Spatio-temporal evaluation of physico-chemical parameters of snow-fed River Poonch in Northwest Himalayan region of India

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Abstract

The rapid deterioration of freshwater ecosystems, particularly rivers, has threatened many living organisms, including human beings. In order to comprehend and maintain the well-being of a river ecosystem, it is important to assess the spatial and temporal variations in its physico-chemical parameters. The aim of the present study was to examine spatial and temporal physico-chemical parameters of snow-fed River Poonch in the Northwest Himalayas from July 2021 to June 2023. In order to generate precise and reliable data, one-way ANOVA, Duncan's multiple range test, Pearson correlation, linear regression, principal component analysis (PCA) and cluster analysis (CA) were used to analyse a total of fifteen physico-chemical parameters of the river. Significant ($p < 0.05$) differences spatio-temporally in physico-chemical parameters were found through one-way ANOVA followed by Duncan's multiple range test. Pearson correlation revealed that majority of the examined physico-chemical parameters exhibited a robust positive association ($r > 0.70$) in most cases, apart from DO ($r \geq -0.80$). Linear regression indicated significant ($p < 0.05$) associations among various physico-chemical parameters, which were substantial both in nature and size, with a coefficient of determination ($r^2 > 0.70$) in most of the cases. PCA showed that physico-chemical parameters such as AT, WT, EC, TDS, FCO_2, TA, TH, NO_2-N, NO_3-N, TP, SO_4^{2-} and F^- were significant for the determination of qualitative characteristics of River Poonch. In CA, two distinct clusters, viz. Cluster-I consisting of Site-III, downstream site prone to pollution and Cluster-II consisting of Site-II and Site-I, mid and upstream sites, respectively, less prone to pollution were obtained. The results of the study revealed that the water quality parameters were found well within the recommended ranges, suggesting that they are conducive for the existence of inhabitant fish species, which influence the local economy of the region.

Keywords Freshwater ecosystems · River Poonch · Northwest Himalayas · River Jhelum · Economy

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Introduction

Water is undoubtedly considered as home to many aquatic flora and fauna in both lentic and lotic ecosystems. Universally, rivers are acknowledged as a primary source of surface water and play a crucial role among many other natural water resources (Mirza et al. 2014; Eliku and Leta 2018). Rivers serve several purposes, including household water supply for drinking, transportation, agricultural irrigation, recreational activities, fishing and aquaculture production as well as the generation of electricity (Mirza et al. 2014; Boyd 2015; Eliku and Leta 2018). However, despite being life-sustaining and economically significant, rivers are most vulnerable to pollution today (Varol 2020; Mir et al. 2023). Currently, rivers are encountering substantial challenges due to the combination of both human activities and natural phenomena (Seth et al. 2016; Eliku and Leta 2018;

Mir et al. 2023). These challenges encompass fluctuations in hydrological patterns, climate change, rapid population growth, uneven urban development, rapid establishment of industries, insufficient treatment of domestic wastewater, improper management of agricultural pesticides and fertilizers besides extraction of gravel from riverbeds for hydropower generation (Ravichandran 2003; Seth et al. 2016; Eliku and Leta 2018; Ustaoğlu and Tepe 2019; Varol 2020). Due to one or the other reason, the quality of riverine water is declining and their levels are decreasing quickly than they can be replenished (Mir et al. 2023).

The water quality in rivers often exhibits significant spatial and temporal variability. The rivers' geographical heterogeneity arises from the dynamic nature of environmental factors such as solar radiation, water temperature, flow rate and river channel shape while the magnitude of temporal variations depends on the classification of the rivers and the specific physico-chemical parameter/s being examined (Chakrapani 2005; Qadir et al. 2008). It is essential to recognize that water quality plays a crucial role in safeguarding the whole environment, particularly in maintaining the soundness of the public health system (Rajini et al. 2010; Arafat et al. 2022).

The existence of resilient riverine ecosystems is correlated with the profusion of aquatic flora and fauna, thus enhancing the overall biodiversity of the region (Lawal et al. 2023). Moreover, the existence, abundance and adaptation of various species, such as fishes, in an aquatic ecosystem are primarily influenced by biotic and abiotic factors, resulting in sustainable production (Samal et al. 2016; Lawal et al. 2023). Environmental disturbances lead to a decline in water quality, which, in turn, harms the overall health of the ecosystem and its related processes. Hence, it is essential to ascertain the origins of pollution, pinpoint the specific locations (sites) and periods (seasons) when water quality fluctuations transpire and undertake measures to mitigate river contamination for the successful implementation of comprehensive management strategies (Tian et al. 2019; Nong et al. 2020). For effective planning and conservation of water resources and its faunal diversity, a comprehensive picture of water quality may be attained by thorough methodological techniques, including the monitoring of physical and chemical parameters in both geographical and temporal dimensions (Eliku and Leta 2018; Kasperson et al. 2022; Lawal et al. 2023). Various statistical approaches, such as mean, standard deviation, ANOVA, Pearson's correlation, linear regression, principal component analysis (PCA) and cluster analysis (CA), have shown their efficacy in the physico-chemical evaluation (Zhao et al. 2012; Ling et al. 2017; Eliku and Leta 2018; Mir et al. 2023).

Himalayan aquatic ecosystems have been duly recognized for their significant contributions to the sustainable economy, enhancement of human well-being and preservation of the integrity of the biological system (Islam et al. 2021; Khanday et al. 2021). The presence of the snow-fed water resources in the region are highly advantageous and promising factor, contributing to livelihood of the sizeable population. The River Poonch, a vital constituent of the Himalayan river ecosystem, stands as a solitary water reservoir in the region. This river is a significant tributary of the mighty River Jhelum and plays a crucial role in supporting the livelihood of a substantial population in the region. But in recent years, the rising population, together with increased economic activity and rapid urbanisation, has caused significant degradation and depletion of the water quality in this river, as well as a reduction in the extent of its watershed. The condition of the river has a direct bearing on the health and economic development of the local population and this fact must be recognized. It is of utmost importance to highlight, that monitoring river water's geographical and temporal properties has been extensively used as a vital tool for evaluating physico-chemical qualities, identifying sources of pollution and implementing effective management measures (Qadri et al. 2008; Tian et al. 2019). Furthermore, effective water management requires knowledge of spatial and temporal variations in water quality (Nong et al. 2020; Mir et al. 2023). Before the initiation of this study, no prior studies were conducted regarding the spatial and temporal fluctuations in the physico-chemical properties of the River Poonch. Simultaneously, it is worth mentioning that this river accommodates a considerable populace of the most coveted game fish of the globe, the imperilled golden mahseer, *Tor putitora* (Hamilton, 1822). Therefore, considering the economic vitality of the River Poonch, the current study was carried out to evaluate the physico-chemical parameters in relation to spatial and seasonal fluctuations. This study utilized a range of statistical methods to establish a comprehensive dataset that can be used for the efficient management and conservation of the River Poonch, in addition to detecting pollution sources and other water quality issues. This study provides valuable insights that might enhance the quality of physico-chemical parameters, which, in turn, may aid in preserving and managing resident fish species, which are essential for the local economy.

Materials and methods

Study area

The Poonch district, located in the Northwestern Himalayas of Indian Jammu and Kashmir, has a rugged terrain and is home to a population of 476,835 individuals (as per the GOI Census 2011). Approximately 20–25% of this population relies directly on the River Poonch for various activities including the harvesting of fish, among others.

The river mostly receives its water from precipitation and thawing of snow. The regional climate shows elevated temperatures throughout the summer season, with June having the highest recorded temperatures. Conversely, the winter season is characterized by low temperatures, with January being the coldest month of the season. This river is located at geographical coordinates of 33.64511° N latitude and 74.43532° E longitude. It originates from one of the pristine high-altitude lake, Katorsar, nestled in the majestic Neel-Kanth and Jamian Gali regions of the Pir Panjal range in the Northwestern Himalayas. The drainage system efficiently covers a substantial region by gathering several hill streams and nallahs from the lofty Pir Panjal range and extends to the lower outer hills. The total length of the main course is 245 km from the point of origin to the destination. After flowing through a stretch of 150 km in Poonch, Jammu and Kashmir, India, it enters Kotli, Pakistan occupied Kashmir, where it is designated as Poonch River Mahseer National Park (Brown et al. 2019) and finally drains into Mangla Reservoir. Some of the prominent tributaries of this river in Poonch, Jammu and Kashmir, India, are Mandi nallah, Betaar nallah, Mendhar nallah, Darungli and Rangar. Along the entire stretch of River Poonch in Indian territory, a meticulous selection was undertaken to identify three sampling sites at important confluence points of the most of river tributaries for physico-chemical evaluation (Fig. 1), viz. Site I. an upstream site (Kalaie), Site II. a midstream site (Chakkan Da Bagh) and Site III. a downstream site (Balnoi).

Collection of water samples

An extensive sampling strategy was formulated to cover various physio-chemical parameters at selected sampling sites of River Poonch. Water samples were collected on monthly basis throughout a period of 2 years, spanning from July 2021 to June 2023. Some of the collected samples were analysed on the spot while the rest were preserved and transported to the Fish Nutrition Research Laboratory, Department of Zoology, University of Kashmir, as per the standard analysis procedures (APHA 1998).

Analyses of water samples

The current study examined a total of 15 physico-chemical parameters, namely air temperature (AT), water temperature (WT), pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), free carbon
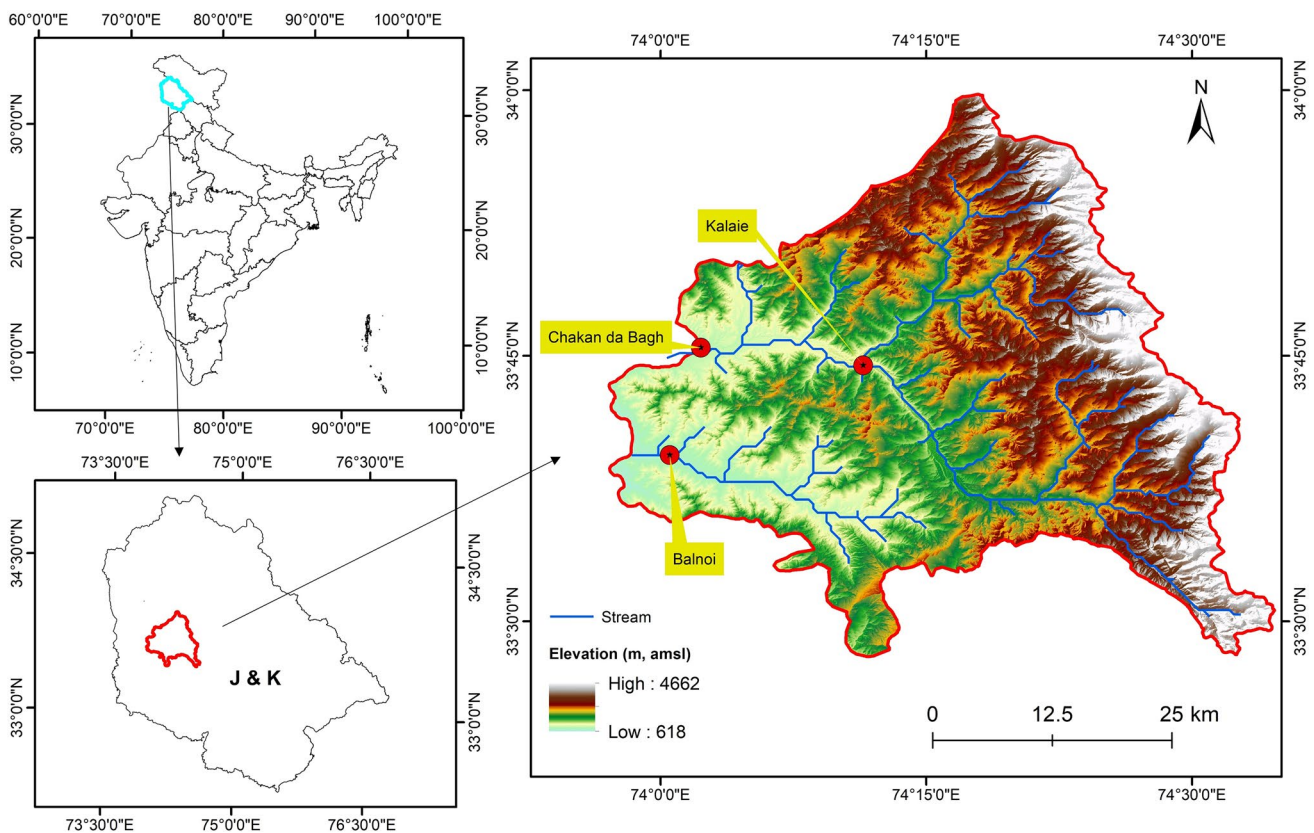

Fig. 1 Location map of selected sampling sites of River Poonch, J&K, India

dioxide (FCO$_2$), total alkalinity (TA), total hardness (TH), nitrite-nitrogen (NO$_2$-N), nitrate-nitrogen (NO$_3$-N), total phosphate (TP), sulphate (SO$_4^{2-}$), chloride (Cl$^-$) and fluoride (F$^-$). AT and WT were recorded by mercury Celsius thermometer, pH, EC and TDS by portable multiparameter (HANNA HI9829), DO by modified Winkler's method (APHA 1998), FCO$_2$ and TA by titrimetric method (APHA 1998), TH by EDTA titrimetric (APHA 1998; HACH 2003), Cl$^-$ by argentometric titration, TP by spectrophotometrically (ammonium molybdenum method) and NO$_2$-N, NO$_3$-N, SO$_4^{2-}$ and F$^-$ by spectrophotometer (Hach DR 5000 USA). Triplicate analyses were conducted in each case and the mean value was calculated. A spatio-temporal data analysis was performed to identify changes resulting from a spatio-temporal hydrodynamics of the river.

Statistical analyses

All the necessary statistical tests have been performed using PAST ver. 4.03, R statistical software ver. 4.3.1 and IBM SPSS ver. 27. The current study included the computation and examination of the average values of the physico-chemical parameters via descriptive analysis. The data were systematically categorised into distinct seasons: spring, summer, autumn and winter. One-way ANOVA and Duncan's multiple range test ($p < 0.05$) were used to identify spatially and temporally significant differences in the physico-chemical parameters. The robustness of relationships among the physico-chemical parameters under study was determined by Pearson's multiple correlation. The resulting correlation plots were mapped using "psych" and "qgraph" packages (Revelle 2020). Furthermore, linear regression analysis was employed to examine the influence of independent or predictor variables on dependent or response variables. Resulting figures were mapped using the "ggplot2″ (Wickham 2016), "ggpubr" (Kassambara 2020) and "ggmisc" (Aphalo 2021) packages.

After being standardized using a *z*-scale transformation, the physico-chemical data was analysed using multivariate statistical methods such as principal component analysis (PCA) and cluster analysis (CA) to reduce the dimensionality of the data (Simeonov et al. 2003; Liu et al. 2003; Arafat et al. 2022; Mir et al. 2023). To elucidate the organization of the fundamental dataset, PCA was conducted using the correlation matrix of the transformed data. The physico-chemical data was subjected to CA, which yielded the dendrogram based on similar sampling sites across the stretch of River Poonch. CA was carried out using hierarchical agglomerative clustering (HAC) following Ward's method and similarity was measured using Euclidean distances (McKenna 2003; Arafat et al. 2022; Mir et al. 2023).

Results and discussion

Prevailing trend and spatio-temporal variations

In the present study, data on the physico-chemical analysis of River Poonch was generated by analysing 15 parameters and the results are presented as minimum, maximum, mean and standard deviation (Table 1). Furthermore, a comprehensive evaluation was undertaken to ascertain the existence of statistically significant and non-significant differences using ANOVA followed by Duncan's multiple range test across spatial and temporal dimensions (Table 2 and 3).

Air temperature (AT) has a significant impact on various environmental factors that influence water temperature (WT) and the overall content of dissolved oxygen (DO) of the rivers (Benyahya et al. 2008; Harvey et al. 2011). Imperatively, the correlation between AT and WT is a crucial factor that significantly impacts the water quality, determines the viability and behaviour of aquatic organisms (Stumm and Morgan 2012). During the present study, a significant ($p < 0.05$) disparity was observed in air temperature (AT) across studied sites, i.e. between upstream site (Kalaie) and downstream site (Balnoi). The observed fluctuations may be ascribed to the prevailing climatic and topographic conditions (Lookingbill and Urban 2003; Shen and Leptoukh 2011; Kattel et al. 2022). The maximum AT, 27.45 ± 7.02 °C, was recorded at downstream site and the minimum, 22.85 ± 6.88 °C, at upstream site. Similarly, the maximum AT, 33.83 ± 3.47 °C, was recorded in summer

Table 1 Overall trend of physico-chemical parameters of River Poonch, J&K, India

Parameters	Min	Max	Mean ± SD
Air temperature (AT) (°C)	10.8	39.2	25.27 ± 7.25
Water temperature (WT) (°C)	7.1	27.8	15.28 ± 5.94
pH	6.9	8.6	7.5 ± 0.3
Electrical conductivity (EC) (μs cm^{-1})	144.8	407.9	271.41 ± 63.19
Total dissolved solids (TDS) (mg/L)	89	258.3	159.99 ± 40.83
Dissolved oxygen (DO) (mg/L)	5.1	12.8	8.92 ± 1.92
Free carbon dioxide (FCO$_2$) (mg/L)	0.5	9.3	4.86 ± 2.47
Total alkalinity (TA) (mg/L)	95.8	153.3	121.49 ± 11.29
Total hardness (TH) (mg/L)	60.4	185.7	126.30 ± 29.47
Nitrite-nitrogen (NO$_2$-N) (mg/L)	0.02	0.32	0.14 ± 0.06
Nitrate-nitrogen (NO$_3$-N) (mg/L)	0.05	0.49	0.21 ± 0.10
Total phosphate (TP) (mg/L)	0.06	0.82	0.35 ± 0.20
Sulphate (SO$_4^{2-}$) (mg/L)	7.1	18.2	12.08 ± 2.71
Chloride (Cl$^-$) (mg/L)	10.3	24.3	16.28 ± 3.35
Fluoride (F$^-$) (mg/L)	0.10	1.15	0.44 ± 0.24

The Mean ± SD is the observation of 24 values

Table 2 ANOVA (Duncan's multiple range test) showing spatial variation in physico-chemical parameters of River Poonch, J&K, India

Parameters	Kalaie	Chakkan Da Bagh	Balnoi
AT (°C)	22.85 ± 6.88^b	25.51 ± 7.37^{ab}	27.45 ± 7.02^a
WT (°C)	13.36 ± 5.27^b	15.30 ± 6.05^{ab}	17.17 ± 6.08^a
pH	7.38 ± 0.22^b	7.46 ± 0.27^b	7.67 ± 0.40^a
EC (μs cm^{-1})	229.14 ± 48.62^c	275.72 ± 52.25^b	309.37 ± 62.01^a
TDS (mg/L)	142.86 ± 32.90^c	171.38 ± 35.05^b	205.72 ± 47.62^a
DO (mg/L)	9.76 ± 1.73^a	8.95 ± 1.98^{ab}	8.05 ± 1.93^b
FCO$_2$ (mg/L)	3.52 ± 2.49^b	4.66 ± 2.41^{ab}	5.93 ± 1.95^a
TA (mg/L)	110.62 ± 6.43^c	121.96 ± 6.88^b	131.90 ± 8.29^a
TH (mg/L)	110.51 ± 25.69^b	127.44 ± 25.94^a	140.95 ± 29.38^a
NO$_2$-N (mg/L)	0.11 ± 0.06^b	0.14 ± 0.63^{ab}	0.17 ± 0.07^a
NO$_3$-N (mg/L)	0.17 ± 0.09^b	0.20 ± 0.10^{ab}	0.25 ± 0.11^a
TP (mg/L)	0.24 ± 0.14^b	0.38 ± 0.18^a	0.41 ± 0.23^a
SO$_4^{2-}$ (mg/L)	9.78 ± 1.61^c	11.60 ± 1.68^b	14.85 ± 1.87^a
Cl$^-$ (mg/L)	13.56 ± 2.68^c	16.49 ± 2.57^b	18.78 ± 2.55^a
F$^-$ (mg/L)	0.25 ± 0.09^c	0.40 ± 0.15^b	0.67 ± 0.23^a

Same superscripts in a row are not significantly different ($p > 0.05$)

season and the minimum, 16.40 ± 2.71 °C, in winter season. These findings corroborate the notion that summers are hot and winters are cold in the study area, with the eastern and northern parts being dry and frigid and the western parts being a little more humid (Mirza et al. 2014).

Water temperature (WT), a critical ecological factor, is mainly responsible for the growth and distribution of aquatic flora and fauna (Van Vliet et al. 2011; Jalal and Sanalkumar 2012; Beechie et al. 2013; Tank and Chippa 2013). Moreover, WT substantially impacts the solubility of oxygen in water, as well as the metabolic rates and reproductive processes of aquatic species (Jobling 2002; Quinn et al. 2007; Boyd 2019). Simultaneously, the incidence and pathogenicity of aquatic infections are significantly affected by WT (Marcogliese 2008). Like AT, a significant ($p < 0.05$) difference in WT was also recorded during the present study among different seasons and sites. The maximum WT, 17.17 ± 6.08 °C, was recorded at downstream site and the minimum, 13.36 ± 5.27 °C, at upstream site. Likewise, the maximum WT, 22.58 ± 3.17 °C, was recorded in summer season and the minimum, 8.91 ± 1.38 °C, in winter season. The results indicate a substantial correlation between WT and AT. Evidently, it is seen that WT is impacted by AT, with lower AT during winter season, gradually increasing throughout the spring season and reaching its peak during the summer season (Arismendi et al. 2014; Khanday et al. 2021; Mir et al. 2023).

The pH of water is often used to ascertain its level of acidity or alkalinity. Aquatic species must maintain an adequate pH for survival and the pH of aquatic environments is primarily influenced by photosynthesis and respiration (Hamid et al. 2020). The current study recorded the overall pH as alkaline with significant ($p < 0.05$) differences among seasons and sites. An increasing trend was evident, with a maximum value of 7.67 ± 0.40 noted at downstream site, while a minimum value of 7.38 ± 0.22 at upstream site. Similar observations were also obtained while analysing the pH of different water bodies in the past (Mirza et al. 2014; Dar et al. 2020; Manzoor and Iqbal 2020). pH also varied significantly ($p < 0.05$) between seasons, with a maximum value of 7.92 ± 0.30 noted during autumn season and a minimum value of 7.33 ± 0.17 during winter season. The observed alkaline pH levels may

Table 3 ANOVA (Duncan's multiple range test) showing temporal variation in physico-chemical parameters of River Poonch, J&K, India

Parameters	Spring	Summer	Autumn	Winter
AT (°C)	28.15 ± 4.05^b	33.83 ± 3.47^a	22.70 ± 2.67^c	16.40 ± 2.71^d
WT (°C)	17.06 ± 4.27^b	22.58 ± 3.17^a	12.56 ± 2.62^c	8.91 ± 1.38^d
pH	7.46 ± 0.19^{bc}	7.55 ± 0.18^b	7.92 ± 0.30^a	7.33 ± 0.17^c
EC (μs cm^{-1})	252.84 ± 41.61^c	332.51 ± 47.83^a	292.82 ± 39.67^b	199.36 ± 36.45^d
TDS (mg/L)	138.90 ± 27.86^c	207.84 ± 28.55^a	164.13 ± 20.59^b	113.08 ± 11.45^d
DO (mg/L)	8.68 ± 1.47^b	6.58 ± 1.04^c	9.35 ± 0.79^b	11.06 ± 0.88^a
FCO$_2$ (mg/L)	5.83 ± 1.67^b	7.55 ± 0.78^a	6.13 ± 1.14^b	3.76 ± 1.62^c
TA (mg/L)	119.91 ± 9.12^b	123.47 ± 11.83^{ab}	129.63 ± 8.36^a	112.95 ± 9.34^c
TH (mg/L)	117.55 ± 14.14^b	147.57 ± 19.60^a	149.59 ± 17.00^a	90.49 ± 16.22^c
NO$_2$-N (mg/L)	0.16 ± 0.04^b	0.22 ± 0.04^a	0.13 ± 0.03^c	0.06 ± 0.02^d
NO$_3$-N (mg/L)	0.22 ± 0.06^b	0.34 ± 0.07^a	0.16 ± 0.04^c	0.10 ± 0.03^d
TP (mg/L)	0.30 ± 0.10^b	0.60 ± 0.14^a	0.34 ± 0.12^b	0.14 ± 0.05^c
SO$_4^{2-}$ (mg/L)	12.50 ± 2.31^b	14.07 ± 2.58^a	11.78 ± 2.23^b	9.95 ± 2.09^c
Cl$^-$ (mg/L)	15.90 ± 2.17^{bc}	16.61 ± 3.10^b	19.54 ± 2.85^a	13.06 ± 2.31^c
F$^-$ (mg/L)	0.43 ± 0.21^b	0.65 ± 0.26^a	0.44 ± 0.19^b	0.25 ± 0.10^c

Same superscripts in a row are not significantly different ($p > 0.05$)

primarily be due to a substantial anthropogenic load and human settlements in the riparian region, particularly at downstream site. Several investigations conducted in the past by different workers yielded similar results (Mirza et al. 2013, 2014; Manzoor and Iqbal 2020).

Electrical conductivity (EC) is a significant physico-chemical feature related to water's inherent ability to facilitate the flow of electric current. This property is primarily determined by the concentrations of total dissolved particles and the extent of ionization (Allan and Castillo 2007). Changes in WT substantially impact EC, with a potential increase of 2–3% for every 1°C rise in temperature (Yilmaz and Koc 2014). It has been noted that rivers traversing regions with clay soil containing ionizing substances tend to exhibit elevated EC (Bhateria and Jain 2016). A significant ($p < 0.05$) spatio-temporal variation in EC was observed in the present study. The minimum EC, 229.14 ± 48.62 μs cm^{-1}, was recorded at upstream site, while the maximum, 309.37 ± 62.01 μs cm^{-1}, at downstream site. Higher EC noted from the downstream site was due to various factors such as increased temperature, increased TDS, agricultural runoff, bank erosion, rapid decomposition and mineralization of domestic waste. A similar trend in EC was also recorded in several studies from River Poonch and its associated nallahs at different places (Mirza et al. 2013, 2014; Manzoor and Iqbal 2020). Furthermore, temporally, the minimum EC, 199.36 ± 36.45 μs cm^{-1}, was recorded during winter season and the maximum, 332.51 ± 47.83 μs cm^{-1}, during summer season. Studies have reported similar findings from the other tributaries/basins of the Jhelum River in the Himalayan region (Khanday et al. 2021; Arafat et al. 2022).

Total dissolved solids (TDS) refer to the concentration of the most abundant ions, both organic and inorganic, present in a specific volume of water in dissolved form. TDS serves as a reliable indicator for evaluating the overall composition of water, enabling us to gauge its level of cleanliness and integrity (Dar et al. 2019). It is important to note that TDS exhibits a direct relationship with the EC of water. The present study documented a significant ($p < 0.05$) disparity in TDS levels across different seasons and sites. The minimum TDS, 142.86 ± 32.90 mg/L, was noted at upstream site, while the maximum, 205.72 ± 47.62 mg/L, at downstream site. In the seasons, the minimum TDS, 113.08 ± 11.45 mg/L, was recorded in winter season and the maximum, 207.84 ± 28.55 mg/L, in summer season. The previous studies have also documented similar findings, suggesting that during the summer season, there is an elevated discharge of household waste materials, municipal waste and agricultural runoff into rivers and this influx of anthropogenic activities is believed to contribute to an increase in the concentration of dissolved ions (Mirza et al. 2014; Mir and Gani 2019; Manzoor and Iqbal 2020).

Dissolved oxygen (DO) in aquatic ecosystems plays a crucial role in controlling the metabolic activities of various aquatic organisms (Yang et al. 2007; Eliku and Leta 2018). Many factors, including temperature, primary production and the breakdown of organic waste, influence water's concentration of DO (Mir et al. 2023). Assessing water quality, organic contamination, ecological state, productivity and water resource health heavily rely on DO content, making it an essential limnological parameter (Lone et al. 2021). Spatial and temporal significant ($p < 0.05$) variation was observed in the DO content of River Poonch. Minimum DO, 8.05 ± 1.93 mg/L, was recorded at downstream site, while maximum, 9.76 ± 1.73 mg/L, at upstream site. The lowest DO level observed from the downstream site was due to anthropogenic burden, less atmospheric diffusion at prevailing atmospheric temperature and reduced water velocity in planar topography, resulting in reduced water recirculation. On the other hand, minimum DO, 6.58 ± 1.04 mg/L, was recorded during summer season and maximum, 11.06 ± 0.88 mg/L, during winter season. The lowest DO level during the summer season was attributed to less solubility at higher temperatures, high organic decomposition and high rates of metabolic activity in aquatic organisms. The results of this study are consistent with other investigations that have been carried out in the past (Khan et al. 2003; Qadir et al. 2008; Eliku and Leta 2018; Manzoor and Iqbal 2020; Bhat et al. 2021).

Free carbon dioxide (FCO_2) is present in the form of dissolved gas in the surface water (Mir et al. 2023). The concentration of FCO_2 is mostly regulated by metabolic activities, i.e. photosynthesis and respiration, apart from atmospheric diffusion (Arafat et al. 2022). Moreover, FCO_2 concentrations are also affected by the inflow of groundwater, frequently enriched with CO_2 owing to soil respiration in the watershed (Allan and Castillo 2007). It is crucial to note that a larger quantity of FCO_2 increases the acidity of water (Maas and Wicks 2017). FCO_2 in the current study depicted a significant ($p < 0.05$) variation among seasons and sites. At upstream site, minimum, 3.52 ± 2.49 mg/L, FCO_2 was observed, while maximum, 5.93 ± 1.95 mg/L, at downstream site. Among the seasons, the minimum FCO_2, 3.76 ± 1.62 mg/L, was recorded during winter season and the maximum, 7.55 ± 0.78 mg/L, during summer season. The results of this study exhibit potential correlations with previously reported studies (Mirza et al. 2014; Manzoor and Iqbal 2020; Mir et al. 2023).

Total alkalinity (TA) refers to the capability of water within an aquatic environment to withstand changes in pH levels. Since it stabilizes pH, it is believed to possess an acid-neutralizing capacity (ANC) (Mir et al. 2023). TA is contributed by various ions such as OH^-, CO_3^{2-} and HCO_3^- as well as by carbonates of Ca and Mg (Kang et al. 2001). An important point to consider is that there is an inverse relationship

between pH and TA concerning water outflow (Rebsdorf et al. 1991; Arafat et al. 2022). The current study revealed a significant ($p < 0.05$) spatio-temporal change in TA, which might be associated with the fluctuation in water flow. The minimum, 110.62 ± 6.43 mg/L, TA was recorded at upstream site and the maximum, 131.90 ± 8.29 mg/L, at downstream site. At upstream site, torrential water flow conditions result in less time for water to interact with parent rock materials and catchment area, thus lowering the TA. Conversely, there is a decrease in water flow downstream site and the riverbed becomes relatively flat, allowing for sufficient time for dissolving parent rock components and other materials from the surrounding regions. Meanwhile, among seasons, minimum, 112.95 ± 9.34 mg/L, TA was recorded during winter season when the water column recedes in addition to less precipitation and maximum, 129.63 ± 8.36 mg/L, during autumn season during monsoon when agricultural runoff, sewage and other organic wastes flow into rivers. The findings of the current study are consistent with those of many previous studies (Singh et al. 2005; Manzoor and Iqbal 2020; Khanday et al. 2021).

Total hardness (TH) of water prevents soap from forming a lather. TH depends on the amounts of soluble salts of bivalent ions, such as bicarbonates of calcium, magnesium, chlorides and sulphates while other ions such as manganese, strontium and iron also contribute (USEPA 2000; Seth et al. 2016). TH varied significantly ($p < 0.05$) with respect to seasons and sites in the present study. Minimum, 110.51 ± 25.69 mg/L, TH was observed at upstream site and maximum, 140.95 ± 29.38 mg/L, at downstream site. The rise in TH downstream site may be attributed to waste inputs from both point and non-point sources. Minimum, 90.49 ± 16.22 mg/L, TH was recorded during winter season while maximum, 149.59 ± 17.00 mg/L, during autumn season. It is important to note that higher TH during autumn season can be attributed to agricultural runoff, sewage waste and pronounced deposition of salts by stone quarrying by stone crushers. These findings are in conformity with those of other workers (Mirza et al. 2014; Mir et al. 2016; Seth et al. 2016; Manzoor and Iqbal 2020).

For aquatic ecosystems to function, they must have a sufficient supply of dissolved inorganic nitrogen, phosphate and other nutrients such as iron, ammonia and silica (Allan and Castillo 2007). Simultaneously, it is important to mention that the concentration of these nutrients above normal levels in water bodies can lead to the eutrophication of water bodies (Arafat et al. 2022). Aquatic ecologists have extensively studied nitrogen as a prominent nutrient among other nutrients (Dodds 2002). Most of the nitrogen comes from sewage inputs, surface fertilizer runoff from agricultural fields and through natural atmospheric diffusion (Bernhardt et al. 2002; Swaney et al. 2012). Inorganic nitrogen exists as NO_3^-, NO_2^-, NH_4^+ and N_2. Recycling of inorganic nitrogen occurs through the nitrogen cycle. During biological intake, dissolved nutrients undergo assimilation, resulting in their conversion into organic form and subsequently, when organic matter is expelled and destroyed, these nutrients undergo mineralization, transforming into an inorganic form (Hamid et al. 2020). Significant ($p < 0.05$) differences in NO_2-N, NO_3-N and TP were found spatially and temporally during the current study. All these nutrients, viz. NO_2-N, NO_3-N and TP, were found minimum, 0.11 ± 0.06 mg/L, 0.17 ± 0.09 mg/L and 0.24 ± 0.14 mg/L, respectively, at upstream site and maximum, 0.17 ± 0.07 mg/L, 0.25 ± 0.11 mg/L and 0.41 ± 0.23 mg/L, respectively, at downstream site. Furthermore, temporally NO_2-N, NO_3-N and TP had minimum concentration, 0.06 ± 0.02 mg/L, 0.10 ± 0.03 mg/L and 0.14 ± 0.05 mg/L, respectively, during winter season whereas maximum concentration, 0.22 ± 0.04 mg/L, 0.34 ± 0.07 mg/L and 0.60 ± 0.14 mg/L, respectively, during summer season. Various factors contribute to the spatial variation of nutrients, which include garbage dumping in the open and runoff from the surface especially at downstream region (Edwards et al. 2000). Moreover, nitrogen and phosphorous concentrations are influenced by anthropogenic activities such as industrial waste and municipal effluents that are pumped into surface water bodies (point source) in addition to surface runoff from the agricultural fields (non-point source) which contain nutrient-rich fertilizers (Goller et al. 2006; Mir et al. 2023). Throughout the summer season, human activities like thorough washing of household objects are more prominent within river catchment regions in contrast to winter season. In addition, high temperatures also serve as a catalyst that accelerates the breakdown of organic nutrient-rich materials, transforming them into inorganic substances. Furthermore, during the summer season, along the river's riparian zones, activities related to agriculture are efficacious sources of an increase in NO_3-N concentration because the flow of nutrients, sediments, etc., in rivers, are determined by patterns of land use through organic inputs and surface runoff as have been reflected in some studies in the past (Poor and McDonnell 2007; Arango and Tank 2008; Kebede et al. 2014; Huang et al. 2014).

Sulphate (SO_4^{2-}) is commonly found in almost all-natural water sources where gypsum and other minerals are naturally found in a significant concentration (Seth et al. 2016). Mainly, sodium, potassium and magnesium sulphates are found in our water as these are highly soluble sulphates. SO_4^{2-} is primarily used in manufacturing industries such as cosmetics, pharmaceutical, cleaning products, etc., besides being used in lead–acid batteries and fertilizers (Singh et al. 2023). Significant ($p < 0.05$) variation in spatio-temporal concentration of SO_4^{2-} was observed in the present study. The minimum, 9.78 ± 1.61 mg/L, SO_4^{2-} was recorded at upstream site, while the maximum, 14.85 ± 1.87 mg/L, at

downstream site. Higher concentration recorded from the downstream site is attributed to the dumping of municipal waste, fertilizer inputs from agricultural fields and other factors where some rocks and soil can contribute to sulphate. Likewise, SO_4^{2-} was found to be minimum, 9.95 ± 2.09 mg/L, during winter season and maximum, 14.07 ± 2.58 mg/L, during summer season. Anthropogenic activities such as agriculture, garbage decomposition, etc., that are more prevalent during summer season and mineral leaching from soil and rocks can be regarded as the factors for enhanced concentration of SO_4^{2-} and other ions. Almost identical findings have been reported in the past by many workers (Mirza et al. 2014; Seth et al. 2016; Singh et al. 2023).

Chloride (Cl^-) ions are often found in many inorganic compounds, particularly as salts of sodium, potassium, magnesium and calcium. It has been reported that apart from anthropogenic activities (sewage discharge, fertilizers containing potash, etc.), there are several sources of Cl^- in nature, such as weathering rocks, basin brines, etc. (Gardner and Royer 2010). Elevated Cl^- concentrations are consistently seen as a sign of pollution and may have a detrimental impact on freshwater ecosystems (Abubakar et al. 2020; Mir et al. 2023). Cl^- levels were found significantly ($p < 0.05$) varying spatio-temporally in the current study. A minimum concentration of Cl^-, 13.56 ± 2.68 mg/L, was found at upstream site, while a maximum concentration of 18.78 ± 2.55 mg/L at downstream site. The observed higher concentrations of Cl^- detected at the downstream site might be ascribed to many reasons, including weathering phenomena, discharge of urban sewage, runoff of agricultural compounds and proximity of animal waste disposal facilities to the riverbank. However, based on season, the minimum Cl^- concentration, 13.06 ± 2.31 mg/L, was recorded during winter season, while the maximum concentration, 19.54 ± 2.85 mg/L, during autumn season. Throughout the winter season, there is a notable decrease in human activity and a drop in salt dissolving and weathering processes. On the other hand, it is worth noting that during the monsoon season (July–August), there is a significant increase in sewage pollution and the discharge of fertilizers from adjacent agricultural areas. These factors lead to an elevated concentration of Cl^- in the environment. Similar to the present findings on Cl^- concentrations, many workers have also documented almost identical results (Mirza et al. 2014; Seth et al. 2016; Manzoor and Iqbal 2020).

Fluoride (F^-) is an inorganic ion occurring naturally in water bodies and its concentration varies depending on the source in natural water. It is linked to a range of health impacts. Sources of fluoride consist of both autochthonous and allochthonous. F^- concentration was found to vary significantly ($p < 0.05$) during the present study. Minimum, 0.25 ± 0.09 mg/L, F^- was found at upstream site, while a maximum, 0.67 ± 0.23 mg/L, at downstream site. Meanwhile, the minimum, 0.25 ± 0.10 mg/L, F^- was observed during winter season and the maximum, 0.65 ± 0.26 mg/L, during summer season. The elevated levels of F^- may be attributed to anthropogenic use of pesticides having fluoride, fertilizers, discharge of sewage as well as the weathering and dissolution of rock salts, in downstream areas during summer season. Results obtained in the current study are in conformity with the findings of other workers (Rajeshwari and Saraswati 2009; Seth et al. 2016; Manzoor and Iqbal 2020).

The present study observed that a noteworthy fraction of the physico-chemical parameters exhibited elevated concentrations in the downstream site compared to the midstream and upstream sites. The fundamental cause for this observation might be due to the buildup of contaminants, including runoff from agricultural areas, urban effluents, hamlets and several other human activities. On the other hand, the levels of different parameters tend to increase in summer season with higher temperatures and higher precipitation apart from DO concentration, which was noted to be higher in winter season. However, it is worth noting that the water quality metrics assessed from the River Poonch fall well within the range recommended by the Bureau of Indian Standards (BIS, IS 10500:2012) and are deemed suitable for promoting optimum growth in fish species by Prakash et al. (2010), which is quite encouraging (Table 4). It is necessary, however, to maintain this salubrious habitat for aquatic organisms to guarantee the perpetuation of a sustainable biodiversity.

Correlation analysis

The correlation analysis provides valuable insights into the complex interrelationships among various physico-chemical parameters, which are useful in enhancing our understanding of the impact of numerous environmental factors on water quality and the general well-being of the aquatic ecosystem. Correlations among various physico-chemical variables in aquatic environments arise from diverse biological, chemical and physical interactions, leading to positive and negative associations. Pearson's correlation was used on a normalized dataset to ascertain the significant ($p < 0.05$) correlations among the investigated physico-chemical parameters (Bhandari and Nayal 2008; Joshi et al. 2009; Seth et al. 2016; Eliku and Leta 2018). The correlation coefficient (r) depicts the strength of the relationship, which lies from $+1$ to -1. Values approaching $+1$ indicate a strong positive correlation, where a rise in one variable is closely and linearly associated with an increase in the other variable while values approaching -1 indicate a strong negative correlation, where an increase in one variable is closely and linearly associated with a drop in the other (Seth et al. 2016). A score of 0 suggests a lack of linear correlation

Table 4 Comparison of range of physico-chemical parameters of River Poonch, J&K, India, with recommendations

Parameters	Ideal values for freshwater fishes (Prakash et al. 2010)	BIS 2012	Current study values
WT (°C)	10–32	10–25	15.28 ± 5.94
pH	7.5–9.5	6.5–8.5	7.5 ± 0.3
TDS (mg/L)	<500	500–2000	159.99 ± 40.83
DO (mg/L)	5–10	6–4	8.92 ± 1.92
FCO_2 (mg/L)	<3	–	4.86 ± 2.47
TA (mg/L)	50–300	200–600	121.49 ± 11.29
TH (mg/L)	50–280	200–600	126.30 ± 29.47
NO_2-N (mg/L)	0.0–0.5	–	0.14 ± 0.06
NO_3-N (mg/L)	0.1–3.0	45	0.21 ± 0.10
TP (mg/L)	0.05–0.4	–	0.35 ± 0.20
SO_4^{2-} (mg/L)	20–200	200–400	12.08 ± 2.71
Cl^- (mg/L)	31–70	250–1000	16.28 ± 3.35
F^- (mg/L)	–	1.0	0.44 ± 0.24

or a weak correlation among the variables (Mudgal et al. 2009; Seth et al. 2016). The present study illustrated intricate interconnections among the examined physico-chemical parameters (Fig. 2a and b). It is important to note that in Fig. 2b, green colour signifies a positive correlation, while red colour indicates a negative correlation. Furthermore, the bold and vibrant colouration signifies robust correlations, whether positive or negative, while the subdued and lacklustre colouration signifies feeble correlations, whether positive or negative. Among the majority of the studied physico-chemical parameters, a robust positive correlation was observed except for DO, which showed a strong negative correlation. There was a significant positive correlation between AT and WT ($r = 0.97$), WT and NO_3-N ($r = 0.97$), WT and TDS ($r = 0.95$), WT and EC ($r = 0.93$) and WT and NO_2-N ($r = 0.90$) whereas strong negative correlation was observed between WT and DO ($r = -0.94$). Apart with WT, DO showed strong negative correlation with TDS ($r = -0.95$) and EC ($r = -0.91$). FCO_2 showed strong positive correlation with AT ($r = 0.92$) depicting atmospheric diffusion and EC ($r = 0.91$). Similarly, TA showed strong positive correlation with F^- ($r = 0.94$) and SO_4^{2-} ($r = 0.93$). TDS showed strong positive correlation with NO_3-N ($r = 0.94$), EC ($r = 0.94$), TP ($r = 0.92$) and NO_2-N ($r = 0.90$). Apart from this, other parameters such as Cl^-, TDS, NO_2-N, NO_3-N and EC showed negative correlation with pH and DO. Various water parameters' interplay led to positive and negative correlations, reflecting the complex dynamics within the aquatic environment (Seth et al. 2016; Eliku and Leta 2018). Moreover, it is important to acknowledge that correlations exhibit a certain level of variability depending on local circumstances, specific geographical areas, human factor and temporal fluctuations, which is also applicable in the current study. It is important to note that in relation to this study, comparable results have been documented previously (Arafat et al. 2022; Mir et al. 2023). Positive and negative correlations among studied physico-chemical parameters also indicated the dynamic changes in water quality across space and time in the present study.

Linear regression

The interconnectedness of various physico-chemical parameters plays a crucial role in advancing information, which may be more effectively examined via linear regression analysis (Shyamala et al. 2008; Mir et al. 2023). The coefficient of determination (r^2) represents the amount of variation explained by independent parameters, thereby indicating a significant proportion of changes taking place in dependent parameters. All the relationships in this study were found significant ($p < 0.05$). Table 5 and Fig. 3a–h provide

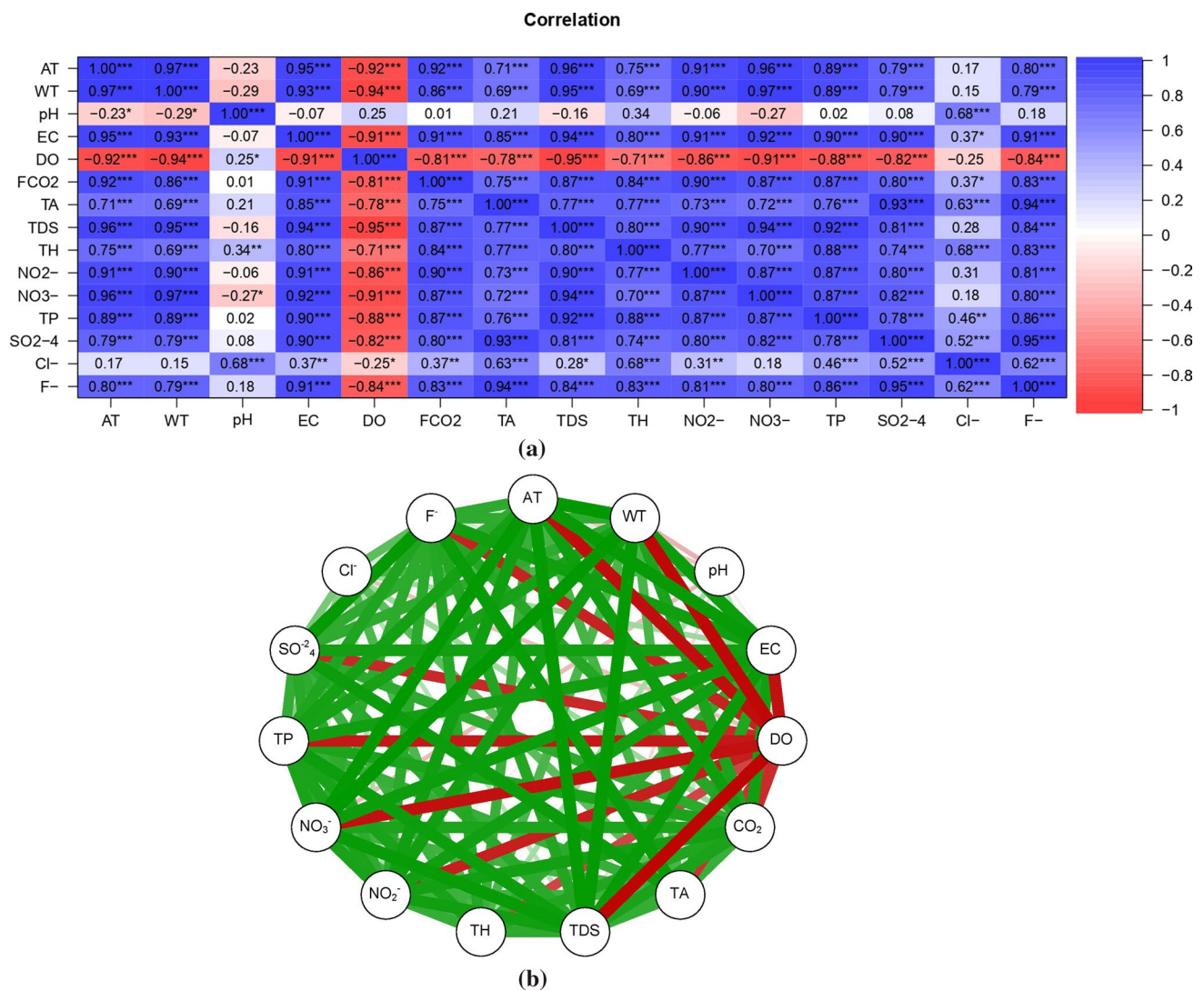**Correlation**

(a)

(b)

Fig. 2 **a** Pearson's multiple correlation plot showing intricate relationships among selected physico-chemical parameters of River Poonch, J&K, India. Significance: *** $P < 0.001$; ** $P < 0.01$ and * $P < 0.05$. **b** Diagrammatic view of same generated using R statistical software through "qgraph" package. For full form of abbreviations, refer to Table 1

a comprehensive overview of the regression statistics about the physico-chemical dataset of the River Poonch. These findings underscore the noteworthy interrelationships that exist within the physico-chemical dataset. The coefficient of determination (r^2) values were recorded from 0.14 to 0.95. It is important to note that the coefficient of determination (r^2) close to 1 indicates a good model. In relation to AT (independent parameter), more than 80% of the aggregate variation in dependent parameters, i.e. WT ($r^2 = 0.95$), DO ($r^2 = 0.85$) and FCO$_2$ ($r^2 = 0.84$), was observed, indicating high interrelationships. Likewise, in relation to WT (independent parameter), more than 70% of total variation was observed in dependent variables, viz. TDS ($r^2 = 0.91$), DO ($r^2 = 0.89$), EC ($r^2 = 0.86$), TP ($r^2 = 0.79$) and FCO$_2$

($r^2 = 0.75$) which indicated most direct relationship, whereas TA ($r^2 = 0.48$), TH ($r^2 = 0.47$) and pH ($r^2 = 0.38$) were least related. In relation to EC (independent parameter), TDS ($r^2 = 0.89$), F$^-$ ($r^2 = 0.84$), NO$_3$-N and NO$_2$-N ($r^2 = 0.83$) and TP and SO$_4$$^{2-}$ ($r^2 = 0.82$) were most highly related as more than 80% of the aggregate variation was observed whereas TH ($r^2 = 0.64$) and Cl$^-$ ($r^2 = 0.14$) were least related. Similarly, in relation to TH (independent parameter), TA ($r^2 = 0.59$) was highly related and DO ($r^2 = 0.49$) was least related. In relation to pH (independent parameter), FCO$_2$ ($r^2 = 0.75$) was most highly related, while TA ($r^2 = 0.48$) and TH ($r^2 = 0.47$) were least related. Most of the parameters examined as dependent factors in the present study strongly correlated with the independent variables, accounting for
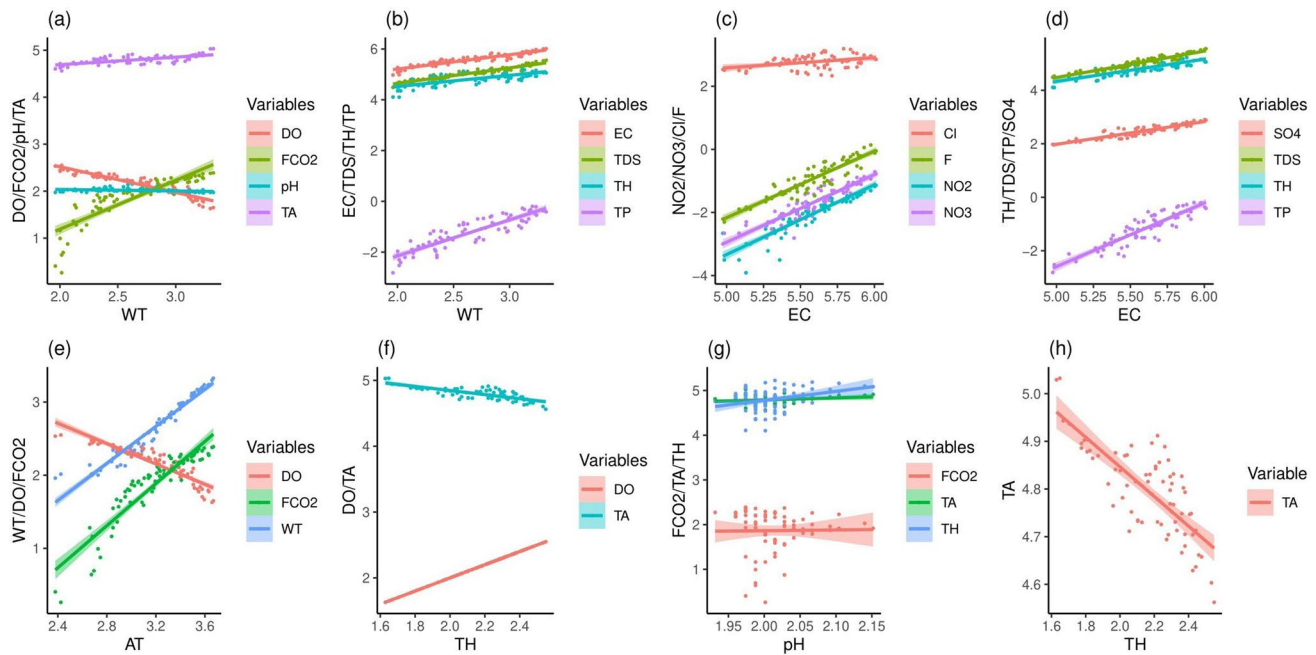
Fig. 3 **a–h** Trend relationships between selected physico-chemical parameters of River Poonch, J&K, India. *Notes* "*y-axis*" represents the selected dependent parameter(s) and "*x-axis*" represents the selected independent parameter. For full form of abbreviations, refer to Table 1

over 70% of the cumulative variation. In the present study, it was observed that a significant negative correlation exists between WT and DO. This correlation may be attributed to the fact that warm waters tend to have lower levels of DO, as they have a higher tendency to get saturated with oxygen (Wetzel 2001). Moreover, the augmentation of WT also promotes the breakdown of organic matter from animal and plant residues, leading to a more substantial release of nitrogen and thus reducing DO levels (Abubakar et al. 2020; Mir et al. 2023). During the linear regression analysis, it was found that the physico-chemical parameters such as WT, DO, FCO_2, pH, EC, TH, TDS, TP, SO_4^{2-}, NO_2-N and NO_3-N were significant in predicting and assessing the general quality of water.

Principal component analysis (PCA)

PCA reduces multivariate data dimensionality and extracts meaningful information from the large datasets. PCA can effectively analyse physico-chemical parameters to identify spatio-temporal fluctuations, uncover environmental impacts and examine connections between variables in datasets (Mir et al. 2023). In PCA, dataset variability is best explained by variables that are correlated with the principal components 1 and 2 (i.e. PC1 and PC2) (Kassambara 2017). During the present study, the first two principal components accounted for 91.9% of the cumulative variation, PC1 76% and PC2 15.9% (Table 6). The first principal component (PC1 76%) with the corresponding eigenvalue 11.40 had significant

positive correlation (> 0.7) with AT, WT, EC, TDS, FCO_2, TA, TH, NO_2-N, NO_3-N, TP, SO_4^{2-} and F^- whereas significant negative correlation (> -0.7) was observed with DO. Loadings of EC, TDS, NO_2-N, NO_3-N, SO_4^{2-} and F^- on PC1 signify the influx of household waste, agricultural runoff besides heavy rainfall and floods during monsoon season leading to surface runoff and erosion. Moreover, these physico-chemical parameters also explain point and non-point source input, besides erosional effects. Several researchers have observed similar findings (Juahir et al. 2011; Holmroos et al. 2015; Hamid et al. 2016; Islam et al. 2023; Mir et al. 2023). Positive loading of WT and negative loading of DO can be explained by the fact that as the temperature increases, organic matter rapidly decomposes by consuming more and more DO. Similarly, the second principal component (PC2 15.9%) with the corresponding eigenvalue 2.38 had a significant positive correlation (> 0.7) with pH and Cl^-. pH was positively correlated with PC2, which can be ascribed to the presence of dissolved organic matter, which produces NH_3 and lowers pH with organic acids (Kim and Cardone 2005). Moreover, a significant positive correlation of Cl^- with PC2 noted during the current study can be attributed to extreme rainfall during monsoon. Notably, PCA has shown that most of the factors that correlate with PC1 play a crucial role in determining the water quality of River Poonch. The finding highlights the significance of these characteristics in assessing and understanding the overall condition of the water quality of the River Poonch. Nevertheless, the physico-chemical parameters associated

Table 5 Linear regression showing trend relationships among physico-chemical parameters of River Poonch, J&K, India

Parameters	Regression equation	r^2	F-value	p-value
In relation to air temperature (AT)				
WT	$y = -1.4 + 1.31x$	0.95	1219.1	$<2.2e-16***$
DO	$y = 4.4 - 0.70x$	0.85	382.4	$<2.2e-16***$
FCO_2	$y = -2.7 + 1.41x$	0.84	380.9	$<2.2e-16***$
In relation to water temperature (WT)				
DO	$y = 3.6 - 0.55x$	0.89	571.2	$<2.2e-16***$
FCO_2	$y = -0.89 + 1.03x$	0.75	206.7	$<2.2e-16***$
pH	$y = 2.1 - 0.032x$	0.38	6.6	$0.012*$
TA	$y = 4.4 + 0.16x$	0.48	63.6	$2.2e-11***$
EC	$y = 4.1 + 0.56x$	0.86	436.8	$<2.2e-16***$
TDS	$y = 3.4 + 0.61x$	0.91	675.2	$<2.2e-16***$
TH	$y = 3.7 + 0.43x$	0.47	62.7	$2.2e-11***$
TP	$y = -5.1 + 1.4x$	0.79	256.2	$<2.2e-16***$
In relation to electrical conductivity (EC)				
TDS	$y = 0.47 + 0.99x$	0.89	561.5	$<2.2e-16***$
TH	$y = 0.18 + 0.83x$	0.64	123.1	$<2.2e-16***$
TP	$y = -14.4 + 2.2x$	0.82	314.9	$<2.2e-16***$
SO_4^{2-}	$y = -2.3 + 0.85x$	0.82	310.7	$<2.2e-16***$
NO_2-N	$y = -14.5 + 2.2x$	0.83	329.1	$<2.2e-16***$
NO_3-N	$y = -13.7 + 2.1x$	0.83	407.3	$<2.2e-16***$
Cl^-	$y = 0.98 + 0.32x$	0.14	10.7	$0.0012**$
F^-	$y = -13 + 2.1x$	0.84	356.1	$<2.2e-16***$
In relation to total hardness (TH)				
DO	$y = -0.65 + 5.3x$	0.49	7.1	$2.2e-16***$
TA	$y = 0.28 + 3.43x$	0.59	101.4	$1.3e-15***$
In relation to pH				
FCO_2	$y = -0.89 + 1.52x$	0.75	16.1	$<2.2e-16***$
TA	$y = 4.4 + 0.16x$	0.48	3.2	$2.2e-11***$
TH	$y = 3.7 + 0.43x$	0.47	9.3	$2.6e-11***$

Levels of significance: *** $p < 0.001$; ** $p < 0.01$ and * $p < 0.05$

Table 6 Correlation of physico-chemical parameters of River Poonch, J&K, India, with the first two principal components (PC1 and PC2)

Physico-chemical parameters	Principal components	
	PC1	PC2
AT (°C)	0.94425926	−0.28338901
WT (°C)	0.93779920	−0.32277480
pH	−0.07795547	0.93537254
EC (μs cm^{-1})	0.97794010	−0.04006429
TDS (mg/L)	0.96795722	−0.14100955
DO (mg/L)	−0.97655484	0.14239416
FCO$_2$ (mg/L)	0.94593390	−0.05100887
TA (mg/L)	0.86217094	0.31875477
TH (mg/L)	0.81309566	0.45700953
NO$_2$-N (mg/L)	0.96746650	−0.15041123
NO$_3$-N (mg/L)	0.93661794	−0.30751635
TP (mg/L)	0.92619387	0.04121728
SO$_4^{2-}$ (mg/L)	0.90337455	0.18075449
Cl$^-$ (mg/L)	0.41037550	0.86367947
F$^-$ (mg/L)	0.90655276	0.26189205

with PC2 exhibited less importance than those associated with PC1.

The PCA biplot illustrates the intricate interrelationships among physico-chemical parameters across selected sampling sites (Fig. 4a). It reveals that variables nearby have a stronger correlation. The sampling sites that overlapped exhibited comparable physico-chemical values, except for a higher pH and Cl$^-$ concentration at downstream site and a higher DO content at upstream site. Likewise, the PCA biplot adeptly illustrates the intricate interrelationships among physico-chemical parameters across different seasons (Fig. 4b), in which increasing proximity of variable points indicates the presence of more robust and more resilient relationships. Significant overlap was detected between the summer and spring seasons, indicating a high degree of similarity in their properties. DO concentration was maximally displayed in winter season, while pH and Cl$^-$ in autumn season. PCA in several previous investigations have produced findings broadly consistent with the present study (Arafat et al. 2022; Islam et al. 2023; Mir et al. 2023).

Cluster analysis (CA)

In cluster analysis (CA), items are categorized according to their similarities and differences within classes, achieved via hierarchical agglomeration (HAC) approach, which allows for the intuitive assessment of similarity between an individual sample and the entire dataset and this similarity is often visualized through a dendrogram (McKenna 2003; Singh et al. 2004; Hajigholizadeh and Melesse 2017; Mir

et al. 2023). The current study also used the HAC technique to analyse the dataset, with the generation of a dendrogram that exhibited two distinct clusters (Fig. 5). Cluster-I consists of Site-III, downstream site (Balnoi), where human habitation is predominantly responsible for contributing waste to the river directly from point and non-point sources. Cluster-II consists of Site-I and Site-II, i.e. upstream site (Kalaie) and midstream site (Chakkan Da Bagh), respectively, which showed similarity in overall physico-chemical parameters and were less susceptible to human interference. Therefore, Site-I and Site-II were grouped under Cluster-II, showing comparability in water quality as compared to Site-III, grouped under Cluster-I. The present study reports site-specific differences in physico-chemical parameters from upstream to downstream locations, similar to those reported in the previous studies (Shrestha and Kazama 2007; Hamid et al. 2016; Sabha et al. 2019; Arafat et al. 2022; Mir et al. 2023). Consequently, CA could provide a handy method for categorizing surface waters following their similarities, besides facilitating the formulation of highly meticulous future sampling strategies.

Conclusion

The current study employed multivariate statistical approaches to evaluate the physico-chemical parameters to monitor the ecological condition of the River Poonch. Notable differences in physico-chemical parameters were revealed, such as nutrient concentrations and total hardness (i.e. pollution load), across different spatial and temporal dimensions. Specifically, downstream site exhibited higher levels of almost all of the parameters than midstream and upstream sites. This disparity can be attributed to the considerable input of waste from both point and non-point sources and the influence of pronounced human activities in downstream site. Notably, during the present study, it was found that the physico-chemical parameters such as WT, DO, FCO$_2$, pH, EC, TH, TDS, TP, SO$_4^{2-}$, NO$_2$-N and NO$_3$-N were vital factors for predicting and assessing the overall quality of water. The findings of the present study showed that the water quality parameters of River Poonch are highly conducive for the native freshwater fish species. Nevertheless, it is important to consistently monitor the physico-chemical parameters to sustain this valuable ecological resource, i.e. the status of the River Poonch. Hence, this study provides policymakers with a structured method to assess the potential negative impacts of forthcoming alterations in water quality in this river ecosystem.
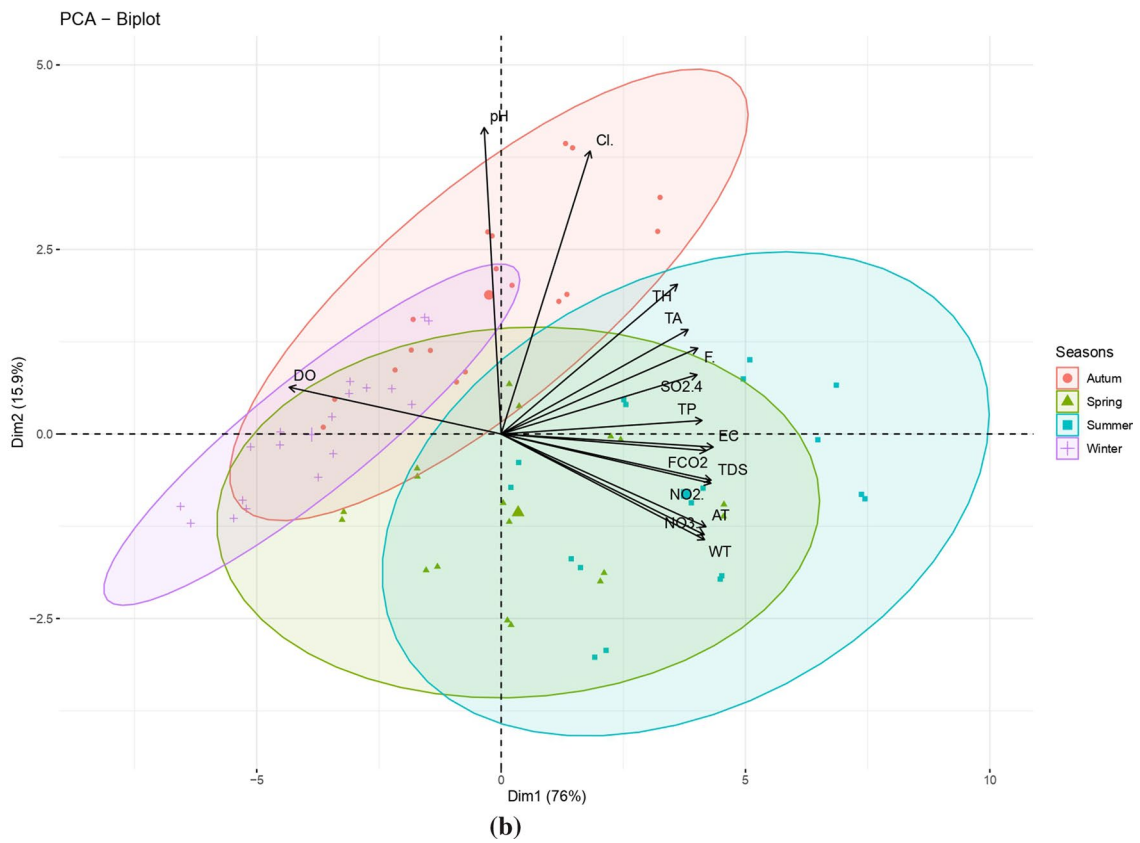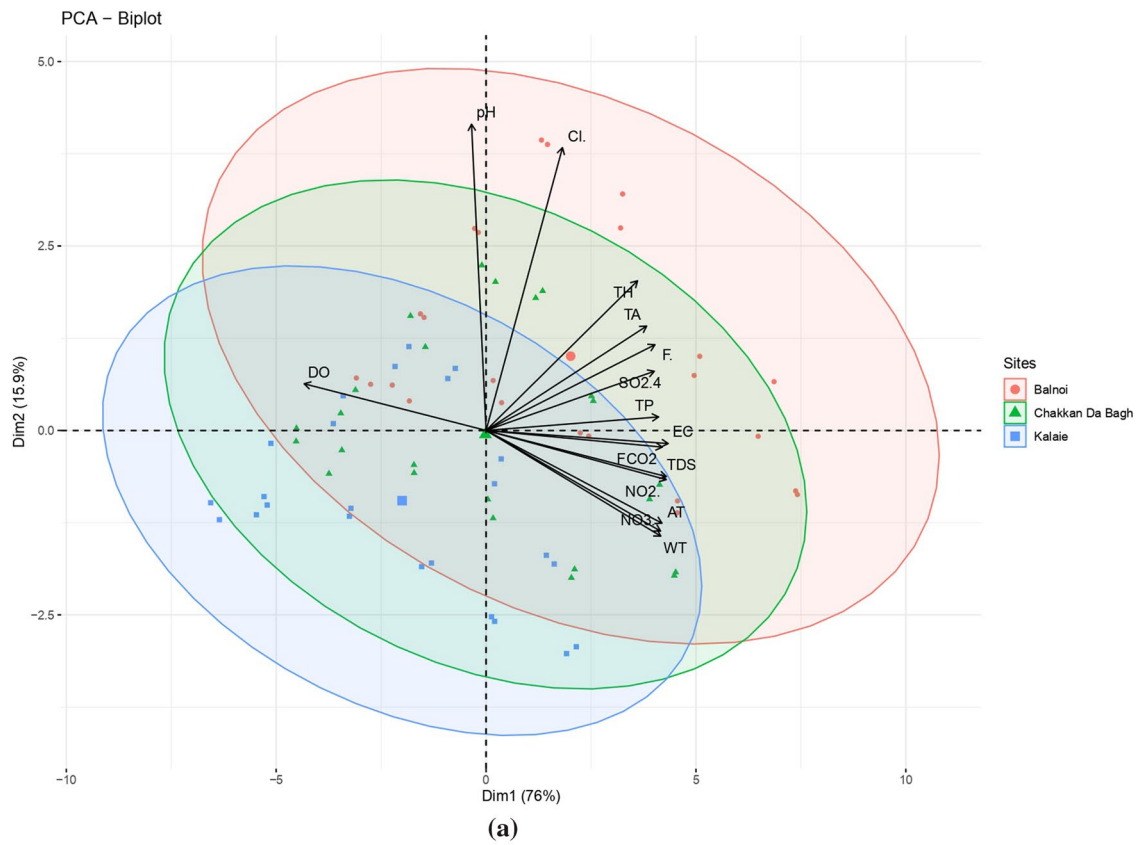
(a)

(b)

◄**Fig. 4 a**, **b** Geographical and temporal correlations of selected physico-chemical parameters of River Poonch, J&K, India, as revealed by principal component analysis (PCA) along the first two principal components (PC1 and PC2), respectively. For full form of abbreviations, refer to Table 1
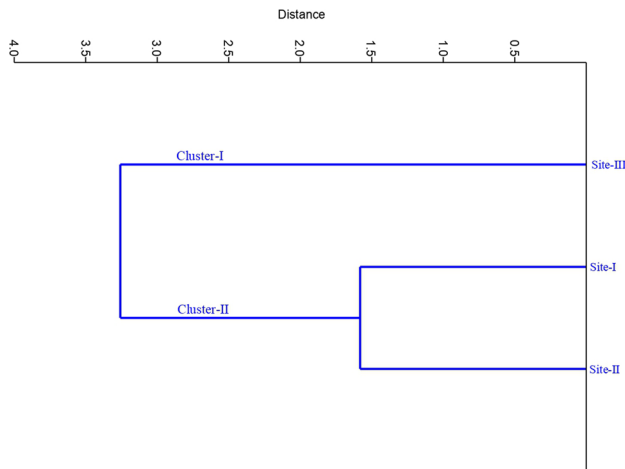

Fig. 5 Dendrogram extracted through cluster analysis (CA) based on Ward's approach showing three sampling sites of River Poonch, J&K, India

Author contributions Waqar Ahmed collected the samples, performed physico-chemical and statistical analyses and wrote the manuscript. Imtiaz Ahmed conceived, designed, supervised and revised the manuscript. Nazir Ahmed Dar supervised and revised the manuscript. Mohammad Abul Farah edited and revised the manuscript.

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

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The authors affirm that this manuscript is original and unpublished elsewhere and adheres to the Ethical Rules relevant for publication in this journal.

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