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Research Article

Seasonal Dynamics of Physico-Chemical Parameters, Heavy Metals, And Water Quality Index in The Giri River Basin

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Abstract

This study evaluated water quality parameters, heavy metal concentrations, and the Water Quality Index (WQI) in the Giri River Basin, focusing on six sites from Giripul Bridge to Shivpur in Paonta Sahib, Sirmaur district. The sites, characterized by distinct topographical features and pollution sources, were sampled during pre-monsoon and post-monsoon seasons to assess seasonal impacts. Surface water samples were analyzed for physico-chemical parameters such as temperature, pH, electrical conductivity, total dissolved solids, turbidity, BOD, and COD. Heavy metals, including chromium, nickel, arsenic, cadmium, and lead, were measured using an Inductively Coupled Plasma Emission Spectrometer (ICAP-6000 Series). The findings indicated significant ($p \leq 0.05$) spatial and seasonal variations in water physico-chemical parameters and heavy metals (Cr, Ni, As, Cd, and Pb) across different sites in the Giri River with water quality deteriorated downstream due to natural processes and anthropogenic factors like agricultural runoff, vehicular emissions, mining, and urbanization, with higher values recorded during the pre-monsoon season. Despite these variations, all measured parameters remained within BIS and CPCB permissible limits, indicating satisfactory water quality. The water quality (WQI) values confirmed excellent water quality, with the highest WQI at Bangran Giri Bridge (16.45) and the lowest at Giripul Bridge (8.22). Seasonal variations showed the highest WQI in the pre-monsoon season (16.91) and the lowest in the post-monsoon season (7.58). The study highlights the need for comprehensive water management strategies to address spatial and temporal fluctuations, ensuring the long-term sustainability of water quality in the Giri River Basin.

Keywords: Giri River; Physico-chemical parameters; Heavy metals; Seasonal variations; Water Quality Index (WQI).

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1. Introduction

Water is an invaluable natural resource, essential for life and the development of civilizations. Beyond its biological functions, water has significantly influenced cultural and societal growth. Although water covers approximately 80% of the Earth's surface, less than 1% is available as freshwater in rivers, lakes, and subsoil reserves (Saha and Paul, 2019; Mohanta et al., 2019). Despite their limited coverage, rivers and lakes are crucial as they provide accessible and cost-effective freshwater for domestic, agricultural, and industrial uses (Kumari et al., 2018; Ali and Khan, 2018; Kumari et al., 2021). Aquatic environments, including oceans, rivers, lakes, and wetlands, are classified based on salinity into freshwater, brackish, or marine ecosystems. The interaction between water, sediment, and aquatic organisms is vital for ecosystem health (Bhutiani et al., 2016; Pandiyan et al., 2021; Rahman et al., 2021). Physico-chemical parameters including temperature, turbidity, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are critical indicators of water quality. These parameters influence biological and chemical processes within ecosystems, directly affecting the survival and reproduction of aquatic organisms (Thakur et al., 2013; Bakure et al., 2020; Miranda et al., 2021). Variations in these parameters, driven by natural and anthropogenic factors, can disrupt aquatic ecosystems, highlighting the need for comprehensive monitoring (Singh et al., 2005; Engin et al., 2015).

Water is indispensable for life, facilitating biochemical reactions, fluid circulation in plants and animals, and sustaining ecosystems through reproduction and cyclic processes (Matta et al., 2018). It connects the atmosphere, lithosphere, and biosphere by transporting chemicals and facilitating reactions. However, contamination from heavy metals and pollutants has severely impacted water quality (Skipin et al., 2016; Bhardwaj et al., 2020). Industrialization, urbanization, and agricultural practices contribute to pollution, with untreated industrial waste and domestic sewage often discharged into water bodies, introducing hazardous compounds (Mohiuddin et al., 2011; Achary et al., 2017; Yua et al., 2021). These pollutants affect water's ecology, environmental chemistry, and biological quality, with usability influenced by both natural conditions and human activities (Saravi and Shokrzadeh, 2013; Rahman et al., 2014).

Heavy metals in aquatic environments originate from natural processes like atmospheric deposition and water-soil interactions (Ekere et al., 2018), as well as anthropogenic sources such as industrial, urban, and mining discharges, and pesticide- and fertilizer-laden irrigation water (Wang et al., 2015). These metals pose significant ecological threats due to their toxic impacts on ecosystems (Mdegela et al., 2009). Heavy metals, characterized by an atomic number greater than 20, an atomic density exceeding 5 g cm⁻³, and toxicity at low concentrations, include elements like lead (Pb), zinc (Zn), cadmium (Cd), mercury (Hg), silver (Ag), copper (Cu), iron (Fe), arsenic (As), chromium (Cr), nickel (Ni),

and members of the platinum group (Zhang et al., 2013; Ali and Khan, 2019). Trace metal contamination arises from fly ash and industrial waste runoff, with anthropogenic sources overshadowing natural contributions in recent centuries (Nyamete et al., 2020). Metals like mercury, cadmium, and lead are highly toxic and accumulate in aquatic organisms through sediments, runoff, air deposition, and wastewater (Gupta et al., 2017; Zafarzadeh et al., 2018). These metals persist in sediments, contaminate water, and bio-magnify through the food chain, posing risks to ecosystems and human health (Rahman et al., 2014; Sibal and Espino, 2018; Ngoc et al., 2020; Rigo et al., 2020). While some trace metals like Fe, Cu, Zn, and Mg are essential in small amounts, others like As, Pb, Cd, and methylated mercury are toxic even at minimal concentrations (Rai, 2009; Tabari et al., 2010; Islam et al., 2015). Excessive intake of both essential and nonessential metals can lead to poisoning and toxicity. The adsorption and accumulation of these metals depend on factors like concentration, water chemistry, and physiological effects, making them persistent pollutants in aquatic environments (Gupta et al., 2009; Malik and Maurya, 2014).

The Giri River, a major tributary of the Yamuna River in Himachal Pradesh, India, supports diverse aquatic life and provides vital resources for local communities but faces threats from anthropogenic activities like agricultural runoff, mining, vehicular emissions, industrial discharge, and urbanization. Limited studies exist on the seasonal variations in its physico-chemical parameters, heavy metal contamination, and their impacts on the aquatic ecosystem. Heavy metals are of particular concern due to their toxic, persistent, and bioaccumulative nature. Once introduced into the aquatic environment, these metals can adversely affect the health of aquatic organisms. This study seeks to address these gaps by investigating the seasonal variations in the physico-chemical parameters and heavy metal concentrations of the Giri River. It also aims to calculate a comprehensive water quality index (WQI) integrating heavy metal data, identify pollution sources, and provide recommendations for mitigation and conservation. The findings are expected to provide insights for policymakers, environmental agencies, and local stakeholders in implementing effective pollution control measures and sustainable practices. Furthermore, the study holds significance for ecological conservation, human health protection, community awareness, and academic research, offering a robust foundation for future studies on aquatic ecosystems and the sustainability of freshwater resources. Therefore, this research aims to provide a comprehensive understanding of the Giri River's health, highlighting the need for informed strategies to preserve its ecosystem and mitigate pollution.

2. Materials and methods

2.1 Study area

Himachal Pradesh, situated in northern India within the western Himalayas, is a mountainous state characterized by its dramatic landscapes, high-altitude peaks, and

extensive river systems. The state spans latitudes 30°22'40" to 33°12'40" North and longitudes 75°45'55" to 79°04'20" East, with elevations ranging from 350 to 6,975 meters above sea level. Known as Dev Bhoomi (Land of Gods) and Veer Bhoomi (Land of the Brave), Himachal Pradesh shares borders with the union territories of Jammu and Kashmir and Ladakh to the north, Punjab to the west, Haryana to the southwest, Uttarakhand to the southeast, and Tibet to the east. This study focuses on the Giri River, the largest river in the southern Sirmaur district of Himachal Pradesh, which encompasses a geographical area of 2,825 square kilometers. The region features hilly terrains and valleys, including the Paonta Sahib valley. Sirmaur, bordered by the Shimla and Solan districts, is traversed by prominent rivers such as the Giri, Yamuna, Bata, Tons, Ghagghar, and Markanda, which are crucial for irrigation and serve as significant tributaries of the Yamuna. The Giri River, also referred to as "Giri Ganga," is a major tributary of the Yamuna River. It originates in the Jubbal hills and flows through Kot-Khai, Tatesh, and parts of the Shimla district before entering the Sirmaur district. The river bifurcates Sirmaur into two regions, Cis-Giri and Trans-Giri, and merges with the Yamuna near Paonta Sahib below Mohkampur Nawada. The river's catchment area is rich in vegetation, including fir, deodar, blue pine, and oak, attracting visitors during the summer months. The Giri River supports local livelihoods through fishing, timber floating, and irrigation. Major tributaries include the Ashani near Sadhupul, Jalal at Dadahu, and streams such as Nait, Palar, Bajhethy, Pervi, Khal, and Joggar, which contribute to its extensive course.

The climate of the Sirmaur district ranges from subtropical to temperate, influenced by its elevation. The district experiences four distinct seasons: winter (November-February), summer (March-June), monsoon (July-September), and a post-monsoon period. The majority of the annual rainfall, averaging 1405 mm, occurs during the monsoon season. Higher elevations above 1500 meters above sea level receive snowfall in winter, with the Choordhar peaks remaining snow-covered. Lower hills and valleys experience occasional winter rainfall. Temperature variations range from a mean maximum of 30°C to a minimum of 0°C.

2.2 Site selection and sample collection

A preliminary survey of the Giri River identified six study sites between Giripul Bridge and Shivpur (near Govt. School) Paonta Sahib in the Sirmaur district comprising a stretch of 150 km. Sites were selected to represent diverse topographical features, pollution sources, and fishing activities. The chosen sites were: Site 1: Giripul Bridge (30.881793° N, 77.210479° E), Site 2: Khairi Bridge (30.774508° N, 77.297364° E), Site 3: Dadahu (30.60113° N, 77.439024° E), Site 4: Ambaun (30.568825° N, 77.549915° E), Site 5: Sataun (30.558016° N, 77.63201° E), and Site 6: Bangran Giri Bridge (30.497487° N, 77.678717° E). Water samples were randomly collected from the selected sites (three equal stretches of 8 km) during the pre-monsoon and post-monsoon seasons for 2022-23 to 2023-24, between 8:00 a.m. and noon. Surface water samples for physico-

chemical and biological analysis were gathered from 10 to 12 cm below the water surface in 500-mL polyethylene bottles. For heavy metal analysis, 500 mL of water was collected from each site according to APHA (2017) guidelines. After collecting, the samples were stored at 4°C in the laboratory for further analysis.

2.3 Assessment of water quality

The physicochemical analysis was performed using standard methods as suggested by the American Public Health Association (APHA, 2017). Water temperature, which is important for microbial growth and redox reactions, was recorded on-site using a graduated Celsius thermometer, with the bulb dipped in water for at least two minutes to obtain the temperature, expressed on a scale of 0-100°C. The pH was determined using a microprocessor-based pH meter, with readings expressed on a scale of 0 to 14. Electrical conductivity (EC) was determined using a digital microprocessor-based conductivity/TDS meter with automatic temperature compensation, and values were recorded as dS m^{-1} . Total dissolved solids (TDS), representing all dissolved solids in water, were measured using the same conductivity/TDS meter and expressed in mg/L. Turbidity, indicating suspended particles in water, was determined using a Nephelometric method with a digital turbidity meter, with results expressed in Nephelometric Turbidity Units (NTU). Biochemical Oxygen Demand (BOD), measuring the oxygen required by microorganisms to stabilize biodegradable organic matter in water, was assessed using a 5-day test following the 5210B method (APHA, 2017). The pH of water samples was adjusted between 6.5 and 7.5, and a 152 mL sample was placed in a BOD bottle with 5-6 drops of nitrification inhibitor and 3-4 drops of KOH solution, sealed, and incubated at 20°C for five days. BOD readings were recorded and expressed in mg/L. Chemical Oxygen Demand (COD), measuring the oxygen needed to oxidize organic and inorganic matter in water, involved oxidizing samples with hot H_2SO_4 and potassium chromate, using silver sulfate as a catalyst, and digesting at 148°C for 120 minutes. The concentration of Cr^{3+} ions was measured photometrically using a Spectroquant 300 instrument (Merck) and expressed in mg/L. Heavy metals analysis (Cr, Ni, As, Cd, and Pb) involved filtering and digesting 500 mL of water with 5 mL of 6N HNO_3 , heating to a slow boil until a clear solution indicated complete digestion (APHA, 2017), filtering with Whatman filter paper (No.1), and estimating metals using an Inductively Coupled Plasma Emission Spectrometer (iCAP-6000 Series, Model No. 6300) and expressed in mg/L. Permissible limits for drinking water standards prescribed by the World Health Organization (WHO), Bureau of Indian Standards (BIS), and Central Pollution Control Board (CPCB) were used to represent the impact of urbanization, industrial developments, domestic sewage, agricultural runoff, and other anthropogenic activities on surface water quality.

2.4 Water Quality Index (WQI)

The water quality index (WQI) is a rating technique that provides a composite assessment of individual water

quality parameters on the overall water quality. The WQI was utilized to obtain a comprehensive picture of the overall quality of surface and groundwater. The Indian standards specified for drinking and outdoor bathing water (CPCB, 2009) were used to calculate the WQI. Each of the 12 parameters (temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), Cr, Ni, As, Cd, and Pb) was assigned a weight (w_i) according to its relative importance in the overall quality of water for drinking purposes. The WQI was calculated using the method outlined by Batabyal and Chakraborty (2015) as described below:

$$WQI = \sum Si_n$$

$$Sli = Wi \times qi$$

Where,

Sli is the sub-index of i th parameter,

Wi is the relative weight of i th parameter,

qi is the rating based on the concentration of i th parameter, and

n is the number of chemical parameters.

$$wi = \frac{Wi}{\sum Wi}$$

Where,

Wi is the relative weight,

wi is the weight of each parameter, and

$$qi = (Ci / Si) \times 100$$

Where,

qi is the quality rating,

Ci is the concentration of each chemical parameter in each water sample in mg/L, and

Si is the Indian drinking water standard for each chemical parameter in mg/L.

According to Mishra and Patel (2001), the WQI values that are safe for human consumption are listed in Table 1.

Table 1: WQI values suitable for human consumption.

Water Quality Index Level	Water Quality Status	Water Quality Grading	Possible Uses
0-24	Excellent	A	Drinking, irrigation, and industrial purpose
25-49	Good	B	Drinking, irrigation, and industrial purpose
50-74	Poor	C	Irrigation and industrial Purpose
75-100	Very Poor	D	For irrigation purpose
>100	Unsuitable for drinking and fish culture	E	Proper treatment is required for any kind of usage

2.5 Statistical Analysis

The data recorded from the present investigation were analyzed using the methodology described by Gomez and Gomez (1984). The data collected for different parameters were statistically analyzed using ANOVA (Analysis of Variance) with a two-factor factorial Randomized Block Design for the assessment of water quality in R-Studio (v4.3.0). Statistical significance was assessed using an 'F' test, and differences in means across treatments were examined using the least significant difference (LSD) at the 5% level of significance.

3. Results and discussion

3.1 Water quality assessment

3.1.1 Temperature (°C)

The present investigation revealed that surface water temperature significantly increased from upstream to downstream sites (table 2). The Giripul Bridge, which is closest to the river's origin, had the lowest mean temperature across both years, with a pooled mean of 20.30°C. In contrast, Ambaun had the highest temperature (22.47°C) among the downstream sites, followed by Bangran Giri Bridge (22.21°C) and Sataun

(22.03°C) (Figure 1), which were within the permissible limits prescribed by the BIS. The significant increase in temperature downstream can be attributed to reduced shade, decreased elevation, and increased exposure to sunlight as the river moves further from its origin. The surface water temperature was consistently and significantly higher in the pre-monsoon season than in the post-monsoon season across all the sites. The pooled mean temperature was 28.29°C in the pre-monsoon season compared to 14.70°C in the post-monsoon season. These results are in line with the findings of Trivedi *et al.* (2010), Puri *et al.* (2010), Gupta *et al.* (2014), Chauhan & Verma (2016), Basu *et al.* (2021), Saha *et al.* (2022), Rahman *et al.* (2023), Nagpurkar *et al.* (2023), Zafar & Kumari (2024), and Monira *et al.* (2024), who also reported a significant decrease in water temperature during post-monsoon months and an increase in water temperature during pre-monsoon months because of greater solar radiation and a higher atmospheric temperature. The seasonal difference likely reflects significant climatic variations, with pre-monsoon months typically being warmer. The pooled seasonal means further confirmed that the pre-monsoon temperature was significantly higher across all the sites,

highlighting a consistent seasonal effect on the river temperature.

3.1.2 pH

The present study demonstrated a significant change in the pH of the surface water as one moved downstream (table 2). Giripul Bridge, the closest site to the river's origin, had the lowest pooled mean pH value of 7.25, whereas among the downstream sites, Ambaun had the highest pooled mean pH value of 7.70, followed by Bangran Giri Bridge (7.69) and Sataun (7.65) (Figure 1). These variations were significant and within the BIS-recommended acceptable limits. This trend suggested a gradual rise in pH as the river flows downstream, which may be due to interactions with various minerals, soil compositions, and organic matter along the river's path. The pre-monsoon season consistently resulted in significantly higher pH values across both years (2022-23 and 2023-24) and in the pooled data. The overall means for the post-monsoon and pre-monsoon seasons in the pooled data were 7.42 and 7.61, respectively, indicating a significant shift toward higher pH values during the pre-monsoon season. The present results are in confirmation with the findings of Pejman *et al.* (2009), Sharma & Capoor (2010), Gupta *et al.* (2014), Ravish *et al.* (2020), Kumar & Prakash (2020), Imran *et al.* (2020), Kadam *et al.* (2021), Ribinu *et al.* (2023), Jayana (2023), Nagpurkar *et al.* (2023), and Zafar & Kumari (2024), who also reported the maximum pH during the pre-monsoon season. The significantly higher pH values of surface water during the pre-monsoon season may have been due to reduced river flow and increased evaporation, which may have concentrated dissolved minerals and ions, contributing to a slight increase in pH. Conversely, post-monsoon pH values may be lower due to dilution from rainfall, which can lower ion concentrations and affect pH. The pH values remain within a moderately narrow range, indicating that the river maintains a significantly stable environment across both seasons, which is favourable for various aquatic species.

3.1.3 Electrical conductivity (EC)

The findings of this study revealed significant spatial and seasonal variations in the electrical conductivity (EC) of surface water in the Giri River Basin, highlighting the influence of both natural and anthropogenic factors (table 2). The Giripul Bridge, which is the site closest to the river's origin, had the lowest pooled mean EC of 0.270 dS m⁻¹, indicating minimal interaction with external factors such as soil and groundwater. In contrast, Sataun recorded the highest pooled mean EC of 0.547 dS m⁻¹ (Figure 1), which was normal and within the permissible limits suggested by the BIS. Other downstream sites, such as Ambaun and Bangran Giri Bridge, also have higher EC values compared to the upstream sites. This increase in EC along the river's course may be due to cumulative factors, such as the addition of dissolved ions from groundwater inflow and potential runoff from agricultural areas. Seasonally, the pre-monsoon period consistently recorded higher EC values across all the sites than the post-monsoon season. The pooled mean

EC during the pre-monsoon season was 0.447 dS m⁻¹, significantly higher than the post-monsoon value of 0.390 dS m⁻¹. This seasonal variation can be attributed to the lower water volume and limited dilution effects during the pre-monsoon season, which concentrate dissolved ions in the surface water. In contrast, the post-monsoon season, characterized by increased rainfall and river discharge, may result in the dilution of ions, thereby lowering the EC levels. These results align with the findings of Makineci *et al.* (2015), Sudarshan *et al.* (2019), Singh *et al.* (2020), Sharma *et al.* (2021), Kadam *et al.* (2021), Hossain *et al.* (2022), Saha *et al.* (2022), Ribinu *et al.* (2023), Gowrabathina & Sivakumar (2023), Jayana (2023), and Nagpurkar *et al.* (2023), who also reported the highest electrical conductivity during the pre-monsoon season and the lowest in the post-monsoon months.

3.1.4 Total dissolved solids (TDS)

The current research established that upstream sites, such as Giripul Bridge, generally had significantly lower total dissolved solids (TDS) levels in surface water, with a pooled mean of 130.99 mg l⁻¹ (table 2). At the same time, downstream sites, particularly Sataun, presented significantly higher TDS values with a pooled mean of 159.04 mg l⁻¹, which was within the permissible guidelines recommended by the BIS. The significant increase in TDS levels downstream may result from combined factors, including natural processes and possible anthropogenic activities such as agricultural runoff and urban wastewater, as the river moves through different landscapes and areas of human activity. A clear seasonal trend emerges, with higher TDS levels recorded during the pre-monsoon season across both years (2022-23 and 2023-24) and in the pooled data. The mean TDS values for the post-monsoon and pre-monsoon seasons in the pooled data were 129.74 mg l⁻¹ and 174.00 mg l⁻¹, respectively, indicating a significant increase in TDS during the pre-monsoon season (Figure 1). The results agree with the findings of Shaikh & Mandre (2009), Gupta *et al.* (2014), Singh *et al.* (2020), Ravish *et al.* (2020), Imran *et al.* (2020), Thapa *et al.* (2020), Kadam *et al.* (2021), Hossain *et al.* (2022), Jayana (2023), Nagpurkar *et al.* (2023), and Ribinu *et al.* (2023), who reported similar trends in total dissolved solids under the influence of seasons. The seasonal increase in the TDS of surface water during the pre-monsoon period could be due to higher evaporation and minimal rainfall, which concentrates dissolved materials in the water. During the post-monsoon months, cooler temperatures reduce evaporation rates, maintaining a higher water volume. This increased water flow may dilute dissolved solids more effectively, leading to lower TDS values. Overall, the findings demonstrated that TDS levels were significantly affected by both seasonal changes and site-specific factors, with consistently higher TDS values during the pre-monsoon season.

3.1.5 Turbidity

The results of the present research indicated that the turbidity of surface water significantly increased from upwards to downwards (table 2). The Giripul Bridge had the lowest pooled mean turbidity, 3.39 NTU, in surface

water. On the other hand, downwards-moving sites such as Bangran Giri Bridge and Sataun exhibited significantly greater turbidity levels, with pooled values of 5.57 and 5.16 NTU, respectively (Figure 2), which were within the acceptable limits prescribed by the BIS. This rise in turbidity at downstream sites may be due to soil erosion, land runoff, and the entry of suspended particles into the river, as these particles flow through areas with increased human activity and natural sediment sources. The pre-monsoon season had significantly greater turbidity (pooled mean of 6.83 NTU) than the post-monsoon season (pooled mean of 2.48 NTU) at all sites. These results are in accordance with the findings of Singh *et al.* (2013), Singh *et al.* (2020), Imran *et al.* (2020), Sharma *et al.* (2021), Abhilash (2022), and Gowrabathina & Sivakumar (2023), who also reported that the pre-monsoon season had the maximum turbidity, whereas the post-monsoon months had the lowest turbidity. This pattern may result from decreased rainfall and water flow in the pre-monsoon season, allowing sediments to remain suspended. During the post-monsoon period, increased water volume might reduce turbidity levels by carrying sediments downstream or depositing them in quieter river sections.

3.1.6 Biological oxygen demand (BOD)

The present investigation revealed that the biological oxygen demand (BOD) values of surface water significantly increased from upstream to downstream sites (table 3). Giripul Bridge, the site nearest to the origin, had the lowest pooled mean BOD values (2.38 mg l^{-1}) across both years, indicating significantly less organic pollution at the river source. However, in both seasons, downstream sites such as Bangran Giri Bridge had the highest pooled mean BOD values (3.69 mg l^{-1}), followed by Sataun (3.41 mg l^{-1}), Khairi Bridge (3.39 mg l^{-1}), and Ambaun (3.36 mg l^{-1}) (Figure 2), which were within the permissible limits prescribed by the BIS. The significant increase in BOD downstream could indicate higher organic pollution from urban runoff and agricultural inputs as the river moves through more populated and cultivated areas. BOD levels had a clear and significant seasonal pattern, with significantly higher values recorded in the pre-monsoon season than in the post-monsoon season across both years and in the pooled data. The mean BOD values of surface water for post-monsoon and pre-monsoon seasons in the pooled data were 2.38 mg l^{-1} and 4.09 mg l^{-1} , respectively, showing a significant increase during the pre-monsoon season. These results are in line with the findings of Pejman *et al.* (2009), Kanakiya *et al.* (2014), Chauhan & Verma (2016), Pal & Maiti (2018), Sharma *et al.* (2021), Basu *et al.* (2021), Abhilash (2022), and Rahman *et al.* (2023), who also reported the highest BOD during pre-monsoon months and the lowest during post-monsoon months. This increase in BOD in the pre-monsoon season might be due to lower water levels, which concentrate organic pollutants and microbial activity. Higher concentrations of organic material in the water increase the oxygen demand for microbial decomposition, resulting in higher BOD. However, the lower levels of BOD in the post-monsoon season were

probably due to rainfall-induced dilution, which can reduce the concentration of organic pollutants in the water, leading to a reduction in BOD. Additionally, cooler temperatures during the post-monsoon months may reduce the rate of oxygen consumption for the breakdown of organic matter, further contributing to the lower BOD levels.

3.1.7 Chemical oxygen demand (COD)

The present study demonstrated that the chemical oxygen demand (COD) values of surface water were significantly lower at upstream sites and increased downstream. The upstream Giripul Bridge had the lowest pooled mean COD level (95.39 mg l^{-1}) (table 3). In comparison, the downstream Bangran Giri Bridge had the highest pooled mean (169.59 mg l^{-1}), which was within the BIS-recommended acceptable limits. This rise in COD from upstream to downstream areas significantly suggests increased organic and chemical contaminants along the river course, possibly from residential, agricultural, and industrial activities closer to downstream areas. Seasonally, the COD levels of surface water were significantly higher in the pre-monsoon period (pooled mean of 157.03 mg l^{-1}) than in the post-monsoon season (pooled mean of 122.71 mg l^{-1}) (Figure 2). The present results are in confirmation with the findings of Ololade & Ajayi (2009), Garg *et al.* (2010), Gupta *et al.* (2014), Pal & Maiti (2018), Singh *et al.* (2020), Sharma *et al.* (2021), Basu *et al.* (2021), Abhilash (2022), Nagpurkar *et al.* (2023), and Monira *et al.* (2024), who also reported maximum COD during the pre-monsoon season and minimum COD during the post-monsoon months. The significant seasonal increase in COD during the pre-monsoon period may be due to the higher organic matter concentration, reduced river flow, higher temperatures, and stagnation of water, which may contribute to elevated COD values. Conversely, the intense flow of water during the monsoon and post-monsoon periods might be able to remove accumulated pollutants, including both organic and inorganic substances, resulting in lower COD levels in the post-monsoon period.

3.2 Heavy metals

3.2.1 Chromium (Cr)

The results of the present study revealed both significant and non-significant variations in chromium (Cr) concentrations across sites and years (table 4). The non-significant variations between sites indicated that chromium concentrations were relatively stable throughout the study area, with minor differences observed at individual locations. Sataun recorded the highest pooled mean Cr concentration (0.0142 mg l^{-1}), which was within the permissible limits set by the CPCB. In contrast, Ambaun and Giripul Bridge tend to have slightly lower Cr concentrations, with pooled mean values of 0.0130 mg l^{-1} and 0.0133 mg l^{-1} , respectively (Figure 2). These differences may be attributed to localized influences, including agricultural runoff, mining activities, wastewater discharge, and industrial effluents. However, significant seasonal variation was observed, with chromium concentrations notably higher during the pre-monsoon season (0.0156 mg l^{-1}) than

during the post-monsoon season (0.0117 mg l^{-1}). These results are in line with the findings of Başak & Alagha (2010), Ravichandran & Jayaprakash (2011), Kumar *et al.* (2013), Giri & Singh (2014), Pal & Maiti (2018), Pandit & Bhardwaj (2020), Kabir *et al.* (2020), Dhaliwal *et al.* (2021), Sahil & Bhardwaj (2021), Banyal *et al.* (2022), and Kiran & Sivakumar (2023), who also observed an increase in the Cr concentration in surface water during the pre-monsoon months and a decrease in the Cr concentration during the post-monsoon months. The elevated Cr concentration during the pre-monsoon period was probably due to a reduction in river flow, evaporation-driven concentration, sediment resuspension, and increased anthropogenic discharge, all of which contributed to the accumulation of metals in the water. The lower concentrations observed in the post-monsoon season can be attributed to the dilution effects of increased rainfall and higher river discharge. The resulting strong water currents may effectively disperse pollutants and reduce their concentration in surface water. Additionally, a significant site-season interaction was detected, with the highest concentration recorded at Sataun in the pre-monsoon season (0.0163 mg l^{-1}) and the lowest at Giripul Bridge in the post-monsoon season (0.0110 mg l^{-1}). This suggests that the accumulation of Cr may be more pronounced at certain sites during dry periods, whereas dilution is more prominent in other areas during the wet season. Overall, the findings emphasize the influence of seasonal variations in river flow on the Cr concentration, with significant increases during the pre-monsoon period and decreases in the post-monsoon months. These fluctuations highlight the need for effective water quality management strategies that account for seasonal variations to mitigate Cr contamination and its potential impact on river ecosystems.

3.2.2 Nickel (Ni)

The findings of this study demonstrate significant spatial and seasonal variations in nickel (Ni) concentrations across the Giri River Basin (table 4). Among the sites studied, Khairi Bridge consistently presented the highest Ni concentration, with a pooled mean of 0.0044 mg l^{-1} , whereas Sataun recorded the lowest concentration (0.0011 mg l^{-1}), both of which were within the permissible limits established by the CPCB. The significant differences in Ni concentration across sites suggest varying levels of exposure to natural and anthropogenic sources, such as agricultural runoff, industrial discharge, and soil leaching. The relatively high Ni concentration at Khairi Bridge may be attributed to site-specific activities or environmental conditions that increase the release or accumulation of Ni. The seasonal trends also revealed significant variations, with pre-monsoon months consistently showing elevated Ni concentrations compared with those in the post-monsoon period. According to the pooled data, the mean Ni concentration during the pre-monsoon season was 0.0039 mg l^{-1} , which was significantly greater than the post-monsoon mean of 0.0006 mg l^{-1} (Figure 3). This pattern aligns with findings from previous studies conducted by Başak & Alagha (2010), Ravichandran & Jayaprakash (2011), Giri & Singh (2014), Matta *et al.* (2020), Sahil & Bhardwaj (2021), Dhaliwal *et al.* (2021), Banyal *et al.* (2022), and Kiran & Sivakumar (2023), which reported similar seasonal influences on Ni concentrations. The higher Ni concentrations observed during the pre-monsoon season could result from reduced river flow and enhanced retention of Ni in the environment, leading to greater accumulation in surface water. Conversely, the post-monsoon dilution effect caused by heavy rainfall may reduce Ni concentrations, as supported by Lashari *et al.* (2009). The interaction of site and season was also significant, with the highest Ni concentration (0.0080 mg l^{-1}) recorded at Khairi Bridge during the pre-monsoon season and the lowest (0.0003 mg l^{-1}) observed at Dadahu during the post-monsoon season. These findings highlight the critical role of both spatial and temporal factors in influencing Ni concentrations in surface water, emphasizing the need for targeted monitoring and mitigation strategies to manage water quality effectively.

3.2.3 Arsenic (As)

This study revealed significant spatial and seasonal variations in arsenic (As) concentrations across the Giri River Basin (table 4). Dadahu consistently recorded the highest mean As concentration (0.0036 mg l^{-1}) across seasons and years, which was significantly higher than that at the other sites. In contrast, Ambaun consistently presented the lowest As concentration (0.0020 mg l^{-1}), which was within the acceptable limits prescribed by the CPCB. The elevated As concentration in Dadahu might be due to localized sources of As contamination, possibly natural geological deposits, or anthropogenic activities such as agricultural runoff. The results demonstrated a distinct seasonal pattern, with significantly high concentrations of As during the pre-monsoon season in both years. According to the pooled data, the average As concentrations in surface water for pre-monsoon and post-monsoon seasons were 0.0034 mg l^{-1} and 0.0018 mg l^{-1} , respectively (Figure 3). The results are in conformity with the findings of Giri & Singh (2014), Chowdhury *et al.* (2015), Pal & Maiti (2018), Shil & Singh (2019), Pandit & Bhardwaj (2020), Sahil & Bhardwaj (2021), and Pant *et al.* (2023), who also reported that the pre-monsoon season had the maximum As concentration, whereas the post-monsoon months had the lowest As concentration. The higher As concentration in surface water during the pre-monsoon season may result from high temperatures causing substantial water evaporation, which reduces surface water volume and concentrates dissolved substances, including arsenic. However, in the post-monsoon period, the concentrations of As were lower, which could be ascribed to the deposition of arsenic-bound sediments at the bottom of the water bodies and increased river flow caused by rainfall, which dilutes the contaminants. Owing to this dilution effect, the contamination levels of river systems may decrease momentarily because of natural monsoonal flows. The interaction effect between site and season was also significant, with the highest recorded As concentration (0.0048 mg l^{-1}) observed at Dadahu during the pre-monsoon season and the lowest (0.0014 mg l^{-1}) at Ambaun in the post-monsoon season. These results revealed the combined influence of site-

specific factors and seasonal hydrological dynamics on As concentrations. Overall, the findings emphasize the critical role of both anthropogenic and natural factors in influencing arsenic concentrations in surface water. The seasonal dilution effect observed during the monsoon period temporarily mitigated As contamination, suggesting that the surface water quality in the Giri River Basin is highly dynamic and influenced by both climatic and site-specific variables. Future studies and management interventions should consider these spatial and temporal variations to ensure sustainable water resource management in the region.

3.2.4 Cadmium (Cd)

The present investigation revealed a significant variation in cadmium (Cd) concentration of surface water, which increased steadily from upstream to downstream (table 4). Giripul Bridge, the closest to the river's origin, had the lowest pooled mean Cd concentration of 0.0004 mg l^{-1} . The concentration then increased as the river flowed downstream, with Bangran Giri Bridge having the highest pooled mean concentration of 0.0019 mg l^{-1} , which was within the permissible limits prescribed by the CPCB. Similar to Bangran Giri Bridge, Sataun also exhibited a comparatively high Cd concentration (pooled mean 0.0017 mg l^{-1}). This gradual increase in Cd concentrations in surface water might be due to both natural and anthropogenic sources along its path, including runoff, industrial discharge, mining activities, and urban effluents, which are typically more pronounced in downstream areas. Across all the sites, the pre-monsoon Cd concentrations were higher than the post-monsoon concentrations. The pooled mean concentration of Cd in the pre-monsoon season was 0.0015 mg l^{-1} , while in the post-monsoon season, it was 0.0007 mg l^{-1} (Figure 3). These results are in line with the findings of Başak & Alagha (2010), Ravichandran & Jayaprakash (2011), Pal & Maiti (2018), Mohanta *et al.* (2019), Matta *et al.* (2020), Kabir *et al.* (2020), Pandit & Bhardwaj (2020), Sharma *et al.* (2021), Dhaliwal *et al.* (2021), Sahil & Bhardwaj (2021), Banyal *et al.* (2022), and Priti *et al.* (2024), who also reported that the concentration of Cd increased during the pre-monsoon months and decreased during the post-monsoon months. The elevated pre-monsoon Cd levels can be attributed to evaporation, sediment resuspension, groundwater contributions, and reduced river flow, resulting in lower dilution and higher concentrations of dissolved metals. Conversely, the post-monsoon period benefits from monsoonal rainfall and increased water movement, which may dilute contaminants, enhance oxygenation, and drive natural purification processes, such as Cd adsorption onto sediments and precipitation, further lowering its concentrations in surface water. This dilution effect highlights the natural capacity of river systems to mitigate contamination temporarily through increased flow. The site-season interaction was also significant, with the highest Cd concentration (0.0024 mg l^{-1}) recorded at Bangran Giri Bridge during the pre-monsoon season and the lowest concentration (0.0003 mg l^{-1}) observed at Giripul Bridge during the post-monsoon season. This interaction underscores the compounded effects of geographical and seasonal

factors on Cd dynamics in the river system. Overall, the results indicate that Cd contamination in the Giri River Basin is influenced by both natural processes and human activities, with significant seasonal and spatial variations.

3.2.5 Lead (Pb)

The present study demonstrated significant variations in lead (Pb) concentrations in surface water across different sites and seasons (table 4). The Khairi Bridge had the highest Pb concentration across both years and seasons, with a pooled mean of 0.0135 mg l^{-1} , which was within the CPCB-recommended acceptable limits and significantly higher than those at the other sites. In contrast, Ambaun presented the lowest Pb concentration, with a pooled mean of 0.0016 mg l^{-1} , respectively. The elevated Pb concentration at Khairi Bridge might be due to localized sources of pollution, such as vehicular emissions and runoff from agricultural fields near this site. Furthermore, the Pb concentrations in surface water were significantly higher during the pre-monsoon season than during the post-monsoon season. The pooled seasonal mean Pb concentration was 0.0031 mg l^{-1} in the post-monsoon season and 0.0057 mg l^{-1} in the pre-monsoon season (Figure 3). The present results are in confirmation with the findings of Başak & Alagha (2010), Chauhan *et al.* (2014), Pal & Maiti (2018), Shil & Singh (2019), Kabir *et al.* (2020), Sahil & Bhardwaj (2021), Sharma *et al.* (2021), Dhaliwal *et al.* (2021), Banyal *et al.* (2022), Karunanidhi *et al.* (2022), and Priti *et al.* (2024), who reported maximum Pb concentrations during the pre-monsoon season and minimum concentrations during the post-monsoon months. This seasonal increase in Pb during the pre-monsoon season might be due to higher temperatures, elevated evaporation rates, reduced dilution from lower water flow, and greater surface runoff, which could carry more Pb from nearby anthropogenic activities, leading to increased Pb concentration in the water. In contrast, the lower concentrations observed during the post-monsoon months can be attributed to the monsoon-induced water flow, which effectively removes accumulated Pb and other contaminants from surface water bodies, transporting them downstream or into sedimentary areas. Moreover, the significant interaction between site and season was also evident, with Khairi Bridge having the highest Pb concentration (0.0153 mg l^{-1}) during the pre-monsoon season and Ambaun having the lowest Pb concentration (0.0004 mg l^{-1}) during the post-monsoon season. Overall, while the Pb concentrations varied significantly and remained within safe limits, revealing the importance of continuous monitoring to identify and mitigate potential sources of contamination.

3.3 Water quality index (WQI)

This study demonstrated significant variations in the water quality index (WQI) of surface water across different sites in the Giri River Basin (Table 5). The highest WQI value was recorded at Bangran Giri Bridge (16.45), indicating relatively poorer water quality than at the other sites. This was followed by Khairi Bridge (14.08), Sataun (13.52), Ambaun (12.22), and Dadahu (9.13), with Giripul Bridge showing the lowest WQI

value of 8.22, signifying better water quality. Although all the sites fall within the excellent category, the slight increase in the water quality index (WQI) downstream could be attributed to natural and anthropogenic factors, including wastewater discharge, mining activities, agricultural runoff, and industrial effluents. Furthermore, the seasonal variations in the WQI were also found to be significant, with the pre-monsoon season exhibiting the highest mean WQI value (16.91). This indicates a deterioration in water quality during the pre-monsoon months, which might be due to reduced water flow, increased evaporation, and higher anthropogenic inputs. In contrast, the post-monsoon season presented the lowest WQI value (7.58), suggesting that improved water quality may be attributed to rainfall-induced dilution, natural flushing of contaminants, increased oxygenation, and pollutant sedimentation. Therefore, the significant interaction between sites and seasons underscores the complexity of water quality dynamics in the Giri River Basin, which is influenced by both localized activities and seasonal hydrological changes. These results are in line with the findings of Egun & Ogiesoba-Eguakun (2018), Roşca *et al.* (2020), Dimri *et al.* (2021), Aydin *et al.* (2021), Dutta *et al.* (2022), Dehghan Rahimabadi *et al.* (2024), and Bahrami *et al.* (2024), who also reported WQIs in the excellent and good categories.

4. Conclusion

The assessment of water quality parameters, heavy metal concentrations, and the WQI across various sites in the Giri River Basin provides critical insights into the ecological and environmental status of the region. The surface water temperature, pH, electrical conductivity, total dissolved solids TDS, turbidity, biological oxygen demand BOD, and chemical oxygen demand COD varied across the sites and seasons, indicating influences from both natural processes and anthropogenic activities. The pre-monsoon season recorded the highest values, reflecting seasonal influences on water quality. All parameters remained within the permissible limits prescribed by BIS, indicating satisfactory water quality. Additionally, the concentration of heavy metals (Cr, Ni, As, Cd, and Pb) in surface water showed significant variations between sites and seasons, likely due to both natural and anthropogenic factors such as agricultural runoff, vehicular emissions, and urbanization. The permissible limits suggested by CPCB were not exceeded, signifying that heavy metal contamination in surface water is within safe levels. Moreover, WQI values indicated that the surface water quality remained excellent across all sites, reinforcing the Giri River's relatively pristine condition despite some localized heavy metal contamination. The Giri River Basin exhibits good water quality, with all measured parameters, heavy metal concentrations, and WQI values falling within acceptable limits. However, the observed seasonal variations and bioaccumulation trends emphasize the need for continuous monitoring and management, especially during the pre-monsoon season when contamination risks are higher. This study highlights the importance of sustainable practices to

maintain ecological balance and ensure the long-term health of the river ecosystem.

The way forward

Based on the assessment of water quality parameters and heavy metal concentrations in the Giri River Basin, several recommendations and directions for future research are proposed to enhance water quality management and ensure ecological sustainability.

- Regular monitoring of water quality parameters and heavy metal concentrations across the Giri River Basin should be conducted to identify seasonal variations and emerging trends throughout the year.
 - Community-based awareness programs should be encouraged to educate local populations about sustainable practices, including reducing industrial effluents, adopting eco-friendly agricultural methods, and regulating fertilizer use to minimize heavy metal contamination in water bodies.
 - The adoption of green technologies, such as constructed wetlands and phytoremediation, is essential for the natural attenuation of pollutants.
 - Advanced technologies, such as remote sensing, GIS-based water quality modeling and bio-indicators for pollution assessment, should be integrated to enhance data accuracy and improve decision-making processes.
 - Collaborative efforts among government agencies, non-governmental organizations and local stakeholders are essential for implementing effective water resource management strategies. Strengthening policies for industrial wastewater treatment, solid waste management and land-use planning is necessary to maintain the pristine condition of the Giri River.
- Implementing these recommendations will support effective management of the Giri River Basin, ensuring the sustainability of its water quality and the health of its aquatic ecosystems. This integrated approach will contribute to preserving the ecological integrity of the river while supporting the needs of the communities that depend on its resources.

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Table: 2. Seasonal variations in physico-chemical parameters in surface water at different sites in the Giri River Basin.

Treatment	Temperature (°C)			pH			Electrical conductivity (EC) (dS m ⁻¹)			Total dissolved solids (TDS) (mg l ⁻¹)			Turbidity (NTU)		
	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean
Season															
Post-Monsoon	14.77 ^b	14.63 ^b	14.70 ^b	7.43 ^b	7.41 ^b	7.42 ^b	0.390 ^b	0.389 ^b	0.390 ^b	130.03 ^b	129.45 ^b	129.74 ^b	2.46 ^b	2.50 ^b	2.48 ^b
Pre-Monsoon	28.38 ^a	28.20 ^a	28.29 ^a	7.62 ^a	7.60 ^a	7.61 ^a	0.450 ^a	0.443 ^a	0.447 ^a	174.12 ^a	173.88 ^a	174.00 ^a	6.86 ^a	6.81 ^a	6.83 ^a
LSD_{0.05} (Season)	0.43	0.47	0.41	0.05	0.13	0.07	0.022	0.021	0.021	5.49	2.97	3.75	0.45	0.40	0.42
Sites															
Giripul Bridge	20.44 ^c	20.17 ^c	20.30 ^c	7.17 ^d	7.33 ^b	7.25 ^b	0.276 ^d	0.265 ^e	0.270 ^d	134.21 ^c	127.76 ^c	130.99 ^c	3.35 ^b	3.43 ^d	3.39 ^b
Khairi Bridge	21.08 ^{bc}	20.28 ^c	20.68 ^{bc}	7.27 ^c	7.13 ^b	7.20 ^b	0.306 ^d	0.303 ^d	0.305 ^d	156.45 ^{ab}	154.46 ^{ab}	155.46 ^{ab}	4.95 ^a	4.77 ^{bc}	4.86 ^a
Dadahu	21.25 ^b	21.33 ^b	21.29 ^b	7.62 ^b	7.58 ^a	7.60 ^a	0.408 ^c	0.399 ^c	0.404 ^c	155.76 ^{ab}	159.52 ^a	157.64 ^{ab}	4.04 ^b	4.14 ^c	4.09 ^b
Ambaun	22.23 ^a	22.70 ^a	22.47 ^a	7.68 ^{ab}	7.71 ^a	7.70 ^a	0.490 ^b	0.485 ^b	0.488 ^b	157.27 ^{ab}	156.32 ^{ab}	156.79 ^{ab}	4.86 ^a	4.85 ^b	4.86 ^a
Sataun	22.15 ^a	21.91 ^{ab}	22.03 ^a	7.68 ^{ab}	7.63 ^a	7.65 ^a	0.548 ^a	0.546 ^a	0.547 ^a	159.26 ^a	158.81 ^a	159.04 ^a	5.15 ^a	5.18 ^{ab}	5.16 ^a
Bangran Giri Bridge	22.30 ^a	22.11 ^{ab}	22.21 ^a	7.72 ^a	7.66 ^a	7.69 ^a	0.495 ^b	0.499 ^b	0.497 ^b	149.50 ^b	153.12 ^b	151.31 ^b	5.59 ^a	5.56 ^a	5.57 ^a
LSD_{0.05} (Site)	0.74	0.81	0.71	0.08	0.23	0.12	0.039	0.036	0.037	9.50	5.15	6.50	0.78	0.69	0.72
LSD_{0.05} (Site×Season)	1.05	1.15	1.00	0.11	0.33	0.17	0.055	0.051	0.052	13.44	7.28	9.20	1.10	0.98	1.02

Seasonal Dynamics Of Physico-Chemical Parameters, Heavy Metals, And Water Quality Index In The Giri River Basin

Table: 3. Seasonal variations in physico-chemical parameters in surface water at different sites in the Giri River Basin.

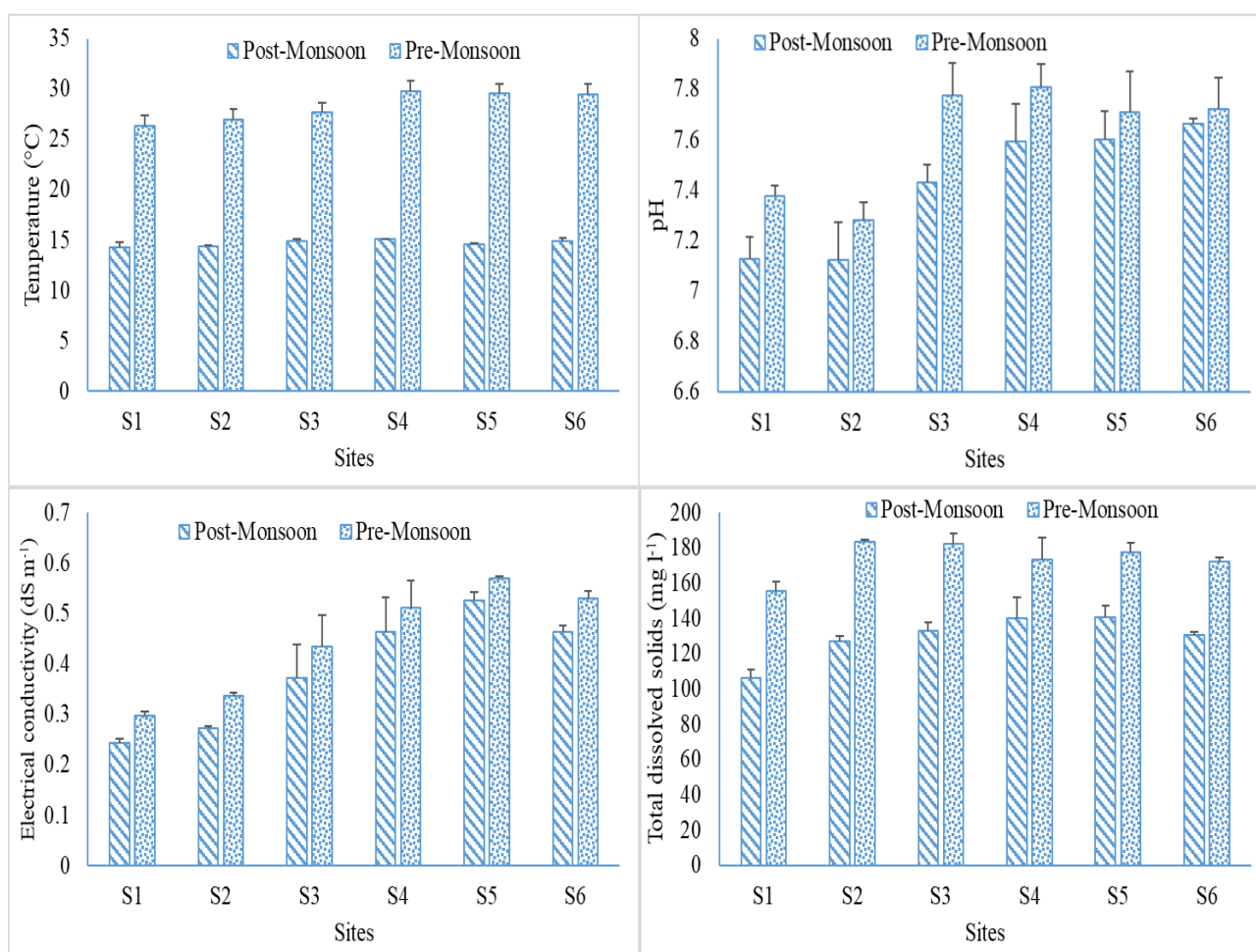
Treatment	Biochemical oxygen demand (BOD) (mg l ⁻¹)			Chemical oxygen demand (COD) (mg l ⁻¹)		
	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean
Season						
Post-Monsoon	2.38 ^b	2.39 ^b	2.38 ^b	121.66 ^b	123.76 ^b	122.71 ^b
Pre-Monsoon	4.13 ^a	4.06 ^a	4.09 ^a	157.37 ^a	156.68 ^a	157.03 ^a
LSD_{0.05} (Season)	0.30	0.23	0.26	8.97	6.26	7.17
Sites						
Giripul Bridge	2.45 ^b	2.32 ^c	2.38 ^c	97.80 ^c	92.98 ^d	95.39 ^d
Khairi Bridge	3.38 ^a	3.40 ^{ab}	3.39 ^{ab}	136.14 ^b	143.33 ^{bc}	139.74 ^{bc}
Dadahu	3.21 ^a	3.19 ^b	3.20 ^b	134.07 ^b	136.79 ^c	135.43 ^c
Ambaun	3.35 ^a	3.37 ^{ab}	3.36 ^{ab}	149.09 ^b	153.57 ^b	151.33 ^b
Sataun	3.40 ^a	3.42 ^{ab}	3.41 ^{ab}	147.63 ^b	147.82 ^b	147.73 ^{bc}
Bangran Giri Bridge	3.72 ^a	3.66 ^a	3.69 ^a	172.37 ^a	166.82 ^a	169.59 ^a
LSD_{0.05} (Site)	0.52	0.40	0.45	15.54	10.84	12.42
LSD_{0.05} (Site×Season)	0.73	0.56	0.64	21.98	15.33	17.57

Table: 4. Seasonal variations in heavy metals in surface water at different sites in the Giri River Basin.

Treatment	Chromium (Cr) (mg l ⁻¹)			Nickel (Ni) (mg l ⁻¹)			Arsenic (As) (mg l ⁻¹)			Cadmium (Cd) (mg l ⁻¹)			Lead (Pb) (mg l ⁻¹)		
	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean	2022-2023	2023-2024	Mean
Season															
Post-Monsoon	0.0117 ^b	0.0117 ^b	0.0117 ^b	0.0005 ^b	0.0006 ^b	0.0006 ^b	0.0017 ^b	0.0019 ^b	0.0018 ^b	0.0007 ^b	0.0007 ^b	0.0007 ^b	0.0031 ^a	0.0030 ^a	0.0031 ^a
Pre-Monsoon	0.0156 ^a	0.0156 ^a	0.0156 ^a	0.0039 ^a	0.0038 ^a	0.0039 ^a	0.0034 ^a	0.0034 ^a	0.0034 ^a	0.0015 ^a	0.0015 ^a	0.0015 ^a	0.0057 ^a	0.0057 ^a	0.0057 ^a
LSD_{0.05} (Season)	0.0005	0.0004	0.0003	0.0019	0.0017	0.0018	0.0005	0.0005	0.0004	0.0002	0.0001	0.0001	0.0035	0.0033	0.0034
Sites															
Giripul Bridge	0.0135	0.0130 ^c	0.0133 ^c	0.0021 ^{ab}	0.0019 ^{ab}	0.0019 ^{ab}	0.0027 ^b	0.0027 ^{ab}	0.0027 ^b	0.0004 ^d	0.0003 ^e	0.0004 ^e	0.0042 ^b	0.0039 ^b	0.0040 ^b
Khairi Bridge	0.0137	0.0144 ^a	0.0140 ^{ab}	0.0044 ^a	0.0044 ^a	0.0044 ^a	0.0025 ^b	0.0026 ^{ab}	0.0026 ^b	0.0005 ^{cd}	0.0006 ^d	0.0006 ^{de}	0.0135 ^a	0.0134 ^a	0.0135 ^a
Dadahu	0.0134	0.0137 ^b	0.0136 ^{bc}	0.0014 ^{ab}	0.0014 ^{ab}	0.0014 ^{ab}	0.0038 ^a	0.0034 ^a	0.0036 ^a	0.0008 ^c	0.0006 ^d	0.0007 ^d	0.0022 ^b	0.0023 ^b	0.0023 ^b
Ambaun	0.0133	0.0126 ^c	0.0130 ^c	0.0014 ^{ab}	0.0016 ^{ab}	0.0016 ^{ab}	0.0020 ^b	0.0021 ^b	0.0020 ^b	0.0014 ^b	0.0014 ^c	0.0014 ^c	0.0015 ^b	0.0017 ^b	0.0016 ^b
Sataun	0.0140	0.0143 ^a	0.0142 ^a	0.0010 ^b	0.0011 ^b	0.0011 ^b	0.0022 ^b	0.0025 ^b	0.0024 ^b	0.0016 ^{ab}	0.0017 ^b	0.0017 ^b	0.0023 ^b	0.0024 ^b	0.0023 ^b
Bangran Giri Bridge	0.0140	0.0140 ^{ab}	0.0140 ^{ab}	0.0029 ^{ab}	0.0027 ^{ab}	0.0028 ^{ab}	0.0022 ^b	0.0024 ^b	0.0023 ^b	0.0019 ^a	0.0020 ^a	0.0019 ^a	0.0025 ^b	0.0027 ^b	0.0026 ^b
LSD_{0.05} (Site)	NS	0.0006	0.0006	0.0033	0.0030	0.0031	0.0008	0.0008	0.0008	0.0003	0.0002	0.0002	0.0060	0.0058	0.0059
LSD_{0.05} (Site×Season)	0.0012	0.0009	0.0009	0.0047	0.0042	0.0044	0.0012	0.0011	0.0011	0.0004	0.0003	0.0003	0.0086	0.0082	0.0084

Table: 4. Seasonal variations in **water quality index (WQI)** in surface water at different sites in the Giri River Basin.

Sites and Seasons	Surface WQI	Classification
Sites		
Giripul Bridge	8.22	Excellent
Khairi Bridge	14.08	Excellent
Dadahu	9.13	Excellent
Ambaun	12.22	Excellent
Sataun	13.52	Excellent
Bangran Giri Bridge	16.45	Excellent
Seasons		
Pre-Monsoon	16.91	Excellent
Post-Monsoon	7.58	Excellent

**Figure 1.** Seasonal variations in physico-chemical parameters in surface water at different sites in the Giri River Basin during two distinct seasons.

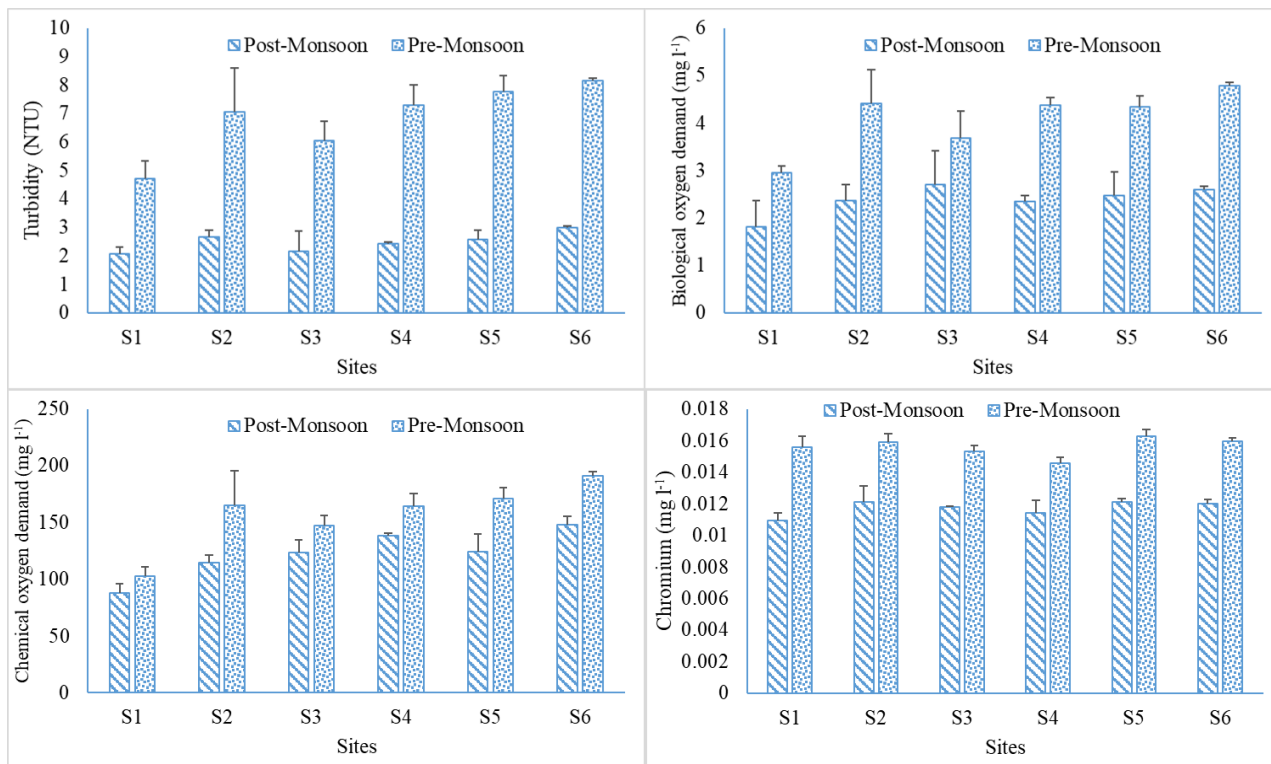


Figure 2. Seasonal variations in turbidity, biological oxygen demand, chemical oxygen demand and chromium content in surface water at different sites in the Giri River Basin during two distinct seasons.

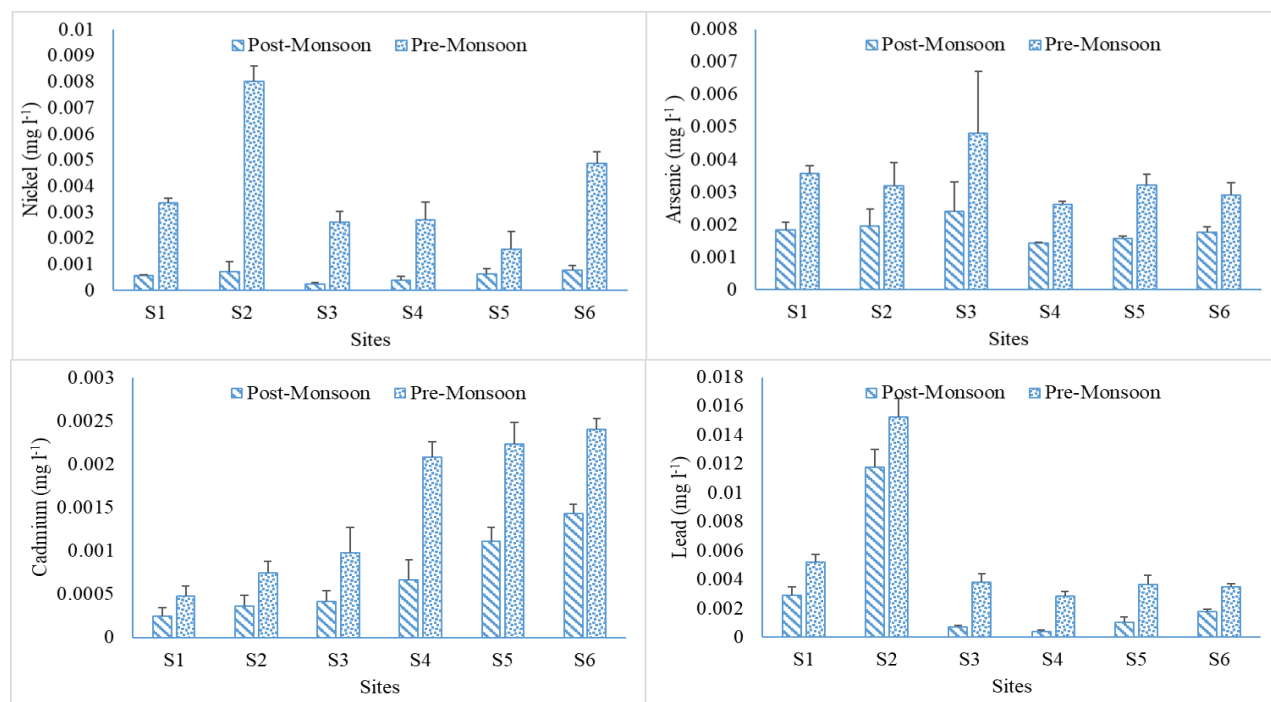


Figure 3. Seasonal variations in nickel, arsenic, cadmium and lead content in surface water at different sites in the Giri River Basin during two distinct seasons.