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СЕЗОННА ДИНАМІКА ЯКОСТІ ВОДИ ПРИТОКИ РІЧКИ БІАС (ЗАХІДНІ ГІМАЛАЇ, ІНДІЯ)

Сезонну динаміку фізико-хімічних параметрів води досліджували у притоці річки Біас у Гімачал-Прадеш (Західні Гімалаї) з метою оцінки ступеня погіршення якості води та визначення джерел забруднення. Зразки води відбирали протягом чотирьох різних сезонів та за стандартними протоколами визначали температуру повітря і води, pH, розчинений кисень, електропровідність, загальні мінералізацію, лужність і жорсткість, вміст хлоридів, фосфатів, нітратів та силікатів. Результати дослідження свідчать про те, що лише температура води та pH послідовно відповідали рекомендованим агентством нормам; всі інші параметри перевищували допустимі межі кожного сезону. Багатодіапазонний тест Дункана (DMRT) (95 % достовірність) підтвердив статистично значущі коливання цих фізико-хімічних показників. Крім того, факторний аналіз з використанням Varimax та кластерний аналіз виявили чіткі сезонні зміни, пов'язуючи коливання головним чином із кількістю опадів, зсувами ґрунту та діяльністю людини. Сезонні тенденції показали пікові концентрації взимку, потім під час мусонів, влітку та після мусонів. За оцінкою індексу якості води (WQI) найгірша якість води спостерігалась під час сезону мусонів, що значною мірою зумовлено надходженням стічних вод та сільськогосподарських стоків, а також ерозією ґрунту, з подальшим зниженням якості води взимку, після мусонів та влітку.

Ключові слова: *сезонна динаміка, фізико-хімічні параметри, кореляція Пірсона, багатодіапазонний тест Дункана (DMRT), факторний аналіз, кластерний аналіз, індекс якості води (WQI), річка Біас, потік Рана.*

Introduction

Water quality is crucial for sustaining environmental health, especially in regions where freshwater serves as the primary source for drinking, agriculture, and industrial activities. The physiochemical characteristics of river water serve as key indicators of its quality, influencing both human communities and

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aquatic life. These water quality parameters can vary seasonally and annually due to a mix of natural processes and human activities, including climate changes, rainfall variations, land-use alterations, and industrial development [18]. This variability is especially significant in mountainous regions such as the Western Himalayas, where freshwater resources are limited and acutely sensitive to seasonal hydrological events like monsoons and snowmelt [21].

The Beas River, an important tributary of the Indus River system, flows through Himachal Pradesh in the northern India. Its waters, along with those of its tributaries, are essential for the Mandi region supporting agricultural, industrial, and residential uses. Water quality in this area is shaped by both natural factors such as precipitation, runoff, and snowmelt and human influences, including agricultural runoff, waste discharge, and hydropower activities [19]. Although the significance of maintaining water quality in the Beas River system is well recognized, there remains a limited understanding of how physiochemical parameters in its tributaries fluctuate seasonally and annually in the Mandi region [17]. These tributaries are affected by a complex mix of seasonal hydrological shifts and anthropogenic pressures. The region undergoes marked seasonal changes with distinct wet and dry periods and climatic variability that directly impacts water quality.

Summers are typically hot and dry leading to lower river flows, while the monsoon season brings heavy rainfall and runoff often increasing turbidity, nutrient loads, and chemical pollutants [4, 22]. Moreover, year-to-year fluctuations in rainfall patterns influenced by global climate change add complexity to the assessment of prolonged patterns in the water quality of the Beas River tributaries [20].

Physiochemical parameters such as pH, temperature, turbidity, dissolved oxygen, total dissolved solids, electrical conductivity, and nutrient concentrations are fundamental indicators of water purity and ecological stability [22]. Among these, temperature plays a pivotal role in regulating dissolved oxygen levels, as warmer water retains less oxygen, which can stress aquatic organisms [21]. The pH of water is of equal significance, as extreme pH values can be harmful to aquatic organisms and impact the solubility and mobility of toxic substances, including heavy metals [9]. In the Beas River system, significant variations in temperature and pH are typically observed during seasonal shifts, particularly during the transition from winter to summer, when snowmelt has a pronounced impact on water temperature.

Dissolved oxygen is a key determinant of water condition, and low dissolved oxygen levels often signal the presence of organic pollution, commonly linked to agricultural runoff, sewage discharge, and heightened microbial activity during warmer periods. Turbidity, reflecting the presence of suspended particles in water, becomes particularly concerning in mountainous areas during the monsoon season. Intense rainfall during this period enhances sediment and nutrient runoff, leading to increased turbidity [7]. Elevated turbidity can hinder light penetration, impairing the growth of aquatic vegetation and disrupting photosynthesis within aquatic ecosystems [19].

Nutrient concentrations especially nitrogen and phosphorus are also crucial for assessing water quality. Excessive nutrient input, often stemming from agricultural runoff, can trigger eutrophication, resulting in harmful algal blooms, degraded water quality, and oxygen depletion [20]. In the tributaries of the Beas River, nutrient levels exhibit seasonal variation, with higher concentrations typically recorded during the monsoon due to increased runoff and soil erosion [22].

The seasonal and inter-annual variability of physiochemical parameters in the Beas River tributaries presents significant challenges for effective water resource management. As pressures on water resources grow due to population expansion, industrial development, and intensified agriculture, understanding these temporal patterns becomes critical for sustainable water use and conservation [21]. Furthermore, climate change-related shifts in temperature and precipitation patterns are expected to intensify existing water quality concerns, such as rising turbidity, nutrient enrichment, and pollutant levels [20].

Previous study [4] examined the relationship between water quality and ichthyofaunal diversity in the Rana Stream. However, there remains a significant gap in the systematic analysis of seasonal variations in physiochemical parameters and their broader implications. The present study seeks to fill this gap by conducting in-depth seasonal evaluation of water quality in the Rana Stream. Utilizing Pearson correlation analysis, varimax-rotated factor analysis, and hierarchical cluster analysis, the study investigates the interrelationships among water quality parameters, identifies potential sources of variation, and evaluates the effects of seasonal changes on overall water quality.

The primary objective of this research is to enhance understanding of the seasonal and inter-annual dynamics of water quality in a tributary of the Beas River located in the Himachal Pradesh region of Western Himalayas. Through multi-seasonal and multi-months monitoring of key physiochemical indicators, the study aims to offer valuable insights into the drivers of water quality fluctuations. These findings are expected to contribute to more informed and sustainable water resource management strategies, supporting the ecological integrity and long-term sustainability of the Beas River system.

Material and Methods

Study area. The Rana stream flows through the Joginder Nagar area in Mandi district, Himachal Pradesh and is known for its steady perennial flow (Figure 1). It begins in the scenic Bir Billing region of Kangra district and travels through the hills before joining the Beas River at Banaruawal, about 27 kilometers from the Joginder Nagar bus stand. This stream is an important resource for the local community. Its water is used for multiple purposes, including irrigation and fish farming. On its right bank, in Joginder Nagar, lies the Mahseer fish farm an important site for freshwater aquaculture. Along its course, the stream also supports several hydroelectric projects, making it a key contributor to the region’s renewable energy supply.

Sampling design. The present study employed a stratified systematic sampling approach (Figure 2). Sampling sites were strategically selected along the

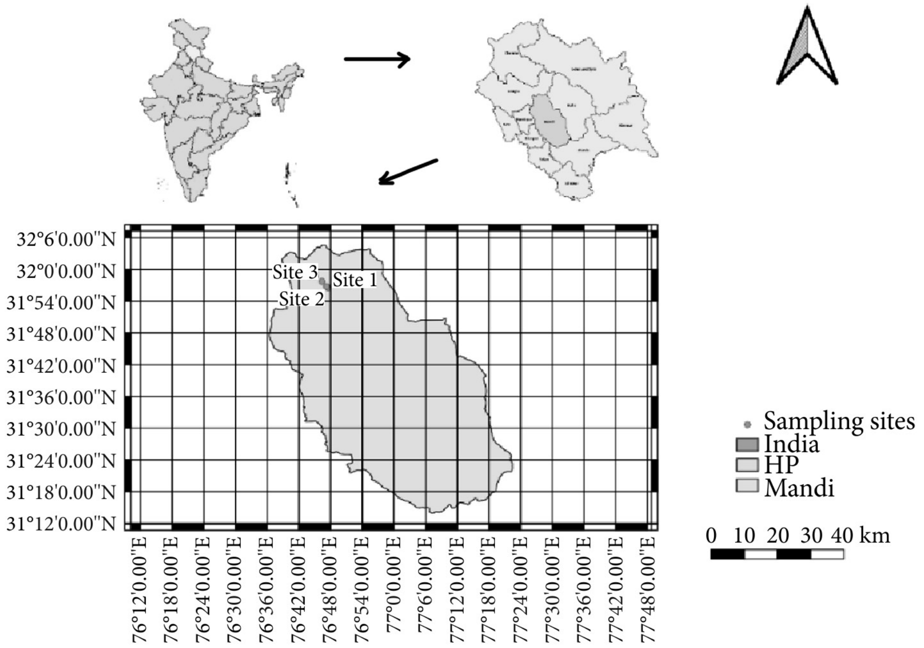

Fig. 1. QGIS map illustrating the study area

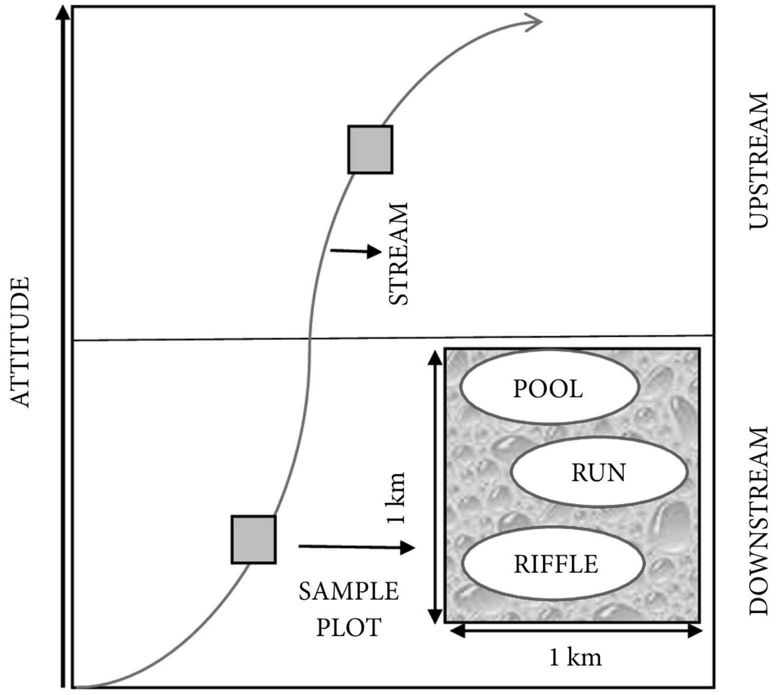

Fig. 2. Sampling design

Fig. 3. Map showing the upstream site

stream, including one upstream and two downstream locations. The upstream site was situated adjacent to the Sahib Bandgi Sant Ashram, Jogindernagar (31°58'12.70''N, 76°46'9.80''E) (Figure 3). The two downstream sites were located near the Uhl water reservoir (31°56'21.49''N, 76°47'42.48''E), (31°57' 17.39''N, 76°46'42.65''E) (Figure 4). All sample collections were conducted within a 1-kilometer radius of the designated sampling points.

Water sampling and processing. Water samples were collected from three designated sites across four distinct seasons: winter (December — February), summer (March — June), monsoon (July — September), and post-monsoon (October — November) (Fig. 5). Approximately 1 L of water was collected at each site during each sampling event. A total of 12 sampling rounds were conducted at 30-day intervals from February 2023 to January 2024. Samples were collected in pre-cleaned, airtight bottles, appropriately labelled with date and site information, and immediately transported to the laboratory for further physiochemical and biological analysis.

Analytical techniques. Twelve key physiochemical parameters were selected for analysis: air temperature, water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), total alkalinity (TA), total hardness (TH), chlorides, phosphates, nitrates, and silicates. Field measurements of EC, TDS, pH, and DO were performed using portable digital meters. Air and water temperatures were recorded using a calibrated thermometer (Thermomate DTM 902, India). EC and TDS were measured with a conductivity meter (Ionix, China), and DO was determined using a digital DO meter (Lutron PDO-519, Taiwan).

Laboratory analyses of total hardness, total alkalinity, chlorides, phosphates, nitrates, and silicates were conducted in accordance with standard proto-

Fig. 4. Map showing the downstream site

cols recommended by the American Public Health Association (APHA) [1]. All measurements were carried out in triplicate to ensure accuracy, and the mean values were used for data interpretation.

Results and Discussion

Water physical and chemical characteristics. The physiochemical parameters, including air temperature, water temperature, pH, total dissolved solids, electrical conductivity, dissolved oxygen, alkalinity, total hardness, chlorides, phosphates, nitrates, and silicates, were measured at both upstream and downstream sites across different seasons, as detailed in Table 2. Table 1 represents the evaluation of water quality parameters in relation to the standards for human consumption, household activities, and agro-based applications.

Table 3 demonstrates the seasonal variation analysis of water quality parameters applying Duncan’s Multiple Range Test (DMRT) at a 95 % confidence level. Table 4 represents the Water Quality Index (WQI). Temporal variation of physiochemical properties of water is presented in (Figure 6).

The mean air temperature of the collected water samples at the upstream and downstream sites ranged from 16.70 °C to 36.40 °C (Figure 6). In comparison, a range of 13 °C to 29 °C was reported previously [2], with the present study observing higher values. Seasonal mean air temperatures for the four seasons winter, summer, monsoon, and post-monsoon were 20.62±6.32 °C, 29.69±6.74 °C, 29.92±4.65 °C, and 22.38±3.43 °C, respectively (Table 2).

The lowest seasonal air temperature (19±1.35 °C) was recorded during winter at point B, while the highest temperature (33.7±2.86 °C) was observed in the monsoon season at the same location. Results from the paired t-test indicated no significant differences among the seasonal air temperature values at a

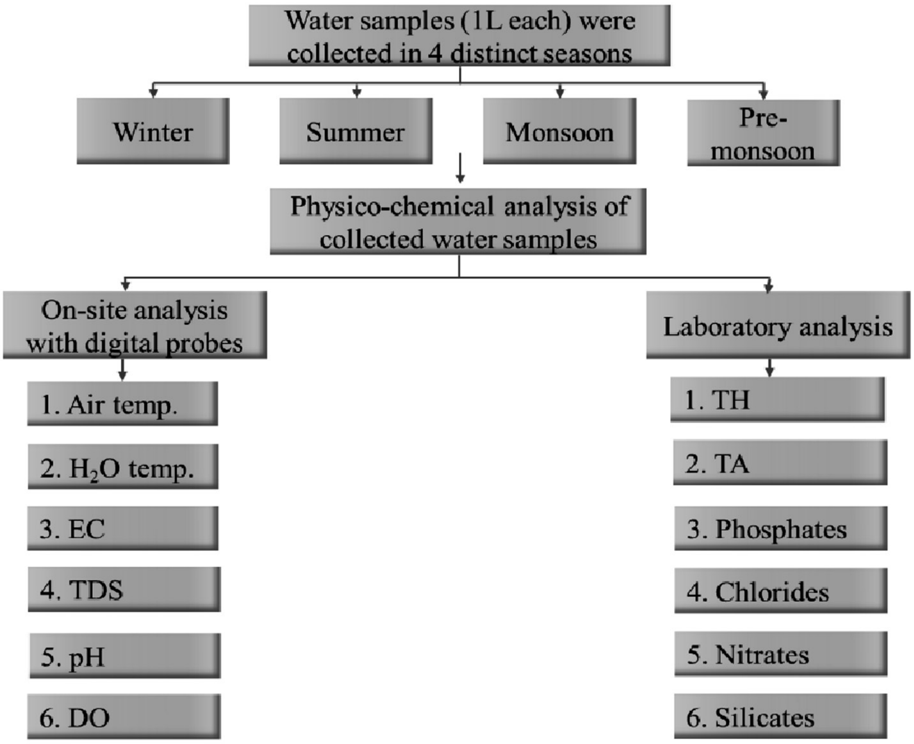

Fig. 5. Strategy of water sampling and their study

95 % confidence interval, with the exception of the comparison between the post-monsoon and monsoon seasons ($p = 0.019$) (Table 3).

The mean water temperature ranged from 12.10 °C to 30.40 °C (Figure 6). Water temperatures ranging from 11 °C to 24 °C [2] were lower than the values observed in the present study. Similarly, water temperatures ranging from 4 °C to 18 °C were also reported [13]. Temperature is a critical environmental factor that directly influences various aquatic processes in ecosystems. It plays a significant role in regulating the self-purification capacity of rivers and reservoirs, making it a key physical parameter in aquatic ecosystems.

The seasonal mean water temperatures, along with their respective variations, for the four seasons were 15.90±4.34 °C in winter, 25.30±5.36 °C in summer, 23.85±2.33 °C in monsoon, and 17.75±2.10 °C in post-monsoon (Table 2). In the duration of summer and monsoon seasons, the observed values met the standards set by the World Health Organization (WHO) [25], the United States Environmental Protection Agency (USEPA) [24], and the Department of Public Health Engineering (DPHE) [11] (Table 1). However, the seasonal water temperatures during winter and post-monsoon periods were lower than the standard limits. The lowest seasonal water temperature (15.17±0.91 °C) was recorded in winter at point B, while the highest (26.23±4.59 °C) was obser-

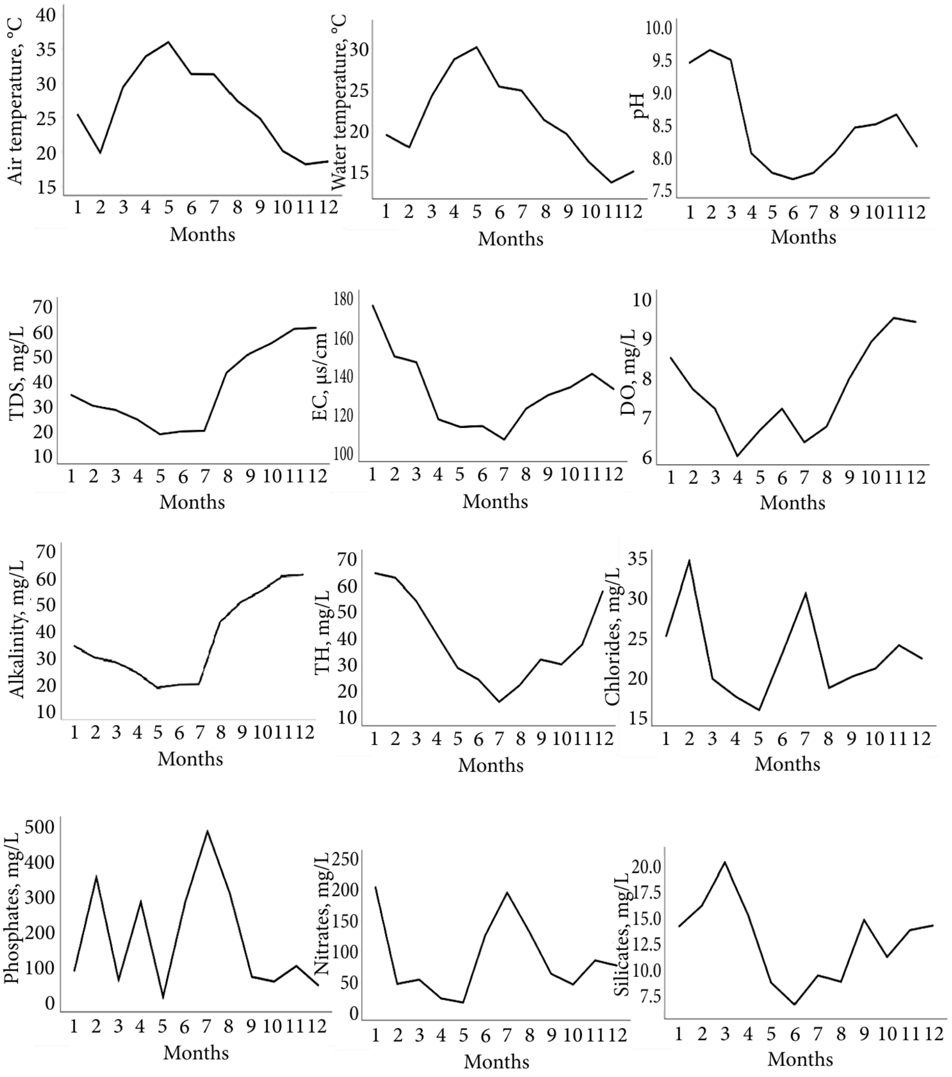

Fig. 6. Temporal variation of physiochemical properties of water in the Rana stream from February 2023 to January 2024

ved in the summer season at point A. Water temperature increased with the lengthening of daylight hours.

Results from the paired t-test revealed significant differences among the seasonal water temperature values at a 95 % confidence interval, with the exceptions of three contrasts (winter vs. post-monsoon, summer vs. monsoon, and summer vs. post-monsoon). The p-values for the significant contrasts (winter vs. monsoon, winter vs. summer, and post-monsoon vs. monsoon) were all below 0.05 (Table 3).

The mean pH of the collected water samples ranged from 7.2 to 9.9. A pH range of 6.3—7.99 [13] was lower than the findings of the present study. The ty-

Table 1

Water quality parameters in relation to the standards for human consumption, household activities, and agro-based applications

Parameters	Guideline value	Standard compliance across seasons and sites							
		W		*S*		*M*		*PM*	
		A	B	A	B	A	B	A	B
Water temperature (°C)	20—30[b], 25[d]			Y	Y	Y	Y		
pH	6.5—8.5[abd]		Y			Y	Y		Y
TDS (mg/L)	500[ad], 600[bc]								
EC (μs/cm)	1000[bd], 2000[c]								
DO (mg/L)	6[b], 5[c]								
Alkalinity (mg/L)	200[a], 120[c]								
TH (mg/L)	200[a], 300[c]								
Chlorides (mg/L)	250[abcd]								
Phosphates (mg/L)	1.5[c]								
Nitrates (mg/L)	45[a], 50[c]								

Note. «a», «b», «c», and «d» denote [8, 25, 26, 27, 24], respectively; and «Y» signifies that water quality variables match the required guidelines. «W», «S», «M» and «PM» denotes winter, summer, monsoon and post-monsoon seasons. «A» and «B» denotes upstream and downstream sites respectively.

pical pH range for surface water systems is between 6.5 and 8.5, with the optimal range for irrigation and fish culture being 6.5 to 8.0 [10].

Seasonal mean pH values reflecting their variation across the four seasons were 8.75±0.91 in winter, 8.74±0.96 in summer, 7.82±0.21 in monsoon, and 8.48±0.33 in post-monsoon (Table 2). During the monsoon and post-monsoon seasons, the pH values met the standards set by the Department of Environment in India (DoE) [10], the Bureau of Indian Standards (BIS) [8], the USEPA [24], the World Health Organization (WHO) [25—27], and the Department of Public Health Engineering (DPHE) [11] (Table 1). However, during the winter and summer seasons, pH values were above the recommended limits. The lowest seasonal pH was recorded in the monsoon season (7.77±0.31) at point A, while the highest pH value of 9.03±0.06 was observed during winter at point A.

Results from the paired t-test revealed significant seasonal variation in pH values, with exceptions noted for two contrasts (winter vs. post-monsoon and winter vs. summer). The p-values for the significant contrasts (winter vs. monsoon, summer vs. monsoon, summer vs. post-monsoon, and post-monsoon vs. monsoon) were 0.05, 0.030, 0.002, and 0.031, respectively (Table 2).

The mean total dissolved solids (TDS) in the collected water samples varied from 21 to 94 mg/L. The TDS values 102—147 mg/L from Beru stream of Mandi district [5] were higher than those in the present study. The permissible

Table 2

Mean values and standard deviations of physiochemical properties of the Rana stream across four different seasons measured at three sites

(February 2023 to January 2024)

Season	Air temperature (°C)	Water temperature (°C)	pH	TDS (mg/L)	EC (µs/cm)	DO (mg/L)	Alkalinity (mg/L)	TH (mg/L)	Chlorides (mg/L)	Phosphates (mg/L)	Nitrates (mg/L)	Silicates (mg/L)
Winter	20.62± 6.32	15.90± 4.34	8.75± 0.91	70.17± 15.38	150.17± 28.00	9.13± 0.60	51.99± 17.15	53.32± 17.19	23.92± 3.78	0.08± 0.03	0.12± 0.10	14.08± 3.71
Summer	29.69± 6.74	25.30± 5.36	8.74± 0.96	67.13± 13.03	132.00± 27.71	7.11± 0.85	25.22± 6.46	46.70± 14.46	22.01± 10.72	0.18± 0.21	0.03± 0.02	15.14± 5.48
Monsoon	29.92± 4.65	23.85± 2.33	7.82± 0.21	33.00± 10.33	114.67± 8.73	6.77± 1.01	27.50± 18.58	20.68± 8.79	24.17± 12.30	0.36± 0.28	0.15± 0.09	8.27± 1.65
Post-monsoon	22.38± 3.43	17.75± 2.10	8.48± 0.33	45.00± 5.42	132.00± 9.80	8.43± 0.92	52.85± 23.45	30.93± 4.41	20.68± 6.31	0.07± 0.02	0.05± 0.01	13.01± 2.20

limits for TDS concentration in surface water for drinking purposes are 500 mg/L according to [8, 24], and 600 mg/L as per [11, 25—27].

The seasonal mean TDS values reflecting seasonal variation were 70.17± 15.38 mg/L in winter, 67.13±13.03 mg/L in summer, 33±10.33 mg/L in monsoon, and 45±5.42 mg/L in post-monsoon (Table 2). All seasonal TDS values were below the safe limits recommended by the relevant guideline agencies (Table 1). The lowest seasonal TDS concentration (32.67±4.51 mg/L) was recorded during the monsoon at point A, while the highest value (72.75± 16.76 mg/L) was observed in the summer at point A.

According to the paired t-test, there were significant differences among the seasonal TDS values at a 95 % confidence interval, with exceptions noted for two contrasts (winter vs. summer and post-monsoon vs. monsoon). The p-values for the significant contrasts (winter vs. monsoon, winter vs. post-monsoon, summer vs. monsoon, and summer vs. post-monsoon) were 0.006, 0.017, 0.005, and 0.035, respectively (Table 3).

The mean electrical conductivity (EC) of the collected water samples from both upstream and downstream sites ranged from 106 to 188 µS/cm. An EC range of 78 to 287 µS/cm [12] is consistent with the findings of the present study. Seasonal mean EC values reflecting seasonal variations were 150.17± 28 µS/cm in winter,

Table 3

Seasonal variation analysis of water quality parameters applying Duncan's Multiple Range Test (DMRT) **at a 95 % confidence level**

Parameters	Winter v/s Monsoon		Winter v/s Post-Monsoon		Winter v/s Summer		Summer v/s Monsoon		Summer v/s Post-Monsoon		Post-Monsoon v/s Monsoon	
	p value	significant	p value	significant	p value	significant	p value	significant	p value	significant	p value	significant
Air temperature (°C)	0.057	No	0.071	No	0.070	No	0.562	No	0.656	No	0.019	Yes
Water temperature (°C)	0.019	Yes	0.104	No	0.010	Yes	0.943	No	0.361	No	0.005	Yes
pH	0.051	Yes	0.819	No	0.614	No	0.030	Yes	0.002	Yes	0.031	Yes
TDS (mg/L)	0.006	Yes	0.017	Yes	1.000	No	0.005	Yes	0.035	Yes	0.244	No
EC (μs/cm)	0.022	Yes	0.591	No	0.483	No	0.180	No	0.301	No	0.062	No
DO (mg/L)	0.003	Yes	0.077	No	0.004	Yes	0.073	No	0.109	No	0.060	No
Alkalinity (mg/L)	0.131	No	0.249	No	0.021	Yes	0.997	No	0.200	No	0.090	No
TH (mg/L)	0.008	Yes	0.143	No	0.956	No	0.004	Yes	0.006	Yes	0.106	No
Chlorides (mg/L)	0.953	No	0.117	No	0.978	No	0.980	No	0.330	No	0.244	No
Phosphates (mg/L)	0.058	No	0.590	No	0.136	No	0.506	No	0.358	No	0.125	No
Nitrates (mg/L)	0.588	No	0.118	No	0.142	No	0.038	Yes	0.723	No	0.138	No
Silicates (mg/L)	0.029	Yes	0.705	No	0.211	No	0.006	Yes	0.193	No	0.088	No

Note. «Yes» indicates that the water quality parameters vary significantly across seasons, while «No» indicates no significant seasonal variation in the parameters.

132±27.71 μS/cm in summer, 114.67±8.73 μS/cm in monsoon, and 132± 9.80 μS/cm in post-monsoon (Table 2). According to [11, 24, 26, 27], the maximum permissible EC limits for drinking water are 1000, 2000, and 1000 μS/cm, respectively. All observed values were below the established safe limits set by [10, 11, 24—27] (Table 1). The lowest seasonal EC (114± 12.17 μS/cm) was recorded during the monsoon at point A, while the highest seasonal EC (163.33± 10.07 μS/cm) was observed during winter at point A. The paired t-test revealed no significant difference among seasonal EC values at a 95 % confidence interval, except for the winter vs. monsoon contrast (*p* = 0.022) (Table 3).

The mean dissolved oxygen (DO) of the collected water samples varied from 5.6 to 9.7 mg/L. The DO range of 8.1—8.8 mg/L [13] falls within the current study findings. Seasonal mean DO values reflecting their variation across the four seasons were 9.13±0.60 mg/L in winter, 7.11±0.85 mg/L in summer, 6.77±1.01 mg/L in monsoon, and 8.43±0.92 mg/L in post-monsoon (Table 2). All DO values were above the permissible limits set by [10, 11, 24, 25—27] (Table 1). The recommended DO concentration for drinking water is > 6 mg/L, for recreational use is 4—5 mg/L, for fish and aquatic life is 4—6 mg/L, and for industrial applications is ≥ 5 mg/L [10, 11, 26, 27]. The lowest seasonal DO (5.97±0.35 mg/L) was recorded in the monsoon at point B, and the highest seasonal DO (9.17±0.92 mg/L) was observed during winter at point A. The paired t-test revealed significant differences in seasonal DO values at a 95 % confidence interval, with exceptions for four contrasts (winter vs. post-monsoon, summer vs. monsoon, summer vs. post-monsoon, and post-monsoon vs. monsoon). The p-values for the significant contrasts (winter vs. monsoon and winter vs. summer) were 0.003 and 0.004, respectively (Table 3).

The average alkalinity (TA) of water samples collected from the selected sites varied from 16.50 to 75 mg/L. Alkalinity values between 150 and 236 mg/L [13] were higher than those observed in the current study. According to [10], the permissible limits for alkalinity are 200 mg/L and 120 mg/L according to [26, 27], respectively. Seasonal mean alkalinity values reflecting seasonal variations were 51.99±17.15 mg/L in winter, 25.22±6.46 mg/L in summer, 27.50± 18.58 mg/L in monsoon, and 52.85±23.45 mg/L in post-monsoon (Table 2). All values were below the standard limits set by [8, 10, 26, 27]. The lowest seasonal alkalinity (21.23±3.72 mg/L) was recorded in the summer at point B, while the highest seasonal alkalinity (72.50±3.54 mg/L) was reported in the post-monsoon season at point B. Paired t-tests indicated a significant difference only between the winter and summer seasons (*p* = 0.021).

The mean values of total hardness (TH) of the collected water samples ranged from 11 to 76 mg/L (Figure 6). The TH values ranging from 30 to150 mg/L [3] were higher than in the present study findings. According to [10] the permissible limits for TH are 200 mg/L and according to WHO [26, 27] the permissible limits for TH are 300 mg/L, respectively. Seasonal mean TH values reflecting seasonal variation were 53.32±17.19 mg/L in winter, 46.70±14.46 mg/L in summer, 20.68±8.79 mg/L in monsoon, and 30.93±4.41 mg/L in post-monsoon (Table 2). All values were below the standard limits set by [8, 10, 26, 27]. The lowest seasonal TH (18.33±9.45 mg/L) was documented in the monsoon at point A, and the highest seasonal TH (61.33±18.90 mg/L) was documented in the winter season at point B. Paired t-tests revealed significant differences in seasonal TH values, with the exceptions of winter vs. post-monsoon, winter vs. summer, and post-monsoon vs. monsoon. Significant contrasts (winter vs. monsoon, summer vs. monsoon, and summer vs. post-monsoon) produced the p-values of 0.008, 0.004, and 0.006, respectively (Table 3).

The mean chloride content of the sampled water varied from 11.28 to 48 mg/L (Figure 6). Chloride values between 11.28 and 48 mg/L were recorded previously [4]. According to [10, 11, 24, 26, 27], permissible limit for chlorides in water is 250 mg/L. Seasonal mean chloride concentrations reflecting their seasonal variation were 23.92±3.78 mg/L in winter, 22.01±10.72 mg/L in summer, 24.17±12.30 mg/L in monsoon, and 20.68±6.31 mg/L in post-monsoon (Table 2). All readings were below the permissible limits set by [8, 10, 11, 24—27]. The lowest seasonal chloride concentration (14.95±3.53 mg/L) was documented in the monsoon at point B, and the highest seasonal chloride concentration (33.40±10.49 mg/L) was documented in the monsoon at point A. Paired t-tests revealed no significant differences in seasonal chloride values at a 95 % confidence interval (Table 3).

The mean phosphate amount of the sampled water fluctuated from 0.01 to 0.83 mg/L (Figure 6). Phosphate concentrations spanning from 0.01 to 0.22 mg/L [16] were lower than the values observed in this study. According to WHO [26, 27], the permissible limit for phosphates is 1.5 mg/L. Seasonal mean phosphate concentrations reflecting seasonal variation were 0.08±0.03 mg/L in winter, 0.18±0.21 mg/L in summer, 0.36±0.28 mg/L in monsoon, and 0.07± 0.02 mg/L in post-monsoon (Table 2). All values were below the permissible limit set by [26, 27]. Lowest seasonal phosphate content (0.05±0.02 mg/L) was recorded in the post-monsoon at point A, while the highest seasonal phosphate concentration (0.51±0.33 mg/L) was documented in the monsoon season at point B. Paired t-tests revealed no significant differences in phosphate concentrations between seasons at a 95 % confidence interval (Table 3).

The mean nitrate concentration of the sampled water spanned from 0.01 to 0.33 mg/L, which is within the range reported by [12]. According to [8, 10], the acceptable limit for nitrates is 45 mg/L and according to WHO [26, 27] acceptable limit is 50 mg/L. Seasonal mean nitrate concentrations reflecting seasonal variation were 0.12±0.10 mg/L in winter, 0.03±0.02 mg/L in summer, 0.15±0.09 mg/L in monsoon, and 0.05±0.01 mg/L in post-monsoon (Table 2). All values were below the standard limits set by [8, 10, 26, 27]. The lowest seasonal nitrate concentration (0.03±0.02 mg/L) was recorded in the summer at point A, while the highest seasonal nitrate concentration (0.20±0.11 mg/L) was documented in the monsoon season at point B. Paired t-tests indicated a significant difference only between summer and monsoon seasons ($p = 0.021$) at a 95 % confidence interval (Table 3).

The mean silicate quantity of the collected samples spanned from 5.38 to 22.31 mg/L (Figure 6). Silicate content values from 0.02 to 0.22 mg/L [2] were lower than the findings of the present study. Seasonal mean silicate concentrations reflecting seasonal variation were 14.08±3.71 mg/L in winter, 15.14±

5.48 mg/L in summer, 8.27±1.65 mg/L in monsoon, and 13.01±2.20 mg/L in post-monsoon (Table 2). The lowest seasonal silicate concentration (7.69±2.02 mg/L) was documented in the monsoon at point A, while the highest seasonal silicate concentration (17.28±1.29 mg/L) was documented in the winter season at point A. Paired t-tests indicated significant differences in seasonal silicate concentrations, with the exceptions of winter vs. post-monsoon, winter vs. summer, summer vs. post-monsoon, and post-monsoon vs. monsoon. Significant contrasts between winter vs. monsoon and summer vs. monsoon had p-values of 0.029 and 0.006, respectively (Table 3).

Water Quality Index. The Water Quality Index (WQI) is a widely used quantitative tool for assessing overall water quality, typically expressed on a scale from 0 to 100. According to standard classification, WQI values between 0—25 indicate «excellent» water quality, 26—50 «good», 51—75 «poor», 76—100 «very poor» and values exceeding 100 denote water that is «unsuitable» for consumption.

For the Rana Stream, WQI values ranged from 47.98 to 53.03, indicating a water quality status that fluctuated between «good» and «poor» (Table 4). The lowest water quality was recorded during the monsoon and winter seasons, while relatively better quality was observed during the summer and post-monsoon periods. The decline in water quality during the monsoon is primarily attributed to the influx of untreated sewage, agricultural runoff, and soil erosion, which intensify with heavy rainfall.

Fig. 7 illustrates the major sources of pollution affecting the water quality. Some of these sources contribute significantly to the degradation of water quality in the region. Contaminated water affects fish reproduction, growth, and can lead to mass die-offs. Many fish species face population decline, leading to their classification as vulnerable or endangered on the IUCN Red List. The IUCN status of fishes in Himachal Pradesh was also discussed [6].

Correlation coefficient matrix. Table 5 presents the Pearson correlation coefficients (r) for all physicochemical parameters along with their respective significance levels (p-values). Air temperature correlated significantly in positive way with water temperature ($r = 0.950^{**}$ and $p = <0.001$) and negatively with DO ($r = -0.811^{**}$ and $p = <0.001$) and poorly correlated with pH ($r = -0.446^{*}$ and $p = 0.029$) and alkalinity ($r = -0.478^{*}$ and $p = 0.018$).

Water temperature correlated negatively with pH ($r = -0.440^{*}$ and $p = 0.031$), DO ($r = -0.736^{**}$ and $p = <0.001$) and alkalinity ($r = -0.617^{**}$ and $p = 0.001$). An inverse correlation of water temperature with pH, likely due to increased decomposition of organic matter at higher temperatures, leading to elevated carbon dioxide levels and a subsequent decrease in pH [7, 14, 15, 23]. According to [13] pH showed positive correlation with TDS ($r = 0.673^{**}$ and $p = <0.001$), EC ($r = 0.764^{**}$ and $p = <0.001$), TH ($r = 0.557^{**}$ and $p = 0.005$), silicates ($r = 0.682^{**}$ and $p = <0.001$) and negative correlation with air temperature ($r = -0.446^{*}$ and $p = 0.029$) and water temperature ($r = -0.440^{*}$ and $p = 0.031$).

Total dissolved solids correlated positively with pH ($r = 0.673^{**}$ and $p = <0.001$), EC ($r = 0.787^{**}$ and $p = <0.001$), TH ($r = 0.760^{**}$ and $p = <0.001$), silicates ($r = 0.619^{**}$ and $p = 0.001$) and negatively with phosphates ($r = -0.457^{*}$

Table 4

Water quality Index

Parameters	S_n	W_i	*W*		*S*		*M*		*PM*	
			Q_i	W_iQ_i	Q_i	W_iQ_i	Q_i	W_iQ_i	Q_i	W_iQ_i
pH	8.5	0.12	102.94	11.86	102.82	11.84	92.00	10.60	99.76	11.49
TDS (mg/L)	1000	0.00	7.02	0.01	6.71	0.01	3.30	0.00	4.50	0.00
EC (µs/cm)	2000	0.00	7.51	0.00	6.60	0.00	5.73	0.00	6.60	0.00
DO (mg/L)	5	0.20	182.60	35.75	142.20	27.84	135.40	26.51	168.60	33.01
Alkalinity (mg/L)	120	0.01	43.33	0.35	21.02	0.17	22.92	0.19	44.04	0.36
TH (mg/L)	300	0.00	17.77	0.06	15.57	0.05	6.89	0.02	10.31	0.03
Chlorides (mg/I)	250	0.00	9.57	0.04	8.80	0.03	9.67	0.04	8.27	0.03
Phosphates (mg/L)	1.5	0.65	5.33	3.48	12.00	7.83	24.00	15.66	4.67	3.05
Nitrates (mg/L)	50	0.02	0.24	0.00	0.06	0.00	0.30	0.01	0.10	0.00
WQI				**51.55**	**47.78**		**53.03**		**47.98**	

Note. S_n — standards for driking water [25].

and $p = 0.025$). EC had showed positive correlation with pH ($r = 0.764^{**}$ and $p = <0.001$ *), TDS* ($r = 0.787^{**}$ and $p = <0.001$), DO ($r = 0.468^{*}$ and $p = 0.021$), TH ($r = 0.528^{**}$ and $p = 0.008$), chlorides ($r = 0.418^{*}$ and $p = 0.042$), silicates ($r = 0.656^{**}$ and $p = <0.001$), and negative correlation with phosphates ($r = -0.423^{*}$ and $p = 0.039$). DO correlated positively with EC ($r = 0.468^{*}$ and $p = 0.021$), alkalinity ($r = 0.485^{**}$ and $p = 0.016$), and negative correlation with air temperature ($r = -0.811^{**}$ and $p = <0.001$), water temperature ($r = -0.736^{**}$ and $p = <0.001$) and phosphates ($r = -0.464^{**}$ and $p = 0.022$).

Alkalinity correlated positively with DO ($r = 0.485^{*}$ and $p = 0.016$) and negative correlation with air temperature ($r = -0.478^{*}$ and $p = 0.018$) and water temperature ($r = -0.617^{**}$ and $p = 0.001$). TH had showed positive correlation with pH ($r = 0.557^{**}$ and $p = 0.005$), TDS ($r = 0.760^{**}$ and $p = <0.001$), EC ($r = 0.528^{**}$ and $p = 0.008$) and silicates ($r = 0.513^{*}$ and $p = 0.010$).

Chlorides correlated positively with EC ($r = 0.418^{*}$ and $p = 0.042$) and did not demonstrate any strong inverse relationships with the rest of parameters. Phosphates correlated directly with nitrates ($r = 0.506^{*}$ and $p = 0.012$) and negatively with TDS ($r = -0.457^{*}$ and $p = 0.025$), EC ($r = -0.423^{*}$ and $p = 0.039$), DO ($r = -0.464^{*}$ and $p = 0.022$). Nitrates correlated positively with phosphates ($r = 0.506^{*}$ and $p = 0.012$) and did not exhibit any prominent relationship with other parameters. Silicates correlated positively with pH ($r = 0.682^{**}$ and $p = <0.001$), TDS ($r = 0.619^{**}$ and $p = 0.001$), EC ($r = 0.656^{**}$ and $p = <0.001$), TH

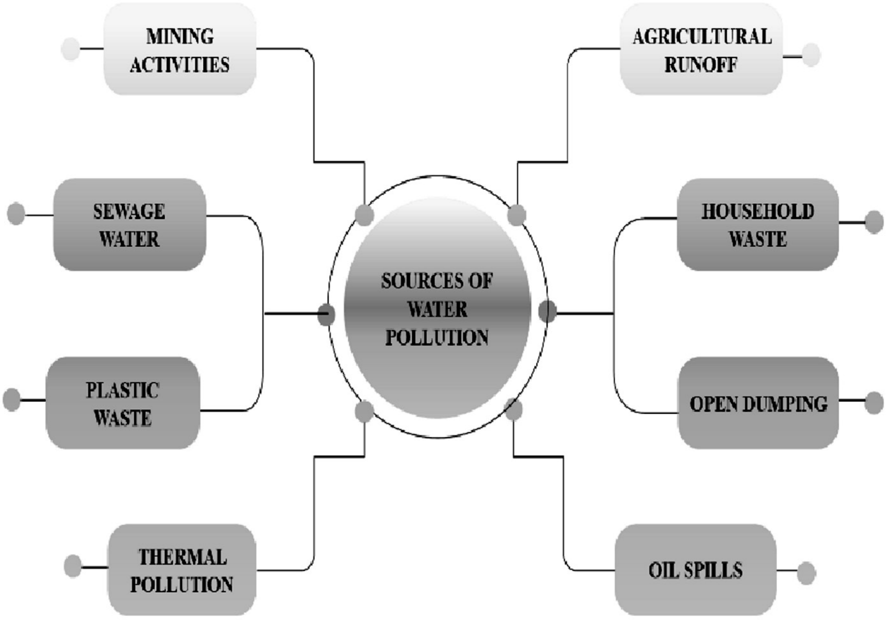

Fig. 7. Different sources of water pollution

($r = 0.513^*$ and $p = 0.010$). The results of this study indicated that air temperature with water temperature and DO, water temperature with DO and alkalinity, pH with TDS, EC, TH and silicates, TDS with EC, TH and silicates, EC with TH and silicates, DO with alkalinity and phosphates were highly correlated.

Factor analysis. Factor analysis, a multivariate statistical technique, was employed to identify underlying relationships among the measured physiochemical variables by reducing them into a smaller set of interpretable factors (Table 6). To enhance interpretability and achieve an optimal factor structure, a varimax rotation was applied. The analysis extracted four principal factors with eigenvalues greater than 1.0, collectively accounting for 82.362 % of the total variance. Specifically, Factor 1 explained 41.007 % of the variance, followed by Factor 2 (19.679 %), Factor 3 (11.714 %), and Factor 4 (9.962 %). Factor 1 exhibited strong positive loadings for total dissolved solids (TDS), pH, electrical conductivity (EC), silicates, and total hardness (TH), indicating a strong positive correlation among these parameters. No significant negative loadings were observed for this factor. Factor 2 showed high positive loadings for dissolved oxygen (DO) and alkalinity, while air and water temperature exhibited negative loadings. This suggests that increases in DO and alkalinity are inversely related to temperature fluctuations. Factor 3 was characterized by high positive loadings for nitrates and phosphates, indicating a shared source or similar behaviour in the aquatic environment. Chlorides displayed a strong positive loading on Factor 4, suggesting a distinct and independent contribution to water quality variability.

Table 5

Correlation among all water quality parameters

Parameter	Correlation coefficients											
	pH	EC	TDS	Alkalinity	TH	H_2O temp.	DO	Chlorides	Phosphates	Nitrates	Silicates	Air temp.
pH	1											
EC	0.764**	1										
TDS	0.673**	0.787**	1									
Alkalinity	-0.019	0.073	-0.036	1								
TH	0.557**	0.528**	0.760**	0.112	1							
Water temp.	-0.440*	-0.383	-0.127	-0.617**	-0.288	1						
DO	0.27	0.468*	0.357	0.485*	0.273	-0.736**	1					
Chlorides	0.253	0.418*	0.209	-0.153	0.013	-0.237	0.388	1				
Phosphates	-0.146	-0.423*	-0.457*	-0.202	-0.232	0.168	-0.464*	-0.115	1			
Nitrates	-0.066	-0.061	-0.313	0.215	-0.254	-0.082	-0.228	-0.149	0.506*	1		
Silicates	0.682**	0.656**	0.619**	0.05	0.513*	-0.206	0.163	0.18	-0.288	-0.271	1	
Air temp.	-0.446*	-0.391	-0.188	-0.478*	-0.307	0.950**	-0.811**	-0.397	0.238	0.075	-0.185	1

Note. * Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 6

Factor analysis of physicochemical parameters using Varimax rotation

Parameter	Factor loading			
	Factor 1	Factor 2	Factor 3	Factor 4
TDS	**0.868**	0.022	-0.332	0.046
pH	**0.863**	0.195	0.127	0.22
EC	**0.82**	0.25	-0.098	0.288
Silicates	**0.809**	0.024	-0.137	0.042
TH	**0.778**	0.154	-0.176	-0.201
Water temp.	-0.213	**-0.931**	-0.097	-0.104
Air temp.	-0.199	**-0.891**	0.047	-0.282
DO	0.164	**0.812**	-0.359	0.24
Alkalinity	-0.041	**0.788**	0.028	-0.448
Nitrates	-0.111	0.118	**0.857**	-0.138
Phosphates	-0.225	-0.244	**0.809**	0.048
Chlorides	0.124	0.185	-0.09	**0.905**
Initial eigenvalue	4.921	2.362	1.406	1.195
Variance explained by each other (%)	41.007	19.679	11.714	9.962
Cumulative variance (%)	41.007	60.686	72.4	82.362

Note. The extraction method used was Principal Component Analysis, and the rotation technique applied was Varimax with Kaiser Normalization. The values in bold highlight the maximum correlations with the corresponding component, helping to identify elements/parameters with similar behavior, their sources, and the interrelationships (positive or negative) within each component.

Cluster analysis. Cluster analysis was performed on the normalized dataset using Ward's method, with squared Euclidean distance employed as the similarity measure (Figure 8). In this method, proximity between clusters is defined by the increase in the total within-cluster sum of squares (squared error). Hierarchical cluster analysis (HCA) was applied to evaluate the temporal similarity among the 12 sampling months across the four seasons.

The resulting dendrogram, constructed using Ward's linkage method, revealed three statistically distinct clusters. The first cluster comprised the months of September, October, November, December, and January, corresponding to the late monsoon, post-monsoon, and early winter periods. These months were characterized by moderate to high concentrations of several physiochemical parameters, likely due to the dilution and flushing effects following monsoon rainfall.

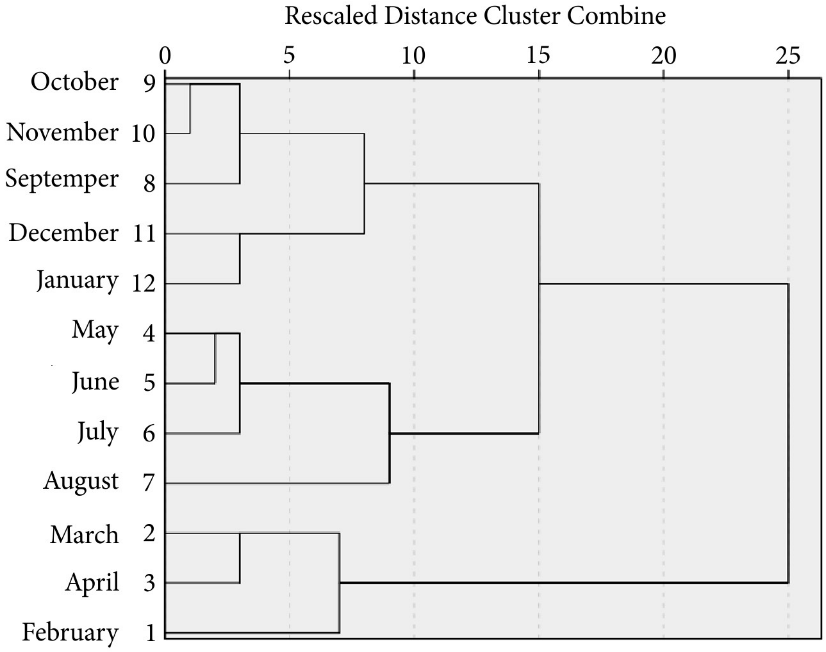

Fig. 8. Dendrogram using hierarchical clustering of sampling months of water sampling

The second cluster included May, June, July, and August, which fall within the late summer and monsoon seasons. These months exhibited low to moderate concentrations of most parameters, which can be attributed to enhanced dilution and runoff caused by increased rainfall and streamflow during the monsoon.

The third cluster encompassed February, March, and April, representing the late winter and early summer seasons. These months showed relatively higher concentrations for more than half of the measured parameters, likely due to reduced water flow and minimal dilution effects. Overall, the analysis indicates that water quality parameters are strongly influenced by seasonal hydrological variations, with higher concentrations generally observed during low-flow periods, and lower concentrations during the high-flow monsoon season.

Conclusion

This study investigated seasonal variations in water quality to assess the extent of pollution in the Rana Stream. Multivariate statistical techniques, including Pearson's correlation, factor analysis, cluster analysis and WQI were employed to examine the seasonal variations in stream water quality. Physiochemical parameters exhibited notable seasonal fluctuations, with the highest values for most parameters recorded during the winter season, followed by monsoon, summer, and post-monsoon. Specifically, dissolved oxygen, electrical conductivity, pH, total hardness, and silicates reached their highest concentrations during winter. Cluster analysis further revealed that winter and summer months generally exhibited higher concentrations of more than half of the measured parameters compared to other seasons. In contrast, monsoon months were characterized by higher dilution effects, resulting in lower concentrations for most parameters, while moderate concentrations were observed during the post-monsoon season. The analytical results revealed that, among all measured parameters, only water temperature and pH consistently fell within the permissible limits set by various regulatory agencies, whereas the remaining parameters didn't meet the standard in at least one season.

The Duncan's Multiple Range Test (DMRT) revealed significant contrasts for pH, total dissolved solids, water temperature, total hardness, and dissolved oxygen at a 95 % confidence interval. Notably, pH and TDS exhibited the highest levels of variation, followed by water temperature, total hardness, and dissolved oxygen. These findings suggest that these parameters are particularly sensitive to seasonal changes, directly influencing water quality. Based on the Water Quality Index (WQI) values i.e. 47.98 to 53.03, indicating water quality fluctuated between «good» and «poor». The seasonal variation in water quality, particularly during the monsoon, is largely attributed to the mixing of sewage, agricultural runoff, and eroded soil with the stream water, leading to the poorest water quality in this period, followed by winter, post-monsoon and summer.

To protect water quality and reduce pollution in the stream, comprehensive and sustainable management strategies are essential. These include the proper treatment and disposal of domestic and industrial wastewater, regulation of agricultural runoff through eco-friendly practices, and afforestation to minimize soil erosion. Regular monitoring of water quality parameters and public awareness campaigns are also critical to promoting responsible water use. Implementing these measures will help preserve the ecological integrity of the stream and ensure its suitability for various uses, including irrigation, aquatic life, and recreational activities.

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SEASONAL DYNAMICS OF WATER QUALITY IN A TRIBUTARY OF THE BEAS RIVER (WESTERN HIMALAYAS, INDIA)

This study examines how physiochemical water parameters fluctuate seasonally in a tributary of the Beas River in Himachal Pradesh (the Western Himalayas), with the goal of assessing the degree of water quality deterioration and pinpointing pollution sources. Water samples were collected across four distinct seasons and analyzed using standard protocols for air and water temperature, pH, dissolved oxygen, electrical conductivity, total dissolved solids, total alkalinity, total hardness, chloride, phosphate, nitrate, and silicate. The findings reveal that only water temperature and pH consistently met agency-recommended guidelines; all other parameters exceeded acceptable limits in every season. Duncan's Multiple Range Test (DMRT) (95% confidence) confirmed statistically significant seasonal variation in these physiochemical indicators. Further, Varimax-rotated factor analysis and cluster analysis identified clear seasonal shifts, linking fluctuations primarily to rainfall, landslides, and human activities. Seasonal trends showed peak concentrations during winter followed by monsoon, summer, and post monsoon. Water Quality Index (WQI) assessments indicated the monsoon season exhibited the poorest water quality, driven largely by sewage inflow, agricultural runoff, and soil erosion, with subsequent declines in winter, post monsoon, and summer.