Journal of Institute of Science and Technology, 28(1), 1-10 (2023)
ISSN: 2467-9062 (print), e-ISSN: 2467-9240
https://doi.org/10.3126/jist.v28i1.47459

Research Article

APPLICATION OF GEOSPATIAL TECHNIQUES FOR ARTIFICIAL RECHARGE TO GROUNDWATER IN RATU KHOLA WATERSHED, CENTRAL NEPAL

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(***Received***: *August 13, 2022;* ***Final Revision***: *January 12, 2023;* ***Accepted***: *February 28, 2023*)

ABSTRACT

Water levels in many existing ponds and shallow tube wells are found lowering day by day in the Bhabar and Terai regions of Nepal. For the sustainable management of the groundwater, development of artificial recharge ponds is considered the best approach in this region. The suitable site selection for the artificial recharge ponds requires surface as well as sub-surface geological investigation along with other land use-related characteristics. The study area is a part of the Ratu Khola watershed in the Mahottari and Dhanusa districts and encompasses parts of the Siwalik, Bhabar, and Middle Terai regions from an aspect of the geological division. The present study has aimed to find suitable sites for the artificial recharge pond. For this purpose, extensive fieldwork was carried out to gather data related to geology, geomorphology, water table, and soil characteristics. However, slope and drainage density maps were developed from the Digital Elevation Model (DEM). The thematic layers of different parameters such as geology, geomorphology, slope, water table, drainage density, land use land cover, and soil type were prepared by using GIS and RS. Based on the field data and prepared maps the suitable sites for artificial recharge ponds were analyzed. The Analytic Hierarchy Process (AHP) method was adopted to assign rank and reclassify the prepared maps. The total area was differentiated into five classes to assess the suitable sites for artificial recharge ponds. These five classes are named as the most suitable, highly suitable, moderately suitable, low suitable, and unsuitable depending on the score of the suitability analysis. The most suitable, highly suitable, moderately suitable, low suitable, and unsuitable area for groundwater recharge is found at about 3%, 7%, 24%, 32%, and 34% respectively. Finally, the ROC/AUC curve was prepared using primary data (point data) collected from the field. An overall accuracy of 82.3% was achieved in this study and is considered satisfactory.

Keywords: Artificial recharge pond, analytic hierarchy process, Ratu Khola watershed, Siwalik

INTRODUCTION

Regeneration of the underneath water is a crucial phenomenon of the earth. These phenomena support balancing the water cycle and ecosphere. From the past to the recent, underground water shows paucity in its abundance due to a huge amount of exploitation, developmental works, and haphazard urban sprawl inclination (Kaliraj *et al.*, 2014). In similar manners, the global population density is rapidly inclined which reflects the negative impact of underground water recharge. In Nepal, the trend is increasing day by day following the world scenario. The Bhabar zones have a composition of unconsolidated or loosely packed materials like boulders, gravels, and granules mixed with silt and sand particles. These are the low-angle slopes having highly permeable materials. Such materials yield a huge amount of water resulting in recharging towards the Middle Terai. There are various ways evolved for recharging the underneath water (Asano, 1985). Incorporating these methods in the context of Nepal could be technically feasible as well as economically viable in mitigating groundwater-induced hazards. In Nepal, only a few studies and research are carried out on the potential methods for identifying the site for the artificial recharge of groundwater (Pathak *et al.*, 2012; Bricker *et al.*, 2014; Ghosh *et al.*, 2016; Pathak & Shrestha, 2016; Pathak & Gautam, 2019; Khadka & Pathak, 2020).

Modern techniques such as geospatial techniques are implemented by several geoscientists, globally to acquire suitable sites for the under-surface water and their recharge formulation process. Ashya *et al.*, (2020), studied predicting groundwater recharge potential in Chittagong City of Bangladesh using geospatial techniques and used eight different layers such as drainage density, slope, rainfall/runoff, groundwater level, soil texture, urban stormwater logging depth, land use land cover, and lineament density. Employing methods of reclassification, the thematic layers have been singly placed into five types and named a definite normalized weighted value using AHP. Likewise, slope, geological, geomorphological, hydrogeological, soil type, land use land cover, lineament density, and drainage density layers have been used to prepare the thematic layers and give the significant weightage value to each layer using GIS to find out the suitable sites for the groundwater recharge (Kaliraj *et al.*, 2014; Rahimi *et al.*, 2014; Mahmoud, 2014; Agrawal & Garg, 2016; Kirubakaran *et al.*, 2016; Sarkawat *et al.*, 2018).

This study has the main motive of developing the skeleton using geospatial techniques to find out the potential sites for the artificial recharge ponds and also to generate the suitability map accordingly. Using the GIS and RS layers, together with results in producing the final products with outrageous validation. In addition, this research also resembles the application of the AHP method in identifying the suitable site for the artificial recharge of the Ratu Khola watershed, in central Nepal.

Study Area

The Ratu Khola watershed is located at the boundary between the Mahottari and Dhanusha districts of Province-2 and the Sindhuli district of Bagmati Province. The watershed is located between 26°52'14" N to 27°08'21" N latitudes and 85°51'19" E to 85°58'47" E longitudes and covers an area of 205 sq. km. (Fig. 1). The upper reaches of the Ratu Khola watershed lie in a subtropical climate. The temperature recorded in that area exceeds 30°C in summer and 15°C to 20°C in winter. Geologically, the study area can be mapped into two units- the northern unit as the Siwalik and the southern unit as the Indo-Gangetic Plains. The major stream of the study area is Ratu Khola and it originated from the Siwalik region. The overall drainage system of the area shows a dendritic pattern. The watershed experiences flash floods during the monsoon period though the river channel remains almost dry in the winter season.

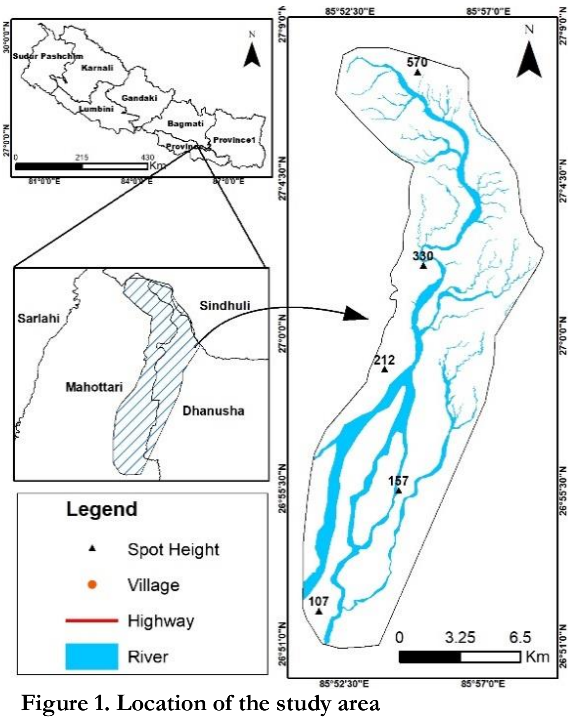

Figure 1. Location of the study area

Geological Setting

Geologically, the Ratu Khola watershed covers the Siwalik Zone in the northern section and the Indo-Gangetic Plain (IGP) in the southern section (Fig. 2). The Main Frontal Thrust (MFT) has demarcated the Siwalik Zone and IGP. The MFT can be traced in the field based on the sharp change in the topography, lithology, and river valley morphology. The MFT is equivalent to the Bardibas Thrust (BT) in this area (Almeida *et al.*, 2018; Shrestha *et al.*, 2019). The rocks of the Siwalik Group can be categorized into two geological units based on lithological similarity and stratigraphic position. The units are the Middle Siwalik and the Upper Siwalik from stratigraphic older to younger respectively. The Patu Thrust has brought the oldest rock sequence (Middle Siwalik) over the younger rock sequence (Upper Siwalik) (Fig. 2, Fig. 3a, 3b, and 3c). The field evidence of the Patu Thrust comprises the fault breccia, slickensides, and other geomorphic features and it has extended longitudinally in the study area. The Middle Siwalik comprises a dominant succession of sandstone with occasional bands of mudstone, and siltstone in various proportions. The sandstone beds are greenish-grey, medium-to coarse-grained, medium-to thick bedded alternating with thin beds of mudstone and siltstone. The parallel and cross-beds are present in the sandstone beds. In general, the rocks are fairly calcareous in nature and have developed sand lenses and sand balls within the beds and the beds are trending NW-SE with moderate dipping (25°-60°) towards NE.

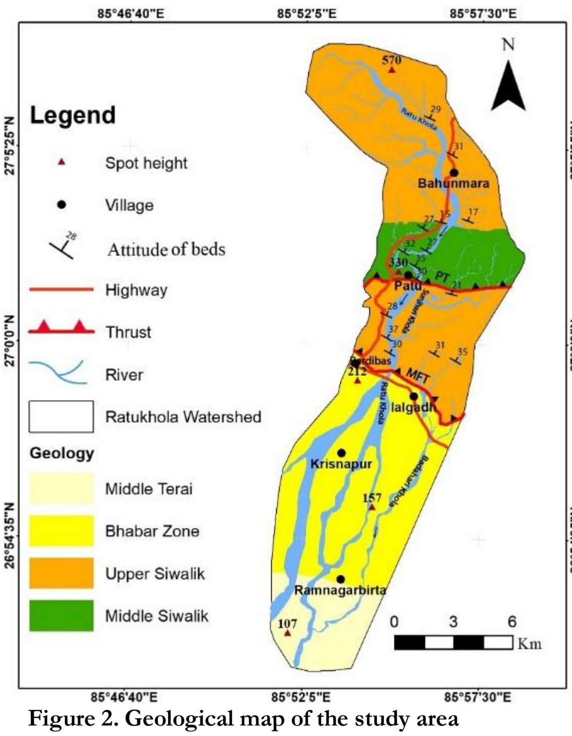

Figure 2. Geological map of the study area

The Upper Siwalik succession is well-exposed at the river section of Ratu Khola at the right bank, 200 m upstream from the Ratu Khola near Bardibas (Fig.3d). The exposure comprises clast supported (pebble to cobble), loosely cemented, grey to yellowish, thick beds of conglomerates interbedded with medium-to-coarse grained, grey to pale yellow, thin-to-medium beds of sandstone and thin beds of mudstones and siltstones. Several cycles of graded beddings are found within this succession. Moving towards the south, IGP covers the study area, and this area can be further classified into two units namely the Bhabar zone and the Middle Terai. These units can be categorized depending on their sediment size, topography break, and river channel morphology. There are coarse materials in the Bhabar zone as compared with the Middle Terai. The Bhabar zone lies immediately south of the MFT (Fig. 3b), and the Middle Terai lies towards the south of the Bhabar area. The sudden decrease in the gradient of the rivers flowing across the Siwalik hill has deposited coarse, unconsolidated sediments like gravel, cobbles, and boulders at the base of the Siwalik hills which has formed larger alluvial fans in this area. The alluvial fans have a gradient of 4° to 5°. The angle is low in the southern part and gradually increases at the foothills. After crossing the river from the Bhabar zone to the Middle Terai, the river has changed from a braided system to a meandering system in the area.

MATERIAL AND METHODS

The geospatial techniques are considered useful to investigate the suitable sites for artificial recharge and to recommend sustainable groundwater management methods (Saraf & Choudhary, 1998; Mandal & Singh, 2004; Ghayaumian *et al.*, 2007; Yeh *et al.*, 2009; Rahman *et al.*, 2013; Masciopinto, 2013). The AHP method is applied to assess the suitable sites for the artificial recharge region in this study and the method has used different thematic layers like land use land cover, slope, geology, drainage density, water table, soil type, and geomorphology (Ghayoumian *et al.*, 2005; Ravi-Shankar & Mohan, 2005; Chowdhury *et al.*, 2010; Sargaonkar *et al.*, 2011; Mahdavi *et al.*, 2013). Slope and drainage density maps were arranged using the elevation model methods termed as Digital Elevation Model (DEM 30*30) whereas the land use land cover map has arranged from the visual interpretation with updated field data. The geomorphological, soil, and geological map are prepared during the fieldwork.

The inventory survey has been carried out to collect the available secondary data of the bore-hole log for preparing the water table map. The detailed procedure of the work is shown in (Fig. 4). Once creating the primary and secondary data of thematic layers, the AHP system registers a scale of crucial pertinent from 1 to 9 during a pairwise comparison of parameters (Satty & Vargas, 2012). The value 1 is assigned for equally crucial, 3 for moderately crucial, 5 for strongly crucial, 7 for very strongly crucial, and 9 value is assigned for extremely crucial, and reciprocal values are assigned for inverse comparison (Satty,1992). Thus, the rating was allocated to their crucial recharge to groundwater, literature reviews, and expert feedback (Table 1).

Satty (1990) estimated the Suitable Site for Artificial Recharge to Groundwater (SSARGW) by using seven thematic layers and preparing a pair-wise comparison matrix from the given rating for the individual layers and following the AHP procedure. Further, a normalized pair-wise comparison matrix has been prepared through the eigenvector method. The accuracy of the pair-wise comparison matrix has been evaluated through the consistency ratio as:

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

Where, λ_{max} is principal eigenvalue which represents number of factors used while the Consistency Ratio (CR) is calculated as follows.

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

Where, CR= Consistency Ratio

CI= Consistency Index

RI= Random Consistency Index

Where RI is the ratio index which depends on 'n' values (Table 2).

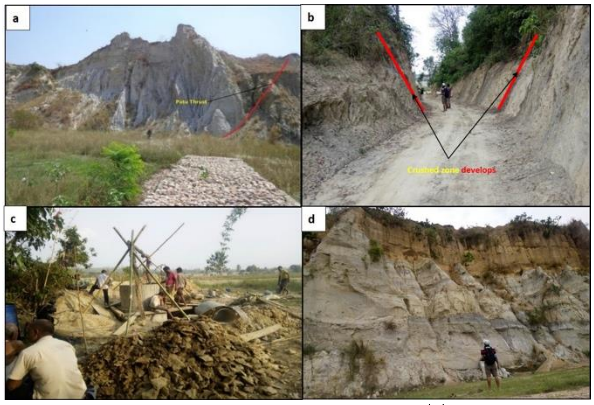

Figure 3. (a). Crushed zone due to Patu Thrust at Ratu Khola section, (b). Crushed zone due to the MFT at the right bank of Ratu Khola, near Bardibas, (c). Inventory survey of under construction well at Krisnapaur area and (d). Exposure of the Upper Siwalik at Ratu Khola section, near Bardibas

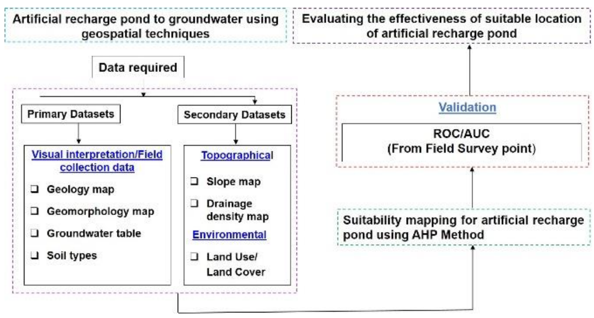

Figure 4. Methodological flow chart used in this study

The CR value should be less than 10% after that model will be accepted otherwise correction is necessary for the given weight (Satty, 1990; 2004; Dalalah *et al.*, 2010; Agarwal *et al.*, 2013; Kumar *et al.*, 2014). The outcome of a suitable site for an artificial recharge pond to groundwater map was validated from the field survey data (based on the marked GPS point on the suitable and unsuitable place for an artificial recharge pond, inside the study area). The field survey data were overlaid on the suitability map of the artificial recharge pond. The Receiver Operating Characteristic (ROC) curve and Area Under Curve (AUC) were used to check the accuracy of the SSARGW map of the study area (Kumar *et al.*, 2014; Sarkawt *et al.*, 2018).

Table 1. Assignment of weight for the influence factor layers classes of individual parameter

S. N.	Parameters	Weight (%)	Classes	Wc (%)	Eigenvalue (λ_{max})	CR (%)
1	Land use	39.00	Barren land	50	5.242	5.4
			Agriculture	26		
			Forest	13		
			Riverbed	7		
			Build up area	4		
			Total	100.00		
2	Slope	19.00	>3	51	5.242	5.4
			3-5	26		
			5-10	13		
			10-15	7		
			>15	3		
			Total	100.00		
3	Water table	18.00	>24	51	5.242	5.4
			24-19	26		
			19-14	13		
			14-9	7		
			<9	3		
			Total	100.00		
4	Soil type	10.00	GM-GC	50	5.242	5.4
			GP	26		
			GC	14		
			ML	7		
			SM-SC	3		
			Total	100.00		
5	Geology	8.00	Middle Terai	13	4.142	5.3
			Bhabar zone	57		
			Upper Siwalik	24		
			Middle Siwalik	6		
			Total	100.00		
6	Geomorphology	4.00	Alluvial fan	47	5.181	4
			Inner river valley	20		
			Alluvial plains	10		
			Siwalik hill	20		
			Younger alluvial plains	3		
			Total	100.00		
7	Drainage density	2.00	0-0.21	51	5.242	5.4
			0.21-0.42	26		
			0.42-0.63	13		
			0.63-0.84	7		
			>84	3		
			Total	100.00		
	Total sum	100.00		700.00		

Table 2. Saaty's ratio index for different values of n

Random Index (RI)										
N	1	2	3	4	5	6	7	8	9	10
R.I. Value	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

RESULTS

Geology/Lithology

The geological map of the Ratu Khola watershed covers an area of about 205.32 square km. The name of the lithological units is adapted from the Department of Mines and Geology (Pradhan *et al.*, 2004) and the geological map was adopted from Sah *et al.* (2000). The rock succession of the study can be mapped under the four lithological units as represented by the Middle Siwalik, the Upper Siwalik, the Bhabar zone, and the Middle Terai from the stratigraphic older to younger respectively (Fig.5). The lithological succession of the Middle Siwalik and the Upper Siwalik is comparable with the lower to the middle part of the Amlekhganj Formation and the Churia Khola Formation of the Hetauda area of central Nepal respectively (Sah *et al.*, 2000). The Upper Siwalik covers a maximum area in the upper part of the Ratu Khola watershed.

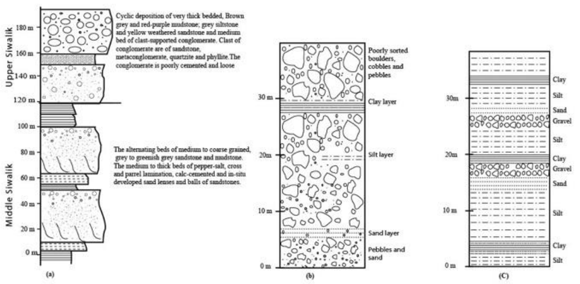

Figure 5. The general vertical lithological distribution in Ratu Khola Watershed (a). Siwalik Zone, (b). Bhabar zone and (c). Middle Terai

Geomorphology

The study area can broadly be divided into two parts: the hilly region of the Siwalik range and the flat land of the Bhabar and Terai regions. The geomorphological features have been found to control the water table and the groundwater recharge processes. By observing the study area under the Landsat images as well as a topographical map; the nature of the land and its distribution can be classified into different geomorphic units. The Ratu Khola watershed can be classified into five geomorphic units based on topography, geology, and sediment distribution. These units were mapped as the Siwalik hills, inner river valley, alluvial fan, alluvial plains, and younger alluvial plains (Fig.6). The northern part of the area like Bahunmara and Patu villages lies on hilly terrain while the places like Kishan Pur and Ramnagarbirta lies on wide flat land. The maximum height of the hilly terrain ranges up to 570 m while the flat lands in the southern parts range with an elevation of 107 m.

Soil Type

The soil properties play a vital role in recharging the groundwater. The soil formation is directly controlled by the rock types, topography, landforms, climate, and river system. The Ratu Khola watershed comprises five different soil types; GC, SP, GP, GM-GC, and SM-SC which have covered areas of 35%, 9%, 17%, 29%, and 10% respectively. These soils are classified based on field identification (field tests include texture, grain size, and plasticity) and laboratory analysis using standard sieve sizes following the Unified Soil Classification System (USCS) (Fig. 7). The notations used in the classification are GC: Clayey gravels, gravel, gravel-sand-clay mixtures, SP: Poorly graded sands, gravelly sands, little or no fines, GP: Poorly graded gravels, gravel-sand mixtures, little or no fines, GM-GC: Silty gravels, gravel-sand-silt mixtures, and clayey gravels, gravel-sand-clay mixtures, SM-SC: Silty sands, sand-silt mixtures; clayey sands, sand-clay mixtures.

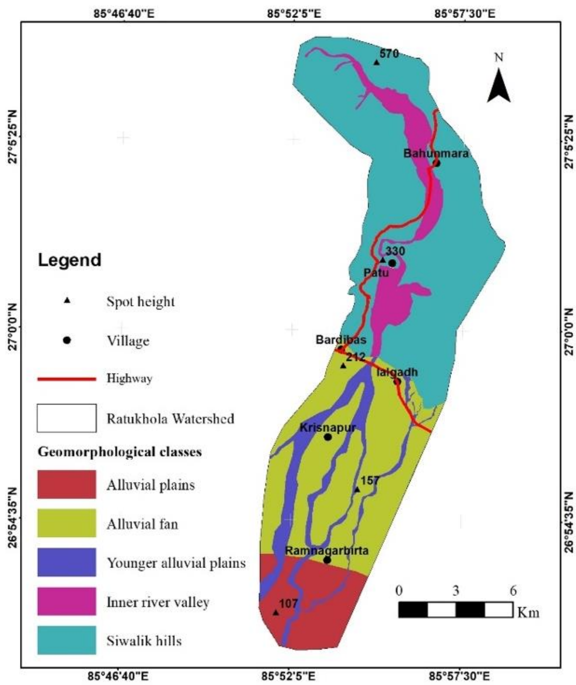

Figure 6. Geomorphology map of the study area

Slope (gradient)

The slope angle of the ground surface which controls the groundwater recharge is one of the important factors in determining the water holding capacity of an area (Razandi *et al.*, 2015). The slope controls the rate of water infiltration and indirectly governs the flow mechanism of the groundwater and understanding the slope helps in knowing the clout in the recharging-discharging phenomena of water (Aluko & Igwe., 2017). The higher the slope, the lower will be the recharge. Thus, the slope controls the recharge of the groundwater (Mandal *et al.*, 2016). The slope of the present study is differentiated into five classes based on the slope angle using GIS (Fig. 8). The northern part of the area has the highest slope (greater than 15) angle and gradually decreases towards the south.

Water Table

An inventory survey of 20 dug wells, 3 tube wells, and 5 deep tube wells was carried out in different places in the study area (Fig.9). On the basis of the survey, it is found that the maximum and the minimum depth of the water table in the area are 27 m and 2 m respectively. The water table depth of the whole area has been classified into five non-similar classes (Fig. 9). The central part of the area- which lies in the thick alluvial fan with coarse, permeable sediments, has a very deep-water table whereas, the southernmost part of the area- which lies in the alluvial plains with fine sediments, has a shallow water table. The areas lying above the deep-water table are one of the favorite sites for artificial recharge ponds if the drawdown was controlled by the over-pumping. The area with the deeper water table gives a high score value while evaluating different parameters for the artificial groundwater recharge (Duraiswami *et al.*, 2009).

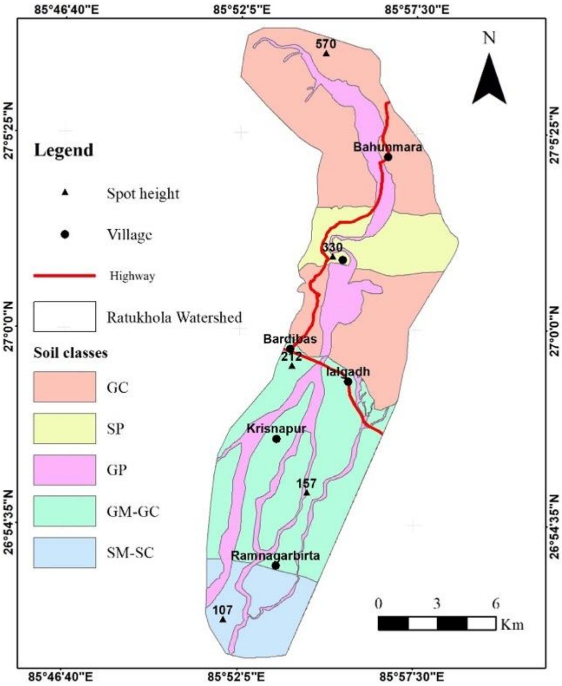

Figure 7. Soil-type map of the study area

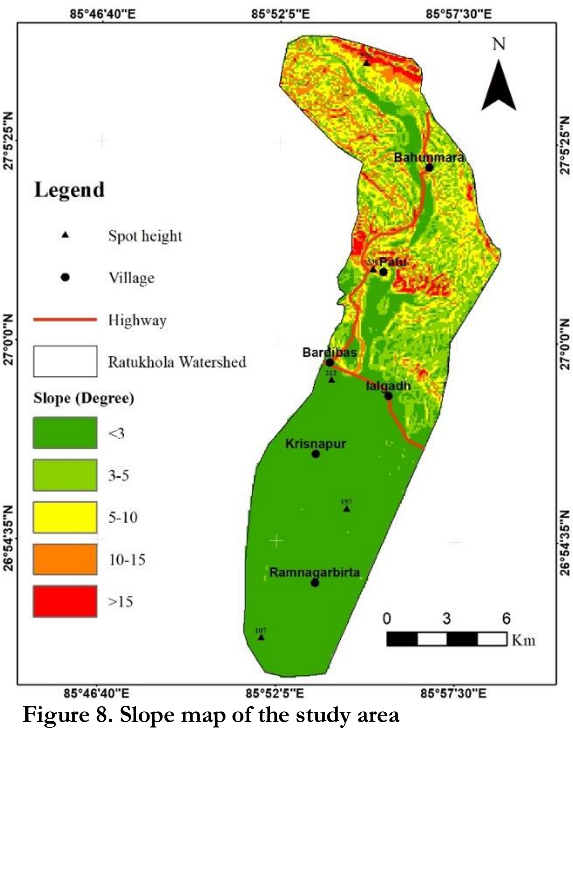

Figure 8. Slope map of the study area

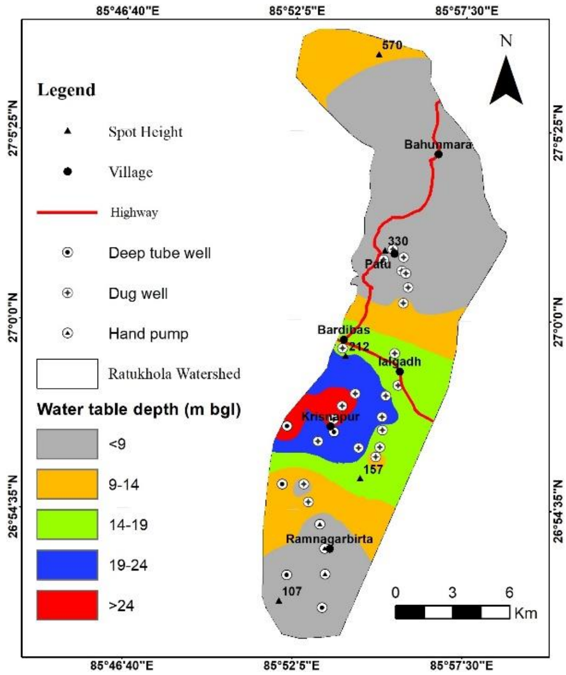

Figure 9. Water table map of the study area

Drainage Density (DD)

According to Rahimi *et al.* (2014), the drainage density is termed as the total length of rivers and streams in a fixed belt per unit area to the area of the same belt. The distance between two streams can also be determined by the drainage density (Agrawal and Garg., 2016). The drainage density of a certain area is governed by different factors like the geology of the area, slope angle, infiltration rate, assimilation of the rainwater, and vegetation (Manap *et al.*, 2013). High groundwater recharge is more appropriate in the zone where there is low drainage density (Mandal *et al.*, 2016). In the present study, a drainage density map has been prepared by computing the DEM in GIS. The area is classified into five zones based on drainage density (Fig. 10). The northern part of the area has a high drainage density in comparison to the southern part.

Land Use Land Cover

Using the Landsat images and field methods, land use, and land cover have been well studied. GIS has been used to set up a land use land cover map. The area is delineated into five non-similar categories: agricultural land, barren land, build-up area, forest, and riverbed (Fig. 11). The forest and agricultural area cover the maximum part with 80.45 sq. km. and 74.31 sq. km. respectively. Taking into account, the barren land is the best area for artificially recharging groundwater which covers an area of 23.54 sq. km. (Sarkawat *et al.*, 2018). In this current study, the arrangement of the barren land is observed in the southern part along the distributaries of the Ratu Khola. This barren land is considered suitable for recharge ponds depending on its moderate and gentle slope and permeable materials at the surface and sub-surface horizons.

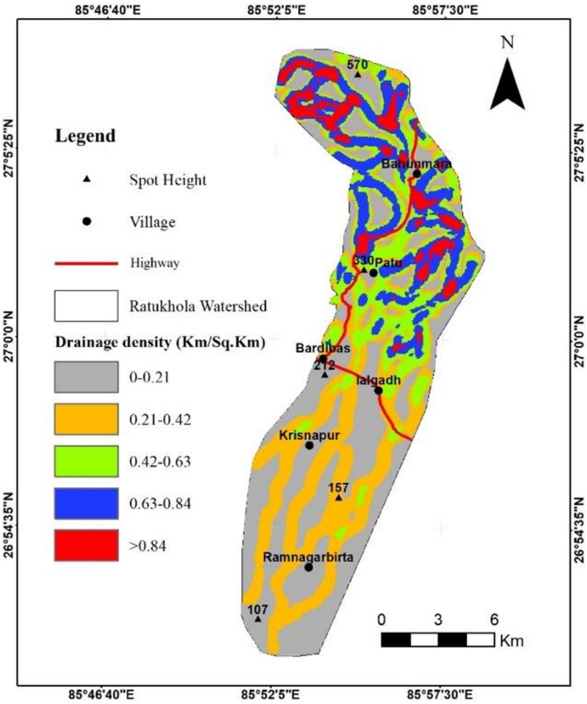

Figure 10. Drainage density of the study area

Suitability Mapping for SSAR using AHP Methods

The different seven thematic layers were prepared and assigned a weight of individual parameters using the AHP method to generate the suitability map in GIS. The suitability map is classified into five classes as the unsuitable area, low suitable area, moderate suitable area, high suitable area, and the most suitable area (Fig. 12). Further, the most suitable area has covered 3% whereas the unsuitable area has covered 34% area within the Ratu Khola watershed. This result shows that areas with an unsuitable and low suitable lie in the northern section of the study. In these areas, there is a steep slope, high drainage density, and shallow depth of water table.

These classes lie in the Siwalik hill, inner valley, and younger alluvial plains. However, the areas with the most suitable and high suitable lie in the central part of the study area where there is a gentle slope (<3°) and low drainage density. Moreover, that area represents an alluvial fan, land with agriculture and barren, the depth of the water table is high and soils with highly permeable (i.e., GM-GC and GP in nature). In the field, the soil depth in the hilly regions is found to range from 0.40 m to 2.0 m while in the flat regions (southern region) the soil depth ranges from 0.50 m to 5.0 m (based on observation wells developed in the study area).

DISCUSSION

The sustainable management of groundwater can only be materialized by delineating the suitable sites for artificially recharging groundwater which reflects in the field outcomes and spatial data sets in the Ratu Khola watershed, as crucial methods. This study has used seven different thematic layers and the result is validated by field survey data. The highly affected to least affected thematic layers are in descending order, land use land covers (39%), slope (19%), water table (18%), soil type (10%), geology (8%), geomorphology (4%) and drainage density (2%). The depth of the water table is found much deeper in the Bhabar zone than in other parts. Similarly, there is not any direct relation with the adverse geological structures like faults/thrusts and regional joins with the depth of groundwater in the region (Fig. 9). Lithology is important to control the depth of groundwater. The areas covered with permeable units in the Bhabar zone are found to be the most suitable recharge zones for groundwater. Many streams while arriving at the Bhabar become dry as it consists of highly permeable coarser sediments like gravel, pebbles, and sands. However, the southern sections of Bhabar have the distribution of finer sediments like sand and silt along with some clay interlayers (Fig. 5). The topography also decreases regularly towards the south. The level of groundwater also increases towards the south. Density and pattern of drainage have the least significance with the depth of groundwater in the present study. Drainage density in the hilly region is mostly found to be controlled by the joints and fractures developed in the rocks and somehow with the differential weathering of rocks due to such structures. Features like joints, fractures, and regional faults and thrusts are observed in the form of lineaments under aerial photos and have fewer effects on the groundwater recharge in the areas. In flat regions, the drainage pattern and density are controlled by topography and Quaternary geomorphic features (Fig. 10). The assigned rank value of individual layers was given from the literature reviews and expert opinions. The analysis was performed using the AHP method by creating a pairwise matrix.

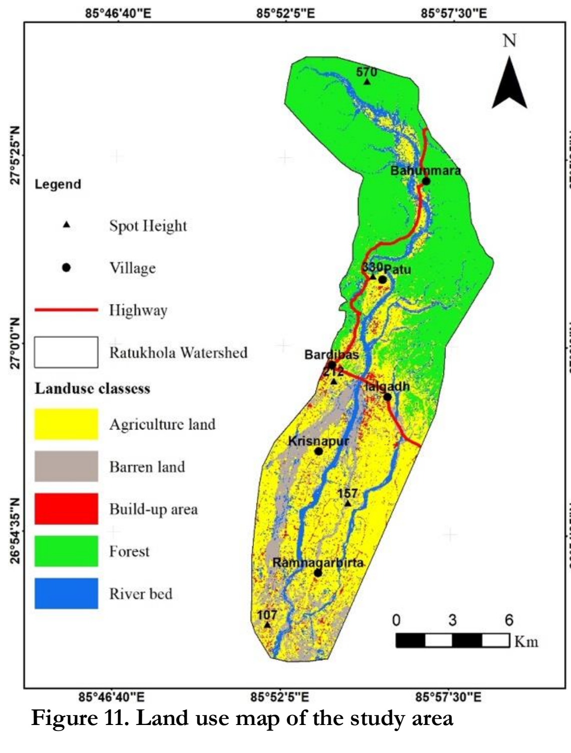

Figure 11. Land use map of the study area

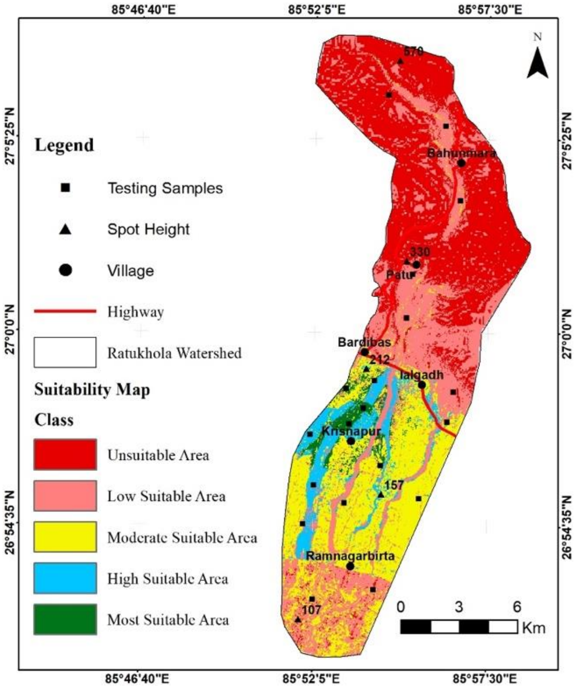

Figure 12. Suitability map of artificial recharge sites in the present study area

The raster data has been generated from the factors that influence the suitability of an area for the artificial recharge ponds, such as geology, geomorphology land use, slope, drainage density, and soil type. The suitability map has been prepared using a GIS and a raster calculator, which is a tool that allows performing a mathematical operation on raster data. Finally, the suitability map has been developed, which shows the relatively suitable sites for the artificial recharge of groundwater. The suitability map has been divided into five classes: most suitable area, highly suitable area, moderately suitable area, low suitable area, and unsuitable area. The most suitable area lies in the central and central-western sections of the study area. Geologically and geo-morphologically that area represents the Bhabar zone and the alluvial fans respectively. This area is comprised of a thick sequence of unconsolidated loose sediments which allows a high rate of water infiltration and is suitable for developing artificial recharge sites. The most moderately suitable area represents the low-angle slope, barren agricultural land, and deep-water table. The steep ground with high drainage density like the northern sections of the Siwalik hill where water that falls on the surface easily gets converted to surface run-off due to higher gradient-reflects as unsuitable for the artificial recharging to groundwater. The Findings of this research are supported by other similar research papers adopted in similar conditions (Neshat *et al.*, 2014; Taheri *et al.*, 2014; Jenifer & Jha., 2017; Mahmood *et al.*, 2017; Sarkawt *et al.*, 2018).

The suitability maps of the artificial recharge pond were validated using the ROC/AUC curve. The ROC/AUC curve is plotted between the True Positive Rate (TPR) and False Positive Rate (FPR) where TPR (field data collected from the field survey) and FPR (raster model of artificial recharge pond) are prepared from the AHP model. The FPR is plotted on the x-axis and the TPR is plotted on the y-axis. The accuracy of ROC/AUC for the suitability analysis of artificial recharge to groundwater is 82.3% (Fig. 13). The most preferable area lies on the barren land.

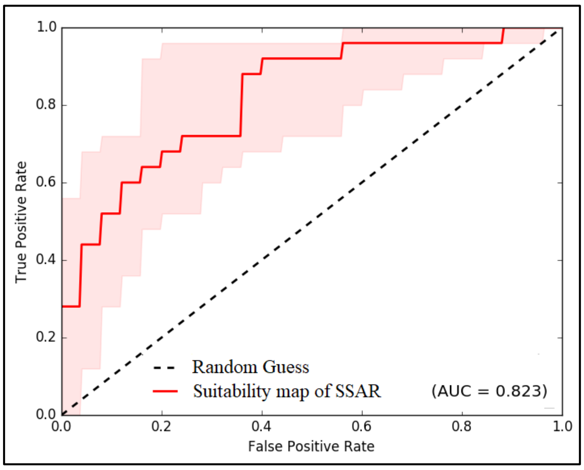

Figure 13. Validation of suitability map of artificial recharge pond of the study area using ROC/AUC

CONCLUSIONS

The present study perceives the SSARGW in the Ratu Khola watershed by applying Remote Sensing and GIS techniques. The suitability map for artificial recharge ponds was created using a GIS and raster calculator based on various factors that impact the suitability of an area for this purpose. These factors included geology, geomorphology, land use, slope, drainage density, and soil type, which were all represented as raster data in the GIS. The raster calculator was used to perform mathematical operations in this study to generate a suitability score for each location, which was then used to create the suitability map. The map shows the relative suitability of different areas for the construction of artificial recharge ponds. Five classes of suitability areas are divided as the most suitable area, high suitable area, moderate suitable area, low suitable area, and unsuitable area and these classes have covered areas as 3%, 7%, 24%, 32%, and 34% respectively. The central part of the area of study, the most suitable area, represents the thick succession of coarser materials and has a high infiltration rate, deep water table depth, and gentle topography. These areas are barren and can be utilized for recharging groundwater by the floor spreading method. The unsuitable area is located in the northern part of the Ratu Khola watershed and that area is covered by dense forest and steep slope landforms with high drainage density.

ACKNOWLEDGEMENTS

This work was partly financed by the G-to-G project between the Central Department of Geology (CDG), Tribhuvan University, and the President Chure-Tarai Madesh Conservation Development Board (PCTMCDB). The title of the project was "Aquifer mapping and sensitivity assessment of the Chure region of Nepal-2020. We are grateful to the CDG and PCTMCDB for the final support. Mr. Yagya Murti Aryal has also received partial financial support as a research grant from the Nepal Academy of Science and Technology (NAST), Nepal to carry out this research.

AUTHOR CONTRIBUTIONS

All the authors have made significant contributions to preparing this research article. First, Dr. Kabi Raj Paudyal and Mr. Yagya Murti Aryal made the study concept and design. Mr. Pranjal Poudel accompanied the field work with Yagya Murti Aryal for three weeks and contributed a lot to field data collection. Dr. Kabi Raj Paudyal took verification traverses in the field with the team members. Mr. Kutubuddin Ansari analyzed the field data and provided technical support to digitize the maps. The first draft of the manuscript was written by Yagya Murti Aryal and all authors contributed to making the draft form of the manuscript into the final version. Finally, all the authors have contributed to making corrections as per the suggestion of reviewers.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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