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Multivariate statistical approach for the determination of physicochemical parameters of trans-Himalayan high-altitude streams of Leh, Ladakh, India

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Abstract

Monitoring physicochemical properties in stream ecosystems is essential for sustaining their ecological health and services. The primary factor contributing to the decline in water quality is human pressure, encompassing land use, pesticide and fertiliser use, urbanisation, forest loss, and climate change. The present study assessed 11 physicochemical parameters at four distinct sites in the snow-fed stream of Ladakh, Trans-Himalaya, from March 2022 to February 2024. Multivariate statistical approaches were employed to generate precise information on the parameters of the streams. Significant ($p < 0.05$) spatiotemporal variations in the above parameters were identified. Linear regression revealed significant ($p < 0.05$) correlations among multiple physicochemical parameters, with substantial magnitudes and extents. PCA shows that seasonal variation was more substantial than site-specific variation in determining water quality patterns. The physicochemical parameters including air temperature (AT), water temperature (WT), electrical conductivity (EC), total dissolved solids (TDS), free carbon dioxide (CO₂), total alkalinity (TA), pH, nitrate-nitrogen (NO₂-N), chloride (Cl⁻), and calcium (Ca²⁺) played a significant role in determining the qualitative characteristics of the snow-fed streams of trans-Himalayan region. Overall, the measured water quality parameters remained within the permissible limits prescribed by various national and international standard-setting agencies. While CA indicated that the high-altitude sites Hanle and Yaya Tso show less-impacted sites, and the low-altitude site Shey is relatively more susceptible to pollution. The present study could serve as a baseline for managing and conserving the most important resource of the aquatic ecosphere, thereby improving water quality for humans and their resident faunal communities. The findings also provide valuable insights for ecologists, limnologists, and policymakers, supporting the formulation of long-term management frameworks and conservation strategies aimed at preserving the freshwater ecosystems of the Trans-Himalayan region.

Keywords Freshwater ecosystem, Water quality, Stream, Trans-Himalaya, Ladakh

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Introduction

In both lentic and lotic environments, water serves as a home for a diverse array of aquatic plants and animals. Among all water bodies, streams and rivers are recognized as fundamental sources of surface water and key components of ecosystems. They are providing a wide range of services, including generating energy, supplying drinking water, facilitating irrigation, and supporting various activities (Mirza et al. 2014; Boyd 2015). Despite their critical role in sustaining life and contributing significantly to the economy, both streams and rivers are currently highly susceptible to pollution (Varol 2020). They currently face considerable challenges in maintaining their good health due to various anthropogenic activities and natural events. (Seth et al. 2016; Mir et al. 2023). A long-term decline in groundwater levels from both lentic and lotic resources has been reported across several Indian states, prompting numerous investigations into this issue. Gupta et al. (2021) assessed the groundwater conditions from Mahoba district of Uttar Pradesh and reported that approximately 80% of the area exhibits low to moderate groundwater potential. Despite this, the region experiences significant water scarcity, primarily due to over-extraction and inadequate water recharge. These findings underscore the critical need for effective water conservation measures with enhanced public awareness. Apart from India, the contamination has emerged as a global concern, as the direct consumption of untreated freshwater exposes people to multiple pollutants. In many states of northern India, the quality of water is reported to be influenced by both geogenic and anthropogenic fluoride (F^-) enrichment and nitrate (NO_3^-) inputs, which globally, alone impact over 300 million people (Paul et al. 2020; Sen et al. 2022; Gupta et al. 2024), underscoring the urgency of effective monitoring and management of these resources. However, despite increasing recognition of the risks, localized assessments of groundwater quality and potential remain limited, particularly in vulnerable agricultural regions. Some of the challenges presently faced by these water bodies include changes in the climate, increasing populations, uneven urbanisation, industrial establishments, a lack of household wastewater treatment, insufficient monitoring of agriculture-related pesticides and fertilisers, different hydrological patterns, and gravel extraction from the beds of rivers for generating hydropower (Seth et al. 2016; Varol 2020). Due to these factors, the quality of freshwater is deteriorating day by day, and water levels are depleting faster than they can be replenished naturally (Ahmed et al. 2024).

Therefore, it is imperative to understand the causes of the decline in these water bodies and to devise a mechanism for monitoring and restoring their good health. Some of the significant initiatives include identifying

pollution sources, determining variations in water quality across specific regions and seasons, and implementing strategies to reduce river and stream contamination to support effective management plans (Tian et al. 2019; Nong et al. 2020). A thorough understanding of water quality is vital for effective planning and management of water sources and the associated faunal diversity. This can only be accomplished through rigorous methodological techniques that monitor physical and chemical variables across geographical and temporal dimensions (Kasperson et al. 2022; Lawal et al. 2023; Ahmed et al. 2024).

Multivariate statistical approaches have demonstrated their efficacy in studying the physicochemical parameters of water bodies (Ling et al. 2017; Ahmed et al. 2024). One of the world's highest regions in the Trans-Himalaya, Ladakh serves as a mountainous transition zone, situated between the Kunlun Mountains to the north and the Himalayas to the south. The region features snow-capped mountains and unique lentic and lotic freshwater resources, including glaciers, lakes, springs, ponds, and streams, which draw global attention. The majority of water sources accessible for human use in the Ladakh region are lakes, streams and rivers. These water bodies host diverse aquatic ecosystems that play crucial roles in promoting a sustainable economy, enhancing human well-being, and preserving the integrity of biological systems (Islam et al. 2021). Besides, it provides a significant contribution to the livelihoods of a sizable population. However, due to urbanisation and the extensive use of fertilisers and pesticides in agriculture and horticulture, these water bodies are experiencing significant pollution.

In general, both rivers and streams are components of hydrological changes over time and space across different catchment areas. The physicochemical properties of these water resources are primarily governed by the prevailing climatic factors and geological features of the surrounding catchment area (Mehari et al. 2014; Docile et al. 2016). In contrast, biotic indicators are significantly influenced by both habitat conditions and the physicochemical quality of the water (Prommi and Payakka 2015). Spatial and seasonal variations in stream environments are often associated with differences in anthropogenic activities, stream ecological features, and temporal patterns specific to the region (Mehari et al. 2014). Although, recent investigations on the water quality of the rivers in the Ladakh Himalaya have revealed the presence of heavy metals, fluctuations in physicochemical parameters, elevated concentrations of sodium (Na), magnesium (Mg), calcium (Ca), aluminium (Al), and the occurrence of *Escherichia coli* (*E. coli*) contamination (Bharti et al. 2017; Giri 2017; Giri et al. 2019). However, studies on evaluating water quality in the high-altitude region of Leh, Ladakh, India, have been sparse. Therefore,

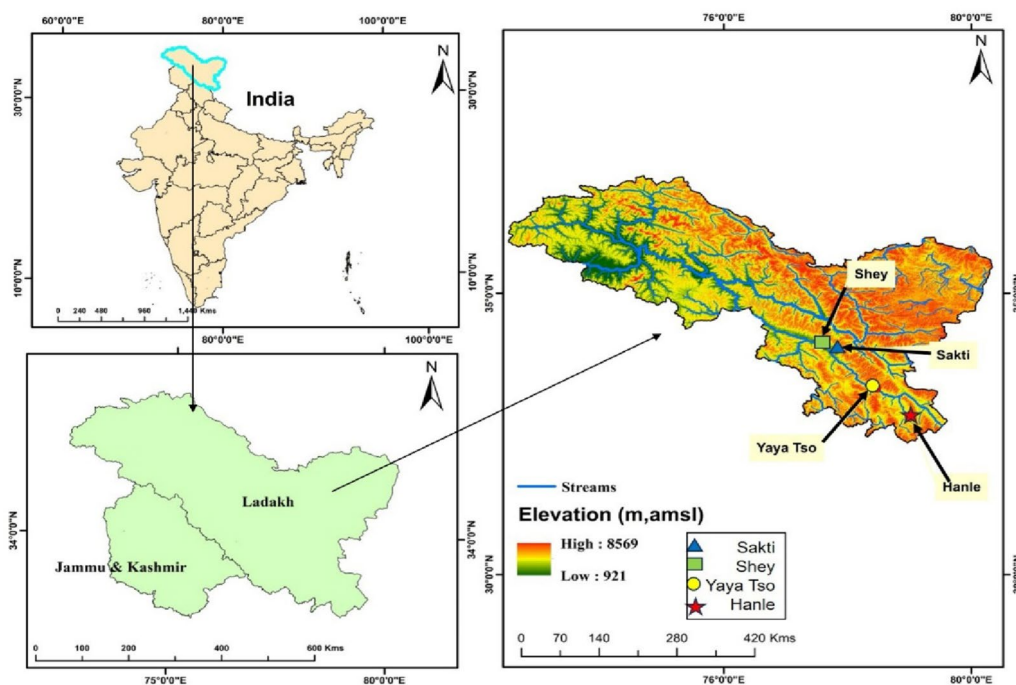


Fig. 1 Location map of selected sampling sites of Leh, Ladakh, India

Table 1 Description of sampling sites of Leh, Ladakh, India

Description	Sites name			
Sampling site	Hanle	Yaya Tso	Sakti	Shey
Site code	I	II	III	IV
Land use types	High altitude cold-water stream with less human habitation.	High-altitude, clear blue water with less human habitation	Slow-moving stream with human habitation and animal grazing	Slow-moving stream with human inhabitation and animal grazing
Coordinates	32.47° N & 78.98° E	33.31° N & 78.47° E	34.00° N & 77.81° E	34.08° N & 77.61° E
Altitude (m a.s.l)	4520	4500	3872	3224

in the present study, an attempt has been made to examine the ecological conditions and spatio-temporal fluctuations in the water quality of four essential water sources found in the trans-Himalayan region of Ladakh: Yaya Tso, Hanle, Shakti, and Shey streams by measuring physicochemical parameters with respect to their correlations with other ecological attributes.

Materials and methods

Study area and sampling sites

The Ladakh Region is geographically and ecologically unique, located in the northernmost part of India, and includes various locations such as Leh and Kargil. In terms of area, Leh is the largest region within Ladakh,

situated between 32° and 36° North latitude and 75° and 80° East longitude, with elevations ranging from 2300 to 5000 m above sea level. The region features frigid, arid environments, often called the “cold desert of the world.” Its climate is characterized by high summer temperatures, peaking in July, while winter temperatures are notably low, with January the coldest month. During the current study period, eleven parameters were selected from four different sampling sites, based on land use and altitude. Figure 1; Table 1 show the layout of the survey area. Site I (Hanle, also spelled Anle) is a village in the union territory of Ladakh, India. Hanle is also known for its Indian Astronomical Observatory station. Site II (Yaya Tso), located at an elevation of 4500 m, is known as a paradise for birds and has been designated as Ladakh’s first biodiversity heritage site (BHS). Site III (Shey) is about 15 km east of the current capital of Ladakh, Leh. It is situated at an average altitude of 3,224 m (11,204 feet). Site IV (Sakti) is a town 45 km from Leh city, at an altitude of 3872 m (12,507 feet). These sites primarily receive water from precipitation and snowmelt.

Collection of water samples

A comprehensive sampling methodology was developed to measure a range of physicochemical parameters at each sampling site in the Leh, Ladakh region. Water samples were collected monthly for 2 years, from March 2022 to February 2024. Before sample collection, all sample bottles were meticulously cleaned, sun-dried, and rinsed twice with water at the sampling site to

eliminate potential contaminants. The bottles were subsequently labelled, and the coordinates of the sampling sites were generated in ArcGIS. Some parameters were documented at the sites. The preserved water samples were brought to the Lab for further analysis of remaining parameters by using standard procedures (APHA 1998).

Analysis of water samples

A total of 11 physicochemical parameters were examined in this study using standard analytical methods (Table 2) recommended by the American Public Health Association (APHA 1998). These parameters include air temperature (AT), water temperature (WT), pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), free carbon dioxide (FCO₂), total alkalinity (TA), nitrate-nitrogen (NO₃-N), chloride (Cl⁻), and calcium (Ca²⁺). Both AT and WT were recorded using a mercury Celsius thermometer, pH, EC, and TDS were measured using a portable multiparameter (HANNA HI9829), DO was measured using a modified Winkler's

method (APHA 1998), FCO₂ and TA were analysed by using a titrimetric method (APHA 1998), Cl⁻ was recorded using an argentometric titration procedure, and NO₃-N and Ca²⁺ were measured using a spectrophotometer (Hach DR 5000 USA).

Statistical analysis

Descriptive statistical analyses, including the calculation of range, mean, and standard deviation of physicochemical parameters, were performed using MS Excel 2016. Data collected from each sampling site over the two-year study period, from March 2022 to February 2024, were compiled to assess spatial variations. To evaluate seasonal trends, the monthly data were grouped into three distinct seasons: spring (March, April, May), summer (June, July, August), and autumn (September, October, November). Collection efforts during the winter season are not feasible due to harsh environmental conditions, including persistent snow cover, icy terrain, and sub-zero temperatures that typically persist until the end of February. Water samples were collected based on the presence of mollusc species and their associated habitats. However, mollusc collection during the extreme cold of winter again was not possible under such conditions. All statistical analyses were conducted in R Studio version 2024.12.1. Data normality was assessed using the Shapiro-Wilk test (stats package). The physicochemical parameters were analysed using multi-factorial ANOVA to evaluate the effects of Site, Season, Month, and Year. Significant differences ($p < 0.05$) were further examined using Duncan's multiple range test for pairwise comparisons, implemented via the agricolae package. Pearson's correlation analysis was performed using the psych package to assess relationships among the variables. Correlation networks were visualised using the qqgraph package. To reduce data dimensionality and identify underlying patterns, Principal Component Analysis (PCA) was conducted on z-standardised data using the FactoMineR and FactoExtra packages. Hierarchical clustering analysis (HCA) was also applied to explore sample grouping based on Euclidean distances and Ward's linkage method, implemented via the cluster package. Figures were generated using the ggplot2, ggpubr, and ggpmisc packages for clear and informative visualisations (Kassambara 2020).

Results

This study generated data on the physicochemical condition of the streams originating from Leh, Ladakh, by examining 11 parameters. The data are summarised by reporting minimum, maximum, mean and standard deviation values (Table 3; Fig. 2). A comprehensive statistical analysis was performed to assess significant and non-significant differences using Analysis of Variance (ANOVA),

Table 2 List of physicochemical parameters and analytical methods applied during the present study

S. No.	Parameters	Abbreviation	Units	Analytical methods
1	Air temperature	AT	°C	By thermometer (ZEAL-76 mm lmm)
2	Water temperature	WT	°C	By thermometer (ZEAL-76 mm lmm)
3	pH	pH	–	Multiparameter meter (HANNA HI9829)
4	Electrical conductivity	EC	µS cm ⁻¹	Multiparameter meter (HANNA HI9829)
5	Total dissolved solids	DO	mg/L	Multiparameter meter (HANNA HI9829)
6	Dissolved oxygen	DO	mg/L	Winkler's method (APHA, 1998)
7	Free carbon dioxide	FCO ₂	mg/L	Titrimetric method (APHA, 1998)
8	Total alkalinity	TA	mg/L	Titrimetric method (APHA, 1998)
9	Nitrate-nitrogen	NO ₃ -N	(mg/L)	Sodium salicylate method (CSIR, 1974)
10	Chloride	Cl ⁻	mg/L	Argentometric method (APHA, 1998)
11	Calcium	Ca ²⁺	mg/L	Titrimetric method (APHA, 1998)

Table 3 The overall trend of physicochemical parameters of streams in Leh, Ladakh, the trans-Himalayan region of India

Parameters	Min	Max	Mean ± SD
AT (°C)	8.7	26.7	18.8 ± 4.9
WT (°C)	3.3	17.6	10.53 ± 4.14
pH	7.5	8.4	7.97 ± 0.22
EC (µS cm ⁻¹)	183.3	343.1	231.1 ± 31.19
TDS (mg/L)	102	201.1	139.52 ± 19.32
DO (mg/L)	5.6	11.8	8.12 ± 1.71
FCO ₂ (mg/L)	0.4	1.2	0.78 ± 0.21
T A (mg/L)	165	207.5	189.40 ± 13.10
NO ₃ -N (mg/L)	0.01	1.0	0.17 ± 0.25
Cl ⁻ (mg/L)	1.8	11.6	6.26 ± 2.72
Ca ²⁺ (mg/L)	10.1	26.9	16.96 ± 3.95

followed by Duncan’s Multiple Range Test to evaluate spatial and temporal variations (Tables 4 and 5).

In this study a significant ($p < 0.05$) difference in atmospheric temperature across sites and season. The highest AT of 21.04 ± 3.80 °C was recorded at Shey, while the lowest value of 15.62 ± 6.18 °C was observed at Hanle. Additionally, the highest AT value of 24.07 ± 1.60 °C was noted during summer, and lowest value of 16.14 ± 3.88 °C in autumn season respectively. These observations support the general climate pattern of the study area, with respect to warm summers and cold winter seasons.

The present study also reveals a significant ($p < 0.05$) difference in water temperature across sites and seasons.

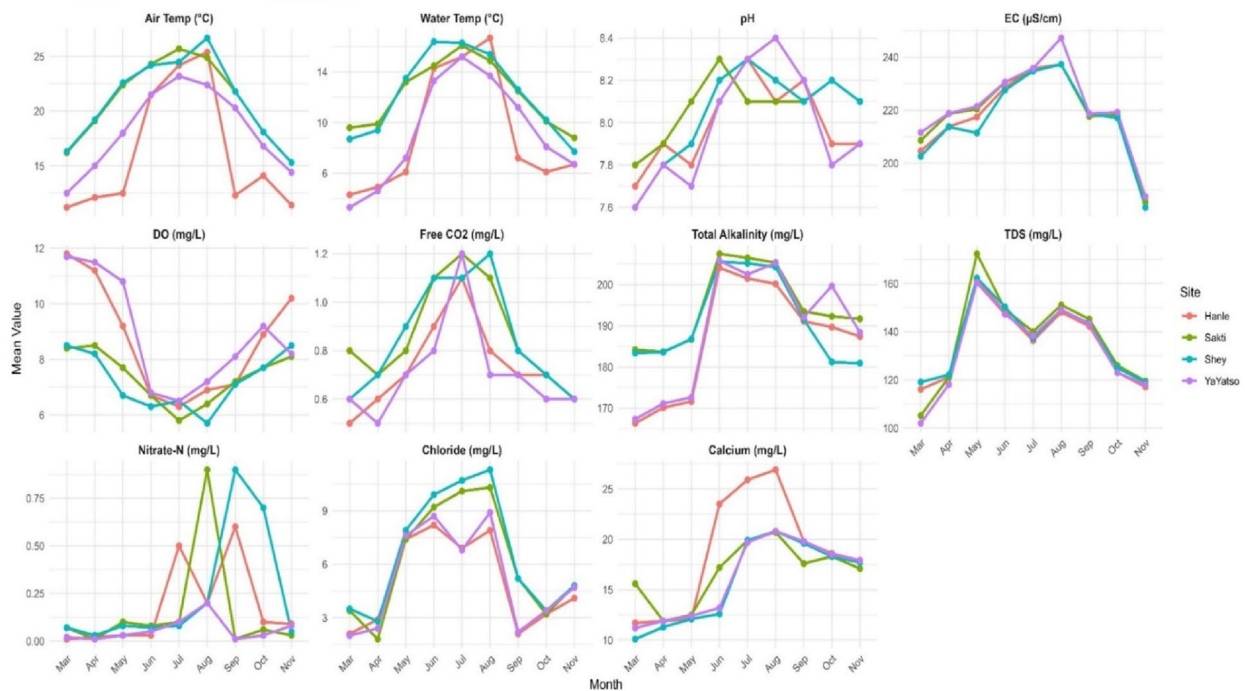


Fig. 2 Comparative analysis of physicochemical parameters across four streams of Leh Ladakh, trans-Himalayan region

Table 4 ANOVA (Duncan’s multiple range test) showing spatial variation in physicochemical parameters of streams of Leh, Ladakh, the trans-Himalayan region of India

Parameter	Hanle	Yaya Tso	Shey	Sakti
AT (°C)	15.62 ± 6.18 ^b	18.22 ± 3.65 ^{ab}	21.04 ± 3.80 ^a	20.69 ± 3.77 ^a
WT (°C)	8.77 ± 5.09 ^c	9.29 ± 4.11 ^{bc}	12.22 ± 3.30 ^a	11.88 ± 2.85 ^{ab}
pH	7.91 ± 0.22 ^a	7.94 ± 0.28 ^a	8.05 ± 0.19 ^b	8.02 ± 0.17 ^b
EC (µS cm ⁻¹)	230.11 ± 31.07 ^a	234.71 ± 35.01 ^a	225.97 ± 25.03 ^a	233.78 ± 34.59 ^a
TDS (mg/L)	138.33 ± 18.61 ^a	137.97 ± 19.96 ^a	139.91 ± 18.21 ^a	141.91 ± 21.75 ^a
DO (mg/L)	8.69 ± 2.00 ^a	9.27 ± 1.84 ^a	7.23 ± 0.92 ^b	7.32 ± 0.88 ^b
FCO ₂ (mg/L)	0.72 ± 0.20 ^b	0.69 ± 0.22 ^c	0.87 ± 0.21 ^a	0.84 ± 0.19 ^{ab}
TA (mg/L)	183.32 ± 15.08 ^b	189.42 ± 14.90 ^{ab}	191.62 ± 10.31 ^{ab}	193.26 ± 10.04 ^a
NO ₃ -N (mg/L)	0.18 ± 0.18 ^a	0.08 ± 0.08 ^a	0.23 ± 0.31 ^a	0.23 ± 0.35 ^a
Cl ⁻ (mg/L)	5.42 ± 2.31 ^a	5.73 ± 2.49 ^a	7.13 ± 2.98 ^a	6.78 ± 2.89 ^a
Ca ²⁺ (mg/L)	18.22 ± 5.12 ^a	16.63 ± 3.86 ^a	16.52 ± 3.68 ^a	16.50 ± 2.89 ^a

*The letters sharing the same superscript in a row are not significantly different ($p > 0.05$)

Table 5 ANOVA (Duncan's multiple range test) showing temporal variation in parameters of streams of Leh, Ladakh, the trans-Himalayan region of India

Parameter	Spring	Summer	Autumn
AT(°C)	16.48±3.83 ^b	24.07±1.60 ^a	16.14±3.88 ^b
WT(°C)	7.91±3.32 ^b	15.22±1.22 ^a	8.49±2.45 ^b
pH	7.77±0.16 ^c	8.16±0.12 ^a	8.00±0.18 ^b
EC (μS cm ⁻¹)	217.25±6.26 ^b	262.53±34.61 ^a	213.66±14.80 ^b
TDS (mg/L)	135.58±19.52 ^b	154.23±18.24 ^a	128.77±8.73 ^b
DO (mg/L)	9.46±1.71 ^a	6.56±0.55 ^c	8.36±1.17 ^b
FCO ₂ (mg/L)	0.67±0.14 ^b	1.02±0.17 ^a	0.66±0.08 ^b
TA (mg/L)	177.50±8.94 ^c	203.10±7.30 ^a	187.60±7.05 ^b
NO ₃ -N(mg/L)	0.07±0.08 ^b	0.34±0.31 ^a	0.13±0.24 ^b
Cl ⁻ (mg/L)	5.55±2.26 ^b	9.17±1.63 ^a	4.07±0.88 ^c
Ca ²⁺ (mg/L)	13.43±3.44 ^c	20.15±3.26 ^a	17.32±1.39 ^b

*The letters sharing the same superscript in a row are not significantly different ($p > 0.05$)

The maximum water temperature, 12.22 ± 3.30 °C, was recorded from Shey, while the lowest, 8.77 ± 5.09 °C, was noted from Hanle. Likewise, the highest WT 15.22 ± 1.22 was observed during the summer season, while lowest values, 7.91 ± 3.32 was recorded in the autumn season from a glacial-fed stream in Ladakh.

The pH of water serves as an initial indicator of water quality, reflecting its acidity or alkalinity. During the present study, the overall alkaline pH of the Leh, Ladakh stream showed a significant ($p < 0.05$) difference between the sampling sites, with the maximum value of 8.05 ± 0.19 °C was observed at the low-altitude site i.e. Shey. In contrast, the minimum pH of 7.91 ± 0.22 °C was recorded at Hanle. pH also varied significantly ($p < 0.05$) between seasons. The maximum pH 8.16 ± 0.12 was recorded in the summer season, while the lowest 7.77 ± 0.16 was found in the spring season of this glacial-fed stream of Ladakh. Increased photosynthetic activity during warmer temperatures and longer daylight hours could be responsible for the summer's higher pH, which lowers dissolved CO₂ concentrations and increases alkalinity.

Although no notable difference in electrical conductivity (EC) was found among the four sampling sites, however there was a significant ($p < 0.05$) variation across different seasons was recorded with respect to EC. The lowest EC, 213.66 ± 14.80 μS cm⁻¹, was recorded in autumn, while the highest, 262.53 ± 34.61 μS cm⁻¹, was observed in summer season of the year. This fluctuation is due to temperature changes that increase ion mobility in water, thus boosting conductivity.

Total dissolved solids measure the concentration of various ions, both inorganic and organic, in a specific volume of water. No significant ($p < 0.05$) difference in TDS was found among the four sampling sites, but there was a notable ($p < 0.05$) seasonal variation was noted in TDS. The lowest TDS, 128.77 ± 8.73 mg/L, was observed

in autumn, while the highest, 154.23 ± 18.24 mg/L, TDC occurred in summer. During the summer, when human activity is at its highest, huge quantities of household, livestock, and agricultural waste are dumped into the stream. These inputs result in elevated amounts of dissolved ions. In the present study a significant ($p < 0.05$) variation was seen in the DO content of high-altitude streams of Ladakh. The minimum DO content of 7.23 ± 0.92 mg/L was recorded from Shey. In contrast, the maximum DO level of 9.27 ± 1.84 mg/L was observed at Hanle. Conversely, the minimum DO level of 6.56 ± 0.55 mg/L was observed in the summer season, while the maximum level of 9.46 ± 1.71 mg/L was seen in the spring season.

The FCO₂ in the present study showed a significant ($p < 0.05$) difference among sites and seasons. A minimum FCO₂ of 0.69 ± 0.22 mg/L was noted at Yaya Tso site, whereas the maximum value of 0.87 ± 0.21 mg/L was observed from Shey. On the other hand, the minimum FCO₂ of 0.66 ± 0.08 mg/L was recorded in autumn, whereas the maximum of 1.02 ± 0.17 mg/L was noted in summer. The maximum FCO₂ recorded during the summer season in the present might be attributed to the highest breakdown of organic matter and the respiratory functions of aquatic organisms. The present study found a significant ($p < 0.05$) variation in TA across sampling sites and seasons. Minimum TA of 183.32 ± 15.08 mg/L was observed at Hanle. In contrast, the maximum value of 193.26 ± 10.04 mg/L was recorded from Sakti site. This variation can be attributed to differences in hydrological conditions associated with high and low discharge periods. The minimum TA was recorded during the spring season, 177.50 ± 8.94 mg/L, while the maximum values of 203.10 ± 7.30 mg/L during the summer season.

In this study, a significant ($p < 0.05$) difference in NO₃-N was found across seasons. Spring season recorded the lowest NO₃-N level of 0.07 ± 0.08 mg/L, while summer showed the highest value of 0.34 ± 0.31 mg/LNO₃-N content. No significant ($p < 0.05$) differences were noted across sampling sites. An elevated Cl⁻ concentrations are frequently interpreted as an indication of pollution and may be harmful to freshwater ecosystems. During the study, no significant ($p < 0.05$) difference in Cl⁻ was observed among different sampling sites, however a significant ($p < 0.05$) in Cl⁻ was noted during different sampling seasons. The minimum Cl⁻ concentration of 4.07 ± 0.88 mg/L was observed in autumn, while the maximum value of 9.17 ± 1.63 mg/L was noted in summer of the year. During the present study, no significant ($p < 0.05$) difference in Ca²⁺ was observed among sampling sites, however a significant ($p < 0.05$) variation in Ca²⁺ was observed across sampling seasons. The minimum Ca²⁺ concentration of 13.43 ± 3.44 mg/L was observed in spring, whereas the maximum concentration

of 20.15 ± 3.26 mg/L was noted in summer season. Moreover, in summer season an elevated evaporation rates characteristic of Ladakh's semi-arid climate reduced water volume in shallow streams and lakes.

Correlation analysis

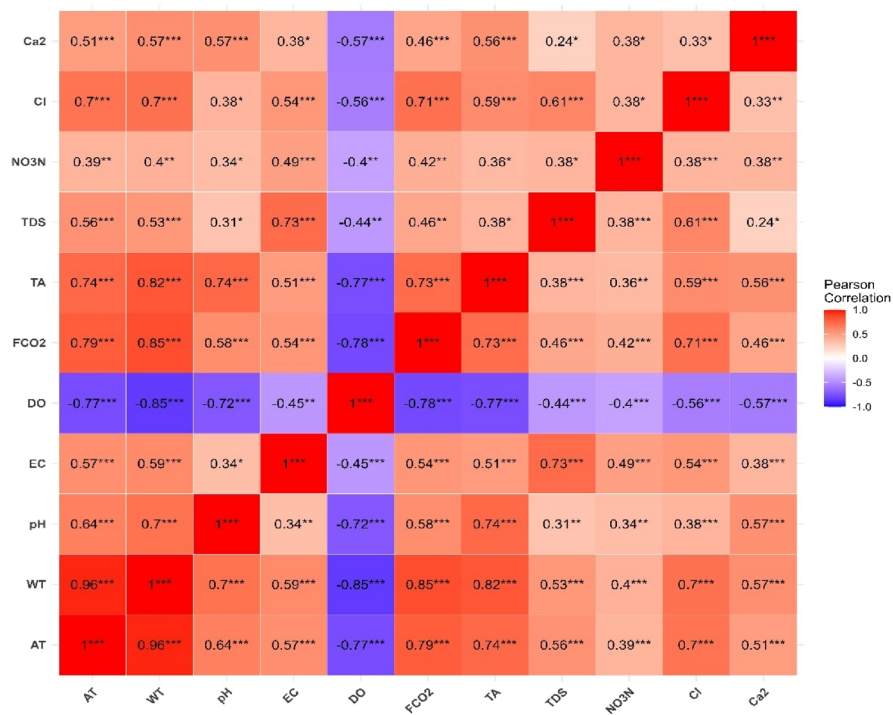
By shedding light on the intricate correlations among different physicochemical characteristics, the correlation study helps us better understand about how many environmental factors affect water quality and the overall health of the water ecosystem. Various biological, chemical, and physical interactions give rise to correlations between different physicochemical variables in aquatic habitats, resulting in both positive and negative connections. In the present study, Pearson's correlation analysis was employed on a normalised dataset to identify significant ($p < 0.05$) correlations among the examined physicochemical parameters. The strength of the relationship is represented by the correlation coefficient (r), which ranges from 1 to -1. Values nearing +1 signify a robust positive correlation, wherein an increase in one variable is closely and linearly linked to an increase in the other variable. In contrast, values near -1 indicate a strong negative correlation, in which a rise in one variable is closely and linearly associated with a decrease in the other (Seth et al. 2016). On the other hand, a score of 0 indicates the absence of a linear relationship or a weak correlation between the variables. The present study clearly demonstrated complex relationships among the analysed physicochemical parameters (Fig. 3a and b). In Fig. 3b, dark green coloration represents positive correlations, while dark red coloration indicates a negative correlation. The intensity of the colour reflects the strength of the correlation: bold and vivid colours denote strong correlations, either positive or negative, whereas pale and subdued colours signify weak correlations, irrespective of direction. During the entire study period, some of the analysed physicochemical parameters exhibited strong positive correlations with one another, except for dissolved oxygen, which showed a strong, significant negative correlation.

A strong positive relationship was found between AT and WT ($r = 0.96$), and between WT and TA ($r = 0.82$). Conversely, a strong negative correlation was observed between WT and DO ($r = -0.85$). In addition to WT, DO showed a significant negative correlation with FCO₂ ($r = -0.78$) and TA ($r = -0.77$). FCO₂ also had a strong positive correlation with WT ($r = 0.85$). Additionally, other parameters such as Cl⁻, TDS, NO₃-N, and EC also negatively correlated with DO. Conversely, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity (TA), and calcium (Ca²⁺) exhibited positive correlations, reflecting their collective role in the ionic composition and mineralization of the water. The

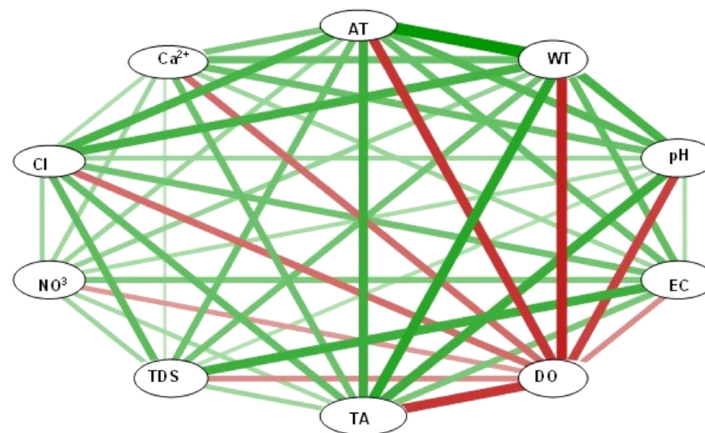
inverse relationship between pH and FCO₂ suggests that increased dissolved carbon dioxide promotes acidification by forming carbonic acid. Furthermore, nitrate-nitrogen (NO₃-N), chloride (Cl⁻), and Ca²⁺ showed positive associations with EC and TDS, indicating their significant roles in determining overall ionic strength. Overall, the interactions among various water parameters resulted in both negative and positive correlations, illustrating the complex dynamics present in the aquatic ecosystem. It is also important to recognize that these correlations can vary depending on local conditions, specific geographic regions, human influences, thermal dynamics, and temporal changes affecting the physicochemical balance of freshwater ecosystems in the high-altitude region of Ladakh. The observed positive and negative correlations among the studied physicochemical parameters highlight the dynamic changes in water quality over both spatial and temporal scales during this study period.

Linear regression

Understanding the interrelationships among various physicochemical parameters is crucial for gaining deeper insights into aquatic ecosystems. These relationships can be more effectively evaluated using linear regression analysis Ahmed et al. (2024). The strength and predictive ability of the model are indicated by the coefficient of determination (r^2), which calculates the percentage of variance in the dependent variable that can be accounted for by the independent variable or variables. In the present study, all observed relationships were statistically significant ($p < 0.05$). A detailed summary of the regression statistics derived from the physicochemical dataset of the Ladakh stream is presented (Fig. 4). The results underscore significant inter-relationships among the measured parameters. Different levels of correlation were indicated by the coefficient of determination (r^2) values, which ranged from 0.10 to 0.92. An r^2 value approaching 1 indicates a robust model fit, indicating that the independent variables account for a substantial proportion of the variance in the dependent variable. Pairwise linear regression analysis identified numerous significant relationships among water quality parameters. The strongest relationships ($R^2 > 0.7$) included EC vs. TDS, TA vs. Ca²⁺, and AT vs. WT. Temperature-DO relationships showed significant negative slopes ($p < 0.001$), confirming the inverse relationship. Models involving NO₃-N generally showed lower R^2 values and higher p-values, indicating weaker predictive relationships. The WT shows significant positive correlation with WT ($r = 0.957$, $p < 0.001$). AT and WT show a positive relationship with EC and FCO₂. On the other hand, DO shows a negative correlation with WT ($r = -0.846$, $p < 0.001$). At the same time, the site-wise analysis shows that the high-altitude sites, Hanle



(a)



(b)

Fig. 3 **a** Pearson's multiple correlation plot showing intricate relationships among selected physicochemical parameters of the streams of Leh, Ladakh, the trans-Himalayan region of India. *Significance: *** $P < 0.001$; ** $P < 0.01$ and * $P < 0.05$. **b** Diagrammatic view of the same generated using R statistical software through the "qgraph" package

and Yaya Tso, have higher DO with less human interference, whereas the sites Sakti and Shey exhibit lower DO and greater anthropogenic activity. The complete regression results, including intercepts, R^2 values, and significance levels, are provided in the supplementary materials (online Table 6). The current study revealed a significant negative relationship between WT and DO. This correlation may be related to the observation that higher water temperatures typically result in lower dissolved oxygen

levels, attributed to increased oxygen saturation potential (Wetzel 2001). The increase in water temperature promotes the breakdown of organic compounds from plant and animal detritus, leading to increased nitrogen release and a subsequent reduction in DO levels (Abubakar et al. 2020).

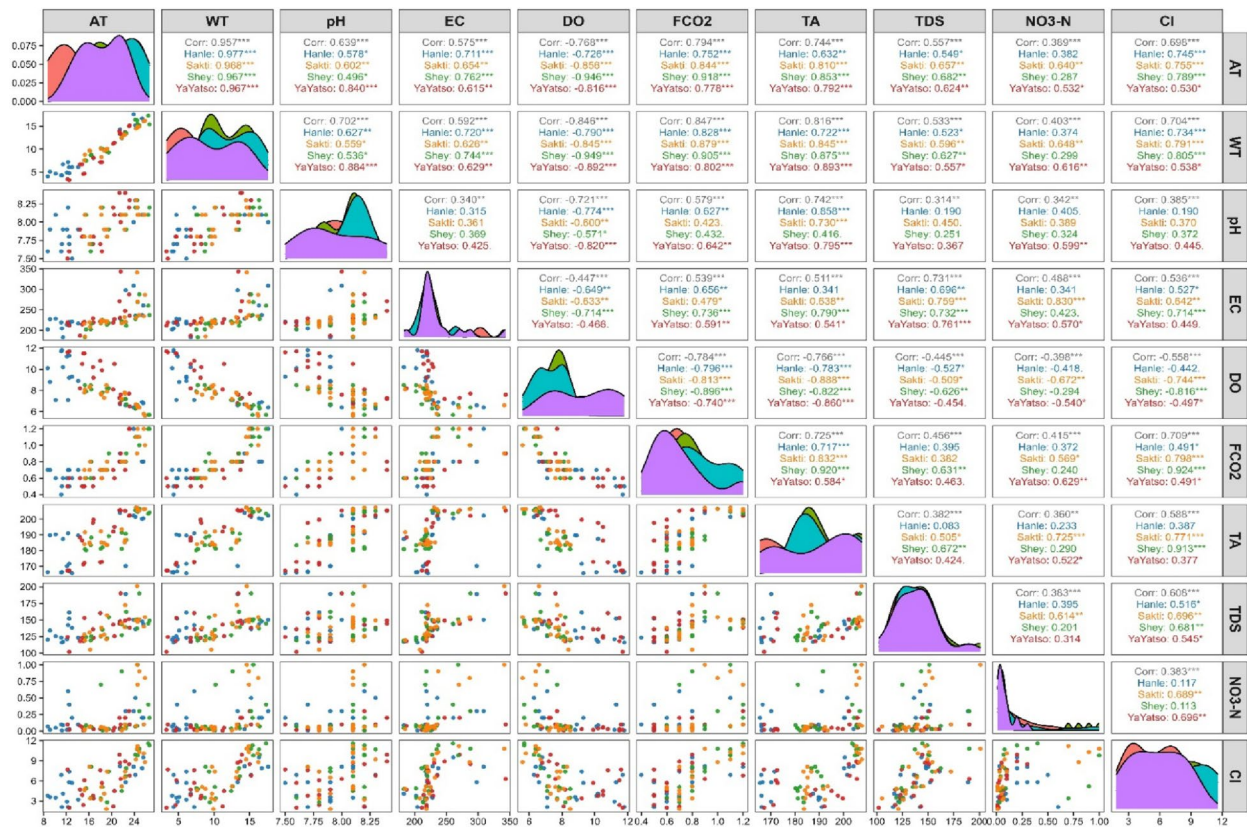


Fig. 4 Regression model indicating the relationship among the various physicochemical parameters and sites of Ladakh, high altitude stream

Principal component analysis

Principal component analysis is a robust multivariate technique for interpreting the multivariable data in a single data set. By transforming and rotating the original variables, PCA maximises the explained variance while reducing the dataset’s dimensionality, thereby facilitating the identification of key contributing parameters in aquatic systems (Togue et al. 2017). Furthermore, PCA facilitates the elucidation of relationships among physicochemical variables and sampling sites, considering the underlying geological conditions, climatic influences, and anthropogenic activities Ahmed et al. 2024). In PCA, the dataset’s variability is most effectively elucidated by variables that correlate with the first and second principal components, such as PC1 and PC2 (Kassambara 2017). The first two principal components (PC1 and PC2) collectively explained 72.5% of the total variance in the water quality dataset. PC1 accounted for 61.3% of the variance, while PC2 contributed 11.2% (Fig. 5). These two components accounted for the majority of the variation in the physicochemical parameters across all sampling sites and seasons.

Variable loadings

The PCA rotation matrix revealed the contribution of each water quality parameter to the principal

components. PC1 showed strong positive loadings for water temperature (WT=0.3659), air temperature (AT=0.3502), free carbon dioxide (FCO₂ = 0.3356), and total alkalinity (TA=0.3299), while dissolved oxygen (DO = -0.3348) exhibited a strong negative loading. This suggests that PC1 represents a thermal and chemical gradient, with warmer waters characterized by higher FCO₂ and TA but lower DO concentrations. PC2 was primarily driven by pH (0.3815), total alkalinity (TA = 0.2315), and calcium (Ca²⁺ = 0.2950) in the positive direction, and by electrical conductivity (EC = -0.4661) and total dissolved solids (TDS = -0.5531) in the negative direction. This component appears to reflect differences in water mineralization and buffering capacity.

The PCA biplot coloured by season revealed distinct clustering patterns (Fig. 6a). Summer samples formed a tight cluster in the positive direction of PC1, indicating elevated temperatures (AT and WT), higher FCO₂ and TA, and lower DO concentrations. Spring samples showed intermediate positioning, while Autumn samples were distributed toward the negative end of PC1, characterized by cooler temperatures and higher dissolved oxygen levels. The ellipses showed minimal overlap between Summer and other seasons, suggesting significant seasonal differences in water quality. When samples were grouped by site, the PCA biplot showed overlapping

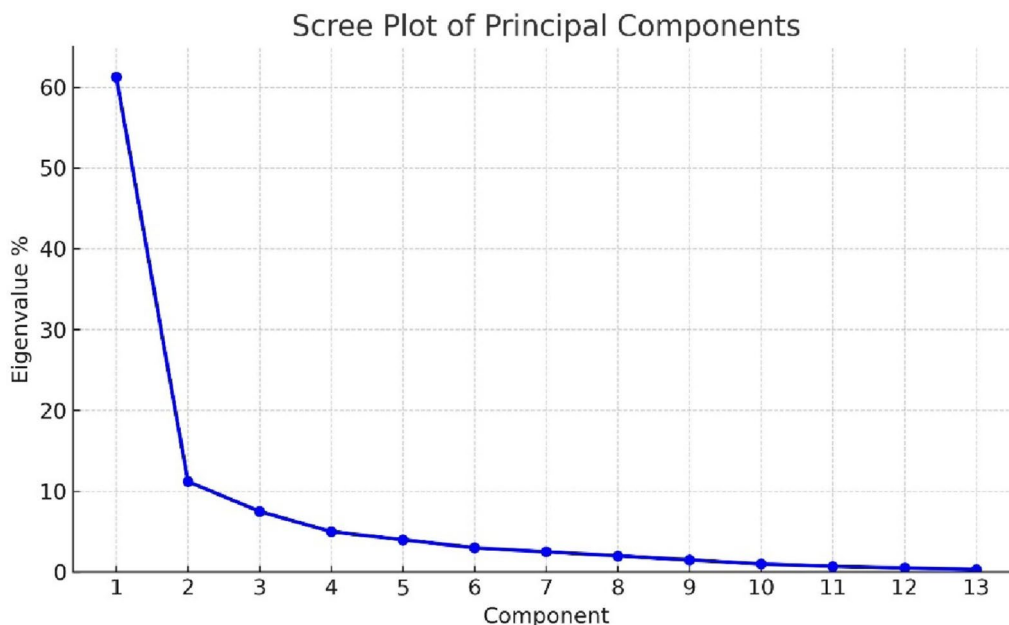


Fig. 5 Scree plot of eigenvalues versus principal components of physicochemical parameters of Ladakh stream

ellipses for all four sites (Hanle, Sakti, Shey, and Yaya Tso), indicating broadly similar water-quality characteristics (Fig. 6b). However, subtle differences were observed along both PC1 and PC2 axes. Sakti samples tended to occupy the positive region of PC1, suggesting relatively warmer conditions, while Hanle samples were more scattered across the ordination space. Shey and Yaya Tso showed intermediate patterns with considerable overlap with other sites. The overlapping ellipses suggest that seasonal variation was stronger than site-specific variation in determining water quality patterns. The loading vectors in both biplots revealed essential relationships among variables. Temperature variables (AT and WT) were strongly aligned with PC1 and pointed in the same direction, confirming their high correlation. DO pointed in the opposite direction to temperature variables, consistent with the inverse relationship between water temperature and oxygen solubility. EC, TDS, and associated ions (Cl^- , NO_3^- , N) were grouped together, indicating their covariation as indicators of water mineralization. TA, pH, and calcium (Ca^{2+}) formed another group, reflecting the carbonate buffering system.

Cluster analysis

Cluster analysis uses the hierarchical agglomeration (HAC) technique to group items based on their similarities and differences within classes. This method allows for quick evaluation of how similar a specific sample is to the whole dataset, often visualized in a dendrogram (Singh et al. 2004; Hajigholizadeh and Melesse 2017; Ahmed et al. 2024). Hierarchical cluster analysis based on site-averaged water quality parameters revealed clear groupings

among the four sampling sites. The dendrogram showed that the sites clustered into two major groups based on their overall physicochemical characteristics (Fig. 7). This analysis identified that the sites form two main groups in the dendrogram, with Yaya Tso and Hanle clustering closely at a minimal linkage distance, indicating shared environmental features such as high-altitude, low-temperature waters with similar ionic compositions and little human disturbance. Conversely, Shey and Sakti also formed a close cluster, reflecting similar physicochemical characteristics influenced by comparable altitude and human activities. Additionally, the low-altitude site Shey appears more exposed to pollution due to its proximity to human settlements, which introduce waste directly into the stream from both point and non-point sources. In contrast, Yaya Tso and Hanle show higher dissolved oxygen (DO) levels and limited human impact, suggesting relatively pristine conditions. These findings align with those of Arafat et al. (2022), who also observed differences in physicochemical parameters from upstream to downstream sites. Therefore, CA can be a useful method for classifying surface water based on environmental similarities and may support the development of more systematic and targeted future sampling strategies (Shrestha and Kazama 2007).

Discussion

The physicochemical parameters of water samples collected from all the study sites examined in the present study conform the acceptable limits set for potability by the Bureau of Indian Standards (BIS 2004 and WHO 2017), as shown in Table 6. Temperature plays a vital role

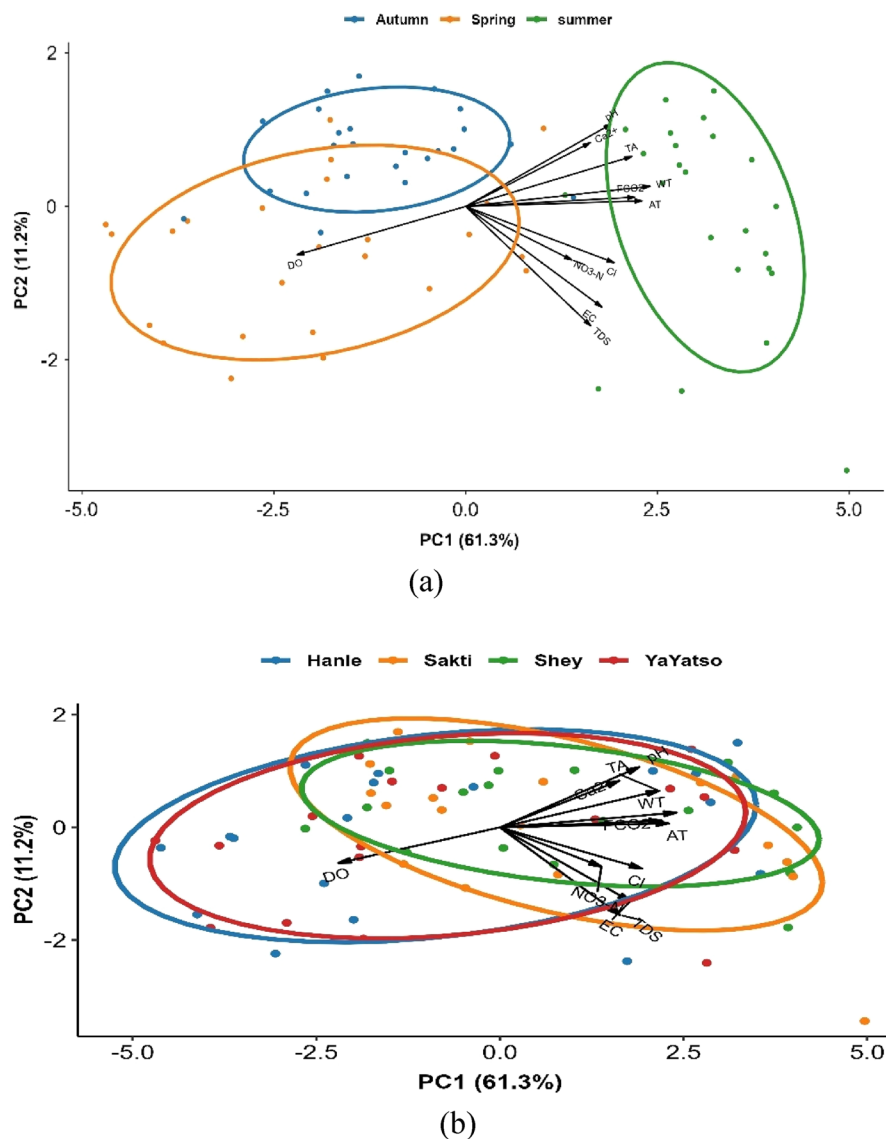


Fig. 6 a, b Shows the geographical and temporal correlations of selected physico-chemical parameters of cold glacier-fed streams in Leh, Ladakh, the trans-Himalayan region of India, as revealed by principal component analysis (PCA), with the first two principal components (PC1 and PC2)

in regulating the decomposition of organic matter, speeding up metabolic reactions essential for the development and growth of aquatic organisms (Fernandes et al. 2014; Mutlu et al. 2016). Water temperature and dissolved oxygen levels in rivers and streams are influenced by several environmental factors, including air temperature (Harvey et al. 2011). The relationship between air temperature and water temperature significantly influences water conditions, ultimately affecting the existence and habitat of aquatic life (Stumm and Morgan 2012). Fluctuations in water temperature are mainly driven by seasonal atmospheric temperatures and various weather-related factors (Kattel et al. 2022; Ahmed et al. 2024). Additionally, WT has a notable impact on metabolic rates, reproductive processes, and the solubility of oxygen in water

(Boyd 2019). In the current study, the highest water temperature, 12.22 ± 3.30 °C, was recorded at Shey, while the lowest value of 8.77 ± 5.09 °C was observed at Hanle. The seasonal variation in spring water temperature clearly reflects altered climatic conditions. Our findings indicate that Shey study site has the warmest water compared to the high-altitude sites of Hanle and Yaya Tso. In contrast, Hanle site has the coldest temperatures, illustrating how climate changes with increasing altitude: decreasing air temperatures, reduced sunlight, and ongoing glacial melt help maintain low water temperatures. These temperature fluctuations are crucial for regulating the metabolic rates, distribution, and community composition of aquatic organisms in extreme environments.

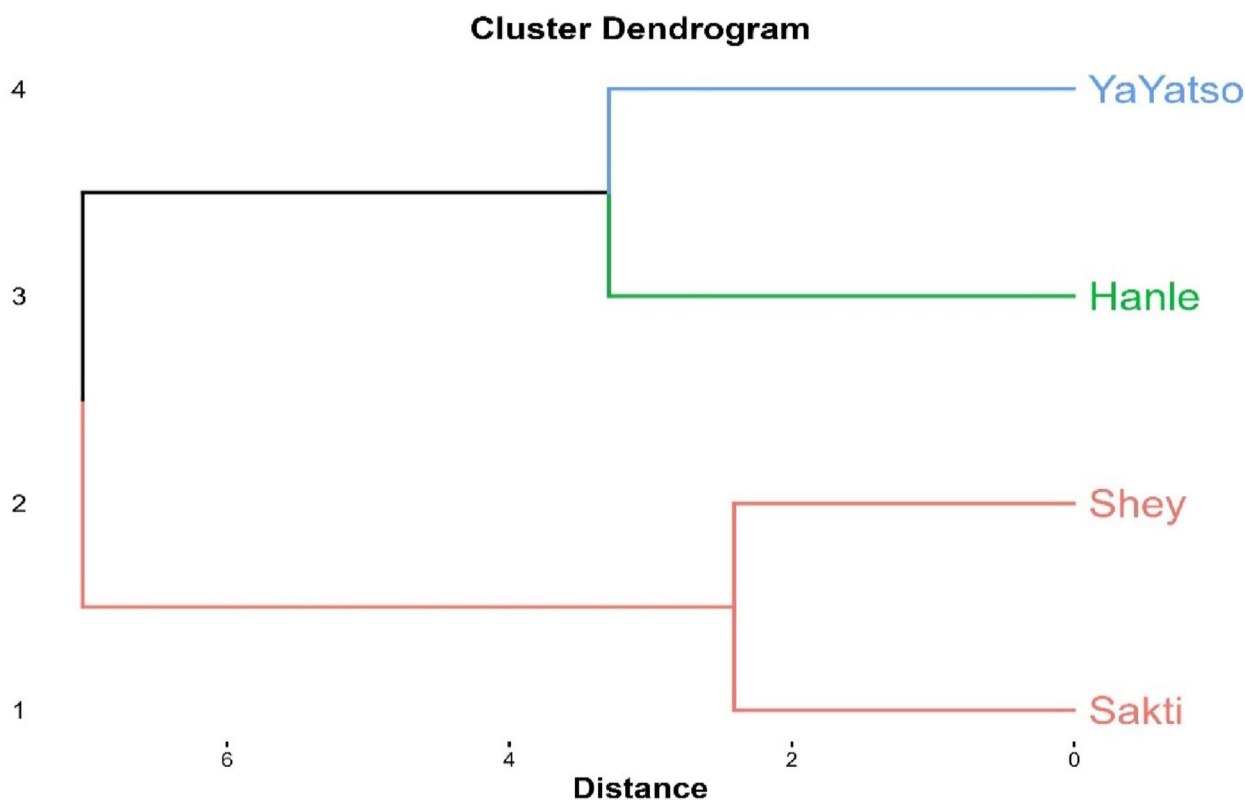


Fig. 7 Dendrogram extracted through cluster analysis (CA) based on Ward’s approach, showing four sampling sites

Table 6 Comparison of the range of physicochemical parameters of streams of Leh, Ladakh, with recommendations

Parameters	BIS 2012	WHO 2017	Current range in the stream
WT (°C)	10–32	–	10.53 ± 4.14
pH	7.5–9.5	6.5–8.5	7.97 ± 0.22
EC (µS cm ⁻¹)	–	–	231.1 ± 31.19
DO (mg/L)	6–4	–	8.12 ± 1.71
FCO ₂ (mg/L)	–	–	0.78 ± 0.21
TA (mg/L)	200–600	–	189.40 ± 13.10
TDS (mg/L)	500–2000	≤ 1000 mg/L	139.52 ± 19.32
NO ₃ -N (mg/L)	45	50	0.17 ± 0.25
Cl ⁻ (mg/L)	250–1000	250	6.26 ± 2.72
Ca ²⁺ (mg/L)	75–200	–	16.96 ± 3.95

A key factor influencing water quality is the presence of various minerals and the dissociated forms of other salts. It has been suggested that waters with a pH between 6.5 and 8.5 are generally suitable for domestic use and aquatic life, besides ideal for all purposes. The absorption of carbon dioxide and bicarbonates, along with the rate of photosynthesis, are all influenced by pH levels (Idowu et al. 2020). The overall alkaline nature of the water bodies in the present study shows minimal variation across seasons and sites. The pH with slightly alkaline, indicating the presence of weakly basic salts (Jameel and Sirajudeen 2006; Rawat et al. 2019). The maximum pH values obtained during summer can be due to increased

anthropogenic inputs, as various human activities contribute to enriching these alkaline substances. A similar pattern in pH data reported from Vishav Stream of Kashmir (Arafat et al. 2022). Several previous studies by different researchers have also reported similar results with respect of pH (Kang et al. 2001; Rawat and Joshi 2019).

Another important water quality parameter is electrical conductivity (EC), which directly correlates with TDS (Rajendran and Mansiya 2015). TDS is a reliable metric for assessing the overall composition of water, enabling an evaluation of its purity and quality (Dar et al. 2019). It shows a direct correlation with water’s electrical conductivity. Dharmendra Kumar (2013) reported that EC was positively correlated with TDS across all water samples. During the present study, both EC and TDS showed no significant differences among the sites. The variation in the summer season is likely due to higher discharges of household waste, municipal waste, and agricultural runoff containing livestock manure into streams, with human activities contributing to the rise in dissolved ions. Similar findings have been documented in previous studies (Mirza et al. 2014; Mir and Gani 2019; Manzoor and Iqbal 2020).

According to Eliku and Leta (2018), DO is crucial for regulating metabolic processes in aquatic organisms. It is a vital respiratory gas used in biochemical processes that support aquatic life. Several factors influence dissolved

oxygen levels, including temperature and the decomposition of organic waste (Mir et al. 2023; Ahmed et al. 2024). The assessment of water quality, contamination, ecological health, productivity, and overall water resource condition heavily depends on DO content, making it a key aquatic parameter (Lone et al. 2021). High DO levels improve water quality (Kumar and Kumar 2013) and indicate lower percolation of organic waste (Sati and Paliwal 2008; Basavaraddi et al. 2012). All water samples analysed in the present study showed DO concentrations above 6 mg/L, indicating these cold waters have a substantial capacity to retain DO content. The highest DO level was observed at Hanle, while the lowest value of DO was noted at Shey. The Hanle site is situated at a higher altitude than Shey. The streams in Ladakh generally display elevated DO content, likely due to the high-altitude, cold-water habitat that enhances oxygen solubility. Lower water temperatures enable cold water to retain a higher concentration of oxygen than warmer water.

Dissolved gases in surface water, including free carbon dioxide (FCO₂), play a vital role in maintaining water body health and serve as key indicators of overall condition (Mir et al. 2023). FCO₂ levels are mainly regulated by metabolic processes, such as photosynthesis and respiration, as well as by atmospheric diffusion (Yang et al. 2007). The higher CO₂ levels observed at the lower-altitude site, i.e. Shey, resulted due to enhanced microbial activity and organic matter decomposition in warmer water, leading to increased CO₂ production via respiration and organic carbon breakdown. The reduced flow velocity and increased influence from humans or livestock may contribute to elevated organic input and respiration rates. Higher CO₂ levels during summer are primarily caused by increased microbial respiration and faster decomposition of organic matter at elevated temperatures. This increase is also linked to heightened biological activity and to decreased gas solubility in warmer waters. Total alkalinity indicates the water's ability in an aquatic environment to resist changes in pH. It is believed to have acid-neutralizing capacity (ANC), which helps stabilization in pH Ahmed et al. (2024). Several ions, including hydroxide (OH⁻), carbonate (CO₃²⁻), calcium bicarbonate (HCO₃⁻), influence total alkalinity (Kang et al. 2001). Notably, pH and alkalinity exhibit an inverse relationship with stream discharge, as observed by Arafat et al. (2022). The lowest TA at site Hanle, caused by torrential flow, reduces the contact time between water and surrounding lithological formations, ultimately limiting the dissolution of carbonate and bicarbonate minerals and resulting in lower alkalinity. Conversely, the lower flow velocity and relatively flat riverbed at Sakti study site promote greater interaction between water and parent rock, involved in enhancing mineral dissolution and increasing alkalinity, as well.

According to Allan and Castillo (2007), aquatic ecosystems require sufficient levels of nitrogen, phosphate, and other essential nutrients, such as ammonia, iron, and silica to function properly. Elevated concentrations of these nutrients in aquatic systems can lead to eutrophication (Khanday et al. 2021). Compared to other nutrients, nitrogen has been suggested as a key nutrient in aquatic ecosystems (Dodds 2002). The primary sources of nitrogen include sewage inputs, agricultural waste, and natural atmospheric diffusion (Bernhardt et al. 2002; Swaney et al. 2012). Several studies indicate that agricultural land use significantly impacts nitrogen dynamics in stream ecosystems (Arango and Tank 2008; Kebede et al. 2014). Presence of highest NO₃-N levels found during summer season might be involved increased in microbial nitrification, greater surface runoff from snowmelt, and higher anthropogenic inputs from agricultural and grazing activities, all of which contribute to nutrient enrichment in the water.

It has been observed that several natural sources of Cl⁻ include rock weathering, basin brines, and human activities such as sewage discharge and fertilizer use containing significant amounts of potash are responsible for increase in Cl⁻ content Gardner and Royer (2010). During autumn, human activity decreases, and processes like salt dissolution and weathering also slow down. However, in summer (July–August), there is a noticeable increase in domestic activity, fertilizer runoff from nearby agriculture, and sewage waste. These factors collectively lead to higher Cl⁻ concentrations in the water. Calcium levels in water vary widely depending on the source and location (Matamoros et al. 2024). Calcium enters water from the dissolution of rock, limestone, gypsum, salts, and soil. It contributes to water hardness and reacts with bicarbonate and carbonates, forming lime deposits, scale, very hard water, and increased salinity (Provin and Pitt 2024). Changes in Ca²⁺ levels in freshwater can indirectly impact aquatic ecosystems (Okland 1986). Understanding the thresholds at which Ca²⁺ concentrations change before causing harm to organisms and ecosystem functions is crucial (Bogart et al. 2019). In the studied high-altitude region of Ladakh, calcium ion (Ca²⁺) levels were higher throughout summer. This seasonal increase results from intensified rock-water interactions driven by more glacier and snowmelt, which accelerates the breakdown of calcium-rich minerals. Additionally, higher summer temperatures promote chemical weathering, and increased evaporation concentrates dissolved ions. Greater human activities during this period, including agriculture and cattle grazing, likely contribute more calcium via surface runoff and organic waste, further elevating Ca²⁺ in the water. This results in the accumulation of dissolved salts, such as calcium (Kaushal et al. 2005). In this study, PCA and CA analyses show that site Shey

records the maximum values for all parameters except DO, while elevated DO concentrations were observed at the high-altitude sites Yaya Tso and Hanle due to their minimal anthropogenic disturbance and low temperature. Among all sites, Shey site are seen more vulnerable to human influence. PCA combined with correlation analyses indicates that anthropogenic impacts have a significant effect on the water quality of springs in the Ladakh trans-Himalaya region.

Conclusion

In this study, the physicochemical parameters of water collected during different seasons from various streams of Leh, Ladakh trans-Himalayan region, were found to fall within the permissible limits set by standard water quality monitoring agencies such as BIS and WHO. PCA, combined with correlation analysis, showed that spring water quality is mainly influenced by mineral content and human activities. Significant differences in physicochemical characteristics were observed across both temporal and geographical dimensions. Cluster analysis indicated that the water quality of the streams at site Shey is more prone to human activities, while the other sites, Hanle and Yaya Tso, share the same environmental characteristics with high DO content. The spatio-temporal hydrochemistry of the Leh stream in Ladakh is predominantly influenced by organic and inorganic pollutants emerging from anthropogenic sources, particularly at the low-altitude location of Shey. The study provides significant insights about monitoring of stream ecosystems and water quality thereby facilitating the planning of management plans and conservation measures to mitigate the detrimental impacts of human activities in catchment areas and watersheds. It is necessary to conduct regular future evaluations of the water quality of these springs to gain a clearer understanding of the impact of anthropogenic activities, geological processes, and environmental conditions on these essential water resources. This study offers policymakers a systematic framework to evaluate the possible effects of future alterations in water quality along with its ecology. The present study will also be useful in identifying the key elements that could threaten ecological stability in near future.

Abbreviations

APHA	American Public Health Association
AT	Air temperature
WT	Water temperature
EC	Electrical conductivity
TDS	Total dissolved solid
DO	Dissolved oxygen
FCO ₂	Free carbon dioxide
TA	Total alkalinity
NO ₃ -N	Nitrate-nitrogen
Cl ⁻	Chloride
Ca ²⁺	Calcium
ANOVA	Analysis of Variance

PCA	Principal Component Analysis
HCA	Hierarchical Clustering Analysis
CA	Cluster Analysis
HAC	Hierarchical Agglomeration

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40068-025-00438-y>.

Supplementary Material 1

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Author contributions

Kunzang Dolma: Conceptualization, validation, visualization, writing original draft, writing review, and writing original draft preparation. Imtiaz Ahmed: Visualization, validation; Supervision, Writing- review. Neelavar Ananthram Aravind: supervision. Mohammad Abul Farah: edited and revised the manuscript.

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Data availability

The authors declare that the data used in this research will be made available upon reasonable request to the corresponding author **.*.

Declarations

Ethics approval and consent to participate

Note applicable.

Consent for publication

Note applicable.

Competing interests

The authors declare no competing interests.

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