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RESEARCH ARTICLE

Investigation of springs and their water quality in Tilagupha municipality of Kalikot district, Karnali province, Nepal

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ABSTRACT

The Tilagupha Municipality, located in the Kalikot district of Karnali Province, Nepal, relies entirely on springs as the sole source of water for domestic and irrigation purposes. This study focuses on spring inventory and water quality assessment within the study area. Field observation recorded a total of 25 springs, of which 22 are perennial and 3 seasonal, with contact springs identified as the dominant type; spring discharge was found to be primarily dependent on the rainfall pattern of the area. Physiochemical analysis of 15 spring water samples was carried out for pH, EC, turbidity, sodium, potassium, calcium, magnesium, chloride, ammonia, phosphate, total alkalinity, total hardness, calcium hardness, magnesium hardness, iron, sulphate, and nitrate. Results show that the water quality of all sampled springs lies well within the National Drinking Water Quality Standard (NDWQS, 2079), and the computed Water Quality Index (WQI) classifies all springs as having good water quality.

Keywords: ***Spring, inventory, water quality, water quality index***

INTRODUCTION

Springs constitute the principal source of water for drinking, irrigation, and other domestic purposes in the Himalayan region, sustaining both highland and lowland habitats. Groundwater, defined as the water present below the water table in the zone of saturation, is one of the major natural resources widely utilized across Nepal. In the hilly and mountainous regions of the country, spring water is the only reliable and sustainable source of fresh water, with approximately 90% of the population in these regions dependent upon springs for their water supply.

A spring is a concentrated point of groundwater discharge appearing at or near the earth's surface as flowing water. It represents that part of precipitation which infiltrates the ground and percolates downward through unconsolidated materials and bedrock openings until it reaches the water table. The emergence of a spring at the surface results from natural discharge processes, broadly categorized as those governed by non-gravitational forces and those governed by gravitational forces. The development and characteristics of springs in any given area are controlled by geology, geomorphology, soil type, rock type, geological structures, and other associated factors (K.C. and Rijal, 2017). Consequently, each spring differs from others in terms of its catchment area, recharge mechanism, and discharge pattern, which are further governed by natural slope, lineament density, drainage density, and land use/land cover.

The suitability of spring water for domestic and agricultural use is determined through the assessment of various physicochemical parameters, the concentrations of which fluctuate considerably with the type of pollution, season, and other environmental factors. Regular monitoring of spring water sources is therefore necessary to prevent contamination. Weather, climate, topography, and the physical characteristics of land and water resources play a vital role in the development and establishment of rural settlements, making the pursuit of suitable water quality for drinking, irrigation, and animal husbandry a central concern in groundwater management.

The quality of spring water is largely governed by the characteristics of the aquifer from which it originates. As groundwater moves through an aquifer, it dissolves and transports minerals from soil particles, sediments, and rock surfaces as it travels through pores, fractures, and the unsaturated zone; these dissolved constituents are collectively referred to as soluble solids. Additional dissolved solids are contributed by rainwater and stream water recharged into the aquifer. Groundwater quality encompasses various physical, chemical, and biological properties. While temperature, turbidity, color, taste, and odor constitute the physical parameters, most groundwater is colorless, odorless, and without distinct taste, making chemical and biological indicators the primary focus of quality assessment. Although spring or groundwater products are often marketed as "pure," their actual water quality differs from that of pure water, underscoring the importance of quality assessment for ensuring sustainable and safe use.

Describing overall water quality remains challenging due to the spatial variability of contaminants and the wide range of physical, chemical, and biological indicators that can be measured. To address this, GIS-based Groundwater Quality Index (GQI) approaches have been proposed, numerically indexing available water quality data (e.g., Cl^-, Na^+, Ca^{2+}) against World Health Organization (WHO) standards (Babiker et al., 2007). Such approaches integrate physical and chemical parameter analysis with GIS-based spatial distribution mapping to identify areas of best water quality for drinking purposes. Seasonal variation also plays a critical role in spring behavior; the constant-rate discharge characteristics of springs, along with their water quality, vary with season, and analysis of these radial groundwater flow systems provides insight into the estimation of discharge and quality using actual field data (Ambiga, 2016).

Several studies conducted across Nepal and the wider Himalayan region have addressed spring inventory and water quality assessment. Inventory-based studies from western and central Nepal report that natural, perennial springs dominate the mountain water supply, though the relative share of spring types and their distribution varies considerably by watershed (Adhikari et al., 2021; Dumaru et al., 2021; K.C. and Rijal, 2017; Pandit et al., 2019). At the same time, global and regional assessments point to an ongoing decline in spring numbers and yield linked to increased surface runoff and reduced groundwater recharge (Ferencz et al., 2022).

Discharge and water quality index (WQI) studies from Nepal and the wider Himalaya consistently link seasonal spring discharge to the monsoon, with WQI values generally falling in the good-to-excellent range for drinking purposes (Pokhrel and Rijal, 2020; Taloor et al., 2020; Panta et al., 2022; Gurung et al., 2019). At the same time, several of these studies report a marked long-term decline in spring discharge and flow across Nepal, underscoring critical gaps in spring conservation and management policy (Thapa et al., 2020; Chauhan et al., 2023).

The present study was carried out in Tilagupha Municipality, Kalikot district, located in the north-western hilly region of Nepal within Karnali Province. The area is tectonically diverse, having developed through the differential uplift of the Himalayan foothills controlled by major thrust systems. The study area covers approximately 7 km in the east-west direction and 9 km in the north-south direction, forming a nearly rectangular watershed outline. The Ghodegadh stream, flowing north to south, is the major perennial drainage passing through the southern part of the study area, while non-perennial streams such as the Dudhekhola and Guiyakhola originate in the northern part and join the Tila River to the south. Erosional activity associated with these streams has produced steep topography in the northern and southern portions of the study area. As the non-perennial streams remain dry during summer, and given the proximity of hilly terrain to settlements, the local population relies primarily on perennial springs located at some distance from villages for their fresh water supply. Spring discharge in the study area is strongly governed by seasonal rainfall and snowfall, being high during the monsoon season and low or completely dry during the dry season.

The study area is bounded by rocks of the Higher Himalayan Crystalline sequence, specifically Proterozoic undifferentiated units comprising predominantly augen gneiss and migmatitic gneiss. Geologically, the study area lies within the Higher Himalaya, which is exposed as a narrow, discontinuous belt immediately south of the Main Boundary Thrust (MBT). This sequence consists predominantly of granite-gneiss, migmatitic gneiss, and augen gneiss, with alternating bands of pelitic and psammitic gneiss. The Higher Himalayan Crystalline rocks occupy the northern and central parts of the study area and are represented by various gneiss types, broadly divided into a lower unit of pelitic and psammitic gneiss and an upper unit of migmatitic and calc-silicate gneiss. Kyanite is present throughout the sequence, while staurolite occurs alongside kyanite in the lower portion but disappears in the upper, high-grade part. The metamorphic grade within the study area increases progressively upward structurally, attaining its highest value near the Main Central Thrust (MCT).

The major objective of this research is to study the overall hydrogeological condition of Tilagupha Municipality using Remote Sensing (RS) and Geographic Information System (GIS) techniques in conjunction with field-based data. The specific objectives of the study are to characterize the spring water resources of the study area, to analyze the seasonal variation in spring discharge and to analyze and interpret the spring water quality to support the municipal water resource management plan.

STUDY AREA

The study area is located in Tilagupha Municipality, in the north-eastern part of Kalikot district, Karnali Province, Nepal, approximately 800 km west of Kathmandu and 200 km north of Surkhet via the Karnali Highway, with the Surkhet-Jumla Road connecting to the area from Manma in the north-east (Figure 1). It lies between longitude 81°52'25" E to 81°52'45" E and latitude 29°10'38" N to 29°11'16" N, falling within toposheet no. 2981 16. Geologically, the area lies within the High Himalayan region, characterized by migmatitic gneiss and augen gneiss. The area is not easily accessible by motor road, with only its southern part touched by the Karnali Highway, the sole road network connecting it to the district headquarters and provincial capital. Topographically, the region is hilly, marked by peaks, ridges, and spurs, with elevations reaching up to 3,284 m above sea level near Raunebhuja; the terrain slopes steeply toward the south and is deeply incised by north-south flowing streams, while a valley-shaped flat stretch of land extends from east to west. The steep hillslopes, combined with a parallel drainage pattern, render the area highly susceptible to soil erosion and landslides, posing significant challenges for farmers cultivating the available land. Land use in the study area is dominated by forest, grassland, cultivated land, and settlement.

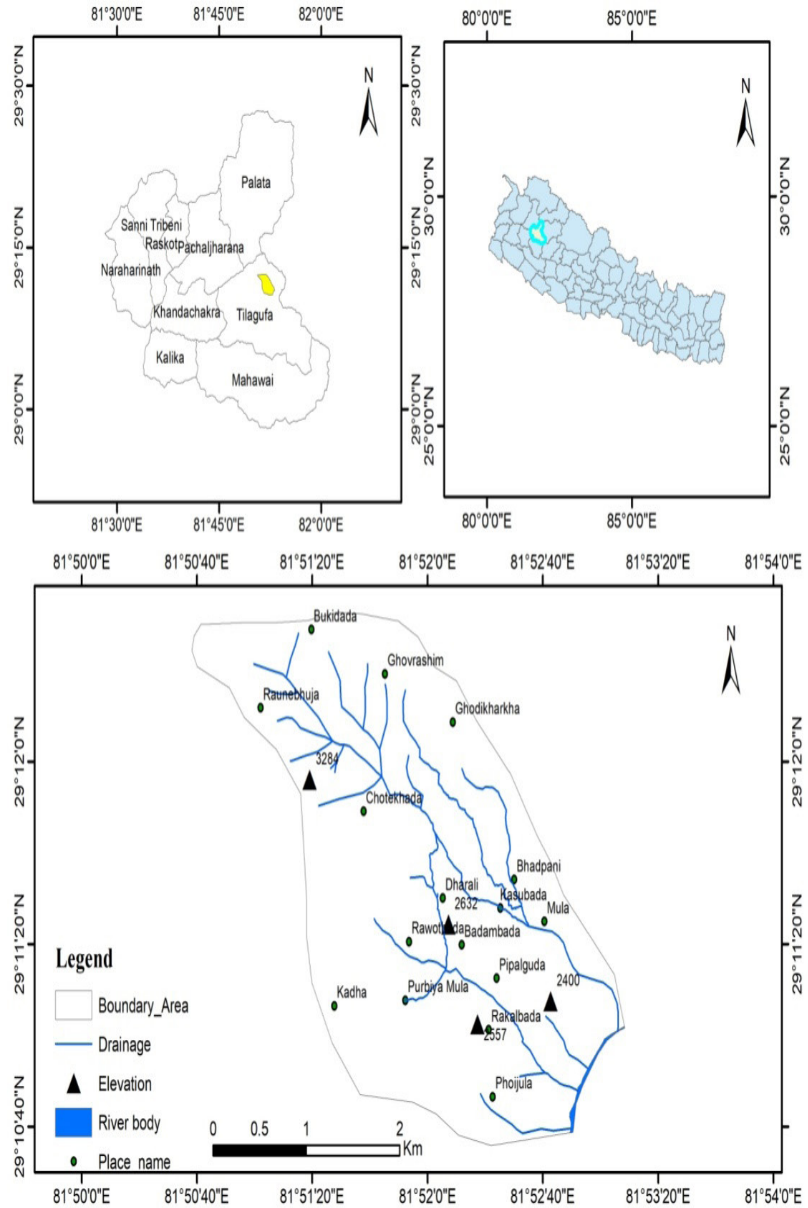

Fig. 1: Location map of the study area (a) Map of Nepal Showing Kalikot District (b) Present study area (c) Drainage pattern of the study area.

DATA AND METHODS

The present study on spring investigation and water quality assessment employed both primary and secondary data collected through desk study, field survey, and laboratory analysis. Materials used included a Brunton compass, GPS, geological hammer, topographic maps (1:50,000 scale, sheet no. 2981 16), sample bottles, a measuring jug, stopwatch, DO meter, and EC-pH meter. The desk study formed the initial stage of the research, involving a review of published and unpublished literature, journals, and topographic maps to plan the fieldwork and select appropriate methods. Field study was then carried out to collect primary data, complemented by secondary data obtained from local government offices, comprising geological and geomorphological surveys to identify lithology, soil type, and land use, alongside hydrogeological investigation involving spring inventory, in-situ testing of pH, EC, and temperature, and discharge measurement using the volumetric method (Q = V/t).

Water samples from 15 representative springs were collected and analyzed at the KUKL Water/ Wastewater Quality Assurance Division for parameters including total alkalinity, hardness, chloride, iron, turbidity, sodium, potassium, sulphate, nitrate, phosphate, and ammonia, using titration (Figure 2a), colorimetry, spectrophotometry, and flame photometry (Figure 2b), and results were correlated with the National Drinking Water Quality Standard (NDWQS, 2079). The Water Quality Index (WQI) was computed following Horton (1965) and Brown et al. (1972) to classify overall water quality, and all collected data were digitized and processed using Google Earth, Microsoft Excel, and ArcGIS, enabling comprehensive spatial analysis and the preparation of graphs, maps, figures, and tables to present the study findings.

Fig. 2: Physiochemical parameters of the spring to determine WQI (a. Titration b. Flame Photometry)

Water quality index (WQI)

Horton (1965) first time defined the water quality index and which displays a specific quality of water. After Horton, Brown et al. (1972) WQI was calculated from analyzing the various physicochemical properties of water and converts them in a single value which indicates the overall quality of water. WQI typically uses a formula that assigns weights to different parameters based on their importance and combines them into a single index value. The index value is then classified into different water quality categories.

Table 1 Classification of WQI value and their respective status (Brown et al. 1972)

S.N.	WQI range	Rating of Water Quality
1	0-25	Excellent water quality
2	26-50	Good water quality
3	51-75	Poor water quality
4	76-100	Very poor water quality

WQI by using the expression given in the following equation:

$$WQI = \frac{\sum qn\, Wn}{\sum Wn}$$

qn = Quality rating of nth water quality parameter.

Wn= Unit weight of nth water quality parameter.

The quality rating (qn) is calculated using the expression:

$$qn = \frac{(Vn - Vid)}{(Sn - Vid)} * 100$$

Vn = Estimated value of nth water quality parameter at a given sample location.

Vid = Ideal value for nth parameter in pure water (Vid for pH = 7 and 0 for all other parameters)

Sn = Standard permissible value of nth water quality parameter

The unit weight (Wn) is calculated using the expression:

$$Wn = k / Sn$$

Sn = Standard permissible value of nth water quality parameter.

k = Constant of proportionality and it is calculated by:

k = [1 / (∑ 1/ Sn=1, 2… n)]

Table 2 Standard permissible value (Sn) and unit weight (Wn) of each parameter used in WQI computation

Parameter	Sn (permissible limit, NDWQS 2079)	Wn (unit weight)
Turbidity (NTU)	5	0.0540
pH	8.5	0.0318
EC (µS/cm)	1500	0.00018
Total Alkalinity (mg/l) *	200*	0.00135
Total Hardness (mg/l)	500	0.00054
Calcium (mg/l)	200	0.00135
Magnesium (mg/l)*	30*	0.00900
Iron (mg/l)	0.3	0.8997
Chloride (mg/l)	250	0.00108
Sulphate (mg/l)	250	0.00108

*NDWQS 2079 does not list independent permissible limits for total alkalinity or magnesium; the values shown here are commonly used literature defaults and should be replaced with the exact standard value applied in the original WQI calculation.

RESULTS

Spring Inventory

A total of 25 springs were identified and inventoried within the study area during the field survey, of which 22 are perennial and 3 are seasonal. Contact springs were found to be the dominant type, with depression and fracture springs also present, and springs were classified based on their nature of origin, discharge, and flow consistency, as their water quality depends largely on the aquifer from which they are sourced. Among the inventoried springs, water samples from 15 springs, including the Purbiya Mul (Figure 3), were collected for physicochemical analysis and the resulting spring inventory map of the study area is presented in Fig. 3.

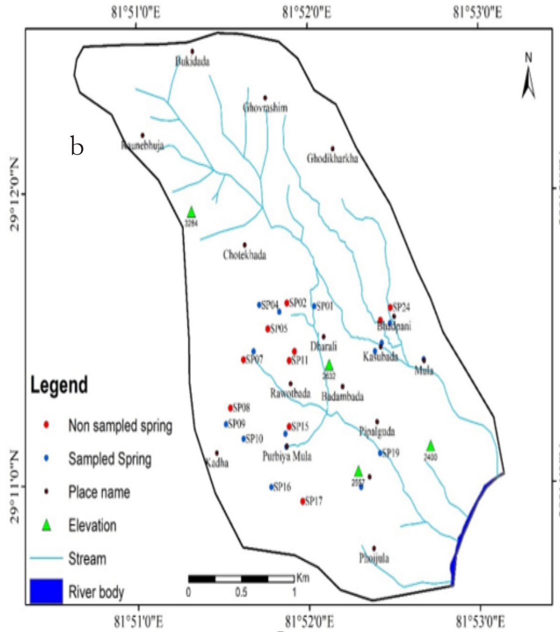

Fig. 3: Purbiya Mul Spring (a) and the spring inventory map of the study area (b)

Discharge Characteristics and Seasonal Variability of Springs

Spring discharge in the study area fluctuates markedly on a monthly basis, being high during the rainy season and low or completely dry for some spring during the dry season, as illustrated in Figure 4. During heavy rainfall in October 2022, most springs exhibited high discharge, with Mughraya Dhara (Sp22) recording a maximum of 24 Lpm, while Sp12, Sp18, Sp19, and Sp23 recorded a minimum of 3 Lpm. Purbiya Mul, Palta Mul, and Mul are perennial springs with discharge exceeding 10 Lpm, whereas Sp15, Mughraya Dhara (Sp22), and Ghothidhara are seasonal.

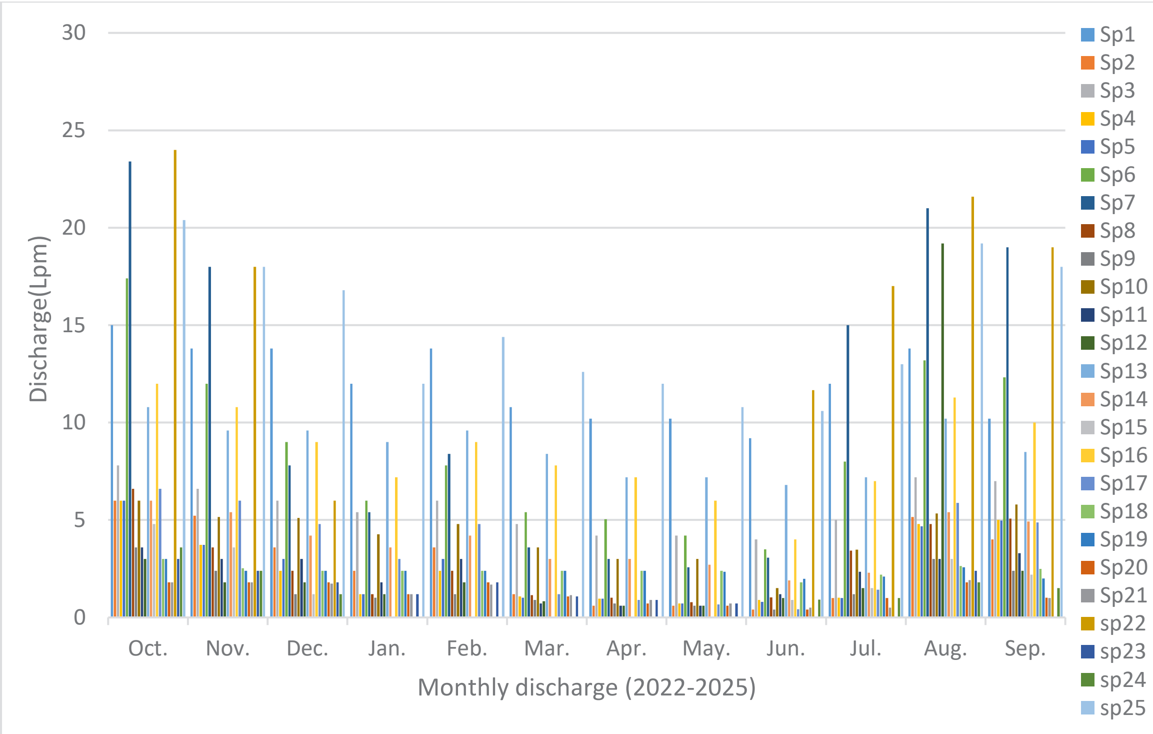

Fig. 4: Monthly discharge of the spring (2022-2025)

A comparison of 13 years (2013–2025) of monthly rainfall data with recent discharge measurements reveals a clear, directly proportional relationship between rainfall and spring discharge (Figure 5), with all 25 springs showing increased discharge during the monsoon and reduced or in some cases zero discharge during the dry season. The rainfall–discharge graph displays two distinct peaks, in July and October, with discharge rising sharply during and immediately after rainfall events. In October, discharge initially increases with high-intensity rainfall before gradually declining, as the steep slope of the study area promotes greater surface runoff at the expense of infiltration. In July, moderate rainfall intensity sustained over a longer duration produces a more gradual rise in discharge that remains stable for an extended period, indicating that rainfall intensity governs the rate of aquifer recharge while rainfall duration controls the degree of aquifer saturation. When rainfall intensity is high, runoff is rapidly concentrated into aquifers through cultivated land, fractures, and sinkholes, producing an immediate spring response; this response diminishes progressively through the post-monsoon period. The high variability between minimum and maximum discharge, together with the close phase correspondence between precipitation and discharge, indicates that the springs respond rapidly to rainfall and that their recharge areas lie in close proximity to the springs themselves.

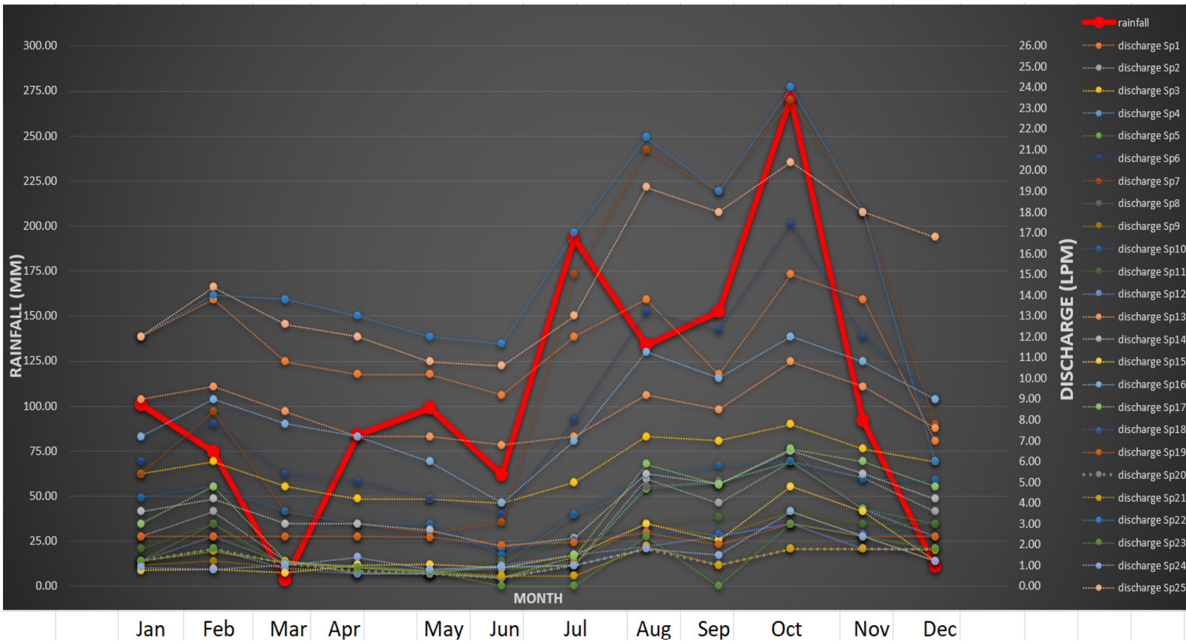

Fig. 5: Relationship between rainfall and spring discharge

Water quality

The physiochemical parameters of the springs are tested on both field and laboratory. In-situ water quality testing of all springs observed during the field, whereas 15 springs are selected for the detailed laboratory physio-chemical tests. The parameters and the tested data are correlated with the National Drinking Water Quality Standard (NDWQS, 2079). The detailed description of different parameters and the data are described below:

i. Hydrogen concentration ion (pH)

The pH refers to hydrogen ion concentration of the water sample. The pH value in water samples lies within the 6.6 to 7.3, pH value of the spring water in the study area shown in Figure 6(a) which is suitable for drinking and agricultural purposes according to the National Drinking Water Quality Standard (NDWQS, 2079).

ii. Electrical Conductivity (EC)

Electrical conductivity is the functions of total dissolved solids dissolved in the relative volume of water. Value of electrical conductivity of spring water lies within 34.5 µS/cm to 15 µS/cm. EC value of the spring water in the study area shown in Fig. 6(b). The electrical conductivity of springs of eastern part of the study area is higher than the western part of the springs.

iv. Total Hardness

The maximum and minimum value of total hardness ranges from 8 mg/l to 30 mg/l which is suitable for drinking according to NDWQS, 2079. Fig. 6(c).

v. Calcium Hardness

Calcium hardness refers to the concentration of calcium present in water, expressed in mg/l. The calcium hardness values of the spring water sample Fig. 6(d), rang from a minimum of 6 mg/l to a maximum of 20 mg/l.

vi. Magnesium Hardness

Magnesium hardness refers to the amount of magnesium ion present in one liter of water. The unit of magnesium hardness is also mg/l.

Magnesium Hardness are shown in Fig. 6(e). The minimum and maximum value of the magnesium hardness ranges from 2 mg/l to 16 mg/l.

vii. Calcium (Ca)

The minimum and maximum value of the calcium ranges from 2.40 mg/l to 8.01 mg/l. According to NDWQS, 2079, the value of calcium below 200 mg/l is suitable for drinking.

viii. Magnesium (Mg)

The minimum and maximum value of magnesium ranges from 0.49 mg/l to 3.89 mg/l. Sp25 has highest magnesium 3.89 and Sp1, Sp6 and Sp9 has lowest value 0.49.

ix. Total iron (Fe)

The value of total iron for all tested 15 spring water sample is 0.1 mg/l as shown Figure 6(f). According to NDWQS, 2079 the value of total iron below 0.3 mg/l is suitable for drinking.

x. Arsenic

Arsenic is not detected to the spring water sample which means arsenic is absent in the sample. According to National Drinking Water Quality Standard (NDWQS, 2079) the value of arsenic below 0.05 mg/l is suitable for drinking.

xi. Manganese

Manganese is not detected to the spring water sample. According to NDWQS, 2079 the value of manganese below 0.2 mg/l is suitable for drinking.

xii. Total ammonia (NH_3)

The value of total ammonia for all 15-spring sample is 0.02 mg/l. According to NDWQS, 2079 the value of total ammonia below 1.5 mg/l is suitable for drinking.

xiii. Nitrate

Nitrate is not detected in 11 water sample. Only Sp (18, 20, 21 and 23) water sample present nitrate below the 3.2 mg/l which is acceptable according to NDWQS, 2079.

xiv. Chloride (Cl)

The minimum and maximum value of chlorine ranges from 4 mg/l to 22 mg/l respectively. According NDWQS, 2079 the value of chloride below 250 mg/l is suitable for drinking. The Chloride ion values are shown in Fig. 6(g).

xv. Phosphate

As shown in Fig. 6(h), phosphate concentrations in the spring water samples range from 0.20 mg/l to 1.5 mg/l, with samples 1, 3, 4, 6, 9, 10, 13, 14, 16, 19, and 25 recording values below the detection limit.

xvi. Sodium (Na)

Out of 15 samples, 7 samples have not detected sodium whereas remaining 8 sample sodium is ranges from 1.16 mg/l to 8 mg/l. Sodium values are as shown in Fig. 6(i).

xvii. Potassium (K)

Twelve samples have potassium value ranges from 0.34 mg/l to 6.80 mg/l, whereas remaining 3 samples Sp9, Sp10 and Sp14 has not detected the potassium Fig. 6(j).

xviii. Sulphate (SO_4)

Sp16 and Sp19 water samples have not detected sulphates and remaining sample has sulphate ranges from 0.40 mg/l to 13.60 mg/l which are shown in Fig. 6(k).

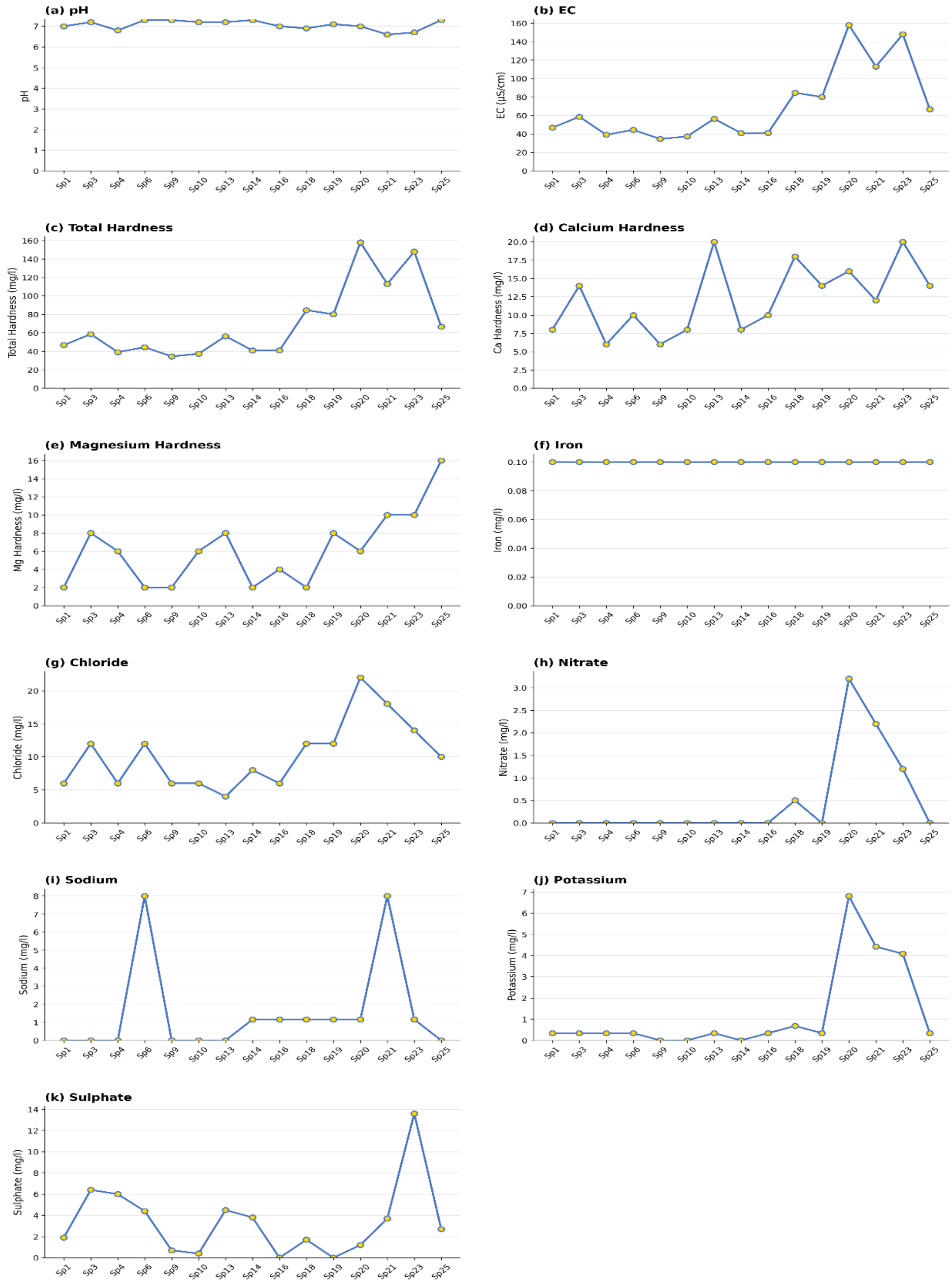

Fig. 6: Spatial variation of physicochemical parameters of spring water samples (a) pH, (b) EC, (c) Total Hardness, (d) Calcium Hardness, (e) Magnesium Hardness, (f) Iron, (g) Chloride, (h) Nitrate, (i) Sodium, (j) Potassium, (k) Sulphate.

Hydrochemical Characterization

The hydrochemical properties of the tested water samples were analyzed using a Piper trilinear diagram (Figure 7), a graphical method widely used in hydrogeology to classify and interpret the chemical composition of water based on the relative concentrations of major cations and anions. The diagram, plotted using Golden Grapher software, reveals Mg^{2+} dominance among the cations in the majority of samples and Cl^- dominance among the anions. Based on the diamond plot, all 15 water samples are classified as calcium bicarbonate and calcium sulphate type waters.

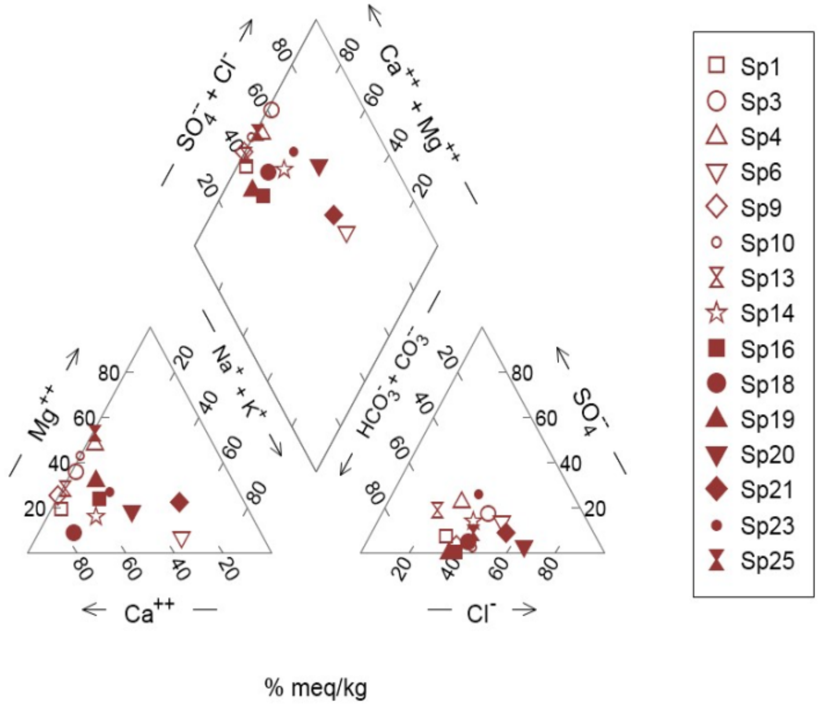

Fig. 7: Piper plot diagram of the major chemical constituents

Water Quality Index (WQI)

The Water Quality Index was first introduced by Horton (1965) to represent the overall quality of water through a single numerical value. Building on this concept, Brown et al. (1972) developed a method for computing the WQI by analyzing various physicochemical parameters of water and combining them into a single composite index. The method assigns weights to individual parameters—including pH, EC, total alkalinity, turbidity, total hardness, calcium, magnesium, iron, chloride, and sulphate—based on their relative significance, and integrates them into a single index value. This value is then classified into water quality categories: excellent (0–25), good (26–50), poor (51–75), very poor (76–100), and unsuitable for drinking. The computed WQI values and corresponding water quality classification of the sampled springs are presented in Table 3.

Table 3 Water Quality Index (WQI) of spring based on Brown et. al (1972)

Sample No.	Location	WQI Value	Types of water
Sp1	Naulikharka	30.8	Good Quality Water
Sp3	Chakudhunga	31.18	
Sp4	Maibasauna	31.69	
Sp6	Dudhakhola	31.65	
Sp9	Kathikharka	30.67	
Sp10	Paltadhar	31.03	
Sp13	Purbiya mul	31.41	
Sp14	Dhana Mul	31.97	
Sp16	Palta mul	30.60	
Sp18	Rakalbada	31.49	
Sp19	Budhika Dhara	30.66	
Sp20	Kasubada	32.29	
Sp21	Naibada	32.21	
Sp23	Naula dhara	31.7	
Sp25	Mula dhara	33.5	

Comparing Table 2 with Table 1, it exhibits the Water Quality Index (WQI) values of spring based on Brown et. Al (1972). The all 15 spring WQI value varies 30.60 to 33.5, which is the ranges of (26-50). It indicates that all spring fall under good water quality.

DISCUSSION

A total of 25 springs were inventoried in the study area, with contact springs identified as the dominant type, along with a smaller number of depression and fracture springs; classification was based on the nature of origin, discharge, and flow consistency of each spring. The dominance of contact springs is consistent with the area's structural geology: contact springs typically emerge where percolating water meets an abrupt change in permeability, such as the boundary between fractured, weathered gneiss and more massive underlying rock, a mechanism plausible given the augen and migmatitic gneiss that underlie the study area. As the principal source of water in the area, spring discharge is directly controlled by rainfall, and the close correspondence in timing between rainfall peaks/troughs and discharge peaks/troughs indicates a rapid recharge response rather than the slow, buffered discharge typical of deep regional aquifers. This points to shallow, fracture-controlled flow paths with recharge areas in close proximity to the springs themselves, rather than a large, laterally extensive aquifer system. Water quality was assessed through both in-situ and laboratory testing of physical and chemical parameters, with results interpreted in the context of natural influencing factors such as geology, hydrogeology, climate, and rainfall, and compared against the National Drinking Water Quality Standard (NDWQS, 2079).

The physicochemical results place spring water quality well within NDWQS (2079) limits across all measured parameters, and the computed WQI values (30.60–33.5) sit toward the lower, better end of the "good" category (26–50), close to the boundary with "excellent" (0–25) — a result broadly consistent with regional WQI studies in the Himalaya, which generally report good-to-excellent spring water quality (Taloor et al., 2020; Panta et al., 2022). The comparatively low EC (34.5–157.9 µS/cm) and total hardness (8–30 mg/l) recorded here indicate limited water–rock interaction, consistent with the rapid, shallow recharge response discussed above: water that moves quickly through shallow fractures has less time to dissolve minerals from the surrounding rock than water in a deeper, slower-flowing aquifer. This is also consistent with the Piper diagram results, where Mg^{2+} emerges as the dominant cation, plausibly reflecting weathering of ferromagnesian minerals in the augen and migmatitic gneiss that underlie the study area, rather than dissolution of carbonate or evaporite minerals, which are largely absent from the local lithology. Taken together, the low mineralization, good water quality, and rainfall-responsive discharge point to a shallow, fracture-controlled hydrogeological system whose water quality and yield are likely to remain closely tied to local rainfall and land use rather than buffered by a large regional aquifer — a consideration directly relevant to how the municipality manages these springs going forward.

CONCLUSIONS

This study characterized the spring water resources of Tilagupha Municipality, geologically situated within the Higher Himalayan zone and underlain predominantly by Higher Himalayan crystalline rocks such as augen gneiss and migmatite. A total of 25 springs were inventoried, classified as contact, depression, and fracture types, with contact springs being the most dominant. Springs were found to be the predominant and sole source of water for drinking, household, and irrigation purposes in the area.

Analysis of the seasonal variation in spring discharge revealed that 22 springs are perennial and 3 are seasonal, with discharge fluctuating in direct response to rainfall. The rainfall–discharge relationship showed an immediate response of spring flow to precipitation, confirming rainfall as the primary source of groundwater recharge in the study area and indicating that recharge zones lie in close proximity to the springs.

Analysis and interpretation of spring water quality, based on detailed physicochemical testing of 15 spring water samples, showed that all measured parameters comply with the National Drinking Water Quality Standard (NDWQS, 2079). The computed Water Quality Index (WQI) values ranged from 30.60 to 33.5, placing all samples within the "good water quality" category (26–50).

Collectively, these findings on spring characterization, discharge behavior, and water quality provide a scientific basis to support the municipal water resource management plan of Tilagupha Municipality, and support specific recommendations for dry-season storage at the seasonal springs, periodic water quality monitoring, and protection of recharge zones immediately upslope of the perennial springs supplying the local population.

ACKNOWLEDGEMENTS

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AUTHOR CONTRIBUTIONS

All the authors have made significant contributions to the preparation of this research article. Prof. Dinesh Pathak, Dr. Kabi Raj Paudyal, Mr. Dhirendra Parsad Pandey, and Mr. Sanjeeb Pandey developed the study concept and design. Mr. Sanjeeb Pandey, along with Mr. Dhirendra Parsad Pandey, conducted fieldwork periodically, significantly contributing to data collection. Prof. Dinesh Pathak and Dr. Kabi Raj Paudyal conducted verification traverses in the field, collaboratively analyzed the field and secondary data with team members, and provided technical support. Mr. Sanjeeb Pandey wrote the first draft of the manuscript, with all authors contributing to the final version. Finally, all authors participated in making corrections based on the reviewers' suggestions.

CONFLICT OF INTEREST

The authors declare no competing 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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