RESEARCH PAPER

Integrated Assessment of Physicochemical, Microbiological and Heavy Metal Characteristics of a Tourist-Influenced Himalayan River in Sahastradhara, Dehradun, Uttarakhand

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ABSTRACT
Freshwater ecosystems located in recreational landscapes are increasingly subjected to anthropogenic pressures that may alter their physicochemical and microbiological characteristics. The present study assessed the water quality of the Sahastradhara River, a popular tourist destination in the Shivalik foothills of Dehradun, Uttarakhand, India. Water samples were collected monthly during 2022 and 2023 from three sites representing upstream (S1), central tourist zone (S2) and downstream (S3) locations. Physicochemical parameters, heavy metals and microbial indicators were analyzed, and water quality was evaluated using the Water Quality Index (WQI) and Comprehensive Pollution Index (CPI). The river water remained slightly alkaline with pH ranging from 6.98 to 8.06. Electrical conductivity and total dissolved solids varied between 1055–2133 µS cm^{-1} and 552–1116 mg L^{-1}, respectively, reflecting mineral-rich groundwater influence. Turbidity ranged from 7.4 to 55 NTU, with maximum values during the monsoon season. Dissolved oxygen and biochemical oxygen demand varied from 3.29–8.09 mg L^{-1} and 2.06–9.95 mg L^{-1}, respectively, indicating moderate organic loading. Heavy metals remained within permissible limits, while microbial contamination was high, with total coliform counts reaching 2419 MPN 100 mL^{-1}. Seasonal WQI values ranged from 169.9 to 260.9, indicating poor to very poor water quality for drinking purposes, whereas CPI values ranged from 1.90 to 2.95, reflecting moderate pollution levels. Multivariate analysis indicated that water quality variations were primarily controlled by natural mineralization processes and tourism-related anthropogenic inputs. Continuous monitoring and improved management strategies are necessary to ensure sustainable use of this recreational river system.
Keywords-Water Quality Index (WQI), Himalayan River, Tourism Impact, Multivariate Statistical Analysis, Microbial Contamination, Heavy Metals, Seasonal Water Quality Variation.
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INTRODUCTION

Freshwater ecosystems play a crucial role in sustaining ecological balance, supporting biodiversity and providing essential resources for human societies (**Dudgeon *et al.* 2006**). Rivers in particular serve as important sources of drinking water, irrigation, recreation and cultural activities. However, increasing anthropogenic pressures such as urbanization, tourism, agricultural runoff and improper waste disposal have significantly altered the physicochemical and biological characteristics of many river systems worldwide (**McAllister *et al.* 1997; Baron *et al.* 2002; Apostolaki *et al.* 2020**; **Bănăduc *et al.* 2022**). The deterioration of river water quality not only threatens aquatic life but also poses serious risks to human health and ecosystem stability.

Water quality assessment is therefore essential for understanding the status of freshwater resources and for implementing effective management strategies. Traditionally, evaluation of river water quality relies on the measurement of various physicochemical parameters including temperature, pH, electrical conductivity, dissolved oxygen, turbidity and nutrient concentrations (**Dudgeon, 2010**). In addition to these parameters total coliform and fecal coliform are widely used to assess the sanitary quality of water bodies which collectively provide valuable information about the ecological health of aquatic environments and the degree of anthropogenic influence affecting them (**Apostolaki *et al.* 2020**; **Lynch et al. 2023**).

In recent decades, the use of water quality indices has emerged as an effective tool for summarizing complex environmental datasets into a single, easily interpretable value. Among these, the Water Quality Index (WQI) is widely used for assessing the overall suitability of water for different purposes such as drinking, irrigation and recreational use (**Poff, 2009**). The WQI integrates multiple physicochemical parameters by assigning relative weights based on their environmental significance. Similarly, the Comprehensive Pollution Index (CPI) provides an integrated evaluation of pollution levels by comparing observed parameter values with established standards (**Geist, 2011**).

Apart from index-based approaches, multivariate statistical techniques have increasingly been applied in water quality studies to understand the relationships among environmental variables and to identify potential pollution sources (**Aylward *et al.* 2005; Lapointe *et al.* 2014**). Methods such as correlation analysis and principal component analysis (PCA) help reveal the underlying factors controlling water chemistry and provide insights into both natural and anthropogenic influences (**Reid *et al.* 2019**). These techniques are particularly useful in river systems where multiple processes, including geological weathering, seasonal hydrological variations and human activities, interact to shape water quality patterns.

Tourism dominated river systems represent a unique category of freshwater environments where water quality dynamics may differ from those influenced primarily by industrial or agricultural pollution (**Cedeno, 2024**). Recreational activities such as bathing, swimming and rafting can lead to localized disturbances in river ecosystems through sediment resuspension, organic waste input and increased microbial contamination (**Parab *et al.* 2025**). Although such impacts are often spatially limited, they may significantly influence water quality in popular tourist destinations. Therefore, systematic monitoring of water quality in tourist-dominated river stretches is necessary to ensure environmental sustainability and public health safety.

The Sahastradhara (thousand-fold spring) River system, located in the Shivalik foothills near Dehradun in Uttarakhand, India, represents an important freshwater ecosystem characterized by natural springs emerging from limestone formations. These springs (numerous small streams that originate from carbonate rocks) merge to form a stream that eventually contributes to the Baldi River. As a result of its scenic beauty and Sulphur-rich waters, which are traditionally believed to possess therapeutic properties, Sahastradhara has become one of the most popular tourist attractions in the Dehradun district, attracting thousands of visitors annually.

While tourism contributes significantly to the local economy, increasing tourist inflow has raised concerns regarding its potential environmental impacts on the river system. Activities such as bathing, litter disposal and disturbance of river sediments may lead to increased turbidity, organic pollution and microbial contamination (**Parab *et al.* 2025**). Additionally, runoff from nearby settlements and tourist facilities may introduce nutrients and other contaminants into the water. These factors highlight the need for comprehensive water quality assessment in order to evaluate the ecological status of the river and to identify potential management strategies for sustainable tourism..

Previous studies on Himalayan river systems have shown that water quality variations are often influenced by a combination of natural geological processes and human activities (**Ali *et al.* 2025; Sharma *et al.* 2026**). Rivers flowing through carbonate-rich terrains commonly exhibit elevated levels of dissolved minerals such as calcium and magnesium, which contribute to increased hardness and conductivity. Seasonal variations associated with monsoon rainfall also play a significant role in controlling water quality by influencing sediment transport, nutrient input and dilution processes (**Pokhrel *et al.* 2025**). Therefore, understanding both spatial and seasonal variations in water quality parameters is essential for accurate assessment of river ecosystem health.

Despite the ecological and recreational importance of the Sahastradhara River, systematic studies evaluating its physicochemical and microbiological characteristics remain limited (**Singh *et al.* 2014**). Most previous investigations have focused on general environmental descriptions or limited parameter assessments (**Xu *et al.* 2019; Lepcha *et al.* 2021; Kattel, 2022**). Comprehensive studies integrating multiple physicochemical parameters, microbial indicators, heavy metal concentrations and water quality indices are necessary to obtain a holistic understanding of the river's environmental status.

The present study was undertaken to provide a thorough understanding of the Sahastradhara River's environmental condition and to support the sustainable management of recreational freshwater ecosystems in the Himalayan region. Its main goals were to investigate the spatial and seasonal variations of physicochemical parameters at three sampling locations that represent the river's upstream, central tourist and downstream sections; to determine the concentration and distribution of specific heavy metals in the river water; to assess the level of microbial contamination using the Water Quality Index (WQI) and Comprehensive Pollution Index (CPI); to assess the overall water quality status using multivariate statistical techniques.

MATERIALS AND METHODS

2.1 Study Area- The present investigation was carried out in the Sahastradhara river system, located in the Shivalik foothills of Dehradun district, Uttarakhand, India. Sahastradhara is a natural spring-fed stream characterized by Sulphur-rich water emerging from limestone formations. Three sampling sites were selected along the Sahastradhara stretch to represent different degrees of anthropogenic influence (**Table 1** and **Figure 1**). The upstream site (S1) was located at a relatively undisturbed location representing background water quality conditions. The central site (S2) corresponded to the main tourist bathing and recreational zone where maximum human activity occurs. The downstream site (S3) represented the cumulative impact zone influenced by upstream and central activities (**Pokhrel *et al.* 2025**).

Table 1: Geographical coordinates and elevation of the sampling sites

Site	Description	Latitude	Longitude	Elevation (above mean sea level)
S1	Upstream reference site	30°23′53″N	78°08′00″E	933 m
S2	Central tourist bathing site	30°23′14″N	78°07′53″E	880 m
S3	Downstream site	30°23′01″N	78°07′25″E	841 m

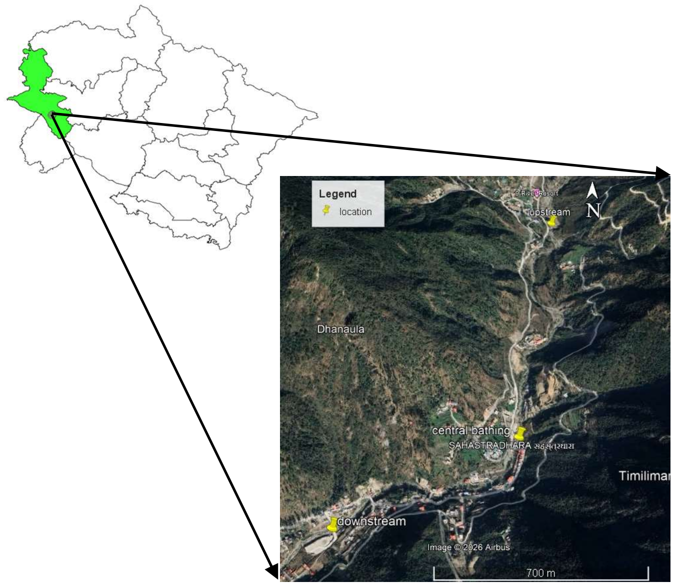

Figure 1: Study area of the work

2.2 Sampling Design

Water samples were collected monthly from all three sampling sites during the period 2022–2023 in order to capture seasonal variations in water quality. The twelve months were grouped into four seasons based on regional climatic conditions as Summer (March – June), Monsoon (July – September), Post-monsoon (October – November) and Winter (December – February). Samples were collected in pre-cleaned polyethylene bottles following standard procedures recommended by the American Public Health Association (APHA).

2.3 Physicochemical Analysis- A comprehensive set of physicochemical parameters was analyzed to evaluate the hydro chemical characteristics of the river water according to the methods used by (**Siddiqui *et al.* 2013; Chaudhry *et al.* 2013**). These parameters included: Temperature (°C), pH, Electrical Conductivity (EC), Turbidity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Hardness (TH), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Chloride (Cl^{-}), Nitrate (NO_3^{-}), Sulphate (SO_4^{2-}), Fluoride (F^{-}), Sodium (Na^{+}), Potassium (K^{+}), Alkalinity, Colour and Odour (**Table 2**). All analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA).

Table 2: Units and analytical methods used to measure various parameters

Variables	**Unit**	**Analytical methods**
Temperature	°C	Digital thermometer
pH	pH unit	pH meter
Electrical conductivity (EC)	µS/cm	Electrometric method
Turbidity	NTU	Nephelo turbidity method
Total dissolved solids (TDS)	mg/l	Electrometric method
Dissolved oxygen (DO)	mg/l	Winkler method
Total hardness (TH)	mg/l	Titrimetric method
Calcium (Ca)	mg/l	Titrimetric method
Magnesium (Mg)	mg/l	Titrimetric method
Potassium (K)	mg/l	Atomic Absorption Spectrophotometry
Sodium (Na)	mg/l	Atomic Absorption Spectrophotometry
Chloride (Cl)	mg/l	Titrimetric method
Sulphate	mg/l	Spectrophotometric
Fluoride	mg/l	Spectrophotometric
Nitrate	mg/l	Spectrophotometric
Chemical oxygen demand (COD)	mg/l	Winkler's azide method
Biological oxygen demand (BOD)	mg/l	Dichromate method
Iron (Fe)	mg/l	Atomic Absorption Spectrophotometry
Lead (Pb)	mg/l	Atomic Absorption Spectrophotometry

Zinc (Zn)	mg/l	Atomic Absorption Spectrophotometry
Copper (Cu)	mg/l	Atomic Absorption Spectrophotometry
Manganese (Mn)	mg/l	Atomic Absorption Spectrophotometry
Alkalinity	mg/l	Titrimetric method
Total Coliform	MPN/100 mL	Most Probable Number (MPN) method
Fecal Coliform	MPN/100 mL	Most Probable Number (MPN) method
Colour	Hazen units (HU)	Spectrophotometric method
Odour	Threshold Odour Number (TON)	

2.4 Heavy Metal Analysis- The concentrations of selected heavy metals including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and lead (Pb) were determined following the methods of **Dudgeon (2010)**, to evaluate potential metal contamination in the river system. Water samples for metal analysis were acidified with nitric acid immediately after collection to prevent precipitation and adsorption losses. The concentrations of metals were determined using Atomic Absorption Spectrophotometry (AAS) following standard analytical procedures.

2.5 Microbiological Analysis- Microbiological quality of the river water was assessed using total coliform and fecal coliform counts (**Dudgeon, 2010**). These parameters serve as important indicators of fecal contamination and potential public health risk in recreational water bodies.Microbial analysis was performed using the Most Probable Number (MPN) method. Water samples were incubated in lactose broth tubes and coliform counts were determined based on the number of positive tubes after incubation. The results were expressed as MPN per 100 mL of water sample.

2.6 Water Quality Index (WQI)

WQI was calculated using twelve selected water parameters, mentioned in **Table 3**. The calculation and formulation of the WQI involved the following four steps (**Alobaidy *et al.* 2010**).

Step 1- Each parameter has been assigned a weight (AWi) ranging from 1 to 4 depending on the collective expert opinions taken from previous studies (**Kangabam *et al.* 2017; Prerna *et al.* 2014** and **Ramakrishnaiah *et al.* 2009**). Assigned weight of 1 stands for the least significant parameter and 4 as the most significant (**Table 3**).

Step 2- The relative weight (RW) was calculated using equation:

$$RW = \frac{AW_i}{\sum_{i=1}^{n} AW_i}$$

where RW = the relative weight.
AW = the assigned weight of each parameter
n = number of parameters

Step 3- A quality rating scale (Qi) for all the parameters (except pH and DO) was calculated by using equation:

$$Q_{i=}\left(\frac{C_i}{S_i}\right) * 100$$

where Ci = Observed value of ith parameter
Si = Standard value of ith parameter.

For pH and DO, the Qi was calculated by using given equation:

$$Q_{i=}\left(\frac{C_i V_i}{S_i V_i}\right) * 100$$

where Vi = Ideal value which is considered as 7.0 for pH and 14.6 for DO.

Step 4- For computing the WQI, first the sub-indices (SIi) were calculated for each parameter using following equation:

$$SI_i = RW * Q_i$$

Finally, WQI was calculated using equation:

$$WQI = \sum_{i=1}^{n} SI_i$$

The WQI values were classified into different categories according to **Ramakrishnaiah et al. 2009** (**Table 4**).

EC was calculated by using the relationship between TDS and EC previously mentioned by **Thirumalini and Joseph (2009)-**

TDS= (0.65) EC

Table 3: List of selected parameters and their relative weight

Parameter	Standard Value	Assigned weight (AW)	Relative weight (RW)
pH	8	2.54	0.076645
EC	780	3.22	0.097164
TDS	500	2.75	0.082981
Turbidity	5	2.43	0.073325
DO	5	4.09	0.123416
BOD	5	3.00	0.090525
COD	10	2.00	0.06035
TH	200	1.46	0.044056
Mg	30	2.35	0.070911
Ca	75	2.71	0.081774
Chloride	250	4.02	0.121304
Nitrate	45	2.57	0.07755

2.7 Comprehensive Pollution Index (CPI)- The Comprehensive Pollution Index (CPI) was used as an additional tool to assess the pollution status of the river system. The CPI was followed by **Kamboj et al. (2017)** and **Matta and Kumar, (2015)** to classify the water quality status. It was calculated by using following equation:

$$CPI = \frac{1}{n} - \sum_{i=0}^{n} PI$$

where, PI = pollution index of individual parameter.

n = number of parameters

$$PI = (\frac{C_i}{S_i})$$

where, -Ci = Observed value of -ith parameter.

Si = Standard value of -ith parameter.

The CPI values were classified into different categories according to **Kamboj, 2017** (**Table 4**).

Table 4:Water Quality scale for various indices

Water Quality	WQI	Water Quality	CPI
Excellent	<50	**Excellent**	<0.20
Good	50-100	**Good**	0.21-0.40
Poor / fair	100-200	**Fair**	0.41-1.00
Very Poor / Unsuitable	200-300	**Poor**	1.01-2.0
Unsuitable / Poor	>300	**Very Poor**	>2.01

2.8 Statistical Analysis- Statistical analyses were performed to evaluate relationships among water quality parameters and to identify the major factors influencing river water chemistry. Descriptive statistics were used to summarize seasonal and spatial variations in the dataset.Pearson correlation analysis was conducted to examine relationships among physicochemical parameters and identify possible interactions between variables such as dissolved oxygen, turbidity,and organic pollution indicators. Principal Component Analysis (PCA) was performed to reduce data dimensionality and determine the dominant factors controlling water quality variations. Prior to PCA, all data were standardized to eliminate the influence of differences in measurement units. Graphical representations including seasonal variation plots, correlation heatmaps and PCA biplots were generated using Python statistical libraries to facilitate visualization and interpretation of the dataset.

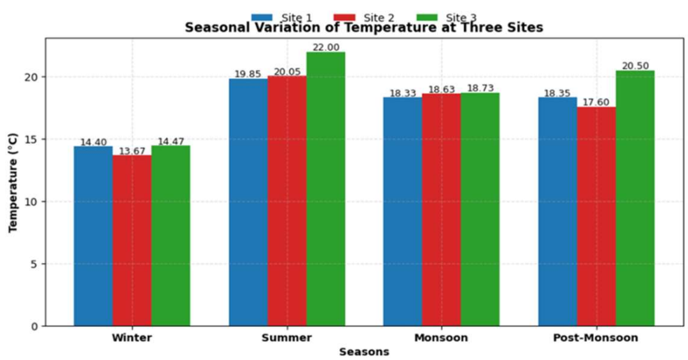

Figure 2: Seasonal variation in temperature at three sites

3 RESULTS AND DISCUSSION

3.1 Seasonal Variation of Physicochemical Parameters- The physicochemical characteristics of the Sahastradhara River exhibited noticeable seasonal variations during the study period. Water temperature ranged from 12.9°C to 25.2°C, with lower values observed during winter months and higher temperatures recorded during summer (**Figure 2**). The relatively moderate temperature range reflects the spring-fed nature of the river system, where groundwater input stabilizes seasonal fluctuations.

The pH values of the river water ranged from 6.98 to 8.06, indicating slightly alkaline conditions throughout the study period (**Figure 3**). Such alkalinity is typical of river systems flowing through limestone formations, where dissolution of carbonate minerals increases bicarbonate concentrations and enhances buffering capacity. Similar alkaline conditions have been reported in Himalayan rivers. For instance, **Kansal *et al.* (2013)** reported that the water quality of several Uttarakhand rivers, including the Ganga and Yamuna systems, generally remained within alkaline ranges due to the influence of carbonate-rich lithology and mineral weathering processes. These findings suggest that the alkaline nature of river water in mountainous regions is largely governed by natural geological controls.

Electrical conductivity (EC) varied between 1055.44 and 2133.84 µS cm^{-1}, while total dissolved solids (TDS) ranged from 552 to 1116 mg L^{-1}. These relatively high values indicate a mineral-rich water composition influenced by carbonate geology in the catchment area (**Figure 4**). Increased EC and TDS values were generally observed during winter months due to reduced dilution caused by lower discharge. **Kangabam et al. (2017)** reported that conductivity and dissolved solids in freshwater bodies are strongly influenced by lithological composition, mineral dissolution and catchment characteristics. The relatively elevated EC and TDS values observed in the present study therefore reflect the mineral-rich hydrogeological environment of the Sahastradhara region.

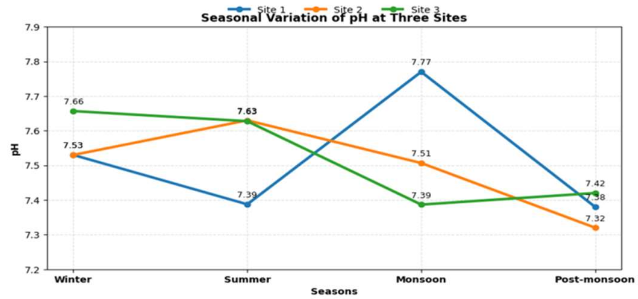

Figure 3: Seasonal variation in pH at three sites

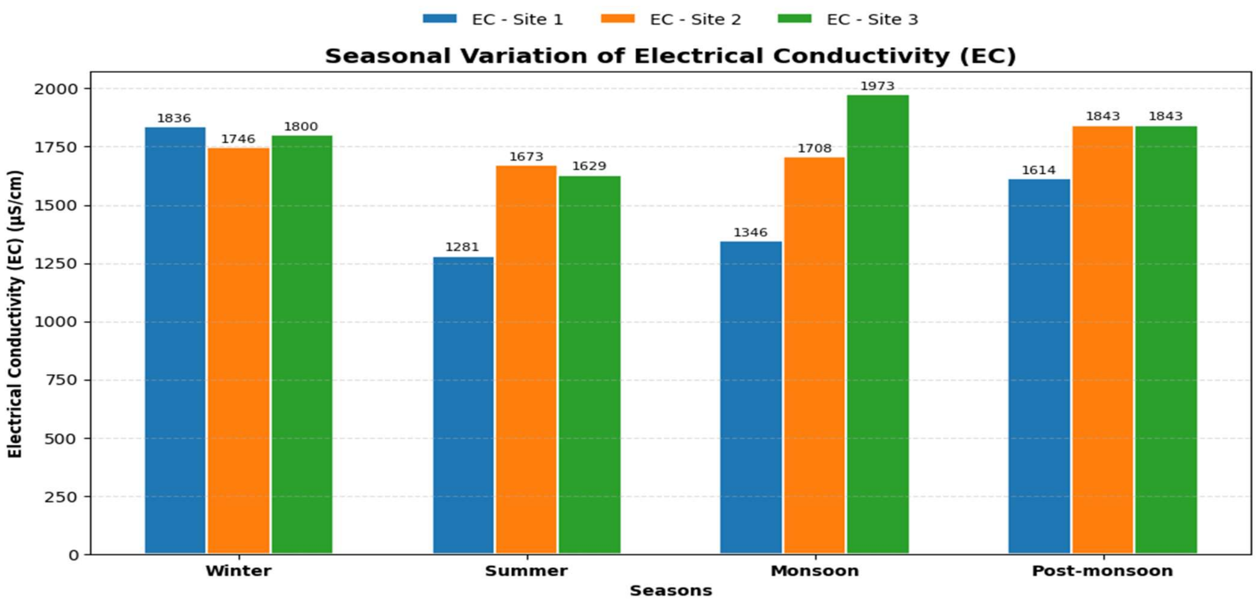

Figure 4 Seasonal variation in EC at three sites

Turbidity values ranged from 7.4 to 55.0 NTU, with the highest turbidity recorded during the monsoon season at the central tourist site. This increase is primarily attributed to heavy rainfall, surface runoff and disturbance of sediments caused by recreational activities. Turbidity in the Sahastradhara River varied from 7.4 to 55 NTU, with higher values recorded during the monsoon season. **Devi *et al.* (2024)** reported that turbidity and suspended particulate matter increase significantly during periods of heavy rainfall and surface runoff in the Giri River Basin of Himachal Pradesh. Such increases have generally been attributed to enhanced sediment transport, catchment erosion and anthropogenic disturbances.

Dissolved oxygen (DO) concentrations ranged between 3.29 and 8.09 mg L^{-1}, with higher values typically observed during cooler months. In contrast, biochemical oxygen demand (BOD) ranged from 2.06 to 9.95 mg L^{-1}, indicating moderate organic pollution in certain locations. Dissolved oxygen and biochemical oxygen demand values in the present study ranged from 3.29–8.09 mg L^{-1} and 2.06–9.95 mg L^{-1}, respectively, indicating moderate organic loading in certain locations. Comparable patterns have been reported in river systems exposed to intensive human activities. **Mishra *et al.* (2025)** observed that during large-scale religious gatherings in the Ganga River at Prayagraj, BOD levels increased significantly and dissolved oxygen levels decreased due to increased organic inputs and anthropogenic disturbances. These observations suggest that human activities can substantially influence the oxygen balance and organic pollution levels in river ecosystems. Furthermore, chemical oxygen demand (COD) varied from 17.3 to 64.9 mg L^{-1}, reflecting the presence of oxidizable organic and inorganic substances (**Matta and Kumar, 2015**) in the river water (**Figure 5**).**3.2 Major Ion Composition and Hardness Characteristics**- Major ion analysis indicated that the Sahastradhara River is characterized by relatively high mineral content (**Figure 6**). Total hardness values ranged from 426 to 792 mg L^{-1} as $CaCO_3$, indicating very hard water conditions. Such high hardness levels are typical of rivers flowing through carbonate-rich geological formations. Calcium concentrations varied from 97.6 to 217.6 mg L^{-1}, while magnesium concentrations ranged from 28.67 to 72.90 mg L^{-1}. These ions contribute significantly to the hardness of the river water and originate primarily from the dissolution of limestone rocks in the catchment area. Alkalinity values ranged from 150.1 to 290.7 mg L^{-1} as $CaCO_3$, reflecting the buffering capacity of the water. Elevated alkalinity values during dry seasons may be attributed to

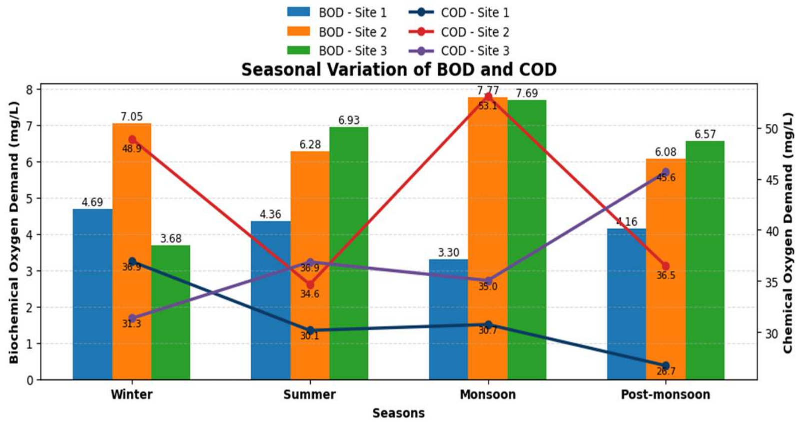

Fig 5: Seasonal Variation in BOD and COD in 03 Sites increased mineral dissolution and reduced dilution (Dudgeon, 2010; Mishra *et al.,* 2025).

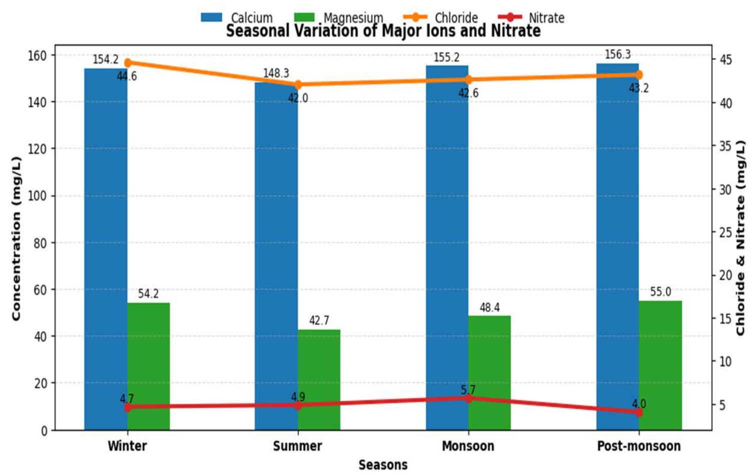

Figure 6: Seasonal variation in major ions and nitrate at three sites

Chloride concentrations ranged from 33.5 to 54.0 mg L⁻¹, which are well below the permissible limit for drinking water. Slightly higher chloride values observed at downstream sites may indicate minor anthropogenic inputs from domestic activities or runoff. Nitrate concentrations varied between 1.35 and 7.96 mg L^{-1}, remaining well below the drinking water guideline value of 45 mg L^{-1}. Slight increases during monsoon months may be attributed to nutrient runoff from surrounding areas.

3.3 Heavy Metal Distribution- Heavy metal concentrations in the Sahastradhara River were generally low and remained within permissible limits for drinking water standards (**Table 5** and **Figure 7**). Iron concentrations ranged from 0.025 to 0.49 mg L^{-1}, while manganese concentrations varied between 0.008 and 0.248 mg L^{-1}. These metals likely originate from natural geological sources and soil erosion processes. Zinc concentrations ranged from 0.018 to 0.581 mg L^{-1} and copper concentrations varied between 0.003 and 0.199 mg L^{-1}. The low concentrations of these metals suggest minimal industrial or anthropogenic contamination in the study area. Lead concentrations were detected in trace amounts, ranging from 0.0011 to 0.0194 mg L^{-1}. Although some values approached the recommended drinking water limit, the overall concentrations remain relatively low compared with heavily polluted river systems. The observed heavy metal distribution indicates that the Sahastradhara River is largely free from significant industrial contamination and that metal concentrations are primarily controlled by natural geochemical processes. Heavy metal concentrations recorded in the Sahastradhara River were generally low and remained within permissible limits. Iron concentrations ranged from 0.025–0.49 mg L^{-1}, manganese from 0.008–0.248 mg L^{-1}, zinc from 0.018–0.581 mg L^{-1}, copper from 0.003–0.199 mg L^{-1} and lead from 0.0011–0.0194 mg L^{-1}. Similar findings have been reported in studies investigating heavy metal contamination in aquatic environments (**Prerna et al. 2014; Kamboj *et al.* 2017; Dippong *et al*. 2024**). **An *et al.* (2024)** reported that heavy metal concentrations in surface waters are often controlled by natural geological processes and environmental factors, although anthropogenic inputs such as agricultural runoff and urban discharge may contributelocally.

Table 5: Seasonal variation in heavy metals at three sites

Metal	Observed Range (mg/L)	Desirable Limit	Permissible Limit	Status
Iron (Fe)	0.082 – 0.424	0.3	1.0	Slightly above desirable
Manganese (Mn)	0.081 – 0.175	0.1	0.3	Above desirable
Zinc (Zn)	0.132 – 0.543	5	15	Safe
Copper (Cu)	0.046 – 0.187	0.05	1.5	Above desirable
Lead (Pb)	0.0049 – 0.016	0.01	0.01 (no relaxation)	Some samples slightly high

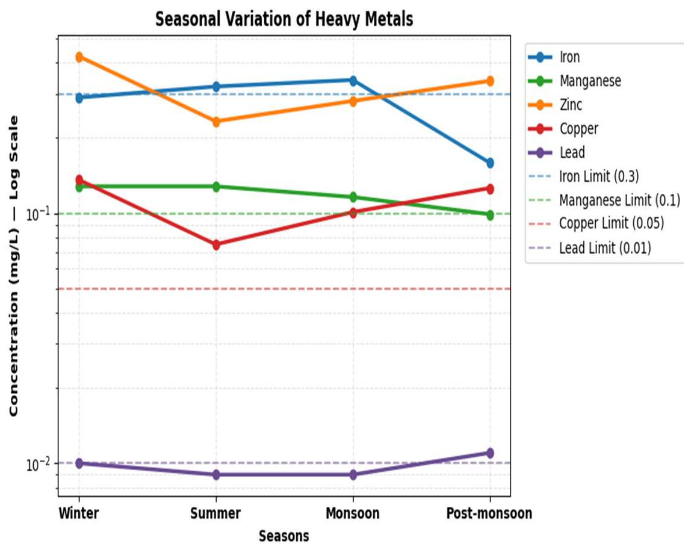

Figure 7: Seasonal variation in heavy metals at three sites

3.4 Microbial Contamination- Microbiological analysis revealed considerable variation in bacterial contamination across seasons and sampling locations (**Figure 8**). Total coliform counts ranged from 488.4 to 2419.6 MPN per 100 mL, indicating substantial microbial contamination in certain locations.Fecal

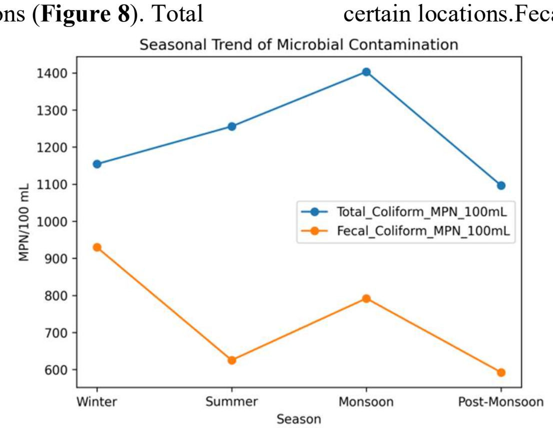

Figure 8: Seasonal variation in microbial contamination at three sites

coliform counts ranged between 156.9 and 1553.1 MPN per 100 mL, suggesting potential fecal contamination associated with human activities.

Higher microbial counts were observed during summer and monsoon seasons exceeded CPCB bathing criteria, suggesting contamination from direct human activity and surface runoff. The elevated microbial counts highlight the potential public health risks associated with direct consumption or recreational exposure to untreated river water. Microbial contamination observed in the present study revealed total coliform counts ranging from 488.4 to 2419.6 MPN 100 mL^{-1}, while fecal coliform counts ranged from 156.9 to 1553.1 MPN 100 mL^{-1}. Elevated microbial loads in freshwater systems have also been reported in several studies (**Reid *et al.* 2019; Parab *et al.* 2025**). **Dippong *et al.* (2024)** reported that the presence of microbial indicators such as Escherichia coli and coliform bacteria in river water reflects fecal contamination associated with anthropogenic activities and environmental inputs.

3.5 Correlation Analysis- Pearson correlation analysis was performed to evaluate the relationships among major physicochemical parameters and to identify possible controlling factors influencing the hydrochemistry of the Sahastradhara River. The analysis revealed several significant correlations between water quality variables (**Figure 9**).A very strong positive correlation was observed between electrical conductivity (EC) and total dissolved solids (TDS) (r = 0.98), indicating that dissolved ionic substances primarily control the conductivity of the river water. This relationship reflects the mineral-rich nature of the Sahastradhara stream system, which originates from carbonate rock formations. Total hardness exhibited strong positive correlations with calcium (r = 0.91) and magnesium (r = 0.88) concentrations, confirming that water hardness in the river is largely controlled by the dissolution of calcium and magnesium-bearing minerals in the catchment area. Dissolved oxygen showed a strong negative correlation with biochemical oxygen demand (r = –0.72) and a moderate negative correlation with chemical oxygen demand (r = –0.61). These relationships indicate that increased organic matter leads to oxygen depletion through microbial decomposition processes. Turbidity displayed moderate positive correlations with BOD (r = 0.42) and COD (r = 0.46), suggesting that suspended particles and organic pollutants may be introduced particularly in areas experiencing recreational activities. simultaneously through runoff and sediment disturbance

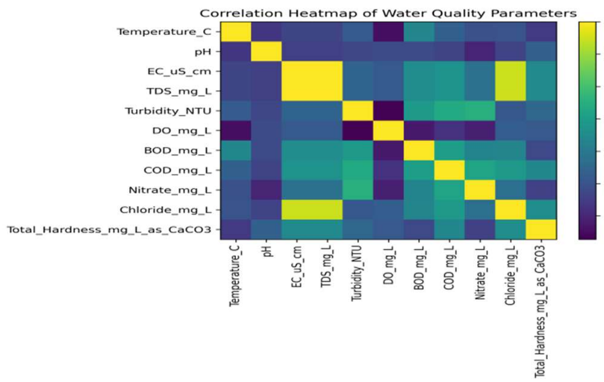

Figure 9: Correlation heatmap of water quality parameters at three sites

A moderate positive correlation was also observed between nitrate and BOD (r = 0.49), indicating that nutrient enrichment may be associated with organic matter inputs from surrounding areas. Similarly, chloride exhibited moderate correlations with organic pollution indicators, suggesting minor anthropogenic contributions from domestic waste and surface runoff. Overall, the correlation analysis indicates that the water chemistry of the Sahastradhara River is influenced by two major processes: natural mineralization associated with carbonate geology and localized anthropogenic inputs related to tourism activities and surface runoff.

3.6 Principal Component Analysis- The PCA extracted several components, of which the first three principal components explained a significant proportion of the total variance in the dataset (**Table 6**). The first principal component (PC1) exhibited an eigenvalue of 3.96 and explained 27.53% of the total variance. This component showed strong positive loadings for electrical conductivity (0.44), total dissolved solids (0.44), chloride (0.43), chemical oxygen demand (0.32), total hardness (0.31), calcium (0.29) and magnesium (0.22). These parameters are associated with mineral content and dissolved ionic species, suggesting that PC1 represents the mineralization factor controlled primarily by geological weathering of carbonate rocks in the catchment area.

The second principal component (PC2) had an eigenvalue of 2.48 and accounted for 17.24% of the total variance. This component showed high positive loadings for nitrate (0.40), BOD (0.38) and turbidity (0.36), while dissolved oxygen exhibited a negative loading (−0.31). The grouping of these parameters indicates the influence of organic pollution and nutrient enrichment, likely associated with anthropogenic activities such as tourism, bathing and runoff from nearby settlements. The third principal component (PC3) explained 13.44% of the variance with an eigenvalue of 1.94. This component showed notable loadings for turbidity (0.36), total hardness (0.38), calcium (0.35), magnesium (0.27) and alkalinity (−0.34). These parameters represent interactions between suspended sediments and carbonate mineral chemistry, suggesting that PC3 reflects the combined influence of sediment transport and geochemical buffering processes within the river system.

Overall, the first three components together explained approximately 58.21% of the total variance, indicating that the water quality of the Sahastradhara River is controlled primarily by natural mineralization processes, organic pollution inputs and sediment–geochemistry interactions. The PCA results confirm that while geological processes dominate the hydro chemical characteristics of the river, localized anthropogenic disturbances related to tourism activities also contribute to variations in water quality.

Table 6: Principal component analysis table

Principal Component	**Eigenvalue**	**Variance Explained (%)**
PC1	3.96	27.53
PC2	2.48	17.24
PC3	1.94	13.44

3.7 Water Quality Index (WQI)- The overall water quality status of the Sahastradhara River was evaluated using the Water Quality Index (WQI), which integrates multiple physicochemical parameters into a single composite value representing the suitability of water for drinking purposes. The calculated WQI values in the present study ranged from 158.56 to 288.46, indicating that the river water falls within the poor to very poor water quality categories according to standard WQI classification (**Table 7** and **Figure 10**).Spatial variations in WQI values were clearly observed among the three sampling sites. The upstream site (S1) generally exhibited comparatively lower WQI values, reflecting relatively better water quality conditions due to minimal anthropogenic disturbances. In contrast, higher WQI values were recorded at the central tourist site (S2), where intense recreational activities, bathing and increased human presence were observed. The downstream site (S3) showed moderately elevated WQI values due to the cumulative impact of upstream inputs and local environmental pressures.

Seasonal variations were also evident in the WQI values. Lower WQI values were generally recorded during the winter season, indicating comparatively improved water quality conditions during periods of reduced tourist activity and lower surface runoff. In contrast, higher WQI values were observed during the summer and monsoon seasons, when increased tourist inflow, recreational activities and runoff from surrounding catchments contributed to elevated turbidity, organic matter, and microbial contamination. The deterioration in WQI values can be primarily attributed to elevated levels of turbidity (7.4–55 NTU), biochemical oxygen demand (2.06–9.95 mg L^{-1}) and total dissolved solids (552–1116 mg L^{-1}) observed in the river water (**Poff,2009; Reid *et al.* 2019; Lynch *et al.* 2023**). These parameters significantly influence the WQI calculation due to their assigned weight factors in the index formulation.

The high WQI values recorded in the present study suggest that although the Sahastradhara River maintains acceptable physicochemical characteristics in certain sections, the water is not suitable for direct drinking purposes without treatment. Similar observations have been reported in several freshwater ecosystems where recreational activities and anthropogenic pressures contribute to localized water quality deterioration (**Aylward *et al.* 2005; Parab *et al.* 2025**). Overall, the WQI analysis indicates that the Sahastradhara River experiences moderate environmental stress, highlighting the need for regular monitoring, improved waste management practices and controlled recreational activities to maintain ecological balance and protect water quality. The Water Quality Index values obtained in the present study ranged from 158.56 to 288.46, indicating poor to very poor water quality for drinking purposes without treatment. In contrast, **Devi *et al.* (2024)** reported significantly lower WQI values ranging from 7.58 to 16.91 in the Giri River Basin, indicating excellent water quality conditions. Such differences highlight the influence of site-specific environmental conditions, catchment characteristics and anthropogenic pressures on the overall water quality status of river systems.

Table 7: Seasonal variation of WQI at three sites

	Seasons	Site 1	Site 2	Site 3
WQI	**Monsoon**	194.554 (Poor)	260.879 (Very Poor)	225.627 (Very Poor)
	Post-monsoon	178.424 (Poor)	220.560 (Very Poor)	229.955 (Very Poor)
	Winter	206.349 (Very Poor)	223.617 (Very Poor)	203.483 (Very Poor)
	Summer	169.901 (Poor)	194.116 (Poor)	201.664 (Very Poor)

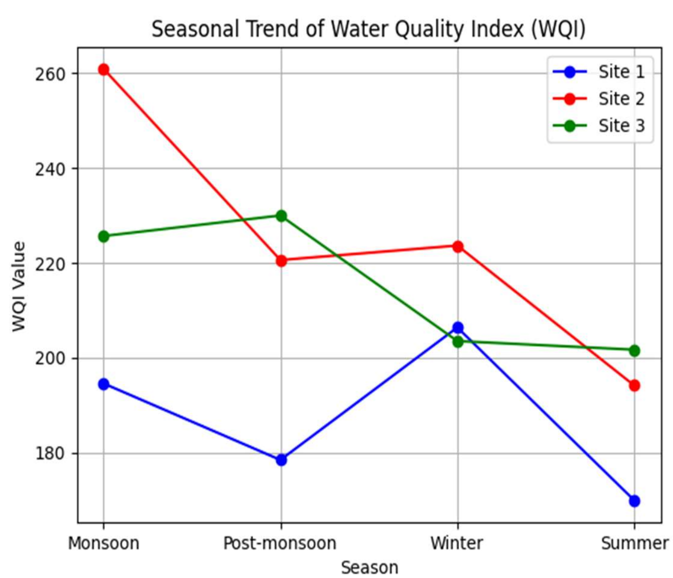

Figure 10: Seasonal trend of Water Quality Index (WQI)

3.8 Comprehensive Pollution Index (CPI)- The Comprehensive Pollution Index (CPI) was used to evaluate the overall pollution status of the Sahastradhara River by comparing the measured concentrations of water quality parameters with their corresponding standard permissible limits (**Table 8** and **Figure 11**). The calculated CPI values ranged from 1.74 to 3.34, indicating moderate to high pollution levels in certain sections of the river.Spatial variations in CPI values were evident across the three sampling locations. The upstream site (S1) recorded relatively lower CPI values, reflecting comparatively better environmental conditions and limited anthropogenic interference. In contrast, higher CPI values were observed at the central tourist site (S2), where intense human activity and recreational use of the river were concentrated. The downstream site (S3) also exhibited elevated CPI values due to the cumulative impact of upstream pollution sources and natural transport processes within the river system.

Lower CPI values were generally observed during the winter season, when reduced runoff and decreased tourist activity resulted in relatively improved water quality conditions. Conversely, higher CPI values were recorded during the monsoon season, primarily due to increased sediment load, surface runoff and transport of organic and inorganic pollutants from the surrounding catchment area (**Cedeno, 2024**). The elevated CPI values were largely influenced by increased concentrations of parameters such as turbidity (up to 55 NTU), chemical oxygen demand (17.3–64.9 mg L^{-1}) and biochemical oxygen demand (2.06–9.95 mg L^{-1}). These parameters indicated the presence of suspended particles and organic pollutants, which contribute significantly to the overall pollution load of the river (**Sharma *et al.* 2026**).

Although heavy metal concentrations in the river water remained relatively low and within permissible limits, the combined influence of organic pollution, suspended sediments and microbial contamination contributed to increased CPI values in certain sections of the river. The CPI analysis therefore indicates that while the Sahastradhara River is not heavily contaminated by toxic metals, localized pollution resulting from tourism activities, runoff and organic inputs contributes to moderate environmental degradation in certain areas (**Singh *et al.* 2014; Kattel 2022; Pokhrel *et al.* 2025**). Overall, the CPI results complement the WQI findings and provide further evidence that the water quality of the Sahastradhara River is influenced by both natural geological processes and anthropogenic activities, emphasizing the importance of continuous monitoring and sustainable management practices for the conservation of this important freshwater ecosystem.

Table 8: Seasonal variation in Comprehensive Pollution Index (CPI) at three sites

	Seasons	Site 1	Site 2	Site 3
CPI	**Monsoon**	2.204 (Very Poor)	2.953 (Very Poor)	2.446 (Very Poor)
	Post-monsoon	1.921 (Poor)	2.463 (Very Poor)	2.583 (Very Poor)
	Winter	2.264 (Very Poor)	2.499 (Very Poor)	2.246 (Very Poor)
	Summer	1.903 (Poor)	2.136 (Very Poor)	2.238 (Very Poor)

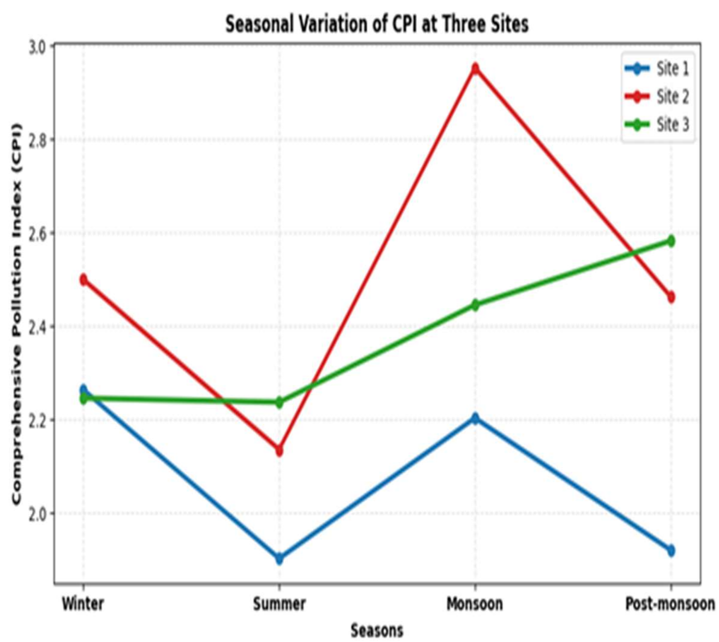

Figure 11: Seasonal variation in CPI at three sites

3.9 Environmental and Public Health Implications- The results obtained in the present study indicate important environmental and public health implications associated with the water quality status of the Sahastradhara River. Although the river represents an important recreational and tourist destination, several water quality parameters suggest that the ecosystem is experiencing moderate environmental stress (**Dudgeon 2010; Bănăduc *et al*. 2022**). The physicochemical characteristics of the river indicate that the aquatic environment is influenced by both natural geological processes and anthropogenic activities (**Reid *et al.* 2019**). Elevated turbidity values ranging from 7.4 to 55 NTU were observed during the study period, particularly during the monsoon season. High turbidity levels may reduce light penetration in the water column, thereby affecting primary productivity and disrupting the photosynthetic activity of aquatic plants and algae (**Parab *et al.* 2025**). In addition, suspended particles can interfere with fish respiration by clogging gill structures and may transport associated pollutants such as organic matter and microorganisms (**Sharma *et al.* 2026**).

Dissolved oxygen concentrations ranged between 3.29 and 8.09 mg L^{-1}, while biochemical oxygen demand values ranged from 2.06 to 9.95 mg L^{-1}. These observations indicate moderate organic loading within certain sections of the river (***Singh et al. 2014).*** Reduced dissolved oxygen concentrations may adversely affect aquatic organisms, particularly fish and invertebrates that require well-oxygenated water for survival (**Xu *et al.* 2019**). Prolonged exposure to low oxygen conditions can lead to physiological stress, reduced growth and altered species composition within the aquatic ecosystem (**Lepcha *et al.* 2021**). Microbiological analysis revealed significant levels of bacterial contamination, with total coliform counts ranging from 488.4 to 2419.6 MPN per 100 mL and fecal coliform counts ranging from 156.9 to 1553.1 MPN per 100 mL. The presence of fecal indicator bacteria suggests potential contamination from human or animal sources (**Siddiqui 2013**). Such microbial contamination represents a potential health risk for individuals using the river water for recreational purposes, bathing or accidental ingestion during tourism activities (**Dudgeon 2010**). Exposure to contaminated water may lead to gastrointestinal infections, skin irritation and other waterborne diseases.

Heavy metal concentrations in the river water remained relatively low and within permissible limits during the study period, indicating that the river system is not currently subjected to significant industrial contamination (**Kamboj *et al.* 2017**). However, continuous monitoring of trace metals remains important because heavy metals are persistent, non-biodegradable pollutants that can accumulate in aquatic organisms and enter the food chain (**Kangabam *et al.* 2017**). The integrated water quality assessment further highlights these environmental concerns. The Water Quality Index (WQI) values ranging from 158.56 to 288.46 indicate poor to very poor water quality for drinking purposes, suggesting that untreated river water is unsuitable for direct consumption (**Alobaidy *et al.* 2010**). Similarly, the Comprehensive Pollution Index (CPI) values ranging from 1.74 to 3.34 reflect moderate levels of environmental pollution in certain sections of the river.

CONCLUSION

The results therefore indicate that although the Sahastradhara River maintains relatively stable hydro chemical characteristics due to its spring-fed nature, localized anthropogenic pressures associated with tourism and recreational activities may contribute to episodic deterioration of water quality. Implementation of effective environmental management strategies, including improved waste disposal systems, regulation of tourist activities and regular water quality monitoring, is therefore essential to protect the ecological integrity of the river system. Overall, maintaining the environmental health of the Sahastradhara River is crucial not only for sustaining aquatic biodiversity but also for ensuring the safe recreational use of this important freshwater resource by local communities and visitors.

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