



Hydrochemical Variations and Toxicological Risks of Arsenic and Chromium in the Ganga River Ecosystem: A Seasonal Assessment At Brijghat

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Abstract

This study evaluates the seasonal dynamics of the physicochemical properties and heavy metal contamination (Arsenic and Chromium) of the Ganga River water at Brijghat, Uttar Pradesh, India, over a two-year period (2018-2020). Water samples were systematically monitored across three distinct seasons: summer, monsoon, and winter. High-precision analytical techniques, including Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and HACH digital instrumentation, were utilized for quantification. Significant temporal variations were seen in all hydrochemical indices according to the empirical results. The pH of the river water was somewhat alkaline, increasing in the summer (8.20–8.51) and falling in the monsoon (7.07–7.13). Water temperature and dissolved oxygen (DO) showed a strong inverse relationship, with DO peaking in winter (9.65–10.05 mg/L) and falling to critical lows in summer (4.90–5.65 mg/L), which coincided with higher levels of chemical and biochemical oxygen demand (BOD: 6.50–6.85 mg/L and COD: 11.75–12.05 mg/L). The monsoon season saw high values for turbidity (5.34–5.69 NTU), total dissolved solids (TDS: 658.30–679.80 mg/L), total hardness, chloride, and phosphate due to severe soil erosion, geogenic leaching, and agricultural runoff. According to toxicological analysis, arsenic levels reached a maximum of 10.388 ppb during the monsoon, above the stringent WHO safety standard of 10 ppb for drinkable water. The total chromium levels varied from 8.820 ppb to 10.328 ppb, demonstrating a dual exposure mechanism caused by low-dilution winter circumstances and monsoonal runoff. In the end, these results demonstrate severe geogenic and anthropogenic stress on the river ecology, offering an essential scientific foundation to support sustainable water resource management in the area and improve future remediation measures.

Keywords: Ganga River, Physicochemical characteristic, Heavy metals, Arsenic, Chromium, Seasonal variation, Brijghat.

1. Introduction

Water pollution is a worldwide problem in the recent era. It damages our oceans, kills beautiful marine life, and makes drinking water unsafe for human beings. The Ganga's unique biodiversity and long-term ecological sustainability are under risk due to the extreme pollution pressures it is currently experiencing. Its water quality has been deteriorated by rapid industrialization, poorly planned construction projects, and population growth. Heavy metal contamination is one of the many contaminants that presents a serious toxicological risk. The river system has been found to contain hazardous materials such as arsenic, chromium, iron, aluminum, tin, lead, nitrate, mercury, and cadmium, which frequently come from old mine workings and industrial discharges. When hazardous materials and untreated effluents are released into aquatic bodies directly or indirectly without sufficient cleanup, water pollution results (Goel, 2006). While lotic waters naturally dilute and decompose contaminants more effectively than lentic systems, global river ecosystems remain critically degraded (Chapman, 1996). This vulnerability stems from the intense concentration of industrial, agricultural, and domestic activities along riverbanks (Trivedi, 2010). From the standpoint of environmental health, arsenic and chromium are by far the most dangerous heavy metals (ATSDR, 2013). The Earth's crust, atmosphere, and aquatic systems are all home to arsenic, a naturally occurring metalloid that is extremely poisonous in its inorganic forms. Although its baseline presence is established by geogenic processes, environmental arsenic levels have increased dramatically in recent decades due to modern anthropogenic activities, such as the extensive use of pesticides, defoliants, wood preservatives, and electronic components, as well as emissions from thermal power plants and the metallurgical industry (Vanitha et al., 2017). As a result, the World Health Organization (WHO) established a strict regulatory threshold of 0.01 mg/L for arsenic in drinking water after the Agency for Toxic Substances and Disease Registry classified arsenic as one of the most dangerous chemical threats in the environment (ATSDR, 2002 and Fatoki & Badmus, 2022). The two main oxidation states of chromium (Cr), a significant transition metal contaminant, are trivalent (Cr^{III}) and hexavalent (Cr^{VI}). Cr^{VI} is extremely permeable to biological membranes and has serious cytotoxic, mutagenic, and carcinogenic qualities, whereas Cr^{III} is a crucial micronutrient for preserving glucose tolerance in animals (ATSDR, 2013). Cr^{VI} is actively released into aquatic systems by anthropogenic discharges from the textile, tannery, and electroplating industries. There, it builds up significantly in sediments and interstitial waters, endangering populations of benthic and pelagic fish. The United States Environmental Protection Agency (USEPA, 2023) sets a maximum allowable drinking water limit

(WHO, 2020) reports that baseline Cr^{VI} levels range from 0.01 to 0.05 mg/L in drinking water and 0.3 to 0.6 $\mu\text{g/L}$ in surface waters. Cr^{VI} and total chromium in industrial effluent are limited to 200 $\mu\text{g/L}$ and 2 mg/L, respectively, by national organizations such as the Central Pollution Control Board (CPCB) and the Bureau of Indian Standards (BIS) (CPCB, 2021).

The ongoing inflow of municipal sewage, agricultural runoff, and heavy metal toxicities has significantly changed the basic hydrochemical features of this river ecosystem despite different regulatory frameworks. Even though the river's macroeconomic and general biological degradation is well documented in the literature now under publication, systematic and localized assessments of its immediate water quality are still crucial. Thus, the goal of this study is to thoroughly assess the physicochemical characteristics of the water in the Ganga River at a number of chosen monitoring sites. This study aims to measure the current level of environmental degradation by examining important indicators like pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), electrical conductivity (EC), and total dissolved solids (TDS), in addition to dominant heavy metal concentrations. In the end, these results are meant to offer a solid, empirical foundation for future remediation tactics, ecological risk mitigation, and sustainable water resource management in the area.

Table 1: Prescribed limits of heavy metal concentration in river water ($\mu\text{g/L}$).

S.No.	Standards	Cr (mg/L)	As (mg/L)
1.	BIS	0.05	0.01
2.	ICMR	0.05	0.05
3.	WHO	0.05	0.05
4.	USEPA	0.1	0.05
5.	CPCB	No relaxation	No relaxation

*BIS: Bureau of India Standards, ICMR: Indian Council of Medical Research, WHO: World Health Organization, USEPA: United States Environmental Protection Agency, CPCB: Central Pollution Control Board.

2. Materials And Methods

2.1 Study Area and Sampling Schedule

The present investigation was conducted at Brijghat, a prominent site located along the Ganga River basin in Uttar Pradesh, India (28.7556° N, 78.1408° E). The sampling station is situated approximately 5 km from Garhmukteshwar and 35 km from the Hapur district headquarters. To capture temporal variations in water quality, systematic monitoring was carried out across three distinct seasons: Summer (March to June), Monsoon (July to September), and Winter (November to February) for a period of two consecutive years spanning from March 2018 to February 2020. Samples were collected from a depth of 0.5 m below the surface of the river Ganga using a pre-cleaned plastic sampler. The collected water was immediately transferred into pristine plastic storage bottles, tightly sealed, labeled, and transported in insulated ice chests maintaining a temperature of approximately 4°C to the Hydrology Department laboratory at the Indian Institute of Technology Roorkee (IITR). At the laboratory, samples required for subsequent heavy metal extraction were transferred into deep-freezer storage maintained at -20°C until analysis. Triplicate samples were systematically collected from the field site during each run, and the calculated arithmetic mean for each parameters was compiled for final reporting.



Figure.1: Ganga River map with sample Collection site.

2.2 Pre-treatment and Quality Control of Glassware

Data collection was conducted under strict quality assurance procedures. All analytical glassware, sampling containers, and storage vessels underwent thorough decontamination prior to field deployment. To remove trace metal residues, this required pre-cleaning with phosphate-free laboratory detergent and then continuously soaking in 10% (v/v) analytical-grade nitric acid (HNO_3) for a whole day. Before being used in the field, each item was cleaned twice with deionized water ($18.2 \text{ M}\Omega\cdot\text{cm}$ resistivity) and allowed to air dry in a dust-free, laminar flow environment.

2.3 Instrumentation and Analytical Framework

High-precision equipment was used to evaluate the river water's physicochemical characteristics and heavy metal trace profile. Below is a summary of the particular analytical layout and related target variables: Inductively Coupled Plasma Mass Spectrometry (ICP-MS): Employed for the ultra-trace quantification of critical heavy metals, specifically total arsenic (As) and total chromium. Ultraviolet-Visible (UV-Vis) Spectrophotometer: Utilized for spectrophotometric evaluation and recording absorbance peaks (OD) of specific chemical variants.

HACH Digital Multimeter: Deployed for the direct electrochemical determination of key baseline variables including pH, electrical conductivity (EC), and total dissolved solids (TDS). HACH Colorimeter: Used for colorimetric assays to evaluate specific nutrient matrices and ion concentrations. HACH Turbidity Meter: Utilized to quantify the nephelometric turbidity units (NTU) of the river system. All laboratory instruments were calibrated daily using certified reference materials and multi-element standard solutions. Operation, signal optimization, and peak integration were executed strictly in accordance with the standard operating procedures and technical guidelines prescribed by the respective manufacturers.

3. Results And Discussion

Table 2: Descriptive Statistical analysis of Water Quality (2018-2020).

Water Quality Parameter	Mean (Average)	Standard Deviation (\pm SD)	Minimum	Maximum
Ph	7.71	0.60	7.00	8.85
EC (μ S/cm)	248.97	105.56	129.50	454.10
Turbidity (NTU)	4.30	1.19	2.63	6.37
DO (mg/L)	8.00	1.78	5.40	10.70
Temperature ($^{\circ}$ C)	24.85	5.80	17.00	34.50
TDS (mg/L)	507.80	138.16	335.80	684.40
Hardness (mg/L)	77.33	11.08	64.00	98.50
COD (mg/L)	9.69	2.53	5.80	13.40
BOD (mg/L)	4.94	1.51	3.20	7.90
Chloride (mg/L)	26.51	7.06	18.15	38.25
Nitrate (mg/L)	0.77	0.36	0.30	1.37
Phosphate (mg/L)	0.38	0.47	0.00	1.38
Arsenic (As) (ppb)	8.37	1.71	5.69	10.56
Chromium (Cr) (ppb)	9.54	0.98	8.22	11.65

Table 3: One-Way ANOVA table for Seasonal Variations

Parameter	F-Statistic	p-value	Significance Level	Interpretation
Chloride	43.043	< 0.001	(p < 0.01)	Highly Significant
TDS	40.325	< 0.001	(p < 0.01)	Highly Significant
Hardness	29.249	< 0.001	(p < 0.01)	Highly Significant
DO	23.652	< 0.001	(p < 0.01)	Highly Significant
BOD	18.365	0.001	(p < 0.01)	Highly Significant
EC	17.906	0.001	(p < 0.01)	Highly Significant
pH	17.182	0.001	(p < 0.01)	Highly Significant
Arsenic (As)	13.629	0.002	(p < 0.01)	Highly Significant
Turbidity	7.192	0.014	(p < 0.05)	Significant
COD	6.657	0.017	(p < 0.05)	Significant
Phosphate	5.802	0.024	(p < 0.05)	Significant

Temperature	5.869	0.023	(p < 0.05)	Significant
Chromium (Cr)	0.007	0.993	(p > 0.05)	Non-Significant

Note: Environmental data are **p-value < 0.05**, then these are seasonal variation statistically significant. If **p-value < 0.01** then the variation highly significant.

Table 4: Pearson Correlation Matrix with Heavy Metals (As & Cr).

Water Quality Parameter	Arsenic (As) Correlation (r)	Chromium (Cr) Correlation (r)	Toxicological/Hydrochemical Meaning
pH	-0.887	-0.182	High alkaline conditions reduce dissolve Arsenic concentration.
EC	-0.756	0.210	Inverse relationship between ionic concentration and free As.
Turbidity	0.432	-0.062	Moderate positive correlation with As due to sediment binding.
DO	-0.267	-0.123	Weak negative correlation with both heavy metals.
Temperature	-0.280	-0.147	Thermal variations show weak direct kinetic impact on metal dissolution.
TDS	0.305	-0.058	Dissolved solids marginally facilitate heavy metal transport.
Hardness	0.702	-0.120	Strong positive correlation with Arsenic. Hard water dynamics support Arsenic release.
COD	-0.747	-0.431	Strong negative correlation; organic loading alters redox potential.
BOD	-0.719	-0.045	Biological oxygen demand shows strong negative coupling with free As.
Chloride	0.538	0.090	Positive correlation; indicative of industrial/domestic co-discharge.
Nitrate	-0.711	-0.485	Strong negative association indicating competing ionic pathways.
Phosphate	0.294	-0.249	Weak positive link with As due to competitive adsorption on sediments.
Arsenic (As)	1.000	0.046	No direct statistical cross-correlation between As and Cr.

Note: r-values represents the relationship of heavy metals to other parameters.

The baseline hydrochemical monitoring of the Ganga River ecosystem at Brijghat over the two-year study period (2018–2020) reveals profound temporal variations driven by distinct seasonal cycles, precipitation patterns, and varying intensities of anthropogenic interventions. In all sampling regimes, the hydrogen ion concentration (pH) varied between 7.00 and 8.85 (mean: 7.71 ± 0.60), retaining a slightly alkaline character that is indicative of carbonate weathering within the upstream Himalayan lithology (Singh & Singh, 2007). The Electrical Conductivity (EC), on the other hand, displayed enormous non-steady-state oscillations between 129.50 and 454.10 (248.97 ± 105.56) $\mu\text{S}/\text{cm}$, indicating concentrated solute loads during low-flow times and significant dilution pulses during peak discharge (Rai & Sharma, 2015). Water temperature exhibited a standard seasonal continuum $24.85 \pm 5.80^\circ\text{C}$, dipping to 17.00°C in winter and climbing to 34.50°C in summer, directly impacting chemical reaction kinetics and gas solubility phases within the aquatic matrix (Wetzel, 2001). Total Dissolved Solids (TDS) tracked closely with EC, yielding an elevated mean of 507.80 ± 138.16 mg/L, with maximum levels reaching 684.40 mg/L, systematically breaching the acceptable drinking water threshold of 500 mg/L established by the Bureau of Indian Standards (BIS, 2012) and World Health Organization (WHO, 2017). At the same time, turbidity varied from 2.63 to 6.37 NTU (4.30 ± 1.19) NTU due to topsoil runoff and monsoonal catchment erosion (Chakrapani, 2005).

A highly dynamic equilibrium is represented by the dissolved oxygen (DO) budget, which ranges from 5.40 to 10.70 mg/L (8.00 ± 1.78 mg/L). Localized dips indicate hypoxia caused by rapid microbial breakdown of organic inputs under high temperature settings (Bhatnagar & Devi, 2013). BOD and COD which averaged (4.94 ± 1.51) mg/L and (9.69 ± 2.53) mg/L, respectively, represent this organic pressure. BOD levels greatly exceeded the crucial Class-3 criterion (>3 mg/L) for outdoor bathing during the dry summer months, underscoring the enormous influx of untreated home sewage and ceremonial activities at the Brijghat ghats (CPCB, 2018). With a mean total hardness of (77.33 ± 11.08) mg/L, the stretch was categorized as moderately soft to slightly hard (Boyd, 2015). As a stand-in for urban wastewater inputs, chloride levels ranged from 18.15 to 38.25 mg/L (26.51 ± 7.06) mg/L (Tare et al., 2013). Nitrate (0.77 ± 0.36) mg/L and phosphate (0.38 ± 0.47) mg/L had uneven distributions

according to nutrient profile; the latter peaked at a concerning 1.38 mg/L because of agricultural runoff and the extensive use of synthetic phosphate-based detergents in local laundry (Jarvie et al., 2006).

From a toxicological risk standpoint, arsenic (As) concentrations showed a mean distribution of (8.37 ± 1.71) ppb, with maximum levels reaching 10.56 ppb and thus exceeding the drinking water safety ceiling of 10 ppb (WHO 2017). On the other hand, chromium (Cr) fluctuated between 8.22 and 11.65 ppb (9.54 ± 0.98) ppb, staying considerably below the allowable limit of 50 ppb but presenting long-term bioaccumulation hazards (Malik & Maurya, 2014). A One-Way Analysis of Variance (ANOVA) was used to thoroughly assess whether seasonal shifts govern this hydrochemical signature. Twelve of the thirteen parameters under observation showed seasonal fluctuations that were statistically to very significant ($p < 0.05$). The most extreme levels of seasonal differentiation were shown by the parameters Chloride ($F = 43.043$, $p < 0.001$), TDS ($F = 40.325$, $p < 0.001$), and Hardness ($F = 29.249$, $p < 0.001$), which peaked during the summer and monsoon phases because of heavy catchment erosion and high evaporation, respectively. Seasonal weather changes also affected DO ($F = 23.652$, $p < 0.001$), BOD ($F = 18.365$, $p = 0.001$), EC ($F = 17.906$, $p = 0.001$), and pH ($F = 17.182$, $p = 0.001$), with lower winter temperatures maximizing DO solubility. Arsenic showed a highly significant seasonal pattern ($F = 13.629$, $p = 0.002$), peaking in late monsoon and winter, suggesting a combination of geogenic reductive dissolution in low-oxygen winter sediments and monsoon agricultural runoff (Smedley & Kinniburgh, 2002). Chromium, on the other hand, showed a completely flat seasonal profile ($F = 0.007$, $p = 0.993$), demonstrating that its concentration is totally unaffected by dilution effects or natural weather cycles and suggesting a continuous, point-source industrial discharge that is active in the upper catchment all year round (Khare & Singh, 2019).

The river ecosystem's geochemical co-associations and heavy metal movement mechanisms were better understood thanks to Pearson correlation coefficients (r -values). The surrounding water chemistry had a strong negative correlation ($r = -0.887$) with arsenic dynamics, indicating that the desorptive release of sediment-bound arsenic into the free-flowing water column is actively triggered as pH falls toward neutral conditions (Dixit & Hering, 2003). A common mineral channel where calcium and magnesium complexes facilitate arsenic transport through co-solubility processes is suggested by the significant correlation between arsenic and hardness ($r = 0.702$) (Garellick et al., 2008). Arsenic, on the other hand, showed negative correlations with COD ($r = -0.747$) and BOD ($r = -0.719$), indicating that highly organic, oxygen-depleted environments change the local redox potential, causing Arsenic to precipitate as sulfide or organic complexes instead of staying dissolved in surface water (McArthur et al., 2001). Chloride showed positive correlation with Arsenic ($r = 0.538$), suggesting a common route via municipal sewage inputs (Tare et al., 2013). Surprisingly, chromium maintained a weak or non-significant association with nearly all parameters, such as arsenic ($r = 0.046$), pH ($r = -0.182$), TDS ($r = -0.058$), and hardness ($r = -0.120$). This total detachment from the overall chemistry of the river demonstrates that chromium acts as an isolated contaminant that is only maintained by consistent industrial point-sources rather than by seasonal agricultural flushes or natural geochemical interactions (Shanker et al., 2005).

In conclusion, this two-year seasonal assessment of the Ganga River ecosystem at Brijghat highlights a system under clear eco-toxicological stress. Due to monsoonal runoff and summer concentration effects, the hydrochemical profile frequently exceeds safe environmental limits for TDS, BOD, and nutrients. Crucially, at a peak of 10.56 ppb, arsenic contents exceeded the regulation WHO safety limit of 10 ppb. Chromium levels remained stubbornly flat and non-seasonal ($p = 0.993$), while sophisticated statistical testing demonstrated that arsenic levels are strongly seasonal and driven by fluctuating pH, hardness, and organic loading. This suggests that chromium pollution is maintained by continuous, unchecked industrial wastewater discharge into the upper watershed, but arsenic mobility is determined by intricate hydrochemical transitions and agricultural pathways. These results highlight the critical need for targeted river cleanup programs and stringent point-source effluent monitoring to protect this delicate aquatic habitat and the consumer population that depends on it.

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