12: ROC curve analysis (a) MRF and (b) FR.

CONCLUSIONS

GWP mapping is an essential tool for estimating the possibility of groundwater in the hilly region. This study presents a comparative analysis of the FR and MFR methods for mapping groundwater potential in hilly region applying geomorphic, landuse and geologic causative factors. The ROC curve revealed that the MFR method demonstrated superior accuracy in classifying spring potential, achieving an AUC value of 0.80 versus the FR method’s 0.65. Both methods showed similar performance in predicting overall distribution, with an AUC of 0.60 for the prediction rate curve, yet the MFR method provides a clearer differentiation between high and low potential zones. These findings highlight the MFR method's enhanced effectiveness for groundwater potential mapping, offering valuable insights for planners and policymakers in managing groundwater resources. However, this technique should be replicated in future research studies conducted in Nepal or other regions globally to validate the reliability of this claim.

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