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Research Article

SPRINGS OUTFLOWS IN DIVERSE GEOLOGY AND GEOMORPHOLOGY OF SETI KHOLA WATERSHED, WESTERN NEPAL

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ABSTRACT

Springs are crucial for supporting life and balancing ecosystems and vary in outflow from place to place. A study was conducted in the mid-hill region of western Nepal, which spans between carbonate (44%) and non-carbonate (56%) lithology. A field survey identified 175 perennial springs, which were categorized based on their outflows using methods such as bucket-stopwatch, weir, and float techniques. Springs were grouped into minimum 0.1-10 liter per minute (lpm), intermediate 10-60 lpm, and maximum outflow 60-300 lpm categories. This study assessed the characteristics of springs, focusing on their lithology, elevation, landforms, and land cover. Springs in carbonate-dominant areas consistently exhibited higher outflows than those in non-carbonate areas. Intermediate outflow was the most frequent, particularly in forested areas. The occurrence of springs is significantly influenced by the underlying geology, fractured networks, conduits, and resulting topography. Soil types, especially eutric cambisols, supported higher outflow in intermediate and maximal, whereas gleyic cambisols had minimal outflows. Springs with intermediate outflows were crucial for local water needs, whereas maximal, although rare, were vital for ecosystem health and larger water supply. These findings underscore the importance of spring conservation and sustainable watershed management in maintaining spring outflow and mitigating water scarcity.

Keywords: Carbonate rocks, Elevation, Outflow, Soil and Land cover, springs.

INTRODUCTION

In the mid-hills of Nepal, spring water is vital for communities and ecosystems, providing drinking water, irrigation, and livestock sustenance, and significantly affecting rural livelihoods (Maskey *et al.*, 2021; Pizarro *et al.*, 2022; Segadelli *et al.*, 2021). However, the region faces water scarcity challenges, worsened by climate change, population growth, and land use changes. The diminishing outflow or drying up of many springs has increased the vulnerability of marginalized communities, posing risks to human health and disrupting ecological balance (Chettri *et al.*, 2020; Shrestha *et al.*, 2023). A recent study revealed that proximity to springs, compared with surrounding upland habitats, results in higher conifer density (Peven *et al.*, 2024). Despite the importance of springs, there is a significant research gap regarding spring characteristics and outflow variations (Gurung *et al.*, 2019).

The Seti Khola watershed (SKW) in the western mid-hills exhibits strong geological and geomorphological heterogeneity, consisting of carbonate rocks such as limestone, dolomite, slate, phyllite, quartzite, and colluvial deposits that form steeply dissected terrain (Stöcklin, 1980; Upreti, 1999). Such contrasting lithologies and geomorphic features including ridge–valley transitions, slope breaks, structural lineaments, and deeply incised river channels strongly influence groundwater pathways and spring emergence. In the northern hemisphere, north-facing slopes are steeper, with denser vegetation and limited water availability. South-facing slopes are less steep because of the reduced soil moisture, resulting in smaller vegetation communities that resist erosion less effectively (Cerdà *et al.*, 2009; Nielson *et al.*, 2021; Shah & Lone, 2019).

A proper understanding of the lithological and geomorphological factors affecting spring outflow is required to address and ensure the long-term viability of community water supplies (Matheswaran *et al.*, 2019). Previous studies in the mid-hill region highlight that spring occurrence is closely associated with lithological contacts, fault and fracture zones, and topographic convergence areas (Ghimire *et al.*, 2019). However, systematic documentation of spring distribution and outflow characteristics remains limited. This gap is critical because communities rely heavily on springs for domestic supply, while the hydrogeology of region is highly sensitive to monsoonal recharge variations and land-use changes (Kulkarni *et al.*, 2021). Developing a baseline understanding of how lithology, slope orientation, and micro-topography influence spring outflows ensuring long-term water security is needed.

This study aimed to examine variations in spring outflows across diverse lithological and geomorphological settings and investigate the contributing factors underlying these variations, which is crucial for identifying water scarcity issues faced by mid-hill communities and ensuring the long-term viability of water supply systems.

MATERIALS AND METHODS

Study Area

The study area SKW in the Kali Gandaki Basin, is situated in the mid-hill region of western Nepal and encompasses approximately 115 sq. km. across the Parbat and Syangja districts (Figure 1). The SKW lies in Bihadi, Paiyun, Mahashila, and Arjunchaupari Rural Municipalities and Bhirkot and Waling Municipalities. The area is located between 83.61° and 83.73° E longitude and 28.01° and 28.12° N latitude, and the climate ranges from subtropical to temperate, with approximately 2500 mm of rain each year. The lithology mapped in the surface is characterized by carbonate- (44%) and non-carbonate-dominant (56%) rocks such as dolomite, and slate, quartzite and phyllite (Pokhrel *et al.,* 2025).

The land cover in the study area is predominantly forested (61.24%), with croplands (34.68%), grasslands (1.56%), and built-up areas (0.03%). Elevation varies considerably from 600 to 2300 m, reflecting the rugged terrain and complex topography. The diverse geological and geographical characteristics of the area render it suitable for studying spring outflows, also referred to in spring discharge.

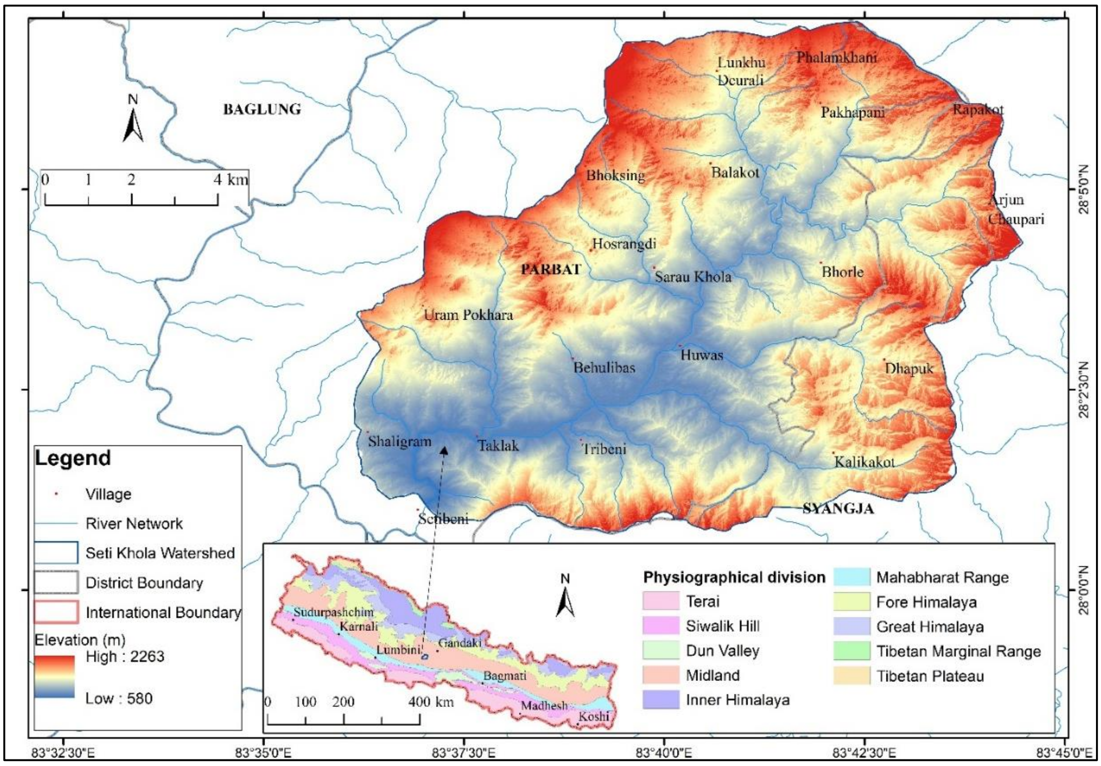

Figure 1. Location map showing the physiographic division of Nepal, the study area SKW within the Parbat and Syangja districts, and the drainage network of SKW.

Primary Data

The methods employed to gather spring locations, outflow measurements, and data analysis of outflows in the SKW region were directly obtained from field observations. The identification of springs locations were performed using aerial-image interpretation for valley morphology, lithological contacts, vegetation moisture patterns. These mapped indicators guided field traverses, which were carried out using contour-based topographical maps, and a handheld Garmin 64S GPS device. A total of 175 perennial springs were identified and mapped to determine their coordinates. All springs were field-verified, and aerial/photo evidence has been added to support the identification process, along with their spatial behavior and usage, involved fieldwork during the wet and dry seasons (i.e., post-monsoon of 2022 and pre-monsoon of 2024), and transect walks across various landforms and elevations.

This study is based on a single post-monsoon outflow measurement, which represents the period of highest recharge. Springs were considered as perennial after monitoring them in wet and dry seasons. Among different outflow measurements throughout years, a post-monsoon spring outflow measurements of year 2022 were used in this study. The bucket-stopwatch, rectangular weir, and float methods were used, depending on the flow conditions from seepage to larger outflows. Community engagement also played a role in identifying springs and distinguishing between perennial and seasonal sources, as seasonal springs tended to dry up later in the post-monsoon period.

The percentile-based springs outflow classification was established for the lower 25% of the values into minimum (MND, 0–10 lpm), middle 50% of the data into intermediate (ID, 10–60 lpm), and upper 25% of the values as maximum outflow (MXD, 60–300 lpm). The bucket-stopwatch method was used for low-flow springs with MND outflow, the rectangular weir method was employed for intermediate flows and the float method for MXD springs where the channel was well-defined. For instance, a spring with a flow of ~10 lpm, a measurement taken using bucket-stopwatch and a rectangular weir were compared, and percentage of variance was reported to demonstrate inter-method reliability.

Secondary Data

The topographic parameters slope, aspect, hillshade and elevation were extracted using DFID-UKRI SHEAR (project number: 201844) (AW3D 5 m DEM ©JAXA, RESTEC, and NTTDATA. Springs were classified into three elevation classes: Class I (<1000 m), Class II (1000-1500 m), and Class III (>1500 m). The slope classes followed Van Engelen & Dijkshoorn (2013), categorizing hill slopes as flat (<2˚), undulating (2˚-8˚), rolling (8˚-15˚), moderately steep (15˚-30˚), and steep (30˚-60˚). The slope aspect was grouped into eight standard orientation classes: N, NE, E, SE, S, SW, W, and NW. Land cover data were derived from the Land Cover 2019 of Nepal (FRTC, 2022) and classified into forest, grassland, and cropland. The dominant soil types in the region are Eutric (CMe), Chromic (CMx), and Gleyic Cambisols (CMg) as described by Gurung (2020).

Data analysis involved mapping and extracting spring attributes using GIS and the Jupyter Notebook, followed by the integration of lithological, elevation, and landform parameters. Statistical and graphical analyses were performed using OriginPro 2025 Learning Edition. Analysis of variance (ANOVA) was applied to evaluate differences in spring outflow across varying settings. In the ANOVA framework, DFmodel represents the degree of freedom of the model, DFerr denotes the error degree of freedom, Fval is the F-statistic describing the ratio of between-group to within-group variance, and pval indicates statistical significance, with $p < 0.05$ considered significant.

RESULTS

Spring Inventory and Outflow Classification

Out of 175 perennial springs in the SKW, percentile thresholds were used to group springs into minimal, intermediate, and maximal outflow classes. Their distribution across lithology, elevation, slope, aspect, land cover, and soil types is presented in Table 1.

Table 1. Spring occurrence in different geological and geomorphological factors of spring outflow.

Factor	Class	Spring outflows class			Factor	Class	Spring outflows class		
		ID	MND	MXD			ID	MND	MXD
Dominant Lithology	Carbonate	35	22	15	Aspect	E	7	7	6
	Non-Carbonate	50	43	10		N	6	6	1
Land cover	Cropland	23	20	7		NE	11	6	5
	Forest	57	40	17		NW	9	8	0
	Grassland	5	5	1		S	19	14	5
Elevation	Class I	11	16	0		SE	9	7	1
	Class II	42	29	17		SW	14	11	5
	Class III	32	20	8		W	10	6	2
Slope	Flat	0	1	0	Dominant soil	CMe	54	41	19
	Moderately Steep	34	25	7		CMg	4	7	0
	Rolling	7	5	2		CMx	27	17	6
	Steep	41	32	14					
	Undulating	3	2	2					

Outflow Variation by Lithology

Outflow differed notably between the two dominant geological settings (Figure 2). The carbonate dominant terrain contained 72 springs with outflows mean 48.5 lpm, while non-carbonate terrain contained 103 springs with outflows mean 28.0 lpm. ANOVA indicated a statistically significant difference in outflow between the lithologies ($p = 0.02$).

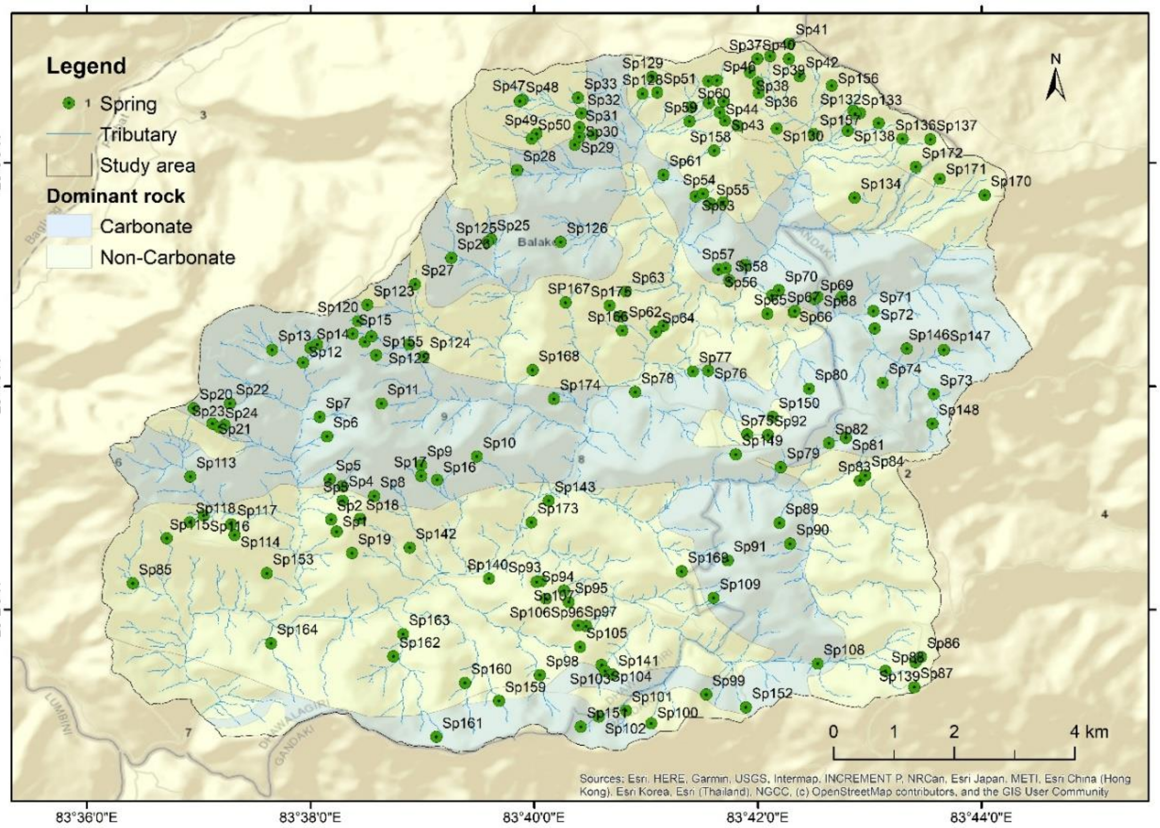

Figure 2. Distribution of springs and spring-fed tributaries in dominant rock type.

Outflow Variation by Elevation

175 springs were distributed across three elevation classes: Class I (27 springs, mean 11.6 lpm), Class II (88 springs, mean 43.9 lpm), and Class III (60 springs, 36.6 lpm). ANOVA showed a significant effect of elevation on spring outflow ($p = 0.04$).

Outflow Variation by Slope and Aspect Class

Springs occurred across all slope classes, with steep slopes hosting 87 springs and moderately steep slopes hosting 66 springs. ANOVA results showed no statistically significant differences in outflow among slope categories ($p = 0.90$). In the slope classes, there were 66 springs in the moderately steep category, 87 in steep, 14 in rolling, 7 in undulating, and 1 in flat (Figure 3).

The aspect-based distribution included 38 springs on south-facing slopes, followed by southwest (30), northeast (22), east (20), west (18), northwest (17), southeast (17), and north (13). Outflow measurements varied within each aspect class, but ANOVA indicated no significant effect on outflow ($p = 0.46$).

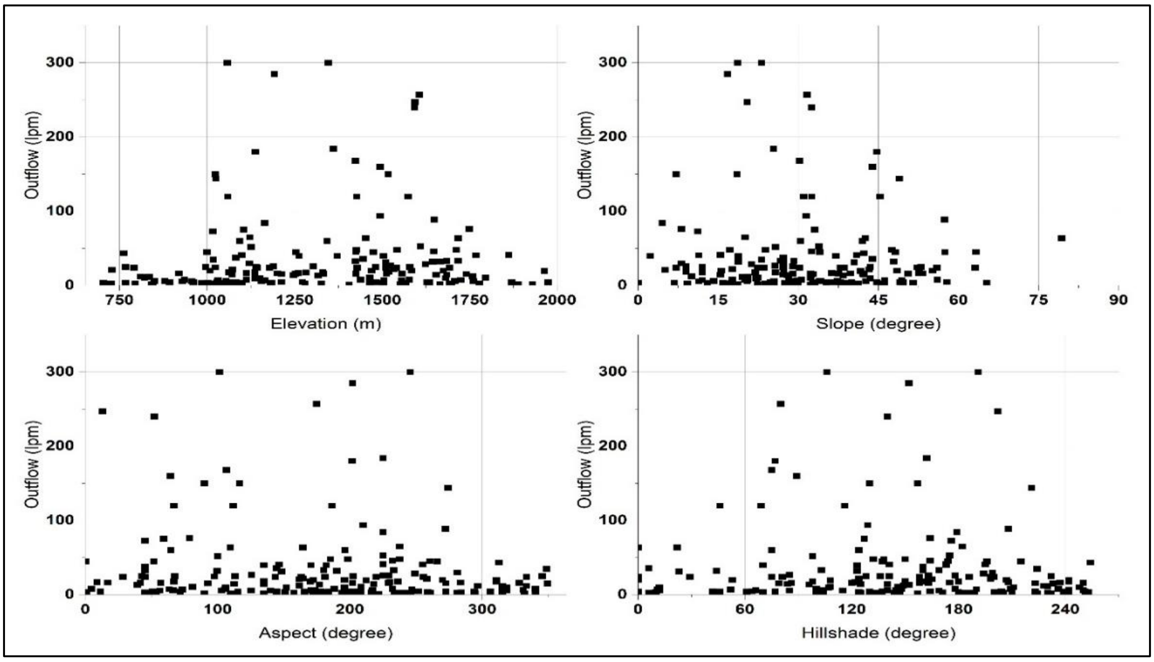

Figure 3. Spring outflow magnitude variation with respect to elevation, slope, aspect and hillshade.

Outflow Variation by Land Cover

Among the mapped springs, forests contained 114 springs, croplands contained 50 springs, and grasslands contained 11 springs. The mean outflows recorded were 39.4 lpm in forest, 32.4 lpm in cropland, and 24.2 lpm in grassland. The differences among land cover classes were statistically insignificant (p = 0.59) and land cover analysis showed that forested areas had the highest outflows (Figure 4).

Outflow Variation by Dominant Soil Type

Three dominant soil types were identified: CMe (114 springs), CMx (50 springs), and CMg (11 springs). Mean outflows were 40.5 lpm for CMe, 33.1 lpm for CMx, and 9.9 lpm for CMg. ANOVA showed no significant differences among soil types (p = 0.21). Soil types range from sandy and loamy at lower elevations to clay-rich at higher altitudes, supporting diverse vegetation and land use patterns. Among the spring types, CMe and CMx in the carbonate areas showed the highest outflows, whereas the CMg type remained consistently low.

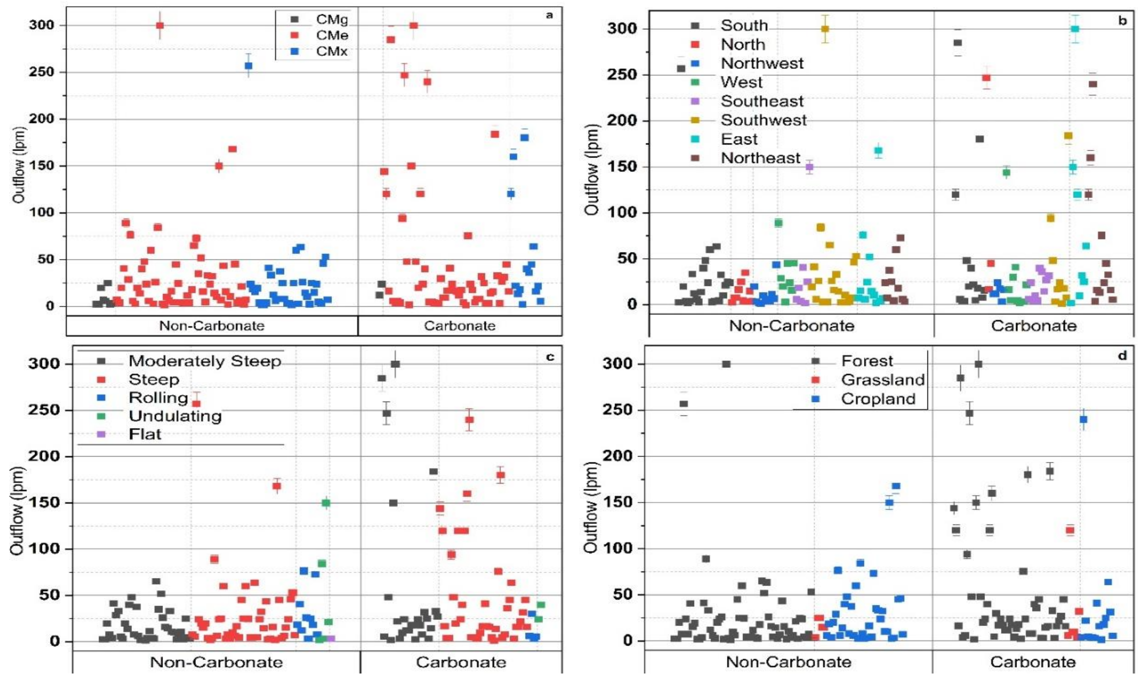

Figure 4. Outflow variation of springs in carbonate- and non-carbonate-dominant terrain versus soil type, slope, aspect, and land cover in the study area.

Summary of Statistical Outcomes

The ANOVA results revealed that elevation and carbonate lithology had statistically significant effects on spring outflow, with p-values of 0.04 and 0.02, respectively. Outflow was notably higher in Class II elevations and carbonate-dominated areas, indicating that both topographic and geological factors influenced spring flow. In contrast, land cover, slope, aspect, and soil/parent material showed no significant variation in outflow, suggesting that these factors have a limited role in controlling the outflow variability within the study area. The detailed ANOVA table, along with the population mean of 175 spring outflows, count of springs in each class, standard deviation, and minimum and maximum outflow magnitudes with summary and fit statistics (see Annex 1).

DISCUSSION

Spring outflow is critical for maintaining ecological balance and year-round drinking water supply systems (Rajasugunasekar *et al.,* 2023). The dynamics of spring outflows in the mid-hill region are influenced by several factors, such as lithology, soil type, and geomorphological characteristics, such as elevation, hill slope, slope aspect, and land use/land cover (Pokhrel & Rijal, 2024). The high coefficient of variation observed in the outflow rates suggests significant heterogeneity and is widely dispersed around the means. Such high variability is attributed to the natural differences in the size and origin of springs. Spring outflows often vary with seasons, peaking during monsoon when recharge is highest (Pizarro *et al.,* 2022; Segadelli *et al.,* 2021).

Lithological Influences and Elevation Effects on Spring Outflow

The lithological data analysis revealed a significant variation in spring outflow between carbonate and non-carbonate geological settings, a trend that holds true across all the influencing factors examined. The findings on the relationship between lithology and spring outflows, such as springs in carbonate-dominant areas, generally exhibit higher outflow, as supported by statistical evidence (Figure 4).

Generally, springs in carbonate lithologies exhibit higher outflows than those in non-carbonate lithologies because the latter allow greater water storage and flow (Buczynski & Rzonca, 2018; Lawan *et al.,* 2018). Springs in non-carbonate lithology, especially, showed a significant decline, with more stable outflow patterns, indicating slower recharge processes than those in carbonate springs. Ghimire *et al*. (2019) indicated that springs mainly originate from weathered, jointed, or fractured rock aquifers in quartzite, schists and gneiss of high-grade metamorphosed rocks in the Melamchi area of central Nepal.

Recharge rates are often higher at higher elevations because of increased precipitation levels. On the Tibetan Plateau, groundwater flow is driven by topographic gradients and high elevation recharge. Springs at different elevations may exhibit distinct recharge and outflow characteristics, reflecting the interplay between topographic, activities (Mastrotheodoros *et al.,* 2020).

Land Cover and Soil Type Effects on Springs Outflow

Land cover changes impact spring outflows, as forests are natural water filters and buffers that mitigate runoff and promote infiltration, which are essential for maintaining water quality and quantity (Artika *et al.,* 2022; Pizarro *et al.,* 2022). Forested catchments have more stable flow regimes than areas dominated by agriculture, which often increases runoff and reduces infiltration. Urbanization and agricultural expansion alter groundwater levels and quality, thereby influencing recharge patterns and flow dynamics (Siddik *et al.,* 2022; Yadav, 2023). Road development and deforestation increase impervious surfaces, diverting precipitation away from infiltration areas (Dinka & Chaka, 2019; Ranjan *et al.,* 2024).

The dominant soil type CMg is prone to waterlogging and supports less spring outflow than well-drained CMe and CMx, which are characterized by reddish or brownish colors in warmer climates than CMg. Soil type significantly affects groundwater spring potential. Interestingly, Hamdan *et al*.. (2016) highlighted that limited soil thickness can increase the vulnerability of groundwater springs to pollution. Areas with thin or absent soil cover and developed epikarst and karst networks contribute to high aquifer sensitivity to pollution.

Slope, Aspect and Hillshade Effects on Spring Outflows

The slope significantly influenced spring recharge and outflow patterns, affecting flow paths and dynamics. For instance, in the steep dolomitic lithology of the area, groundwater has shorter paths and faster transit times, leading to rapid outflows (Warix *et al.,* 2023) more prone to stream drying, as springs discharged rapidly through interflow from adjacent hillslopes. Flatter slopes were associated with longer paths and slower movements, allowing longer residence times and more stable flow patterns, as in Class II Elevation (Ghimire *et al.,* 2019). Studies have shown that hillslope recharge can account for 15-50% of valley floor recharge (Meles *et al.,* 2024). North-facing slopes are more shaded and retain moisture better, which can enhance infiltration (Ghimire *et al.,* 2019; Mathenge *et al.,* 2020).

The study suggests that north-facing slopes, which typically receive less sunlight and have better moisture (Nielson *et al.,* 2021), gentle slopes, and elevations with longer residence times, do not always function as spring outflow zones in the mid-hills. The underlying geology, fractured networks, conduits, and resulting topography play critical roles in the occurrence of springs. Although such regions may support and enhance spring recharge potential downstream, they are not the sole determinants of spring formation. Aspect analysis showed that south-facing slopes had the highest outflow in the carbonate zone. Similarly, steep and moderately steep slopes corresponded to higher outflows, particularly in carbonate areas.

Overall, this study investigated the factors influencing spring outflow in the Seti Khola watershed, with carbonate rocks such as dolomite and slate, phyllite and quartzite as non-carbonate lithologies. By analyzing 175 perennial springs, the research concluded that lithology and elevation are the most significant factors, with springs in carbonate-dominant areas and at intermediate elevations (1000–1500 m) showing substantially higher outflows. The discussion highlights that while factors like land cover and soil type play a role, the underlying geology, including fracture networks, is the primary driver of spring outflows, even challenging common assumptions about slope aspect. This study recommends targeted conservation of recharge zones in carbonate areas and forested slopes to mitigate water scarcity, while acknowledging the limitation of using only a single wet-season measurement and calling for continuous monitoring in future research.

CONCLUSIONS

This study highlights the interactions between lithological and geomorphological factors, such as elevation, slope aspect, hillshade, and land cover that influence spring outflow in the SKW. Springs in carbonate-dominant lithology exhibited significantly higher outflow rates (mean 48.5 lpm) than those in non-carbonate areas (mean 28.0 lpm), with peak flows observed at intermediate elevations (1000–1500 m). The forested regions, steep slopes, and south-facing aspects were positively associated with spring outflow. These findings underscore the importance of targeted conservation strategies, such as protecting recharge zones in carbonate areas and self-protected forested slopes, which are believed to sustain spring outflow and address water scarcity.

As a result, the reported outflow values may overestimate year-round outflow conditions, particularly for springs in non-carbonate terrains and at lower elevations that experience stronger seasonal fluctuations. The absence of dry-season measurements also limits ability to assess the persistence of minimum-flow springs and the stability of intermediate outflows. Future multi-season monitoring, including pre-monsoon and monsoon recession periods, is needed to quantify seasonal variability and improve confidence in long-term flow patterns. Future research should focus on spring outflows monitoring and advanced hydrogeological techniques to refine management approaches and ensure long-term water security for local communities. Moreover, incorporating community-based participatory methodologies may yield valuable insights into local perceptions of spring outflows and their implications for public demand and well-being.

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AUTHORS CONTRIBUTION

Conceptualization: GP, MLR; Investigation: GP; Methodology: GP, MLR; Data curation: GP, MLR; Data analysis: GP, MLR; Writing – original draft: MLR; Writing - review and editing: GK.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ETHICAL STATEMENT

This manuscript is the product of our original research work and is not a part of any previously published work. This manuscript has only been submitted to this journal and not elsewhere.

DATA AVAILABILITY STATEMENT

Researchers interested in obtaining the datasets employed in this study can request the first author, and the data will be made available depending on the purpose of data use.

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Annex 1: Spring outflow statistics, ANOVA summary, and fit statistics under categories and their sub-categories.

Class	Sub-Class	Descriptive Stats					ANOVA Summary				Fit Statistics		
		Min	Max	N	μ	SD	DF_{model}	DF_{err}	F_{val}	p_{val}	R_{sq}	RMSE	CV
Elevation	Class I	1.5	45.0	27	11.6	11.9	2	172	3.4	0.04	0.04	56.5	1.6
	Class II	1.3	300	88	43.9	64.2							
	Class III	1.9	257	60	36.6	56.3							
Land Cover	Forest	1.5	300	114	39.4	63.4	2	172	0.52	0.59	0.01	57.47	1.6
	Grassland	4.1	120	11	24.2	33.1							
	Cropland	1.3	240	50	32.4	45.7							
Slope	Moderately Steep	1.5	300	66	37.8	69.6	4	170	0.3	0.9	0.01	57.8	1.6
	Steep	1.3	257	87	36.9	51.5							
	Rolling	3	76.4	14	24.7	23.9							
	Undulating	2	150	7	46.4	53.5							
	Flat	3.6	3.6	1	3.6	-							
Aspect	S	2	285	38	39.3	65.3	7	167	0.96	0.46	0.04	57.35	1.57
	N	2.5	247	13	33.1	65.6							
	NW	1.5	43.5	17	11.7	10.6							
	W	2.4	144	18	30.1	35.9							
	SE	2	150	17	26.1	34.6							
	SW	1.3	300	30	38.8	62.3							
	E	1.9	300	20	54.6	76.6							
	NE	3.3	240	22	45.9	59.0							
Dominant Soil	CMg	2.5	25	11	9.9	8.9	2	172	1.55	0.21	0.02	57.1	1.57
	CMe	1.3	300	114	40.5	62.7							
	CMx	2	257	50	33.1	48.9							
Carbonate Dominant	Non-Carbonate	1.3	300	103	28.0	45.18	1	173	5.6	0.02	0.03	56.6	1.6
	Carbonate	1.5	300	72	48.5	69.8							