Int. J. Econ. Environ. Geol., Vol. 17, Issue 2, 2026, 103-113 doi: 10.46660/int.j.econ.environ.geol. v17i2.642.
Journal home page: www.econ-environ-geol.org

PROSPECTING NATURAL SPRINGS IN THE FRAGILE HIMALAYAN ENVIRONMENT OF AZAD JAMMU AND KASHMIR, PAKISTAN

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Received: *24 November, 2025* ***Accepted:*** *2 April, 2026*

Abstract: Water demand has been multiplied many times due to growing population, urbanization and climate change in the Himalayan region, where most of the mountain communities depend on the spring resource for their sustenance. It is necessary to assess the available spring resource and develop strategies to improve spring management to ensure water security in the region. An attempt has been made to identify spring potential in the Himalayan region of Azad Jammu and Kashmir (AJK), Pakistan through integrated geospatial and ground-based approach. The results of the study revealed a total of 1109 springs in the AJK. The density of springs was found to be high, i.e., 0.12 springs/km² in the 1250–1500 mm rainfall zone, followed by 0.08 springs/km² in the 1000–1250 mm zone. The spring density appears to exhibit an exponential increase with rainfall, which shows a greater influence of precipitation in nurturing the springs in this region. According to the Gibbs diagram, the spring-derived water samples were found in the rock dominance zone pointing toward chemical weathering of rocks as the major factor contributing ions to the water. The Spearman correlation analysis exhibited a close positive association between Ca and Mg, likely due to weathering of the carbonate rocks. Future studies should be focused on detailed hydrogeological investigations and spring shed management to ensure sustained supplies of spring water in this region.

Keywords: Groundwater system, hydrogeology, spring management, Himalayan region.

Introduction

The demand for freshwater is increasing rapidly in wake of increasing population, urbanization, economic developments, and climate change worldwide (Selvam *et al*., 2015). Accurate assessment of the water availability is necessary for ensuring water and food security in the Himalayan mountain regions including Pakistan (Rasul and Hussain, 2015; Ashraf *et al*., 2025). Natural springs are critical to the domestic and agricultural requirements of most of the mountain communities of the Himalayan region (Chapagain *et al*., 2019; Adhikari *et al*., 2021). The Himalayan region's water budget is greatly influenced by spring water, which benefits more than 40 million people (Bookhagen and Burbank, 2010; Andermann *et al*., 2012; Gurung *et al*., 2019). Springs are formed when groundwater flows towards the surface and emerges. Apart from being copious sources of potable water, perennial springs enhance biodiversity, contribute flows to streams, rivers, and wetland ecosystems, and offer cultural services (Cuthbert and Ashley, 2014; Junghans *et al*., 2016; Rashid *et al*., 2017; Stevens *et al*., 2021; Sakai *et al*., 2021). The spring water quality is generally influenced by different factors, including rainfall composition, regional geology, and human activities, i.e., unplanned urban growth and overexploitation of natural resources (Bastiancich *et al*., 2022; Shrestha *et al*., 2023).

The spring resource urgently needs to be managed sustainably to achieve sustainable development goals (SDGs), such as no hunger (SDG 2), enhancing health and well-being (SDG-3), and reviving water resources (SDG-6) in the region.

Springs are among the main sources of rural and urban drinking water in the mountainous region of Pakistan, including Azad Jammu and Kashmir (AJK). The local communities rely on spring resource for drinking and household use, considering them a safe source of water. The population of AJK has increased from 2.973 million in 1998 to over 4.333 million during 2023 (GoAJ&K 2012, 2025). The situation demands rigorous efforts to improve food security and livelihoods through development of land and water resources in the region. There exist major gaps in effective management of springs due to the insufficient and fragmented knowledge about geographical location and ecological integrity of the springs (Panwar, 2020; Stevens *et al*., 2021). Previous studies do not provide any systematic analysis of springs' physical setting and attributes contributing to better living conditions and economic development in this region. It is hypothesized that significant potential of spring resource exists in this Himalayan region, which could be managed to meet the growing demand for freshwater in the future.

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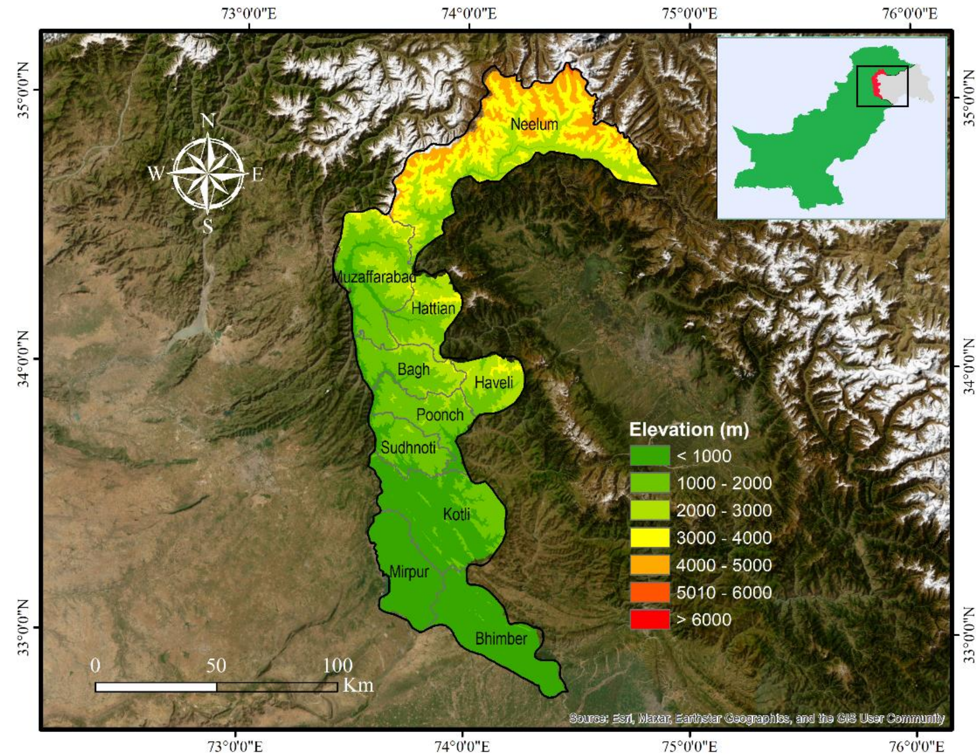

Fig. 1 Location of AJK study area in northern Pakistan.

In the current study, spring resource potential has been assessed in AJK, Pakistan, through the integration of geospatial and ground-based techniques. The findings of the study would be helpful in effective management of water resources and achieving food and health-related goals in this region.

Geographical Setup

The study area of AJK covers about 13,297 km² between 73° and 75° E longitudes and 33° and 36° N latitudes in the northeastern Himalayan orogenic belt of Pakistan (Fig. 1). It is marked by steep ravines and rugged mountainous terrain within an elevation range of 360-6,326 m. The altitude declines from northern high mountainous districts (Neelum, Muzaffarabad, Hattian, Bagh, Haveli, Poonch, and Sudhnoti) to southern low mountainous/plain districts (Kotli, Mirpur, and Bhimber). Of the whole population, 87.5% reside in rural areas and 12.5% live in urban areas, with a general population density of around 246 persons/km². The average household size is 6 individuals. The area has a diverse climate, with alpine conditions found at higher elevations and moderate conditions in the valley regions. The climate in the southern part is subtropical, with warm summers and moderate winters. In some of the northern and central parts, the weather remains moderately hot in summers and cold and chilly in winters. The area receives heavy rains during the summer monsoon (July to September), i.e., exceeding 1200 mm annually. Winter brings a lot of snowfall in the higher reaches, which is essential for the area's water supplies. Peak temperature in the valleys ranges from 20 to 32°C during the summer, while it reaches -8°C during the winter. The main crops include wheat, maize, rice, pulses (red kidney beans), fodder, vegetables, and fruits. Forests cover 20% of the total area. The coniferous forest is predominant above 1200 m altitude, while broad-leaved, deciduous/evergreen trees and varied shrubs generally occur below this elevation. Agriculture and livestock are the major economic sectors. More than 13% of land is under cultivation, of which 92% of the arable land is rain-fed. The streams and springs are the primary sources of water for domestic and irrigation use. More than 30% of villagers walk one or two kilometers a day to fetch the spring water for domestic use. Spring water contributes partially to the base flows, besides the melt water of snow and glaciers, in the stream/river network of the region.

Geology and Hydrology

The region is characterized by a complex geological setting marked by vast relief variation, with rock formations of Precambrian to Cenozoic in age. A well-developed stratigraphic succession of Paleozoic, Mesozoic, and Cenozoic rock formations exists throughout the Kashmir basin and its peripheries (Yousuf *et al*., 2023). Major tectonostratigraphic features are strikingly parallel to the Himalayan fold-thrust belt in the regionally known Kashmir-Hazara Syntaxis, bending in the NS direction (Kazmi and Jan, 1997). Major landforms consist of gravelly fans, glacial moraines, weathered bedrock, and alluvial valleys (Soil

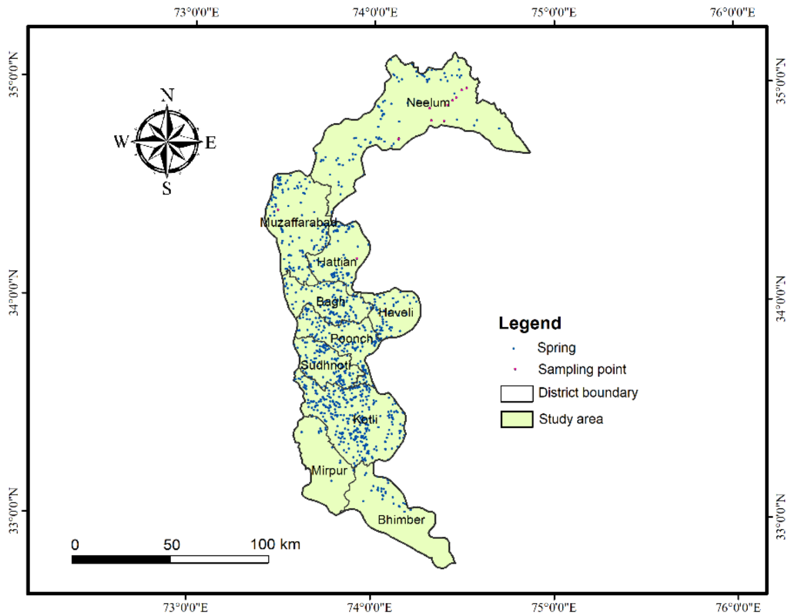

Fig. 2 Spring concentration in different districts of the AJK.

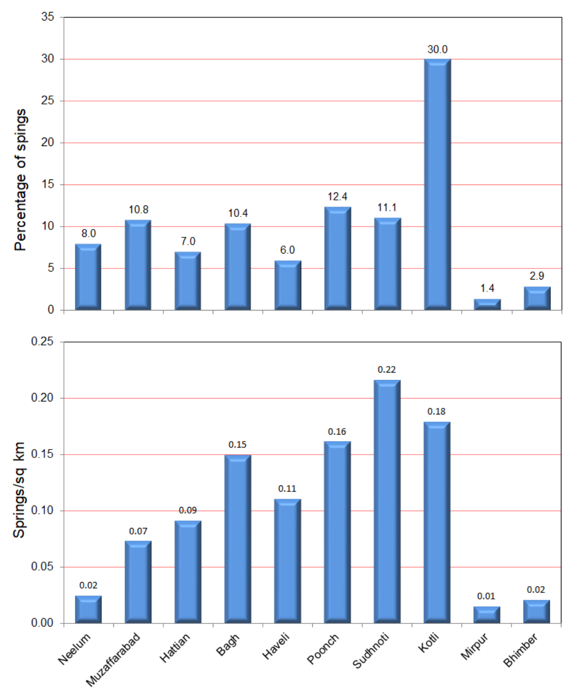

Fig. 3 Percentage of total springs and spring densities in different districts.

Survey Report, 2006). The soils are medium-textured, relatively deep, and gravelly in the lowlands, whereas they are sporadic, gravelly, and well-drained on the mountain slopes. The majority of the region features patchy and irregular aquifers due to the folding and faulting of the underlying rock formations (Zahid, 2009). Groundwater occurs in the fractures of igneous and metamorphic rocks in the Neelam Valley of upper Kashmir and in the sediments of the Miocene-Pliocene mollase of the Potwar Group in lower Kashmir (Malkani, 2020). At places, the groundwater in the fractures and pores yields freshwater and thermal springs that exist in variable geomorphic, structural, and hydrogeological conditions. The sedimentary rocks in the area have a good bedding plane, porosity, and yielding capacity by retaining primary and secondary permeability (Malkani, 2020).

The major spring types in the region include gravity/ depression springs, fracture springs, artesian springs, and thermal springs (Stevens *et al*., 2021; Pandit *et al*., 2024). The thermal springs in Tatta Pani, Kotli, have discharge ranging

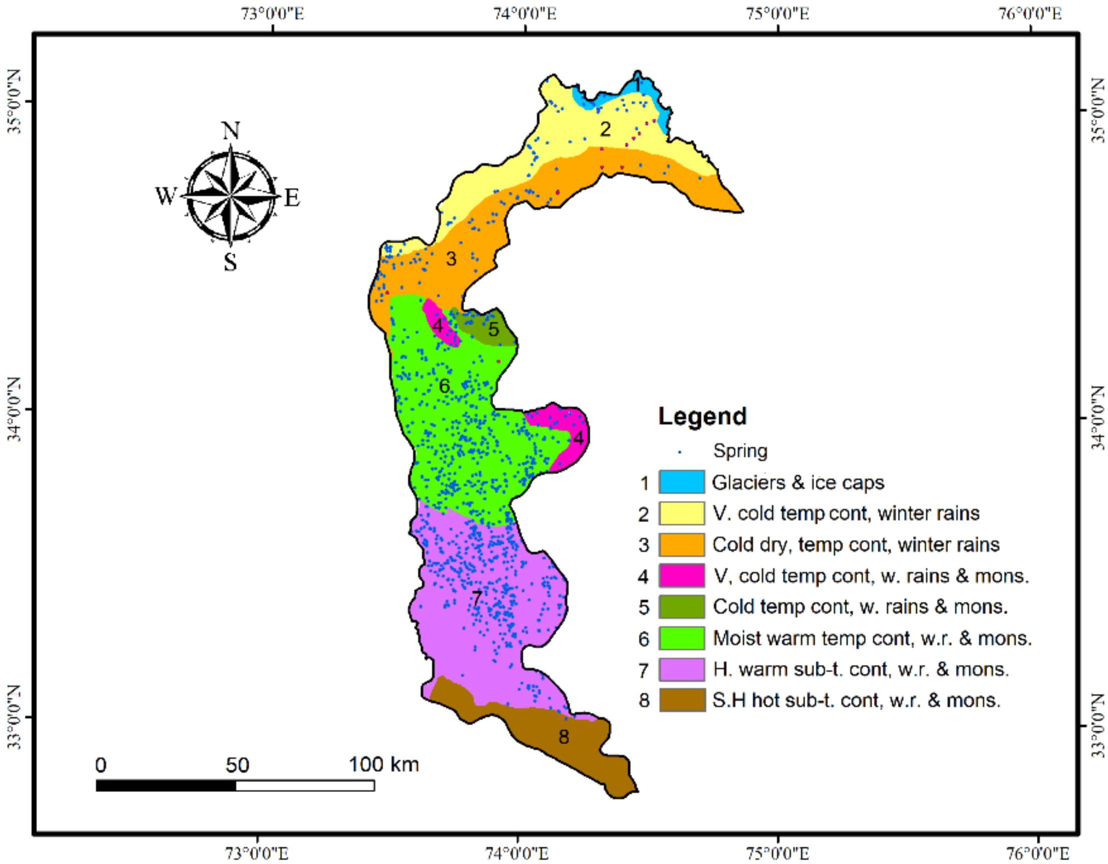

Fig. 4 Spring concentration in various agro-climate zones.

Table 1. Spring concentration in different agro-climate zones of AJK.

Zone	Agro-climate	Coverage %	Springs		Density (sp/km^2)
			Number	%	
1	Glaciers and ice caps (GIC)	1.5	10	0.9	0.06
2	Very cold temperate continental winter rains (VCW)	13.4	55	5.0	0.04
3	Cold dry temperate continental winter rains (CDW)	17.9	77	6.9	0.04
4	Very cold temperate continental winter rains and monsoon (VWM)	3.2	24	2.2	0.07
5	Cold temperate continental winter rains and monsoon (CWM)	1.6	35	3.2	0.19
6	Moist warm temperate continental winter rains and monsoon (MWM)	27.0	460	41.5	0.15
7	Humid warm sub-tropical continental winter rains and monsoon (HWM)	27.1	447	40.3	0.15
8	Sub-humid hot sub-tropical continental winter rains and monsoon (SWM)	8.2	1	0.1	0.0
	Total	100	1109	100	0.10

between 0.5 and 30 liters per second (lps) and surface temperature from 35°C to 94°C (Bakht 2000). Precipitation is the primary source of spring recharge in the region. In the upper reaches, snow cover remains for a few months and slowly seeps down and recharges the aquifer. Springs are either perennial, which flow year-round, or intermittent, which run during the rainy and snowy seasons only. Spring water contributes partially to the base flows, besides the melt water of snow and glaciers, in the stream/river network of the region.

Table 2. Spring distribution in different bio-physical regions of the study area.

Physiography	Coverage		Springs		Density (sp/km^2)
	km^2	%	Number	%	
High Mountains	2594	19.5	82	7.4	0.03
Middle Mountains	2541	19.1	159	14.3	0.06
Low Mountains	2889	21.7	393	35.4	0.14
Siwaliks	2399	18.0	305	27.5	0.13
Hilly area	2558	19.2	170	15.3	0.07
Lowlands	316	2.4	-	-	-
Slope					
<5°	1400	10.5	93	8.4	0.07
5° to 15°	2809	21.1	304	27.4	0.11
15° to 30°	4926	37.0	479	43.2	0.10
>30°	4162	31.3	233	21.0	0.06
Rainfall (mm)					
>1250	5102	38.4	619	55.8	0.12
1000-1250	5835	43.9	440	39.7	0.08
750-1000	1099	8.3	17	1.5	0.02
500-750	1260	9.5	33	3.0	0.03
NDVI					
≤ 0	1673	12.6	44	4.0	0.03
0–0.2	618	4.6	10	0.9	0.02
0.2–0.4	1987	14.9	159	14.4	0.08
0.4–0.6	7652	57.5	793	71.5	0.10
>0.6	1367	10.3	102	9.2	0.07
Total	13297	100.0	1109	100.0	0.08

Materials and Methods

Data Used

Thematic data of topography, infrastructure, soils and landforms, geology, land use, climate and hydrology (drainage network, river discharges) were obtained from different sources, such as the Soil Survey Department, Geological Survey of Pakistan, Pakistan Meteorological Department and Water and Power Development Authority. The rainfall data was gathered for the 1990-2019 period to analyze its spatial pattern in the study area. The spatial data of springs was acquired from Survey of Pakistan (SoP), which was collected by the SoP team by conducting Global Positioning surveys in various parts of the study area. The SRTM (Shuttle Radar Topography Mission) DEM 90 m resolution available at the https://www.usgs.gov/programs site was employed for topographic analysis. The Normalized Difference Vegetation Index (NDVI) eight-day seamless) product 250 m resolution (2020) was downloaded (https://modis.gsfc.nasa.gov) to analyze vegetation density in the study area. The product is created from Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance data and is important for differentiating between vegetated and non-vegetated areas (Huang *et al*., 2021). Owing to geographic limitations, spring discharge was difficult to collect; therefore, an analog approach following previous studies was adopted for its approximation. Pandit *et al*. (2024) had estimated spring discharge within the range of 0.01-10 liters/sec in the Himalayan region.

Spatial Data Preparation

The thematic layers of climate, elevation, and landforms were prepared, and spring concentration was determined in different agro-climate zones, physiographic regions, slope classes, rainfall zones, and administrative units of the study area using ArcGIS software. The physiographic zones identified using the DEM data are high mountains (> 3000 m), middle mountains (2000-3000 m), low mountains (1200-2000 m), Siwaliks (700-1200 m), hilly areas (300-700 m), and lowlands (<300 m elevation). As slope is an important part in the characterization of a spring resource, the slope of the area was determined from the DEM. The association of

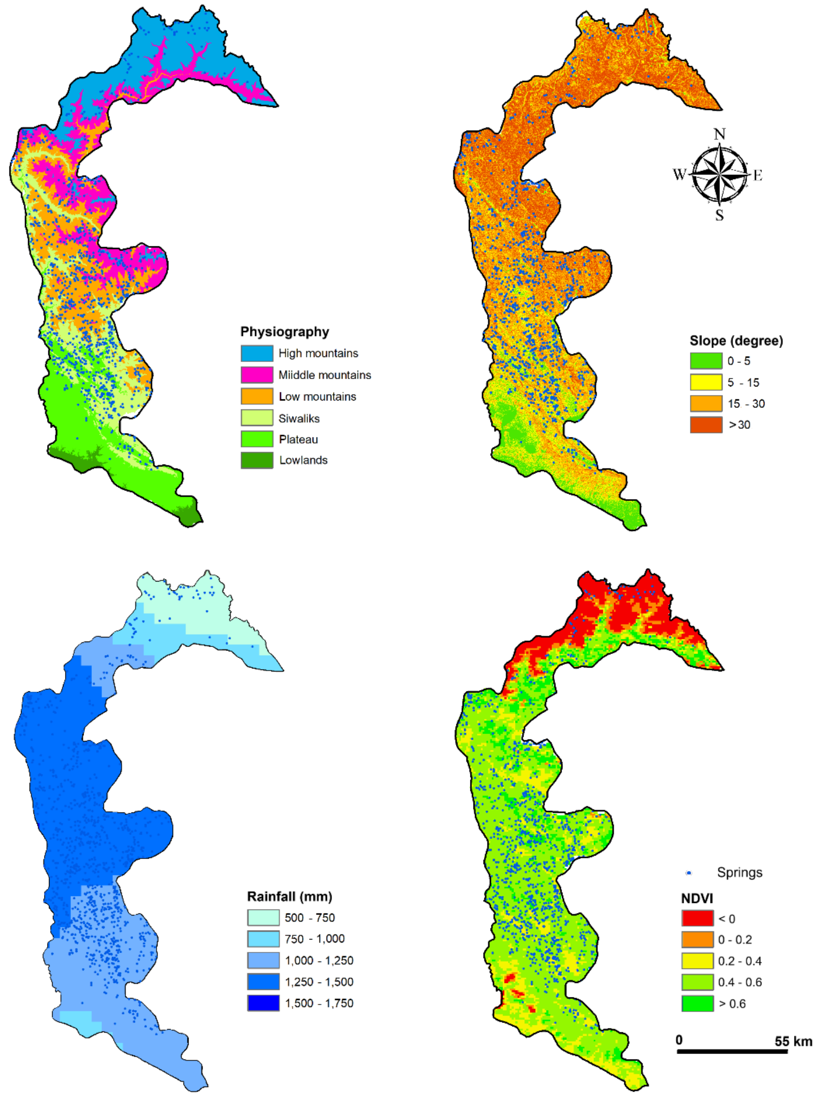

Fig. 5 Spring concentration in various physiographic, slope, rainfall and NDVI classes of the AJK area.

springs was studied with various slope classes, i.e., flat to gentle (< 5° slope), gentle to moderate (5° to 15°), moderate to high (15° to 30°), and very steep (> 30°) (Ashraf and Ahmad, 2025). The mean annual rainfall was mapped by employing the inverse distance weightage (IDW) method and analyzed with spring concentration. The IDW interpolation technique has been commonly used in hydrology for mapping rainfall distribution in different regions (Tiwari *et al*., 2019; Hussain *et al*., 2021). After finalizing the thematic data layers, spring density in each class of that layer was determined through overlay analysis. The springs were counted in each class of the thematic layer, and the number was divided by the area of that class to obtain density in springs/km² in each layer.

The random sampling method was used to collect the water samples from various spring fed draining sites of the study area. The physicochemical tests conducted include pH, turbidity, electrical conductivity (EC), calcium (Ca), chloride (Cl), total dissolved solids (TDS), sulfate (SO_4), magnesium (Mg), nitrate-N, total hardness (TDS), sodium (Na), bicarbonates (HCO_3), alkalinity, and potassium (K). TDS is contributed mainly by inorganic salts, i.e., Ca, Cl, K, Na, Mg, HCO_3, and SO_4, along with a few other trace amounts of organic materials (Valiallahi and Yazdani, 2025). The samples were analyzed from the water quality laboratory of the Pakistan Council of Research in Water Resources (PCRWR). The water quality parameters were statistically analyzed using techniques such as Gibbs diagrams to

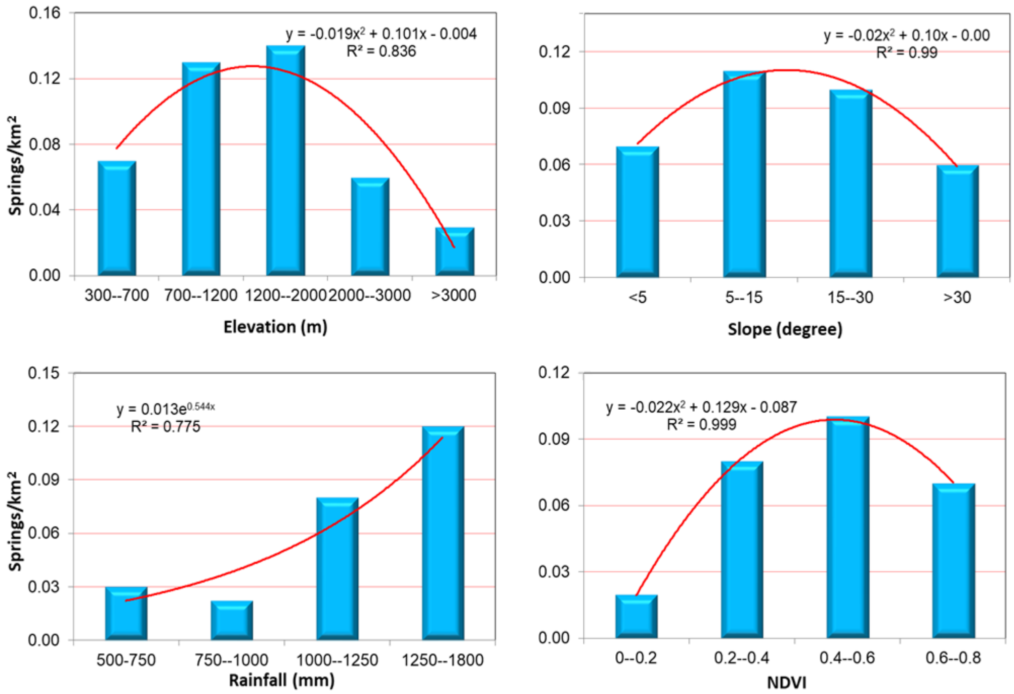

Fig. 6 Relationship of spring density with different bio-physical factors in the study area.

evaluate sources of solute in the water, and the Spearman correlation test for relationship analysis between various water quality parameters. A Gibbs diagram was plotted, which ascertains the source of ion contribution in the samples, i.e., whether precipitation, rock-water interaction (weathering), or evaporation-crystallization predominates the dissolved chemical ingredients (Gibbs, 1970; Marandi and Shand, 2018). The Excel software was used to create a Spearman correlation matrix that shows non-parametric rank-based correlations between pairs of distinct parameters. This correlation is suitable for multiple variables with non-normal data distributions (Muloogi *et al.*, 2026). The coefficient value -1 represents a perfect negative monotonic trend, while +1 shows a perfect positive monotonic trend in the matrix.

Results and Discussion

Spring Distribution Analysis

The study revealed a total of 1109 springs in ten districts of the study area (Fig. 2). About 30% of the springs, were observed in the Kotli, 12.4% in the Poonch, and 11.1% in the Sudhnoti district (Fig. 3). The spring concentration was found to be between 50 and 100 in the Neelum, Hattian, and Haveli districts, while it was found to be less than 50 springs each in the Mirpur and Bhimber districts. Among different agro-climate zones defined in the AJK (Soil Survey Report, 2006), moist warm temperate continental (MWM) and humid warm sub-tropical continental winter rains and monsoon (HWM) were found to cover collectively about 54% of the study area (Table 1). The cold dry temperate (CDW) extends over 17.9%, and the very cold temperate continental winter rains (VCW) over 13.4% of the area. About 8.2% and 3.2% of the areas were found to be contributed by the sub-humid hot sub-tropical continental (SWM) and very cold temperate continental winter rains and monsoon (VWM) zones, while other zones, i.e., cold temperate continental winter rains and monsoon (CWM) and glaciers and ice caps (GIC), occupy less than 2% of the area. The majority of about 41.5% of the springs were identified in the MWM zone and 40.3% in the HWM zone, while the least number of springs were observed in the SWM, followed by the GIC zones (Table 1, Fig. 4).

Higher concentrations of spring were observed in the low mountains (393), followed by Siwaliks (305), likely due to favorable hydrogeological conditions. The alluvial deposits and shallow groundwater conditions typically allow springs to emerge easily. The majority of springs were observed in the slope classes 15° – 30° (i.e., 479) and 5° – 15° (i.e., 304) (Fig. 5, Table 2). Pandit *et al.* (2024) identified nearly 43% of springs over a <30° slope class in the Rangun Khola watershed of the Nepal Himalaya. Mean annual rainfall was 500-1516 mm in the period 1990-2019 in the study area. The maximum number of springs, i.e., 619, was recorded in the 1250–1500 mm rainfall zone, followed by 440 in the 1000–1250 mm zone (Table 2). Most of about 71.5% springs were observed in the 0.4–0.6 NDVI class, followed by 14.4% springs in the 0.2–0.4 class. About 9.2% of springs were identified in the >0.6 NDVI class (representing dense vegetation), while only 0.9% were noticed in the 0–0.2 class (representing least vegetation cover) in the area (Table 2).
Overall, the spring density was found to be over 0.08 springs/km² in the study area. It was observed approximately

Table 3. Water quality analysis of different springs in the study area.

Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
EC(us/cm)	334	170	188	133	231	607	200	88	106	56	180	305
pH	8.06	8.11	8.18	8.12	8.22	8.04	8.05	8.03	7.95	7.94	7.95	7.83
TDS	155	77	82	57	102	272	92	37	42	22	77	142
HCO3 (mg/L)	72	32	32	32	42	112	42	22	27	17	42	42
Ca (mg/L)	41	13	17	11	15	61	29	11	11	BDL	13	41
Cl (mg/L)	50	22	26	24	30	20	14	BDL	BDL	BDL	18	16
Mg (mg/L)	13	11	10	7	16	29	5	2	4	5	11	10
K (mg/L)	0.9	2.5	1	2.5	5.4	6	4.4	1.5	2.9	1.5	2.2	2.5
Na (mg/L)	5	4	4	4	4	4	4	4	4	4	5	5
SO4 (mg/L)	25	23	24	BDL	30	141	37	19	24	16	21	84
Nitrate-N (mg/L)	0.28	0.41	0.38	0.36	0.36	0.37	0.46	0.44	0.87	0.52	0.53	0.98
TDS (mg/L)	184	94	103	73	127	364	110	48	58	31	99	168
Turbidity (NTU)					BDL	BDL	BDL	0.7			BDL	BDL

BDL denotes Below detection limit

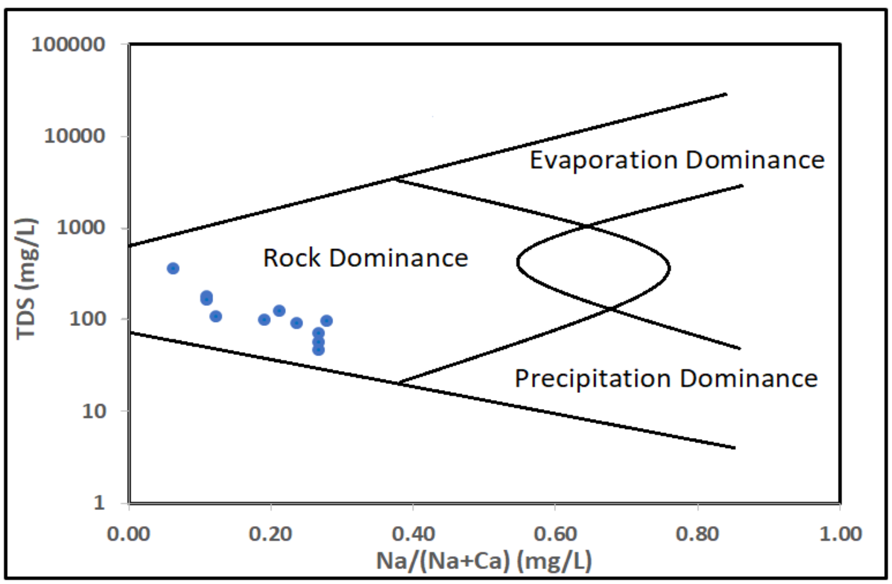

Fig. 7 Gibbs diagram indicating water samples in various zones.

0.22 springs/km² in the Sudhnoti, 0.18 springs/km² in the Kotli, and 0.16 springs/km² in the Poonch district, likely due to the prevalence of the monsoonal effect and fractured rock formations in the area (Fig. 3). Minimum spring density, i.e., about 0.01 springs/km², was observed in the Mirpur district. The spring densities of about 0.11 springs/km² and 0.1 springs/km² were observed in the slope classes 15°–30° and 5°–15°, respectively (Table 2). The spring densities of over 0.14 and 0.13 springs/km² were found in the low mountains and Siwaliks, respectively. The spring density was found to be at its maximum, i.e., approximately 0.12 springs/km² in the 1250–1500 mm rainfall zone, followed by 0.08 springs/km² in the 1000–1250 mm zone. The density appears to exhibit an exponential increase with annual rainfall (Fig. 6), pointing towards a significant role of rainfall in maintaining the spring resource in the area. According to Negi and Joshi (2004) and Agarwal *et al*. (2012), springs in the Himalayan region are largely influenced by rainfall. A spring density of 1.63 springs/km² was assessed by Pandit *et al*. (2024) in one of the watersheds of western Nepal influenced by the monsoonal effect. Shah *et al*. (2026) noticed an increase in spring discharge during the post-monsoon season as compared to the pre-monsoon season in Nepal, exhibiting the effective role of rainfall in sustaining

Parameter	EC	pH	TH	HCO3	Ca	Cl	Mg	K	Na	SO4	Nitrate-N	TDS
EC	1.000	0.228	0.998	0.950	0.968	0.592	0.770	0.293	0.418	0.855	-0.354	1.000
pH	0.228	1.000	0.247	0.181	0.147	0.776	0.386	0.074	-0.391	0.002	-0.818	0.228
TH	0.998	0.247	1.000	0.939	0.970	0.600	0.771	0.300	0.391	0.860	-0.368	0.998
HCO3	0.950	0.181	0.939	1.000	0.891	0.556	0.788	0.333	0.486	0.747	-0.347	0.950
Ca	0.968	0.147	0.970	0.891	1.000	0.473	0.652	0.228	0.394	0.881	-0.244	0.968
Cl	0.592	0.776	0.600	0.556	0.473	1.000	0.754	-0.099	0.197	0.198	-0.797	0.592
Mg	0.770	0.386	0.771	0.788	0.652	0.754	1.000	0.229	0.308	0.488	-0.521	0.770
K	0.293	0.074	0.300	0.333	0.228	-0.099	0.229	1.000	-0.366	0.509	0.057	0.293
Na	0.418	-0.391	0.391	0.486	0.394	0.197	0.308	-0.366	1.000	0.195	0.195	0.418
SO4	0.855	0.002	0.860	0.747	0.881	0.198	0.488	0.509	0.195	1.000	-0.007	0.855
Nitrate-N	-0.354	-0.818	-0.368	-0.347	-0.244	-0.797	-0.521	0.057	0.195	-0.007	1.000	-0.354
TDS	1.000	0.228	0.998	0.950	0.968	0.592	0.770	0.293	0.418	0.855	-0.354	1.000

-1.00	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00

Fig. 8 Spearman correlation matrix of various water quality parameters.

the spring resource. Among various NDVI classes, higher spring densities were observed in the 0.4–0.6 class, i.e., 0.1 springs/km², and the 0.2–0.4 class, i.e., 0.08 springs/km². The spring density was found to be about 0.07 springs/km² in the >0.6 NDVI class, while it was noticed least, i.e., 0.02 springs/km² in the 0–0.2 class (Table 2).

Water Quality Analysis

There is growing concern about the quality of spring water due to contamination from natural and anthropogenic sources. Since the socio-economic importance of these springs cannot be underestimated, it is essential to evaluate their water quality. EC is an important measure of metal ion concentration dissolved in drinking water. The sample S6 exhibited higher EC (607 µS/cm), TDS (272), HCO_3 (112 mg/L), Ca (61 mg/L), Mg (29 mg/L), K (96 mg/L), SO_4 (141 mg/L), and TDS (364 mg/L) values than other samples (Table 3). The elevated values of parameters in S6 are likely caused by localized sources, i.e., geologic deposits, ground composition, or anthropogenic sources, i.e., agricultural runoff and industrial waste. Areas with abundant calcium-bearing minerals, groundwater movement, and carbon dioxide uptake can influence the concentration of calcium (Zhang *et al*., 2024). During the study period, the pH in the samples ranged from 7.83 to 8.22, which are within the safe limits (6.5-8.5) of the World Health Organization (WHO 2022). The maximum concentration of Chloride was found to be 50 mg/L in the sample S1 (less than the permitted Cl level of 250 mg/L set by WHO). The chloride concentration in water or soil can be influenced by factors such as evaporation rates, runoff, and pollution (Svensson *et al*., 2021). The turbidity of the samples was observed to be less than 5 NTU, which is considered clean for the surface water.

The nitrate (NO_3) levels were found within the WHO recommended limit of 50 mg/L (Table 3) which are generally associated with agricultural runoff, especially from fertilizers or manufacturing processes, and have a great influence on human health and environmental quality. The hydrochemical data analysis using Gibb's diagram exhibited all the samples in the rock dominance zone (Fig. 7), which shows that the primary source of ions in the water is chemical weathering of rocks. A strong positive relationship between EC and TDS is shown by the Spearman rank-correlation matrix points (Fig. 8) toward an increase in conductivity with dissolved ions in the water. In mountainous areas, springs are mainly controlled by lithological contacts, fractures, and structural breaks in hard-rock formations. The close correlation between Ca and Mg shown in the matrix is likely as a result of carbonate rock weathering. The previous studies revealed water quality of the springs and other sources mostly within acceptable limits of WHO in the Muzaffarabad and Rawalakot areas of the AJK (Javaid *et al*., 2008; Ali *et al*., 2019; Aziz *et al*., 2025). The researchers intimated that water sources are vulnerable to growing environmental problems.

In this study, the water samples were mostly collected from the open, less populated areas, so there may be springs in the urban areas that may be facing pollution problem and need proper monitoring. In this mountainous region, soil erosion arising from intense rainfall and landslide events, unplanned urban growth, poor farming practices, and deforestation are the major problems (Afsar *et al*., 2025) influencing recharge sources, discharge, and quality of the springs.

Conclusion

The current study focuses on evaluating spring resource potential in the AJK region, Pakistan, for sustainable water resource management. Out of a total of 1109 springs located in the AJK, about 30% of springs lie in the Kotli, 12.4% in the Poonch, 10.8% in the Muzaffarabad, and 10.4% in the

Bagh district. There were 479 springs identified in the 15°–30° slope class, followed by 304 springs in the 5°–15° class with densities of approximately 0.1 springs/km² and 0.11 springs/km², respectively. The spring density was found to be highest, i.e., approximately 0.12 springs/km², in the 1250–1500 mm range, followed by 0.08 springs/km² in the 1000–1250 mm range. The spring density appears to exhibit an exponential increase with annual rainfall of the area, which shows a significant influence of precipitation in sustaining the spring resource. The findings of the study would provide base to develop viable spring management strategies and policies for sustainable development in the region.

For sustaining the spring resource, adoption of an integrated water resource management coupled with effective water use is essential in the region. Spring water may be channelized and kept in tanks and reservoirs for sustained supply for domestic and local irrigation use. Rain harvesting techniques may be adopted in areas where people have no excess to spring and surface water, which is scarce or has become contaminated. There is a need to raise awareness and build capacity of local communities and institutions in advanced water conservation and management techniques for sustainable development in the region. As the spring water quality changes over time and location depending on factors like aquifer supply, mineral dissolution, ion exchange, rock formations, and pollution exposure, long-term monitoring of the spring resource would be beneficial to prevent potential health risks and formulate effective risk mitigation policies. Moreover, impacts of ongoing and expected changes in climate and land use on the spring resource need to be assessed to support water security in the region.

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