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Groundwater potential assessment using an integrated AHP-driven geospatial and field exploration approach applied to a hard-rock aquifer Himalayan watershed

Sanjib Sapkota [a], Vishnu Prasad Pandey [b,*], Utsav Bhattarai [a,c], Suman Panday [a,d], Surendra Raj Shrestha [e], Sudan Bikash Maharjan [f]

[a] Water Modeling Solutions Pvt. Ltd. (WMS), Lalitpur, Nepal
[b] Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal
[c] Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, QLD, 4350, Australia
[d] Graduate Institute of Applied Geology, National Central University, Zhongli, Taiwan
[e] Groundwater Resources Development Board (GWRDB), Babarmahal, Kathmandu, Nepal
[f] International Centre for Integrated Mountain Development (ICIMOD), GPO Box 3226, Lalitpur, Nepal

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ABSTRACT

Study Region: Eastern Nepal, The Himalayas.
Study focus: This research is aimed at delineating groundwater potential zones in a hard-rock aquifer Himalayan watershed integrating geo-spatial and field exploration techniques. A customized indicator-based weighting method, consisting of six indicators, was developed and applied in the study watershed. Spatially-distributed maps for the indicators were produced based on information from primary as well as secondary sources. The indicators were further aggregated and groundwater potential map was prepared using relative weights derived from Analytical Hierarchy Process with inputs from key hydrogeology experts. The map was then validated using observed data of springs as well as results from Electrical Resistivity Tomography (ERT).
New hydrological insights: The novelty of this study lies in the application of two-step validation (using springs data from the field and ERT) of the groundwater potential mapping approach which demonstrates the robustness of the overall methodology for data scarce regions and paves way for its wider applicability in decision support for groundwater exploration activities. Further, this is one of the very few groundwater potential studies in the Nepal Himalaya hydrogeological setting.

1. Introduction

Global water demand is continuously increasing and projected to rise by 55 % by 2050 (WWAP, 2015). Groundwater, which supports lives and livelihoods of about two billion people worldwide (Misi et al., 2018), continues to play a dominant role in supplying water to meet the growing demands. Drilling tubewells is the most common intervention to extract this resource. Unfortunately, limited understanding of the complex groundwater system has resulted in lower success rates of drilling for the groundwater production wells, particularly in the developing countries (Serele et al., 2020; WRRDC, 2017). The understanding of aquifer systems is

* Corresponding author.
E-mail address: vishnu.pandey@pcampus.edu.np (V.P. Pandey).

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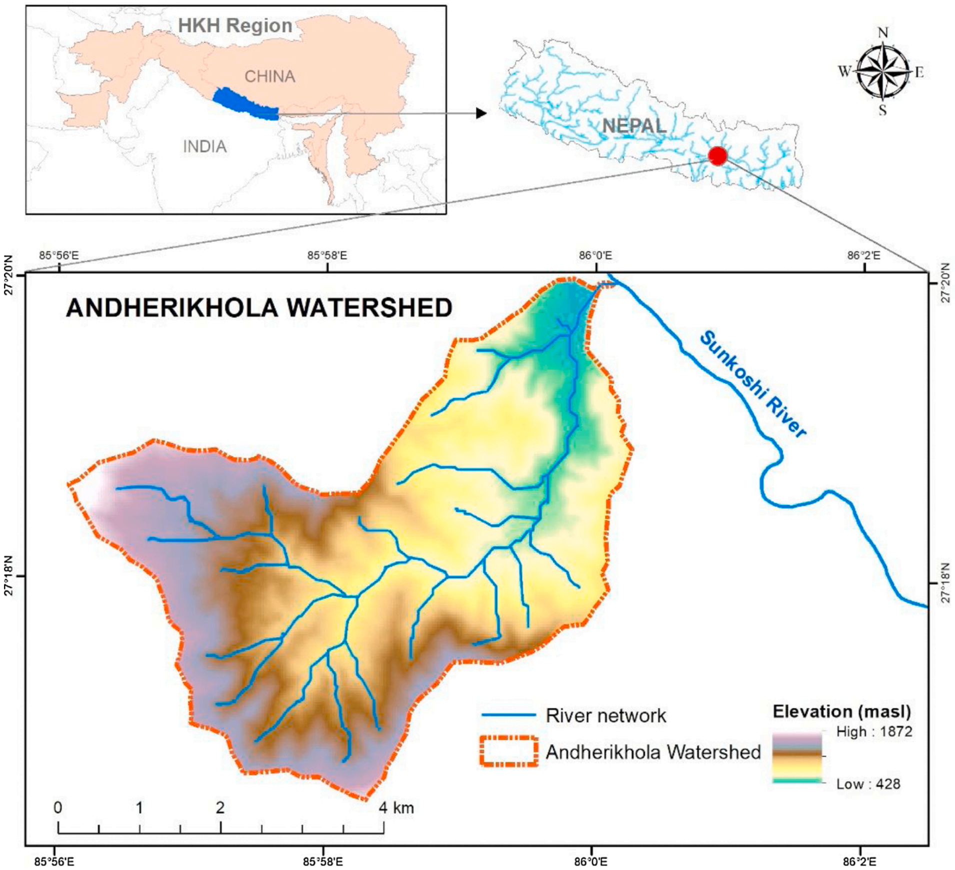

Fig. 1. Geographical setting of Andherikhola Watershed.

further complicated in hard-rock aquifers such as in the Nepal Himalaya, which is characterized by wide ranging lithological units from unconsolidated alluvial deposits to high-grade metamorphic rocks (Dhital, 2015). Furthermore, development of appropriate groundwater simulation models is limited in the absence of groundwater monitoring data. Groundwater, which is available through springs and seepages in the hills and mountains, buffers surface water shortages in many instances (Sharma et al., 2016). However, problems of springs drying-up in recent times (Poudel and Duex, 2017) for various reasons such as improper road construction are expected to worsen in view of demographic conditions and changing climate. This will ultimately impact a large part of the population in the hills of Nepal who are currently meeting their domestic, irrigation and small-scale industrial water demand through groundwater. Although significantly important, exploring groundwater and its potential in this geographical region is not getting adequate attention.

Several conventional and relatively costly methods such as geological, hydrogeological, geophysical and photogeological techniques are available for studying groundwater potential (Lillesand et al., 2015; Shahid et al., 2000). On the other hand, cost effective approaches for groundwater potential assessment, used widely across the globe, are primarily based on information of geology/lithology, land use/cover, lineaments, slope, geomorphology, drainage density, soil and rainfall (Abdalla, 2012; Chihi et al., 2015; Hammouri et al., 2012; Naidu et al., 2015). Although some of this information can be obtained through visual inspection, it is time-consuming, prone to high manual errors, and applicable only to easily accessible areas. Furthermore, studies show that the estimation of groundwater potential requires accurate, continuous and spatially distributed data (Sinha et al., 2018). Remote Sensing (RS) and Geographic Information System (GIS) are proven to be efficient techniques for such analyses with significant recent technological advancements (Ghimire et al., 2019; Andualem and Demeke, 2019; Lentswe and Molwalefhe, 2020; Oikonomidis et al., 2015; Serele et al., 2020). Arshad et al. (2020) integrated GIS with Analytical Hierarchy Process (AHP) to map recharge potential zones in agricultural and urban areas. Lentswe and Molwalefhe (2020) delineated groundwater recharge potential zones using a GIS-based weighted overlay method guided by AHP in a semi-arid region. Patra et al. (2017) applied a similar GIS/RS-AHP method to identify dominant parameters for groundwater potential in the Ganges alluvial plains. Similarly, Oikonomidis et al. (2015) used an integrated GIS/RS method based on AHP to assess the groundwater potential areas in the European context. GWRDB (2015); Pathak and Shrestha (2016); WRRDC (2017) and Pradhan et al. (2020) adopted an indicator-based approach by integrating various factors responsible for controlling the groundwater occurrences in hilly and mountainous terrains of Nepal. The commonality of all these studies is the application of indicator-based weighted overlay method using GIS/RS and recommendation of wider replicability of the method with

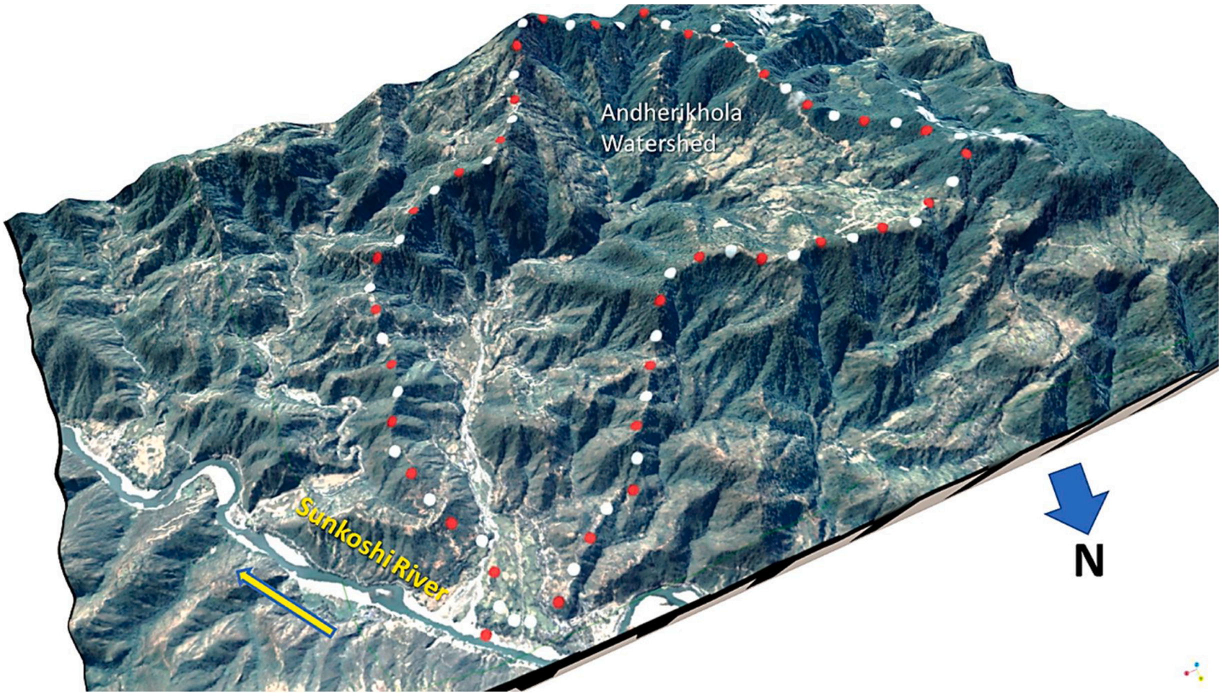

Fig. 2. 3-D view of Andherikhola Watershed.
(Source of satellite data: Google Map; 3-D view generated by the authors in GIS).

Fig. 3. Spring sources visited during field work: in granite (a, b); in gneiss (c, d); in colluvium (e, f) and in schist (g, h).

some customization; whereas the differences being in the scale of application, hydrogeology of the area, choice of weighted parameters and method of validation. Most groundwater potential assessment studies have utilized borelogs and well data for validation (Berhanu and Hatiye, 2020; Serele et al., 2020). However, in rugged terrains and areas difficult to access, this information might not be always available or could be misleading. Therefore, considering springs data could result in a better estimation and validation of the method and findings. Furthermore, geophysical tests such as Electrical Resistivity Tomography (ERT) can be an alternative for assessing groundwater potential.

The overarching objective of this research is to customize and test a methodology for groundwater potential assessment integrating an indicator-based GIS/RS technique with a simplistic validation strategy (Serele et al., 2020) through a combination of ERT and field exploration of springs in a hard-rock aquifer Himalayan watershed located in Nepal. There is a high degree of complexity in the inaccessible Himalayan mountainous region to carry out subsurface studies like drilling and geophysical survey. Therefore, this study attempts to analyze groundwater potential with limited surface data and key indicators and then validate the results using location and primary discharge data of springs as well as ERT results. Thus, the novelty of this research lies in the application of two-step validation

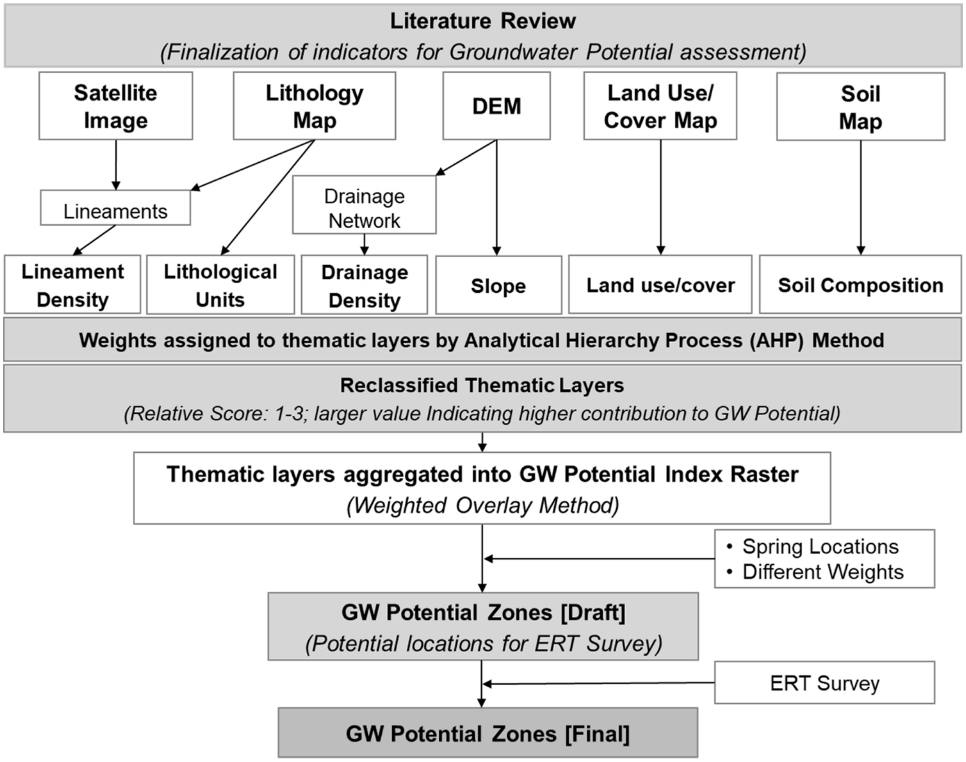

Fig. 4. Methodological framework adopted in this study for delineating groundwater potential zones.

(springs data from the field and ERT) of the overall approach. Moreover, this is one among the very limited studies in the hard-rock aquifers in the Nepal Himalaya. Results demonstrate the robustness of the overall methodology and paves way for its wider applicability in similar hydrogeological settings. The outcome is expected to be useful for water users, practitioners, planners and policy makers for understanding and evaluating the current status of groundwater resources in the study area and also for identifying potential sites for future groundwater development.

2. Study area

This study has been carried out in the Andherikhola Watershed (drainage area of 21.8 km^2) located in eastern Nepal (Fig. 1) in the central Hindu Kush Himalayan (HKH) region. The Andherikhola Watershed is portrayed by steep and rugged terrain with variation in elevation from 428 to 1872 m above sea level (masl). The watershed has the highest elevation at the north-west corner and the lowest at the north-east corner, where Andheri Khola (*khola* meaning small river in the dialect of Nepal) plunges into the Sunkoshi River (Figs. 1 and 2).

Geomorphology of the Andherikhola Watershed is characterised by colluvial with patches of alluvial deposits along the streams. Lithologically, the watershed is dominated by gneiss and schist along with granitic and pegmatitic intrusions. Number of springs in the rock-mass and colluvium demonstrate the watershed potential for groundwater (Fig. 3). The study area has a sub-tropical type climate with mean annual temperature varying from 8 to 24 °C and an average annual rainfall of about 2500 mm (DHM et al., 2013). As can be seen from Fig. 1, Andheri Khola originates from the southern side of the watershed and flows in the north-east direction to its confluence with Sunkoshi River exhibiting a dendritic drainage pattern. The average channel slope of the watershed is 0.139 m/m, length of the longest flow path is 10.26 km and the time of concentration is approximately 50 min. The study watershed is predominantly rural with a sparse distribution of 3400 residents (CBS, 2011). Sixty-two percent of the watershed is covered by forest while 36 % is cultivated land (ICIMOD, 2013) and most parts are accessible by earthen roads. Our field survey shows that although some rural water supply schemes are present locally, reliable utility water supply from the government is not available and thus people are facing water shortages. A few springs have been tapped with local initiatives in recent years to meet the increasing domestic water demand but with limited yield.

3. Methodology and data

This study has adopted an indicator-based weighting method, consisting of six indicators, for groundwater potential assessment of a hard-rock aquifer in a Himalayan watershed integrating geo-spatial and field exploration techniques. Spatially-distributed maps for

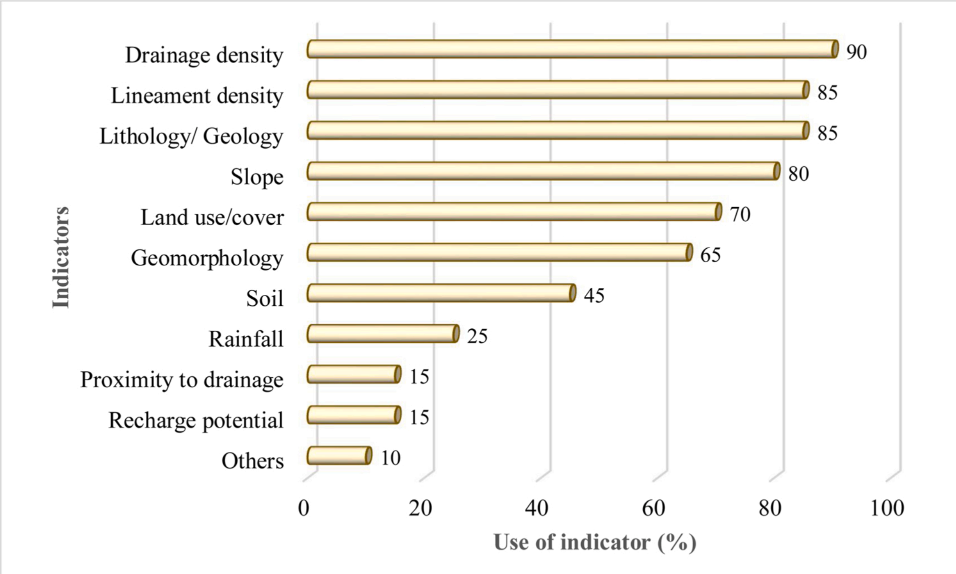

Fig. 5. Indicators influencing groundwater potential and their frequency of occurrence (in percentage) based on literature review.

Table 1
Data used in this study.

Dataset [Unit]	Description/Properties	Source(s)	Resolution
Terrain [masl*]	Digital Elevation Model (DEM)	Generated from Department of Survey, GoN	30m × 30m spatial grids
Land use/cover [-]	Landsat land use/cover classification (4 classes)	ICIMOD (2013)	30m × 30m spatial grids
Lithology [-]	Lithological description	Field survey (2017)	–
Soil [-]	Soil composition	Field survey (2017)	–
Lineament density [km/km^2]	Length of lineament per unit area	Derived from Sentinel 2 MSI satellite imagery** and Field Survey (2017)	–
Water sources [-]	Distribution of water sources with respective discharge	Field Survey (2017)	–

* masl: meters above sea level.
** Downloaded from https://glovis.usgs.gov/ on 12/29/2016.

the indicators were produced based on information from primary as well as secondary sources. The indicators were further aggregated using relative weights derived from AHP with inputs from key hydrogeology experts to prepare the groundwater potential map. This map was then validated using observed data of springs as well as ERT results. The overall methodological framework is presented in Fig. 4 and the details are described subsequently.

3.1. Selection of indicators

Based on the review of a considerable number of relevant literature on groundwater potential (presented in Supplementary material (S-1)) from different regions across the globe, ten most-influencing indicators, namely, drainage density, lineament density, geology (or lithology), slope, land use/cover (LULC), geomorphology, soil, rainfall, proximity to drainage (or surface water) and recharge potential (or amount) were shortlisted in the first step (Fig. 5). After extensive consultation with hydro-geological experts having an in-depth understanding of the local context of hard-rock aquifers in the mountainous regions of Nepal along with the experience of the study team, six indicators - drainage density, LULC, lineament density, lithology, slope and soil composition - were finally selected for the groundwater potential study of the Andherikhola Watershed.

Although rainfall plays an important role in recharge, however, this study is not focused on quantification, rather on the qualitative investigation and relative comparison of potential zones. Studies have shown that the variability of precipitation within an area of interest is useful for comparative assessment of the groundwater potential, particularly if the study area is quite large (Arshad et al., 2020; Oikonomidis et al., 2015; Patra et al., 2017). In our case, there is only one observed precipitation station in the vicinity of the study area and moreover, the watershed area is too small to see a notable variation of precipitation within it. Hence, precipitation (and its variation) has been excluded in this study.

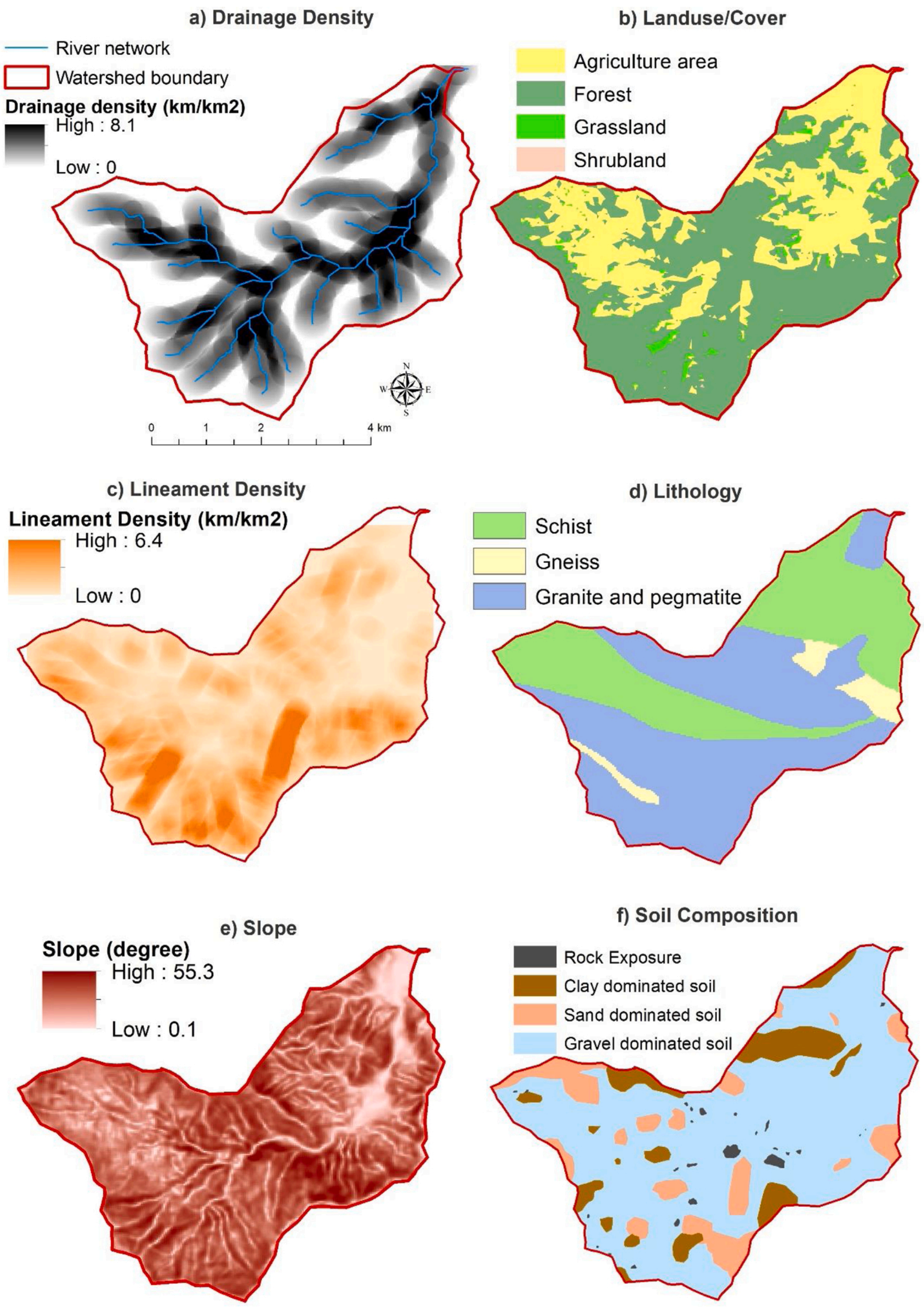

Fig. 6. Spatial distribution of different physical parameters in Andherikhola Watershed: (a) drainage density, (b) land use/cover, (c) lineament density, (d) lithology, (e) slope and (f) soil composition.

3.2. Data and sources

Primary as well as secondary data were collected from various sources, including field survey (Table 1). The digital elevation model (DEM) was prepared using the contour and spot heights published by the Department of Survey, Government of Nepal (GoN) into a 30m × 30m raster file. The LULC data available at a spatial resolution of 30m × 30m was downloaded from ICIMOD (2013). Information related to lithology, soil composition and distribution of water sources (springs in particular) was collected during field survey conducted by the study team. Lineament density was extracted from Sentinel 2 MSI satellite imagery. Locations (coordinates) of water sources were collected using a Global Positioning System (GPS) receiver while their discharges were measured with the help of

Table 2
Normalized comparison matrix for selected indicators (in alphabetical order).

	Drainage density	Land use/ cover	Lineament density	Lithology	Slope	Soil composition	Normalized Principal Eigen Vector (Rating)
Drainage density	0.14	0.17	0.17	0.12	0.12	0.14	0.142
Land use/cover	0.03	0.03	0.02	0.04	0.04	0.04	0.035
Lineament density	0.17	0.29	0.21	0.31	0.22	0.12	0.220
Lithology	0.35	0.28	0.20	0.30	0.36	0.40	0.314
Slope	0.14	0.09	0.11	0.10	0.12	0.14	0.118
Soil composition	0.17	0.14	0.29	0.13	0.14	0.17	0.171

bucket/measuring cylinder and stop-watch.

3.3. Preparation of thematic layers

After selection of the indicators, thematic layer of each indicator was prepared using GIS. Drainage network was derived from DEM and was further processed to prepare a drainage density map using a search radius of 1 km. The drainage density of the Andherikhola Watershed was found to be in the range of 0–8.1 km/km^2 (Fig. 6a). The land use/cover adopted from ICIMOD (2013) was reclassified into four classes – agriculture area, forest, grassland and shrubland. Most of the areas of the study watershed is covered by forest (61.2 %) and agriculture area (35.9 %). Grassland (2.1 %) and shrubland (0.8 %) are found as patches (Fig. 6b). Preparation of the lineament density map initially involved derivation of lineaments from the lithological map. These lineaments were overlaid on satellite image and finer lineaments were extracted by visual inspection to produce a final lineament map, based on which, lineament density map was prepared using a search radius of 1 km. The lineament density of the study watershed was found varying between 0 and 6.41 km/km^2 (Fig. 6c). Lithological map was prepared based on data from the field survey. Information of different lithological units was collected and mapped by traversing through rivers and foot trails. Lithological contact identified in the field was extended to the entire watershed. The watershed comprised of three types of rocks: gneiss (56.4 %), schist (39 %) and granite/pegmatite (4.6 %) (Fig. 6d). Slope of the watershed was derived from the DEM and varies from flat (near to zero) to 55.3° (Fig. 6e). Soil mass dominated by gravel and larger sized particles (observed during the field survey) was categorized as gravel-dominated soil. Soil mass, of which grain could be distinguished in the field but particles were smaller than gravel, was categorized as sand-dominated. Similarly, the soil mass was categorized as clay-dominated if its grain could not be distinguished in the field. Areas without soil mass were demarcated as bedrock. The study watershed was found to be pre-dominantly gravelly (77.1 %) followed by sand-dominated soil (12.5 %), clay-dominated soil (9.5 %) and bedrock (0.9 %) as shown in Fig. 6f. All the thematic layers were resampled to 30m × 30m spatial resolution raster grids for further processing.

3.4. Assigning weights

The AHP method (Saaty, 1980) was adopted for assigning the weights to each indicator. AHP is a method to identify the most influential factors for complex systems such as groundwater based on qualitative expert judgement. This is a convenient way to compare decision elements which are difficult to otherwise quantify. Experts in the field of hydrogeology having an in-depth understanding of the local context of hard-rock aquifers in the mountainous regions of Nepal were requested to provide pair-wise comparison of the selected indicators based on a scale of values ranging from 1 to 9 (Saaty, 2001). This method relies on building a hierarchy of decision elements and then making pairwise comparisons in a matrix form (Eq. (1)). This hierarchy incorporates the experience and judgement of the decision maker.

$$\boldsymbol{A} = \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & a_{23} & \dots & a_{2n} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 & \dots & a_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \frac{1}{a_{3n}} & \dots & 1 \end{bmatrix} \tag{1}$$

Where $\boldsymbol{A}$ is a $n \times n$ comparison matrix in which a_{ij} are the alternatives with respect a given criteria; $a_{ij} > 0$; $1 \leq i \leq n$; $1 \leq j \leq n$ and n is the number of parameters being compared.

The new normalized matrix was obtained by dividing each element of the comparison matrix by normalized relative weight (sum of its column) (Table 2).

Principal eigen value (λ_{max}) was computed to be 6.16 from the summation of the products between normalized eigen vector (from the normalized matrix) and normalized relative weight (from the initial reciprocal matrix).

The consistency index (CI) was calculated by Eq. (2)

Table 3
Selected groundwater potential indicators and their relative score classes.

SN	Indicator: Description	Classes	Relative Score
1	*Drainage density*: Lower (surface) drainage density takes less water away from the watershed and therefore enhances possibility of infiltration and GW storage.	High	1
		Moderate	2
		Low	3
2	*Land use/cover*: Agriculture area has higher porosity for better GW recharge; water bodies such as ponds, lake, streams may result in higher GW recharge; forests and shrublands also support percolation of water through their root systems and also by obstructing the overland flow of water; barren land, grassland and rocky terrain contribute very less to GW recharge as they permit more surface flow.	Grassland	1
		Forest/ Shrubland	2
		Agriculture area	3
3	*Lineament density*: Higher lineament density provides more space to store GW and also facilitates GW movement due to interconnections of factures.	Low	1
		Moderate	2
		High	3
4	*Lithology*: Granite and pegmatite, having higher porosity, have higher chances for interconnected pore spaces to store and transmit more water and therefore possibility of higher GW potential; impervious rocks like schist are less likely to retain sub-surface water, therefore chances of less contribution to GW potential; gneiss has moderate impacts on GW potential.	Schist	1
		Gneiss	2
		Granite & Pegmatite	3
5	*Slope*: Mild/Gentle slope provides favorable condition for GW storage and flow.	Steep (>35°)	1
		Moderate (10–35°)	2
		Gentle (0–10°)	3
6	*Soil composition*: Gravelly soil has high permeability and therefore has high influence on GW potential; clayey soil has less influence due to very low or no permeability; sandy soil has moderate impact.	Clay-dominated	1
		Sand-dominated	2
		Gravel-dominated	3

Note: GW - groundwater; 1 and 3 in the 'Relative Score' column refer to possible low and high contribution to groundwater potential, respectively.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Where, n is the number of parameters (= 6). Thus, CI was calculated to be 0.032.

Finally, the consistency ratio (CR) was calculated by Eq. (3)

$$CR = \frac{CI}{RI} \tag{3}$$

Where, RI is the random consistency index dependent on the number of parameters being evaluated (Saaty, 1980) and is 1.24 for $n = 6$. Thus, consistency ratio (CR) was calculated to be 0.026.

Pair-wise comparison is consistent only if $CR \leq 10\%$. The computed CR value (2.6 %) meets the consistency criteria ratifying the assumptions made to build the pair-wise matrix. Therefore, maximum weightage has been assigned to lithology (31 %) followed by lineament density (22 %), soil composition (17 %), drainage density (14 %), slope (12 %) and land use/cover (4 %).

3.5. Aggregated index and groundwater potential zones delineation

Classifying the selected indicators is always a challenge as different researchers have put forward a variety of diverse arguments. Nevertheless, we have adopted a classification schema based on our past experience of comparable works in similar physical settings.

Drainage is the path of surface flow and thus retards infiltration; hence, higher drainage density is inversely proportional to the groundwater potential (Jenifer and Jha, 2017; Naidu et al., 2015). Plants require water for germination and also occurrence of a variety of plant species indicate water availability (particularly groundwater). Hence, it can be anticipated that barren land has less groundwater potential compared to forest and cultivated land (Lamichhane and Shakya, 2019, 2020; Ouyang et al., 2019). Generally, lineaments consist of linear and curvilinear features of the earth surface like faults, joints, crustal fractures having high permeability that indicate groundwater potential in terms of recharge, storage and discharge (Berhanu and Hatiye, 2020; Dar et al., 2020; Pradhan, 2009). So, higher the lineaments density, higher will be the probability of groundwater occurrence. The topographic gradient plays a considerable role in groundwater storage, flow rate, depth of availability along with geology (Lentswe and Molwalefhe, 2020; Naidu et al., 2015). The composition domination by grain size in the soil has a significant contribution on surface as well as subsurface hydrodynamic phenomenon. Gravel and sand bearing soil have higher chance of infiltration than clay-dominated soil because low permeability of clay-dominated soil enhances surface runoff (Zomlot et al., 2015). Based on the aforementioned arguments, each indicator was classified for relative scoring from 1 to 3, larger value representing higher influence to groundwater potential and vice-versa (Table 3). Choice of segregating the indicators into three classes was further strengthened by consultation with experts who are well-acquainted with the hydrogeology of the study area and our observations and judgement gathered from past experience of working in similar geo-physical conditions.

Raster datasets of each input indicator were prepared according to the finalized classes at a horizontal resolution of 30m × 30m. Groundwater Potential Index (GWPI) was computed as the weighted sum of the scores of the indicators using the raster datasets in GIS. The pixel-wise GWPI was calculated as follows:

Table 4
Classification of the thematic layers contributing to groundwater potential.

Layer	Actual Distribution	Classification	Effect on groundwater potential	Percentage of watershed area (%)
	≤ 1.0	1	High	58.4
Drainage density [km/km^2]	1.0 - 2.0	2	Moderate	27.5
	> 2.0	3	Low	14.1
	Grassland	1	Low	2.1
Land use/ cover	Forest/ Shrubland	2	Moderate	62.0
	Agriculture area	3	High	35.9
	≤ 1.0	1	Low	14.6
Lineament density [km/km^2]	1.0 - 2.0	2	Moderate	38.0
	> 2.0	3	High	47.4
	Schist	1	Low	39.0
Lithology	Gneiss	2	Moderate	56.4
	Granite and Pegmatite	3	High	4.6
	≤ 10	1	High	11.5
Slope [Degree]	10 – 35	2	Moderate	66.8
	> 35	3	Low	21.7
	Clay-dominated	1	Low	10.4
Soil composition	Sand-dominated	2	Moderate	12.5
	Gravel-dominated	3	High	77.1

$$GWPI_t = \left(\sum_{i=1}^{6} W_i S_i\right) \tag{4}$$

where, *GWPI* is the Groundwater Potential Index at any pixel t within the watershed; i represents the number of indicators used ($1 \leq i \leq 6$, integer value only); W_i represents the weight (in percentage) for a particular indicator i at the tth pixel; S_i represents the relative score for the ith indicator at the tth pixel ($1 \leq S_i \leq 3$, integer value only).

Then finally, groundwater potential zones were classified into three categories: low (GWPI $<$ 185), medium (185 $\leq$ GWPI $\leq$ 230), and high (GWPI $>$ 230) to prepare the groundwater potential map. Choice of segregating groundwater potential into three classes and the relative score-range of each class was primarily decided upon the observations made by the study team during the field survey and our judgement based on similar previous studies. It was further augmented by consultation with experts who are very much familiar with the hydrogeology of the study area and its geo-physical settings. It is to be noted here that the magnitudes of GWPI in absolute terms have no direct physical significance and are to be considered for relative comparison only.

3.6. Validation of groundwater potential map

A two-step simplistic validation strategy was adopted for evaluating the performance of the implemented methodology (Fig. 4). First-level evaluation of the groundwater potential map was carried out using the spring distribution map as presence of springs corroborate the reliability of the results (Berhanu and Hatiye, 2020; Pradhan et al., 2020). Distribution of springs along with their discharges (one-time measurement) were mapped using data from field investigation. This map was overlaid on the generated groundwater potential map. If higher groundwater potential areas correspond to the presence of larger number of springs (or higher yield), the generated map was considered reasonable at this level because presence of springs is a clear indication of the availability of groundwater in that area.

Since ERT is widely used in groundwater prospecting (Arsène et al., 2018; Gyeltshen et al., 2020), the second-level evaluation was made based on the results of ERT survey at two sites. The electrical resistivity of earthen materials primarily depends on the resistivity of minerals and the fluid contained within the pores of the material. ERT accounts the difference of electrical resistivity of two particular surveyed points. If electric current is introduced into the medium, it will flow variably giving rise to a potential difference between the surveyed points depending upon its electrical resistance. In ERT, electrical current of very low frequency is passed and the resistivity data is collected with the help of electrodes by covering the line of investigation continuously. In general, ERT is conducted by various arrangements of four electrodes - two current electrodes and two potential electrodes. For this study, Wenner configuration was chosen with electrode spacing of 5 m. Wenner configuration is a special type of four-electrode arrangement in which current and potential electrode pairs have a common mid-point and the distances between adjacent electrodes are equal (Lowrie, 2007). Geomative GD-10 machine, which provides the apparent resistivity of the survey profile, was used for data collection. Apparent resistivity was then converted to true resistivity with the aid of RES2DINV Version 3.53 g software. As ERT is a resource-intensive and expensive method, we could limit it to two sites only in the study watershed within the scope of this research.

4. Results and discussion

4.1. Spatial distribution of thematic layers

Groundwater potential zones were delineated based on six thematic layers as discussed in Section 3. They are briefly described

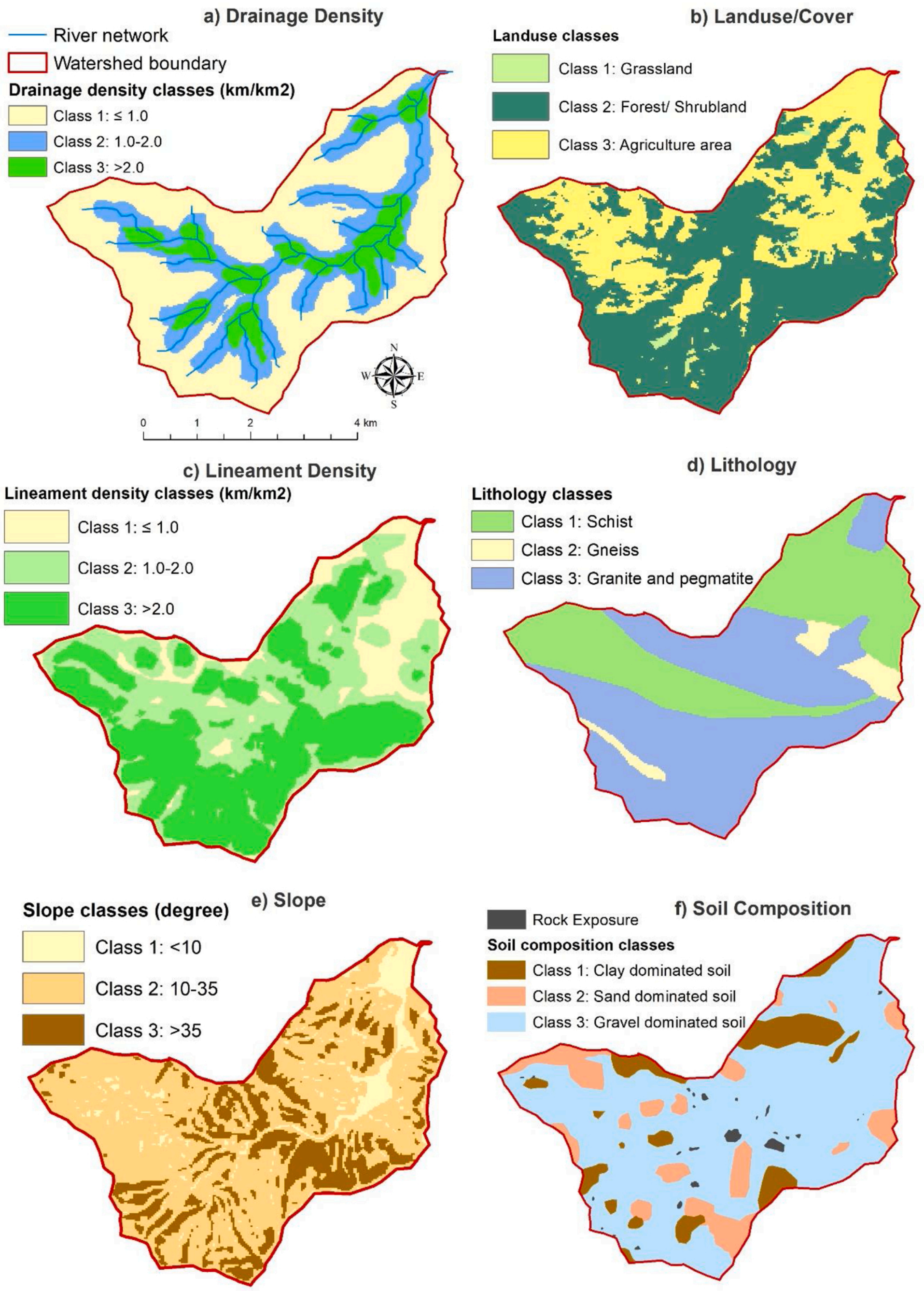

Fig. 7. Classification of the selected indicators in Andherikhola Watershed: (a) drainage density, (b) land use/cover, (c) lineament density, (d) lithology, (e) slope and (f) soil composition.

hereunder.

4.1.1. Drainage density

Drainage density of the Andherikhola Watershed was grouped into three classes: Class 1 ($\leq$ 1.0 km/km^2), Class 2 (1–2 km/km^2), and Class 3 (>2 km/km^2) (Table 4, Fig. 7a), indicating high, moderate and low effects on groundwater potential, respectively. Classes 1, 2 and 3 respectively cover 58.4 %, 27.5 % and 14.1 % of the watershed area.

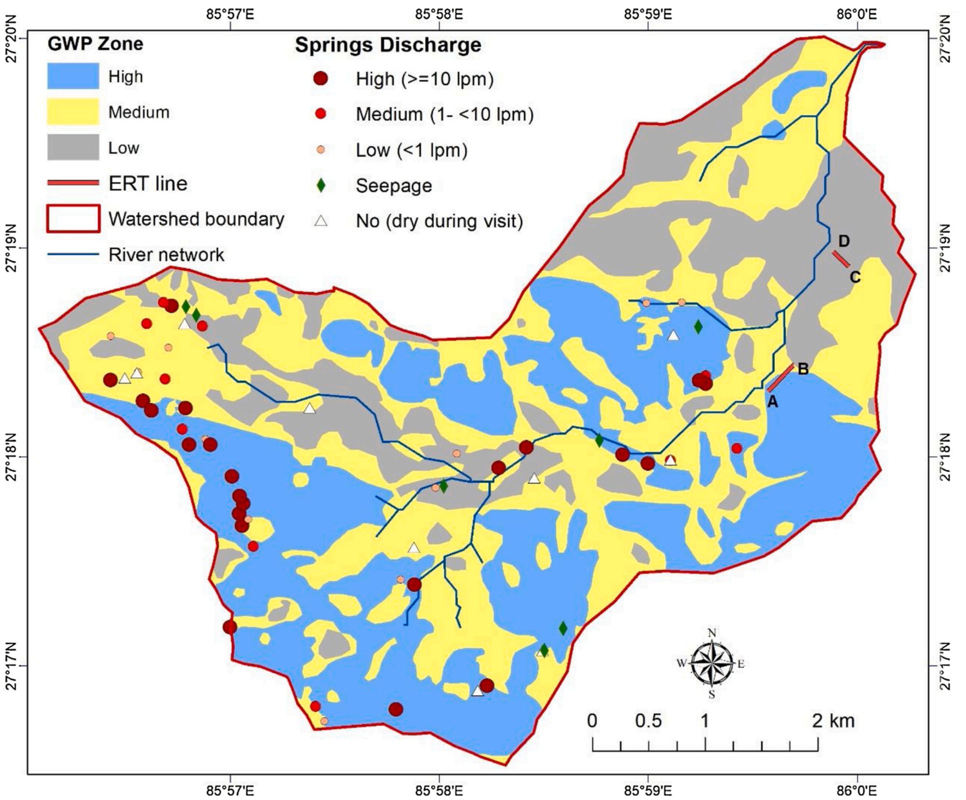

Fig. 8. Groundwater potential map showing springs distribution & ERT-survey-lines of Andherikhola Watershed.

4.1.2. Land use/cover (LULC)

LULC was grouped into three classes – Class 1 (grassland), Class 2 (forest/ shrubland) and Class 3 (agriculture area) (Table 4, Fig. 7b), representing low, medium and high effects on groundwater potential, respectively. They respectively cover 2.1 %, 62.0 % and 35.9 % of the watershed area.

4.1.3. Lineament density

Andherikhola Watershed was categorized into Class 1 ($\leq$1.0 km/km^2), Class 2 (1.0–2.0 km/km^2), and Class 3 (>2.0 km/km^2) (Table 4, Fig. 7c), denoting possible low, moderate and high effects, respectively of lineament density, on groundwater potential. Classes 1, 2 and 3 cover 14.6 %, 38.0 %, and 47.4 % of the watershed area, respectively.

4.1.4. Lithology

The study watershed was divided into 3 categories: Class 1 (schist), Class 2 (gneiss) and Class 3 (granite and pegmatite), indicating low, moderate and high effects of lithology on groundwater potential, respectively. These occupy 39.0 %, 56.4 % and 4.6 % respectively of the watershed area (Table 4, Fig. 7d).

4.1.5. Slope

The watershed slope was classified into three: Class 1 ($< 10°$), Class 2 ($10° – 35°$) and Class 3 ($> 35°$) indicating high, moderate and low impact, respectively on groundwater potential. Class 1 covers 11.5 %, Class 2 66.8 % and Class 3 21.7 % of the watershed area (Table 4, Fig. 7e) showing that Andherikhola is a steep watershed.

4.1.6. Soil composition

For groundwater potential zonation, the study watershed was classified into three soil classes: Class 1 (clay-dominated, 10.4 % of the watershed area), Class 2 (sand-dominated, 12.5 %) and Class 3 (gravel-dominated, 77.1 %) indicating low, moderate and high effects on groundwater potential, respectively (Table 4, Fig. 7f).

4.2. Groundwater potential zones

Based on the normalized GWPI values, a groundwater potential map was prepared delineating it into three zones: low, medium and high. Results show that 21 % (4.5 km^2) of the watershed area falls in the low, 36 % (7.8 km^2) in the high and 43 % (9.5 km^2) in the

Table 5
Cross validation of the results based on springs data.

Class of GWPZ	Spring class based on discharge (lpm)	No. of springs in respective GWPZ class	Total spring discharge in respective GWPZ class (lpm)	No. of springs satisfying GWPZ and spring classes	Spring discharge satisfying GWPZ & spring classes (lpm)	Agreement based on	
						No. of springs	Spring discharge
High	*High* (≥ 10)	22	355.0	17	285.0	77 %	80 %
Medium	*Medium* (1−10)	11	48.8	4	19.8	36 %	41 %
Low	*Low* (< 1)	10	5.3	2	0.3	20 %	6 %
Total		43	409.1	23	305.1	53 %	75 %

GWPZ: groundwater potential zone; lpm: liters per minute.

medium groundwater potential zone, indicating that the study area has a good groundwater prospect (Fig. 8). It is evident from the figure that central and southern regions of the watershed have high groundwater potentials; areas on the northeast have lower potential whereas medium potential areas are found distributed throughout the watershed.

Low groundwater potential zone consists of areas having less water bearing lithological units such as schist. Medium to high groundwater potential areas are distributed over the region having granite, pegmatite and gneiss in addition to areas having granular soil. The gneissic lithological regions consisting of coarse gravelly to sandy soil and high density of lineaments with moderate slope (south-western part of the watershed) lie in the high to medium groundwater potential zones. These areas also include a large share of agricultural land which could be an indication of the choice of land for agriculture traditionally considering the availability of groundwater for irrigation. Granite and pegmatite rock dominant central portion of the watershed lies in high to medium groundwater potential zones with several springs having high discharge (≥10 L per minute, lpm), most originating through fractured rock aquifers. Occurrence of high drainage density along the valley regions indicate a lesser potential of groundwater.

Thus, strong influence of the geomorphological set-up is distinctly visible in the groundwater potential zones delineated in this study. In addition to lithology, soil composition and slope are also found to influence the groundwater potential but to a lesser extent. Lithology has been reported as the most influential parameter for groundwater potential and recharge assessment, for example, in Upper Blue Nile Basin (Andualem and Demeke, 2019); semi-arid region in Botswana (Lentswe and Molwalefhe, 2020) and high relief area in Greece (Oikonomidis et al. (2015). Similarly, (Patra et al., 2017) showed geology to have the strongest influence on groundwater potential in the alluvial plains of India. Results of all the aforementioned studies are concurrent with our findings. Therefore, it can be surmised that geological factors play the most important role in groundwater potential zonation and the adopted methodology is found to be satisfactory for application in complex rugged hilly and mountainous terrains with hard-rock aquifer systems.

4.3. Validation of groundwater potential map

Validation of groundwater potential is always a challenging task, especially if the study area is rugged, inaccessible and data scarce. The challenge is even more pronounced in mountainous regions, where people fulfill their household and small-scale irrigation demands from spring sources and streams rather than dug wells or boreholes. In this study, the groundwater potential map was validated using a two-step simplistic strategy in which the first step consisted of field exploration. The second step involved the application of ERT at two locations in different groundwater potential zones within the study watershed.

Field work was carried out during the dry pre-monsoon period. And surprisingly, several springs had significant discharge. Based on their discharge, all the identified springs were classified into five different categories, namely, *high*, *medium*, *low*, *seepage* and *dry*. Springs having discharge greater than or equal to 10 lpm were classified as *high*, those with 1−10 lpm were classified as *medium* and those with discharge less than 1 lpm were denoted as *low*. Likewise, spring sources located in moist areas and/or slightly dripping were categorized as *seepage*. Those springs which were dry during the field visit but based on the information from the local people, that yield up to several months during the monsoon and post-monsoon period were categorized as *dry*. Details of the visited spring sources are provided in Supplementary Material (S-2). Among the identified 61 springs, 43 had yield data, 7 were *seepage* and 11 were *dry* (Fig. 8). Out of the 43 spring-sources having yield, 22 were in the *high*, 11 in the *medium* and ten in the *low* groundwater potential zone. Since more than 50 % of surveyed springs lie in the high groundwater potential zone, it is found to be in good agreement with the prepared groundwater potential map.

Cross-validation analysis is a simple and effective tool to evaluate the groundwater potential map based on available springs data (Berhanu and Hatiye, 2020). For this purpose, the total number of spring sources in each groundwater potential zone was compared with the number of spring sources having *high*, *medium* and *low* discharges (Table 5). It was seen that there is an agreement of 53 % among the two considered variables. Another criteria was set based on the total yield in each groundwater potential zone versus yield by *high*, *medium* and *low* spring discharges (Table 5), which further showed very good results (75 % agreement). Thus, the first level validation of the GW potential zones delineated in this study was found to be satisfactory in representing the groundwater condition of the study watershed.

ERT survey was done at two selected locations (Fig. 8) as the second level validation of the groundwater potential map. The first site AB was chosen in a *high*-to-*medium* whereas the second site CD was considered in a *low* groundwater potential zone. Profile results of the ERT showed that the top layer varies in terms of its composition and thickness along AB (Fig. 9). It can be seen that the northern part has a 20 m thick unsaturated gravel layer; the middle part has a 20 m thick saturated gravel layer while the southern part has a 10

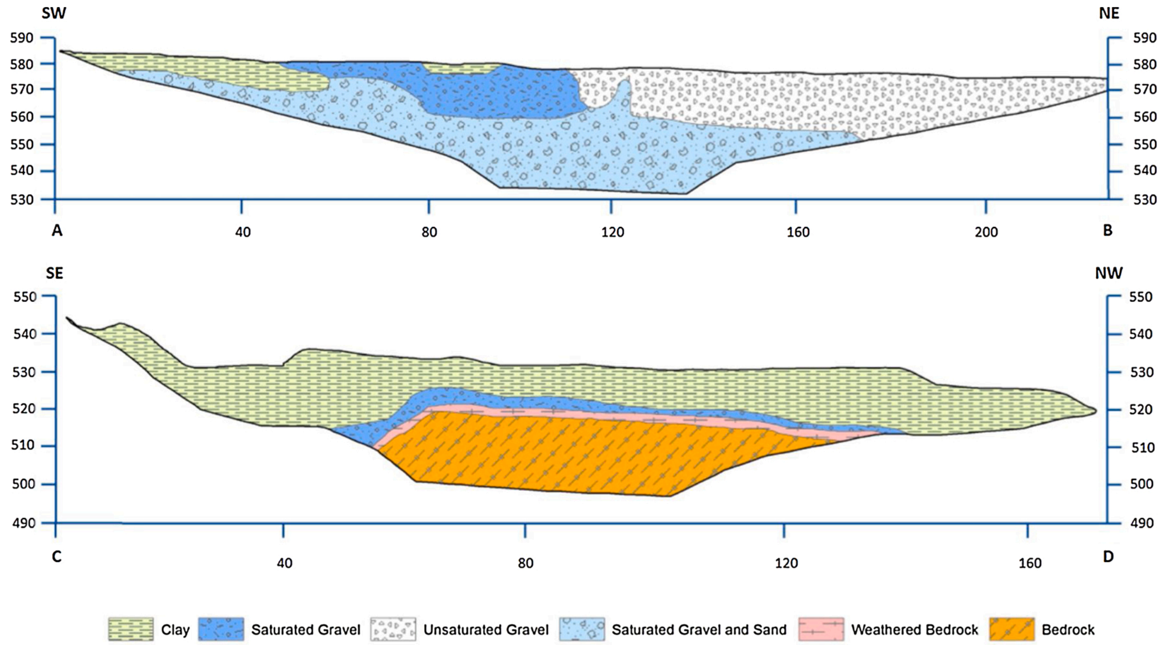

Fig. 9. Lithological interpretation of ERT profile along AB (top) and CD (bottom). Please refer to Fig. 8 for location of AB and CD within the study watershed.

m thick clay layer. The layer immediately below consists of a layer of saturated sand and gravel with an average thickness of about 25 m. Layers having higher groundwater potential is observed in the southern part, which is in good agreement with the groundwater potential zones of the groundwater potential map. The vertical profile of CD shows that the top layer of clay, has an average thickness of about 15 m from the east to the west and is slightly squeezed in the middle (Fig. 9). The underlying layer consists of uniformly distributed saturated gravel with an average thickness of about 5 m. The third layer of weathered bedrock is approximately 5 m thick and rests above the 20 m thick basal bedrock. Hence, from the ERT results, this section can be interpreted as a low groundwater potential area synchronous with the desk-based findings of the study.

5. Conclusion

This study applied a customized indicator-based methodology for delineating groundwater potential zones in a hard-rock aquifer watershed of Nepal Himalaya. The groundwater potential map was evaluated using a two-step simplistic validation strategy. The first step was based on cross-validation using the existing springs data (location and discharge). And the second level validation was done by conducting ERT at two locations. Results from the desk study were found to be in good agreement with the observed field information and thus the devised methodology and findings are considered satisfactorily validated.

It can be concluded that six indicators, namely, lithology, lineament density, soil composition, drainage density, slope and land use/cover, can adequately characterize groundwater potential zones in the Andherikhola Watershed with varying levels of influence. Higher weightages of 31 % and 22 % are suitable for lithology and lineament density respectively. Similarly, respective moderate weightages of 17 %, 14 % and 12 % for soil composition, drainage density, and slope whereas a low weight of 4 % for land use/cover is proposed for such hard-rock aquifers in a Himalayan watershed. Additionally, 36 % of the total watershed area under *high* and 43 % under *medium* groundwater potential zones signify it has a good prospect for detailed future studies related to groundwater development projects. Furthermore, qualitative validation with springs data and ERT has been found to be satisfactory for evaluating groundwater potential assessment in data scarce watersheds.

During the field study, one-time spring data and 2D ERT survey at two locations were conducted due to limited resources. Authors have a view that collection of year-round spring data and conduction of ERT survey with cross-profile at more locations spatially distributed within the study watershed will further strengthen the validation process. In light of the limitations of this study, future research direction of groundwater development could be in the quantification of groundwater volume and recharge; assessment of recharge zones by adopting latest technologies such as isotopes or tracers and estimation of safe yield. Such operation research could provide direct inputs to implementation of shallow/deep boring systems in these terrains to cater the current as well as future water supply needs. The tested methodology can be conveniently replicated in similar settings with some customization.

Authors' statement

Sanjib Sapkota: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft

Preparation, Writing - review & editing. **Vishnu Prasad Pandey**: Conceptualization, Methodology, Visualization, Writing - original draft Preparation, Writing - review & editing. **Utsav Bhattarai**: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Visualization, Writing - review & editing. **Suman Panday**: Data curation, Formal analysis, Investigation, Software, Field work, Writing - review & editing. **Surendra Raj Shrestha**: Data curation, Supervision, Field work. **Sudan Bikash Maharjan**: Software, Supervision, Validation.

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Declaration of Competing Interest

All authors would like to declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100914.

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