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RESEARCH ARTICLE

Mountain hydrogeology and influence of active fault: A study of the Bhimgethi-Devisthan section in Western Nepal

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ABSTRACT

Mountain springs are the sole dependable water sources in the hilly region for peoples' daily needs. The current study examines the hydro-geological scenario in the area of the active fault zone. Through fieldwork and questionnaire survey, the study analyzes the characteristics of natural mountain springs in relation to geology, slope, aspect, type of deposit, spring type, discharge rate, and electrical conductivity. All the springs surveyed are perennial. About 71 % of springs are fracture and fault-dominated, indicating that the fractured and deformed rock plays a significant role in controlling the groundwater occurrence. Current study has shown that discharge of springs near the fault zone has decreased considerably over the last decade, with some springs shifting to lower elevation due to landslides triggered by shearing. Fault zones can act as either a conduit or a barrier to groundwater flow. The numerical analysis of fault zone architecture and permeability structure reveals a conduit-barrier fluid flow system. The damage zone, constituting of fractures, facilitates for rainwater recharge, while the core functions as a barrier, particularly in the southern half of the study area. Additionally, the findings related to electrical conductivity further support the presence of a barrier-type fluid flow system in the southern part along the fault core. However, the springs associated with silicified breccia indicate a conduit flow system in the northern section. Overall, the fault zone significantly influences the origin, discharge rate, and flow direction of spring sources across the study area.

Keywords: ***Mountain Hydrogeology, Natural Springs, Active Fault, Fracture Aquifer***

INTRODUCTION

The Mountain aquifer system in the hilly region of Nepal is essential to understanding the water resources of the region to overcome the ever-increasing water demand. Spring is the major source of water supply in the hills and mountains of Nepal generally used for domestic and agricultural purposes. It is the precious access to safe drinking water that occurs when groundwater naturally flows from geo-materials onto the Earth's surface or into a body of surface water. It has dynamic movement that varies considerably concerning variations in the condition of climate, topography, geology, and geomorphology (Pitts and Alfaro, 2001; Todd and Mays, 2005). Spring sources in the Mid-hill region of Nepal have been depleted and even dried due to the combination of bio-physical (e.g. climate changeability, changes in land use pattern) and socioeconomic (e.g. spring maintenance) variables (ICIMOD, 2015).

Bari Gad Fault is a strike-slip active fault in Lower Himalaya which trends approximately northwest-southeast, parallel to Badi Gad Khola and Nisi Khola (Nakata, 1882; Nakata, 1889). Landform present in the area shows 15 m and 240 m of vertical and horizontal slip respectively. Arita et al. (1984) and Sakai (1985) have defined this fault as Barigad Kaligandaki Fault (BKF) after observing its extension along Kaligadaki River in southeast. The active nature of the fault triggers numbers of large landslides along the fault zone (Timilsina and Paudyal, 2018). Lamsal et al. (2023) reviewed the stratigraphy of the Jajarkot thrust sheet and mentioned the fact that the actual boundary of the thrust sheet is not well defined. Bhusal and Gyawali (2017) have worked on springs within the catchment of the Badi Gad Khola focused on water quality of those springs. However, there is a lack of research on how active fault impacts mountain springs. To fulfill this gap, this study examines the hydro-geological scenario within the active fault zone.

It is well known that structural features do affect groundwater movement. An active or potentially active fault largely governs the majority of groundwater in bedrock as this zone can act as either a conduit or barrier to groundwater flow (Barton et al., 1995; Gudmundsson, 2000; Gudmundsson et al., 2001; Mayer and Sharp, 1998). Since springs are widespread along fault zones, active fault zones collect and transmit large amounts of groundwater, typically under considerable fluid pressure (Curewitz and Karson, 1997; Léonardi et al., 1998; Muir-Wood and King, 1993). Additionally, the trends of faults in the local hydraulic gradients can greatly affect groundwater flow (Phillips, 1991). The fault pattern and associated stress concentration, the trend of the fault plane zone about that of the groundwater flow, and the changing permeability and size of the resulting fault slip plane are the considerable parameters that affect the flow of groundwater (Gudmundsson, 2000).

Study area

The study area lies in the Gulmi and Baglung district of western Nepal about 350 km west of Kathmandu Valley (Fig. 1). It belongs to the hilly region experiencing sub-tropical to alpine climatic conditions with altitudes extends from 820 meters to 2425 meters above sea level. The overall drainage system is dendritic and makes deep V-shaped valleys. Major river systems include Badigad Khola, Darlin Khola, Kut Khola and Nisi Khola.

Fig. 1: Political map of Nepal showing location area (white polygon) within the Gulmi and Baglung district.

OBJECTIVES

The research work focuses on the scenario of the hydro-geological condition along the Badi Gad fault, an active fault of the Lesser Himalayan region. The specific objectives are as follows:

- To characterize the springs from various aspects.
- To access the interrelation between fault zone and mountain springs.

METHODOLOGY

The methods that were adopted to achieve the objectives of the research can be broadly classified into three sections: desk study, fieldwork, data interpretation and analysis. Firstly, relevant literature, research journals, and maps from different sources were reviewed. During the field traverse the geological data were collected and the fault zone was thoroughly investigated throughout the study area to prepare the geological map and evaluate the architecture and permeability condition of the rocks of the region. The evidence of active fault was gathered through a detailed field investigation. Special efforts were focused on clarifying the nature of active faulting and its impact on various aspects of groundwater resources. Satellite images were used to determine well exposed localities of the fault zone and eight localities were verified from the field study for measuring the fault core and damage zone width. For this measurement, a vertical traverse of about 700 m was made in each location to cover the well exposed region of the fault zone.

Spring inventory was a fundamental part of the research as it provides data on groundwater sources and their distribution (Fig. 2 a and b). The spring sources and their distribution were evaluated from the questionnaire survey. With the cooperation of local people, the spring sources were visited and the source data were collected, recording the information using a designed inventory sheet which includes the name of the spring, an attitude of bedrock (if present), soil types, types of spring, water discharge, land use of a surrounding area, the shifting case of springs and variation in water volume within the last decade. The discharge rate of springs was measured by the volumetric method with the help of a bucket and stopwatch during the field.

Fig. 2: Photographs of spring sources a) Fault/shear zone spring at Bhimgethi (GPS: 00420437E, 03127705N). b) Measuring the electrical conductivity of spring water at the Huldi/Chhis village (GPS: 00413611E, 03134816N).

RESULTS

Geological Setting

Geologically, the study area is dominantly characterized by low-grade meta-sedimentary units of the Nawakot Group and this succession is overlain by the metamorphic crystalline rocks separated by the Mahabharat Thrust as described in central Nepal (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). These crystalline rocks are equivalent to the rocks of the Kahun Klippe (Paudyal and Paudel, 2013) (Fig. 3).

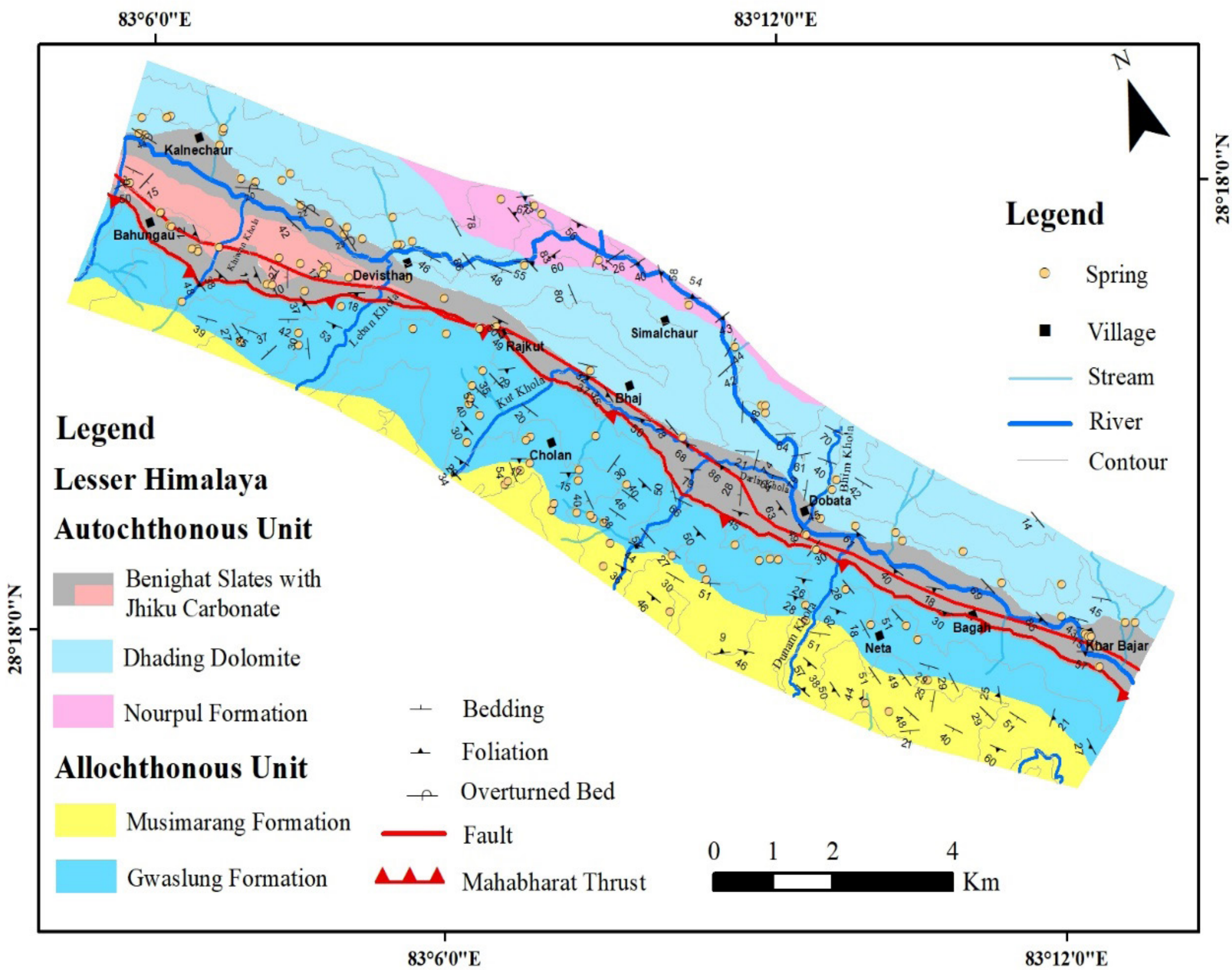

Fig. 3: Geological map of the study area with distribution of springs.

The Nawakot Group in the mapped region include the Nourpul Formation, Dhading Dolomite, and Benighat Slates (DMG, 2003). The stratigraphy of this group is a extension of the rock strata defined by Timilsina and Paudyal (2018), and Gaire and Paudyal (2021) from adjacent area in the east. The Nourpul Formation is exposed to the northeast section of the study area by making assorted succession comprising fine- to medium-grained, thin- to thick-bedded metasandstone, white to grey quartzites inter-bedded with thinly laminated phyllites and slates (Fig. 4a). The ridge forming Dhading Dolomite consists of monotonous, massive to highly fractured and folded, dense to fine crystalline stromatolitic, siliceous and cherty dolomite with grey phyllite partings, occasionally found in its basal portion (Fig. 4b). The Benighat Slates comprise the thinly bedded, black ferruginous slates with occasional beds of dolomites and limestones (Fig. 4c). The Jhiku beds are also exposed in the northwest section of the study area within this unit and are characterized by thin-bedded, siliceous dolomite inter-bedded with slates and some siliceous limestone.

The transported thrust sheet sharply overlain on rocks of the Nawakot Group by the Mahabharat Thrust. This rock succession is lithologically divided into two different units in the study area which are correlable with the Gwaslung Formation and the Musimarang Formation from the Kahun Klippe, eastern part of the present study area (Paudyal and Paudel, 2013). Fine-to-medium-grained, platy to thin-bedded, grey to bluish-colored, siliceous, dolomitic marble represents the Gwaslung Formation (Fig. 4d). This unit is transitionally underlain by the younger Musimarang Formation which is distributed in the southern section of the study area. This younger Musimarang Formation consists of white to dirty-white, platy-to-medium-bedded quartzite intercalated with well-foliated, quartz and mica schist (Fig. 4e).

The black ferruginous slates of the Benighat Slates appear to be heavily crushed and converted to fault gauges/breccia because of the movement of fault within this unit (Fig. 5a and b). Additionally, the shear sense indicating features and outcrop scale faults shows the movement along the strike which defines fault plane propagation as strike-slip fault. Number of asymmetrical boudinage and multiple folds are frequently developed within the fault zone due to the fault movement (Fig. 5c and d).

Fig. 4. (a) The mixed lithology of the Nourpul Formation along road section towards Devisthan from Burtibang (GPS: 00416803E, 03134916N). (b) The monotonous sequence of the Dhading Dolomite along the left bank of Nisi Khola section at Kalnechaur (GPS: 00411148E, 03138050N). (c) Dark ferruginous slate of the Benighat Slates exposed at Bhimgethi (GPS: 00419414E, 03128502N). (d) The outcrop of dolomitic marble with schist partings of the Gwaslung Formation at the Cholan village. (GPS: 00416156E, 03130578N). (e) The alternating quartzite and schist succession of the Musimarang Formation at the Darlin Deurali village (GPS: 00419510E, 03125704N).

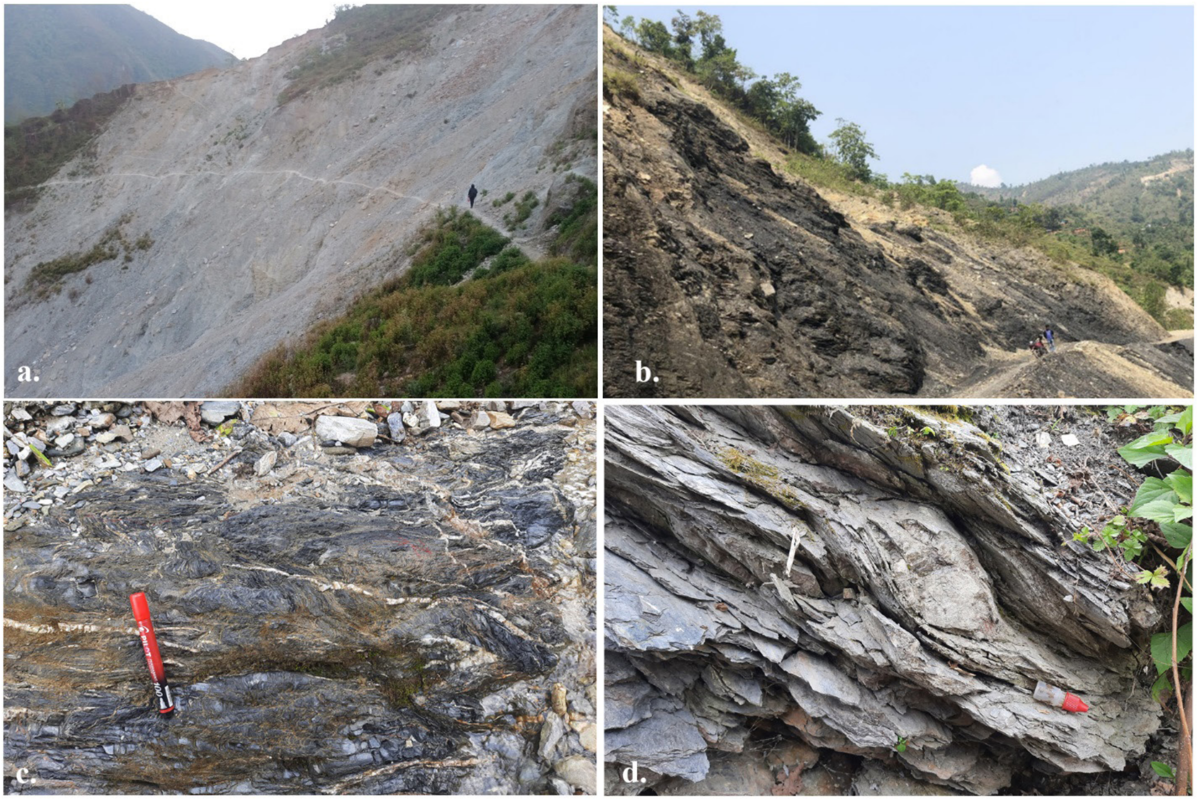

Fig. 5: (a) Outcrop of shear zone induced landslide at the Huldi village (GPS: 00412704E, 03134772N). (b) Outcrop of shear zone in the Benighat Slates at Bhimgethi on the right bank of Badi Gad Khola (GPS: 00420437E, 03127705N). (c) Multiple folding observed in slate of the Benighat Slates at Balghas village (GPS: 00420447E, 03127789N). s(d) Asymmetrical boudinage of quartz vein observed in the Benighat Slates at the Bahungau village (GPS: 00410988E, 03136844N).

Distribution of springs

There was a total of 122 springs identified in the study area, all of which are perennial, and their distribution is presented in Fig. 3. These springs are the major source of water supply for drinking, domestic use and agricultural needs in the area. However, only in some areas, the river water is lifted to a higher altitude for irrigation purposes. Especially during the dry season, the population suffers from severe water shortage since water discharge of existing springs has been significantly reduced than in past years and some perennial springs are going to become seasonal. In some communities, the water shortage has become so bad that residents have had to bring drinking water from about 5 – 10 km away to fulfil their basic water demands.

Generally, the recharge system of a particular area is highly influenced by the rainfall pattern and its variation and ultimately affects the discharge rate of spring in that area. Moreover, the discharge rate also depends on the other factors which can control the topography of the area. The discharge of 122 springs was measured in the pre-monsoon season and categorized based on Meinzer's (1923) classification system. As a result, there are 67 springs of seventh magnitude, 53 springs of sixth magnitude and 1 spring of fifth magnitude (Table 1). Fig. 6a shows the variation of discharge in the study area which ranges from 0.2 lpm to 60 lpm. The discharge of springs on the left bank of Nisi Khola is higher than on the right bank. The landslides and shear zones, frequently observed along the fault line, have a greater effect on the groundwater resource since the discharge of the spring is found to be lower along the fault zone area than in other sections. Also, from the discussion with people, they claim that the spring sources have been relocated downslope owing to landslides and discharge of springs has decreased greatly since the last ten years (Fig. 6b). Thus, water scarcity is worse along the fault zone than elsewhere in the region.

Table 1: Types of spring of the study area based on discharge rate.

Discharge Rate (lps)	Magnitude	No. of springs
1-10	Fifth	1
0.1-1	Sixth	53
0.01-0.1	Seventh	67

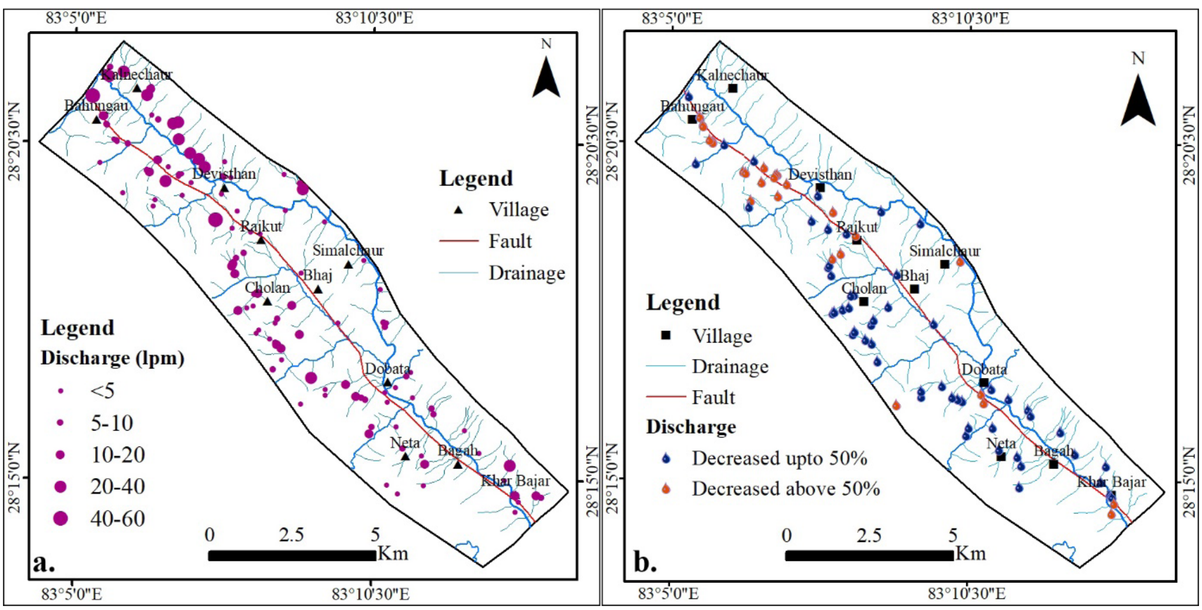

Fig. 6: (a) Distribution of springs by discharge rate. (b) Water volume situation in last ten years.

By inventory of springs, most of the springs are of fracture and fault types, making up 49 % and 22 % respectively; only 12 % are contact springs and 17 % are depression springs (Fig. 7a). But sometimes, a single spring includes two types of spring mechanisms. In terms of slope, 74 % of springs are located on moderate slopes 18 % are on steep slopes and only 8 % are on gentle slopes (Fig. 7b).

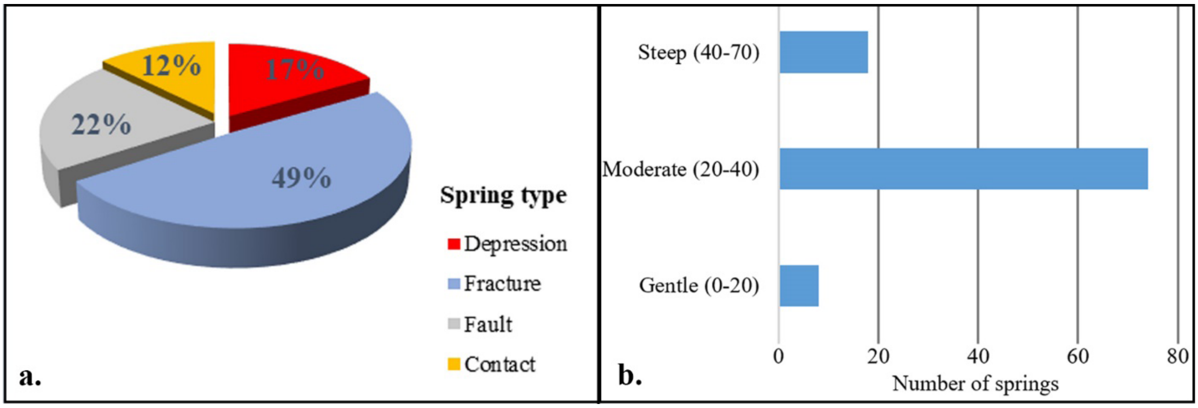

Fig. 7: Distribution of springs based on (a) Spring type (b) Slope.

There are more springs facing southwest than in any other direction (Fig. 8a). In terms of land use around the source of springs, the maximum area is covered by forest region followed by cultivation, barren land, and others. Forest areas make up 55 %; 25 % are in cultivation areas and 20 % are in bushes (Fig. 8b). Mainly three types of deposits have been identified around the spring sources, namely colluvium, residual and rock deposits in which 54 % of springs belong to rock deposits while 25 % are colluvium deposits and 21 % are residual deposits (Fig. 8c). The study shows that the electrical conductivity of springs ranges from 42 µS/cm to 489 µS/cm which was measured in pre-monsoon season (Fig. 2b). The highest value of EC is observed around in southern section whereas it is lowest in the northern section of the study area (Fig. 9a).

Daily precipitation records of three stations were manually checked, compared with surrounding nearby stations, and analyzed to examine the trend of rainfall patterns in the study area over these recent periods. The arithmetic mean method is used to calculate the average annual rainfall of the study area and is found to be 2182 mm. The graph shows a slightly increasing trend of rainfall in the study area (Fig. 9b).

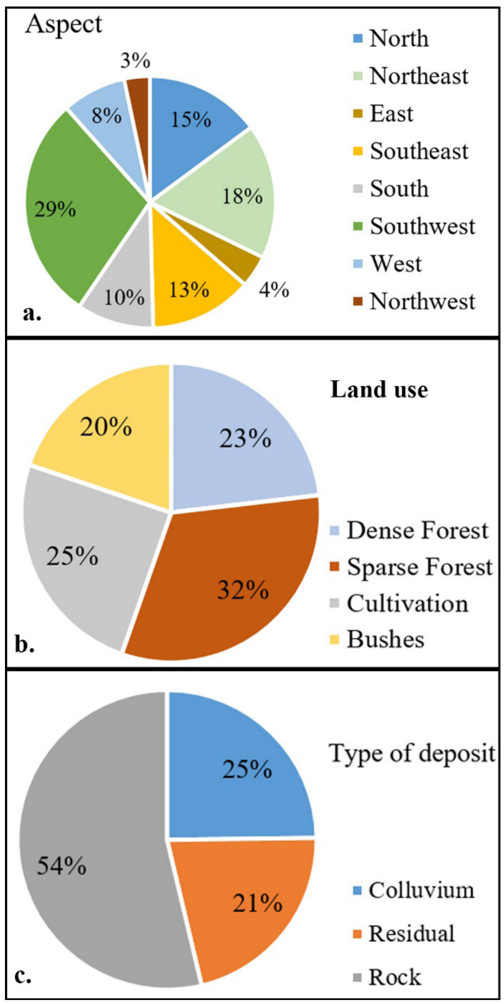

Fig. 8: Distribution of springs based on (a) Aspect (b) Land use and (c) Type of deposit.

Numerical measures of fault zone architecture and permeability structure

Basically, two major components of fault zone include the fault core and damage zone, which are surrounded by the host rock, have different geometrics and structures (Bruhn et al., 1994; Caine et al., 1996; Evans et al., 1997; Gudmundsson et al., 2001). The fault core comprises the fault gauge and breccia with intense deformations based on the host rock composition while damage zone is characterized by the numerous fractures of various sizes, highly folded/crushed bedrock. The width between the fault core and damage zone, which significantly regulates groundwater flow as a barrier or conduit, is revealed by (Caine et al., 1996).

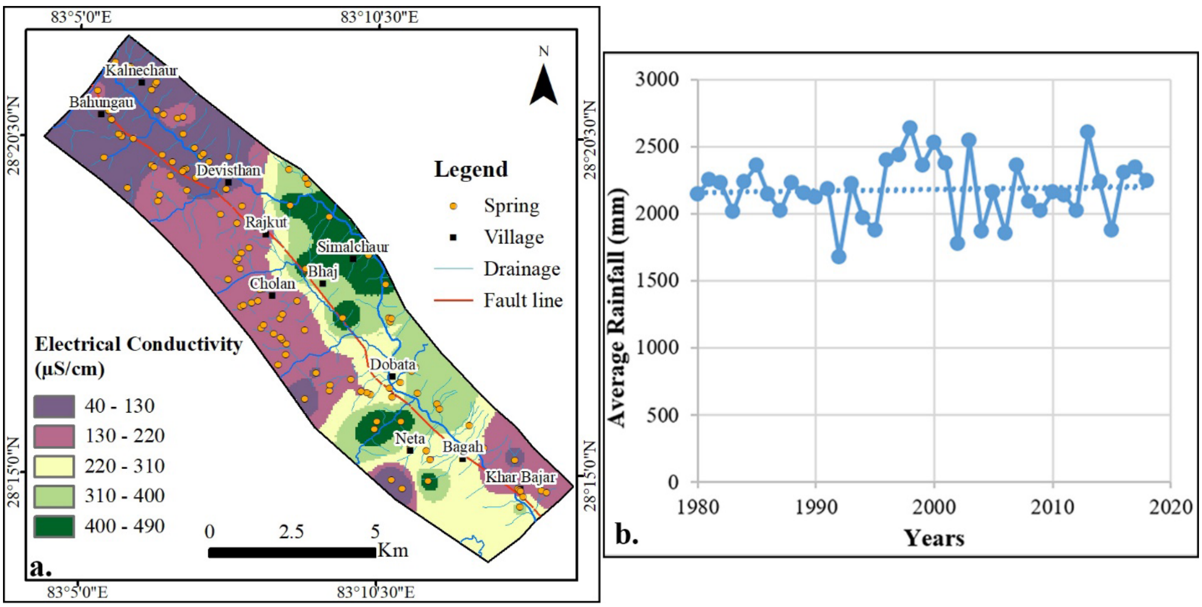

Fig. 9: a) Distribution of electrical conductivity of spring water. b) The average rainfall of the study area (source: Department of the Hydrology and Meteorology, 2022).

Three numerical indices- Fa, Fm, and Fs are used to describe the architecture and permeability structure of fault zones (Caine et al., 1996) and calculated by the given formula:

$$F_a = \frac{damage\ zone\ width}{total\ fault\ zone\ width} = \frac{damage\ zone\ width}{core\ width + damage\ zone\ width} \quad (1)$$

$$F_m = mean\ of\ F_a\ values\ for\ a\ single\ fault\ zone \quad (2)$$

$$F_s = (F_a)_{max} - (F_a)_{min} \quad (3)$$

The relative width of the fault core and damage zone at a chosen area is expressed by the value of Fa, a fault zone architectural index, whose value ranges from 0 to 1. The value near 1 ideally tells that the fault core is absent whereas near 0 tells the damage zone is absent. Fm is the mean value of Fa while Fs gives the spatial variability index.

In the study area, the fault core comprises the fault breccia and fault gauge with extensive deformations whose exposed width ranges from around 20 m to 120 m. Likewise, the damage zone thickness is found to be several hundred meters, thicker along ridge section than river section, and characterized by numerous fractures of various sizes, highly folded and crushed bedrock (Fig. 5a and b). The width of the fault core and damage zone is calculated from eight locations using the equation (1) mentioned above, and found the value of architectural index as Fa = 0.80. The value of Fs = 0.17 is obtained from the maximum and minimum value of Fa using the equation (3) and this obtained small value tells about the uniform homogeneity of fault zone.

DISCUSSION

In the hilly region, groundwater existence and their movement, that is spring distribution in a particular area is closely connected to the topography, rainfall, land use/ land cover type (Agarwal et al., 2012; Negi and Joshi, 2004; Tambe et al., 2012; Todd and Mays, 2005), geomorphology, lithology, slope and lineaments (Sitender and Rajeshwari, 2011). Regarding slope, 74 % of springs emerge through moderate slopes ranging from 200 to 400 while 18 % of springs are from the steep slope (400 - 700). However, only 8 % are from a gentle slope (00 - 200). In comparison with gentle slopes, the residual hills and structural hills have excellent potential for groundwater only if they have high lineament density (Sitender and Rajeshwari, 2011). In addition, the local geology, bedding and joint orientation, water table located above the ground surface and nature of the fracture significantly define the surfacing of springs (Pacheco and Alencoao, 2002; Valdiya and Bartarya, 1989). In the study area, most of the springs (about 71 %) are fracture and fault-dominated because of highly fractured and deformed bedrock, with contact springs and depression springs being less common. Consequently, the fractured and deformed rock plays a significant role in controlling groundwater occurrence.

Spring discharge is highly influenced by changes in rainfall and human activities in the recharge area (Negi and Joshi, 2004; Pant and Rawat, 2015). In the research area, from Fig. 3A, the discharge rate of the spring is varied from place to place. Of the total 122 springs surveyed, 36 % have a consistent water discharge volume, 20 % have experienced a reduction of more than 50 % inn their water volume, and 42 % have seen a decrease within a certain limit over the last decade (Fig. 6b). The carbonate rock shows the highest discharge rate (up to 40 lpm) even on the southwest slope as contact and fracture spring around the Kalnechaur section (GPS: 00411148E, 03138050N) of the study area. However, the middle study section has only fewer spring sources with less discharge (0.2 lpm to 9 lpm) (Fig. 2b). More specifically, spring discharge in the fault zone has considerably declined over the years (Fig. 2), with some springs are shifting to lower elevations due to landslides triggered by shearing. This shows that the springs originated near the fault zone are more vulnerable. Hence, besides the factors like rainfall and human activities, the active fault might have a significant role in decreasing the water discharge of springs.

An active or potentially active fault largely governs the majority of groundwater in bedrock (Barton et al., 1995; Gudmundsson, 2000; Gudmundsson et al., 2001; Mayer and Sharp, 1998). The fault zone behaves either as a conduit, barrier, or conduit-barrier flow system depending on the proportion of the fault core and damage zone structure as well as grain size and fracture permeability (Caine et al., 1996). Furthermore, deformational conditions and chemistry of the fault zone fluid make critical understanding of fault zone architecture and permeability structure. Laboratory permeability examination on oriented samples taken from the field reveals that the core is a low permeability barrier parallel and perpendicular to the fault plane whereas the damage zone is often a high permeability conduit parallel to the fault plane (Chester and Logan, 1986; Caine et al., 1996). Taking eight locations' data from the study area, the architectural index is found to be 0.80. From the field observations, the damage zone appears to be fracture-dominated while the fault core section has clay-rich gauge. However, in the northern section, the fault core lithology is dominated by silicified breccia. As mentioned above, when the width of the fault core is significantly greater than that of the damage zone, the fault zone acts as a barrier to flow. In the study area, the damage zone is highly developed, and the lower permeability of the fault core causes the fault zone to partially impede groundwater flow. Hence, the result from the calculated value of the architectural index and field observations with present lithology, the fault zone architecture is a conduit-barrier fluid flow system. The value of Fs = 0.17, obtained small value suggests about the uniform homogeneity of the fault zone.

Taking into consideration the finding of fault zone architecture and the orientation of bedding, the damage zone allows the recharge of rainwater but the core functions as a barrier in the southern half of the study area which is also valid from the spring sources. Due to this reason, the residents of the Simalchaur, Malarani have faced a water deficit so significantly that they have had to bring drinking water from about 8 – 10 km away. Meanwhile, the spring sources with the silicified breccia suggest the conduit flow system in the northern section. Hence, the geological distribution has greater control over the fault zone characteristics and ultimately spring sources. Besides this, the movement of the fault zone is a major concerning factor which has a considerable effect on spring sources throughout the study area in terms of their origin and discharge rate. Even being a slightly increasing trend of rainfall (Fig. 9b) with a fractured zone, the discharge of the springs has been reduced significantly year after year and this may experience a serious issue in future.

CONCLUSION

Geologically, the study area comprises the units of the Nourpul Formation, Dhading Dolomite and Benighat Slates of the Nawakot Group. And, the crystalline rocks of thrust sheets are classified as the Gwaslung Formation and the Musimarang Formation. The Mahabharat Thrust and Badi Gad Fault are the major regional geological structures observed in the study area. Among the identified springs in the study area, 74 % of springs emerge through moderate slopes ranging from 200 to 400. Most of the springs (about 71 %) are fracture and fault-dominated because of highly fractured and deformed bedrock. The carbonate rock shows the highest discharge rate even on the southwest slope. The result from the calculated value of architectural index and field observations with present lithology, the fault zone architecture is a conduit-barrier fluid flow system. The damage zone, consisting of fractures, facilitates for rainwater recharge, while the core functions as a barrier, particularly in the southern half of the study area. Additionally, the findings related to electrical conductivity (300 μS/cm to 489 μS/cm) further support the presence of a barrier fluid flow system in the southern section which is because of more time for water in rock contact, also suggest the more depth of water with slower movement. There is a high variability of spring discharge between around the fault zone and another region, indicating that the fault zone has many influences on groundwater. The flow rate of springs has been decreasing considerably along the fault zone over the years, with some springs shifting to lower elevation due to shear-induced landslides. The increased mass movement could pose a serious issue for deficiency of spring resources or possibly dried-up springs in future.

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AUTHOR CONTRIBUTIONS

All the authors have made significant contributions to preparing this research article. Asmita Sapkota and Sunil Lamsal have equal contribution for data collection, data analysis and interpretation and final manuscript preparation. Dr. Kabi Raj Paudyal took verification traverses in the field and has the role of manuscript review, data analysis and interpretation. The first draft of the manuscript was written by Asmita Sapkota and all authors contributed to making the final version.

CONFLICT OF INTEREST

The authors declare that the paper has not previously published in another journal/bulletin.

DATA AVAILABILITY STATEMENT

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

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