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Assessment of Heavy Metal Concentration and Water Quality Status in Selected Sites of the Ganga River Basin Using ICP–OES Analysis

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Abstract

Heavy metal contamination in riverine ecosystems has emerged as a major environmental concern due to its persistence, toxicity, bioaccumulative nature, and potential risks to ecological and human health systems. The Ganga River Basin, one of India's most significant freshwater systems, is increasingly exposed to contamination from industrial discharge, agricultural runoff, municipal wastewater, and urban expansion. The present study aimed to assess heavy metal concentrations in selected locations of the Ganga River Basin and evaluate their compliance with national and international water quality standards. Water samples collected from five monitoring locations—Devprayag, Rishikesh, Haridwar, Kanpur, and Garhganga—were analyzed using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP–OES), a highly sensitive analytical technique for multi-element quantification. Heavy metals including Iron (Fe), Zinc (Zn), Chromium (Cr), Copper (Cu), Lead (Pb), Cadmium (Cd), and Uranium (U) were investigated. The results revealed considerable spatial variation in heavy metal concentrations across sampling sites. Kanpur exhibited the highest contamination levels and exceeded permissible BIS IS:10500:2012 and WHO drinking water standards for Iron, Chromium, Lead, and Cadmium, indicating severe industrial pollution influence. Haridwar showed elevated concentrations of Iron and Lead, while Garhganga demonstrated complete compliance with all measured parameters, representing a relatively uncontaminated reference location. Correlation analysis indicated strong positive associations among Uranium, Lead, Cadmium, and Iron concentrations, suggesting common anthropogenic pollution sources and shared transport mechanisms.

Keywords: Heavy Metals, Ganga River Basin, ICP–OES, Water Quality Assessment, Industrial Pollution, Environmental Monitoring, Heavy Metal Contamination.

Introduction

Heavy metal pollution of aquatics has become one of the most important environmental issues around the world as the result of the long-term ecological impact, long environmental persistence and potential health risks. Heavy metals like lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), copper (Cu), zinc (Zn) and iron (Fe) are naturally occurring elements, but their levels in riverine environment have been significantly elevated due to the rapid industrialization, urbanization, intensive farming and anthropogenic activities. Heavy metals, unlike many organic pollutants, are not biodegradable and can bioaccumulate in sediments, water and, as a result of the bioaccumulation process, biological organisms throughout the food chain. Therefore, it is essential that heavy metals are monitored, especially in major river basins, as part of environmental assessment and sustainable water resource management. Ganga River Basin is one of the most ecologically, culturally and economically important river systems in India. The river is the source of water for drinking, irrigation, fisheries, transportation, domestic and industrial uses, supporting several million people as it flows from the Himalayan glaciers through multiple states into the Bay of Bengal. This basin is comprised of very large agricultural areas and high-density residential settlements, making it extremely susceptible to contamination from municipal sewage systems, industrial discharges, agricultural runoff, mining operations and poor waste management. The increased environmental stress caused by unplanned development along the river corridor and rapid population growth, has led to a degradation of water quality and the characteristics of the sediments. The presence of heavy metal pollution within the Ganga River Basin has grown in scientific concern as low levels of these pollutants have been found to have toxic, carcinogenic, mutagenic and teratogenic effects. Industrial complexes close to the river basin, such as tannery industries, textile industries, electroplating industries, fertilizer factories, chemical industries, paper industries and thermal power stations, discharge substantial amounts of metal laden effluents in the environment around them. Furthermore, surface waters and groundwaters can be contaminated with trace metals from agricultural applications of chemical fertilizers and pesticides via runoff and leaching. Pollution from urban wastewater discharge also contributes significantly to the contamination, as untreated wastes or partially processed wastes are carried into the river channels.

Literature Review

The spatial and temporal distribution of heavy metals in the sediments and suspended particulate matter of the Ganga River Basin were studied by Kushwaha et al. (2024). Twenty-five sampling points were analysed and found that the level of Copper (Cu) and Zinc (Zn) were significant near the Prayagraj, Fulhar and Bansberia region. The results showed that the metal contamination patterns are greatly influenced by industrial discharge, agricultural runoff, and tributary flow. Selected stretches of the rivers were identified as having potential ecological risks using the risk assessment indices and this further reinforces the need for continued environmental monitoring for river basin management purposes.

The objective of the study of Kumar and Anshumali (2025) was to study heavy metal contamination and health concerns in both upland and riparian soils of the Ganga River Basin. Their research compared several metals, such as cadmium (Cd), arsenic (As), chromium (Cr), and lead (Pb) in cultivated and uncultivated landscapes. Results showed that riparian soils were more contaminated, and that cadmium was the greatest ecological risk contributor. Ingestion routes were identified as more critical routes for children to be exposed to cancer causing and non-cancer causing health risks. The study focused on sustainable management of land use and regulation of agriculture to reduce exposure to heavy metals.

Dhiman et al. (2022) analyzed the distribution of the various heavy metals in water, suspended particulate matter and bed sediments across the Ganga River Basin. Several areas had concentrations of iron (Fe), manganese (Mn), lead (Pb), nickel (Ni), cadmium (Cd), chromium (Cr), and zinc (Zn) that were higher than the thresholds. Industrial discharge, sewerage and farm effluent became significant sources of contamination. The study pointed to the possibility of bioaccumulation and ecological risks due to chronic exposure with metals in aquatic environments.

Radhakrishnan et al. (2023) addressed the mobility, source identification and profiles of heavy metal contamination in Ganga River sediments. Sediment quality was found to be a long-term indicator of river pollution as sediment acts both as a sink and also as a secondary source of heavy metals, the researchers observed. They showed that pollutants from industrial emissions, domestic sewage, and farming can be concentrated in sediment and potentially released when the environment changes. The research highlighted the importance of sediment analysis as part of river pollution assessment procedures.

Dubey et al. (2021) studied the level of heavy metal (HM) contamination in the water and sediment of the Ganga River and its influence on the environment and human health. The study revealed high levels of heavy metal contamination of river sediments and their potential ecological impacts on aquatic organisms. All anthropogenic activities were linked to high levels of toxic metals, and also discharge patterns of the city. The study highlighted the need of periodic monitoring strategies for effective river quality management and pollution mitigation planning.

Patel et al. (2020) reviewed the toxicity effects of heavy metals and environmental contamination in the ecosystem of the Ganga River. They reviewed the occurrence of toxic elements in river ecosystems and the health effects such as neurological disorders, carcinogenic effects, and ecological damage. The review also explored mitigation strategies, such as bioremediation, pollution control measures, and wastewater treatment measures. The scientists said that it is essential to reinforce environmental policies to minimize heavy metal pollution in large river systems.

The researchers of Indian Institute of Technology Kanpur (2020) studied the dissolved trace metals concentration and toxic heavy metal concentration of the Ganga River system. The results did not show any significant heavy metal contamination throughout the river as is commonly thought, but instead dissolved inorganic constituents of some sections stayed similar to the world water composition standards. But there were contamination hot-spots identified around the urban and industrial areas. The study indicated that the intensity of pollution is not uniform and therefore site specific assessment methods are recommended.

Kushwaha et al. (2024) showed how the mobility and availability of heavy metals in sediments from the Ganga Basin are influenced by physicochemical parameters including pH, sediment texture and organic carbon content. Pollution clusters were determined by statistical analysis such as hierarchical cluster analysis and were related to anthropogenic influences. This study affirmed the importance of the integrated approach to sediment quality assessment to better understand contamination pathways and ecological vulnerability.

Recent basin scale investigations (2023–2025) have been growing more attention on the integrated ecological risk assessment approaches with the consideration of contamination factors, enrichment indices, geo-accumulation indices and health risk modeling to assess the pollution of heavy metals in river basins. Altogether, these studies indicate that these factors (rapid industrialization, discharge of urban effluents and agricultural intensification) are still leading to the deposition of heavy metals in the vicinity of the Ganga River Basin and long-term monitoring and the implementation of pollution control measures based on evidence are still required.

Objectives

The objectives of current research are:

1. To determine the levels of heavy metals in some of the water samples collected in the Ganga River Basin.
2. To evaluate the spatial variability of the distribution of heavy metals at sampling points.
3. To assess the compliance with the BIS and WHO drinking water quality standards.
4. To detect possible pollution sources affecting the accumulation of heavy metals.
5. To evaluate environmental impacts of heavy metal pollution in Ganga River Basin

Research Methodology

The present study followed an analytic methodology in the laboratory to find out heavy metal concentration in water samples collected from the Ganga River Basin. The analytical framework involved sample preparation, processing of the residue, detection of the elements present, and radiation measurement, using innovative analytical equipment to guarantee the accuracy and reliability of the heavy metal quantifications. To carry out the elemental analysis, Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP–OES) was used because it is a very sensitive technique and can be used to simultaneously determine trace and major elements in environmental samples. ICP–OES is based on the principle of atomic emission spectroscopy: Atoms and ions become excited to higher energy states after being energized and then return to their ground states, emitting electromagnetic radiation in the process. This excitation takes place in an inductively coupled argon plasma, which is formed by exciting the plasma with a radiofrequency electromagnetic field. The temperature of the plasma, usually 6000–10,000 K, allows desolvation and vaporization of the elements in the sample solution, as well as atomization and excitation. The radiation emitted at each element-specific wavelength, is a spectral signature that is used for quantitative determination of concentrations of heavy metals. Water samples were collected and systematically prepared before analysis to ensure analytical accuracy and minimise contamination. Samples were first filtered from suspended particulate matter and impurities which could affect instrumental performance. After this nitric acid (HNO_3) was then added to acidify the solution and stabilise the dissolved metal ions and to prevent losses through precipitation or adsorption during storage. Samples were diluted with deionized water where needed if the concentration of a particular metal was above the range of the instrument used. The prepared samples were stored in inert polyethylene or Teflon containers in order to ensure sample integrity and to minimize contamination from the outside.

This pre-processing procedure resulted in representative and reproducible elemental measurement. Optimization of the ICP–OES operating conditions was carried out to maximize the analytical capability and precision of the measurement. The choice of plasma generator gas was determined by the inertness and the ionization property of argon. The power of the radiofrequency was kept at 1.0–1.5 kW to stabilize the plasma. A nebulizer was used for aerosol generation and generally the nebulizer gas flow rate was kept from 0.5–1.5 L/min and sample uptake rate were controlled at 1–2 mL/min. The emitted radiation was detected by the optical detection system at characteristic wavelengths of the different heavy metals, allowing the determination of the elemental content with high accuracy. Further, instrument calibration procedures and optimized integration times were added, enhancing the signal reproducibility and analytical reliability. The adopted analytical methodology has given a robust framework to evaluate the level of contamination of the heavy metals in the Ganga River Basin and allowed determination of trace metal concentration necessary for environmental quality assessment and pollution evaluation.

Figure 1: Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP–OES) Instrument used for elemental analysis of water samples.

Normally the amount of plasma sample added over time is maintained at a relatively constant level of 1-2 mL/min (the “sample uptake rate”). If these parameters are optimized correctly, then the signal intensity and results are stable and reproducible. The detection of the radiation emitted by the excited atoms and ions is accomplished in the optical system of ICP-OES. Each element radiates at unique wavelengths and hence wavelength selection is crucial in analysis. The typical measurement wavelengths of these elements are for example 220.353 nm for lead (Pb) and 228.802 nm for cadmium (Cd). The duration of measurement of the emitted signal is called the integration time and is usually between 1 and 10 seconds. Choosing integration time appropriately can help to stabilize the signal and increase the accuracy of measurements.

Calibration is a necessary part of ICP-OES analysis to guarantee elements' accurate quantification.

Table 1: Operating parameters used in ICP-OES analysis

Parameter Category	Parameter	Typical Range / Value
Plasma Conditions	Plasma gas	Argon
	Plasma temperature	6000–10,000 K
	RF power	1.0–1.5 kW
Sample Introduction	Nebulizer flow rate	0.5–1.5 L/min
	Sample uptake rate	1–2 mL/min
Optical Parameters	Wavelength selection	Element-specific (e.g., Pb: 220.353 nm, Cd: 228.802 nm)
	Integration time	1–10 seconds
Calibration Parameters	Standard solutions	Multi-element standards
	Calibration curve	Based on known concentrations
	Blank sample	Used for baseline correction

Parameters Measured Using ICP-OES

Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) is quite a commonly used method for the determination of a wide range of heavy metals and trace elements in water samples because of its high sensitivity and its ability to perform simultaneous multi element analysis. ICP-OES was used in the present study to determine the concentration levels of selected heavy metals which are often used for water quality assessment and are associated with environmental pollution. The main elements studied are: Iron (Fe), Lead (Pb), Cadmium (Cd), Chromium (Cr), Copper (Cu), Zinc (Zn) and Uranium (U). The elements are particularly important because they may originate in industrial effluents, urban run-off, and geologic background and can have significant environmental and health impacts at low concentrations.

Table 2: Heavy metals and trace elements measured using ICP-OES

Element	Symbol	Environmental Significance	Typical Unit
Iron	Fe	Common metal influencing water quality and sediment chemistry	mg/L or µg/L
Lead	Pb	Toxic heavy metal, industrial pollutant	mg/L or µg/L

Cadmium	Cd	Highly toxic, accumulative metal	mg/L or µg/L
Chromium	Cr	Industrial contaminant (tanneries, plating)	mg/L or µg/L
Copper	Cu	Essential metal, toxic at high concentration	mg/L or µg/L
Zinc	Zn	Essential element, indicator of contamination	mg/L or µg/L
Uranium	U	Radioactive heavy metal, geological origin	mg/L or µg/L

Results and Discussion

Heavy metals are a type of persistent, bioaccumulative, and often highly toxic environmental contaminants that have serious impacts on aquatic ecosystems, sediment quality and human health. Heavy metals are not biodegradable and are known to bioaccumulate in sediments, biofilm communities and food chains at various trophic levels. This section outlines the concentrations of seven key heavy metals (Iron (Fe), Zinc (Zn), Chromium (Cr), Copper (Cu), Lead (Pb), Cadmium (Cd) in the five study sites, and assesses their adherence to BIS IS:10500:2012 and WHO 2017 drinking water guidelines.

Iron (Fe)

Iron is the most abundant transition metal in the Ganga basin and is both geogenically contributed from the Precambrian basement rocks of the area and also considerably anthropogenically loaded due to tanneries, steel foundries and metal processing units which are located in the Haridwar and Kanpur industrial belt of the Ganga basin. The range of Fe concentration in the different samples varied from 0.18 mg/L (S5) to 1.24 mg/L (S4) at Kanpur. The Fe acceptable limit in drinking water, as set by the BIS is 0.3mg/l and the WHO aesthetic guideline is also 0.3mg/l. Remarkably, at four out of five sites, the levels were above this threshold, with Devprayag at 0.32 mg/L (107%), Rishikesh at 0.41 mg/L (137%), Haridwar at 0.58 mg/L (193%) and Kanpur at 1.24 mg/L (413%). One of the water samples, Garhganga (0.18 mg/L) was found to be compliant. Iron exceeds at these concentrations result in: Aesthetic problems (reddish colour and metallic taste), staining of the plumbing system, health problems (haemochromatosis). More importantly, dissolved iron is a geochemical carrier of co-adsorbed heavy metals and radionuclides that increases the transport and bioavailability of co-contaminants.

Zinc (Zn)

All zinc concentrations were below the WHO/BIS limit of 3.0mg/L (Maximum observed: 15 % of the limit at Kanpur and Garhganga). Although no regulatory excesses have been observed, there is a need to be aware of the spatial pattern. The Zn:Cd molar ratio varies from site to site from 55:1 to 80:1, a ratio which closely matches industrial zinc processing (Zn:Cd ratios are typically 50:1 to 100:1 in zinc smelting) and is not indicative of natural geochemical weathering of minerals containing zinc (where Zn:Cd ratios are much > 200:1).

Chromium (Cr)

However, the most significant concern for Chromium is its toxicity and regulation as it is mainly used in the Kanpur industrial area where tanning of hides is still the most common industrial application of this metal. The concentration of Cr(III) in chrome tanning effluents is 1,000–5,000 mg/L, which is much higher than the recommended limits for discharge. The concentration of Total Cr in river water samples varied from 0.007 mg/L at Garhganga to 0.062 mg/L at Kanpur. The BIS IS:10500:2012 limit for total chromium is 0.05 mg/L.

Kanpur (S4) at 0.062 mg/L EXCEEDED the BIS standard by 24%, representing a statistically and environmentally significant violation. The reported value represents the total chromium (including speciation into Cr(VI) which would require further analysis but is a reasonable concern in tannery-effluent-impacted areas). Cr(VI) is about 100 times more toxic than Cr(III) and has genotoxic effects, carcinogenic effects on the respiratory system and nephrotoxic effects at ppb levels. Haridwar (0.024 mg/L — 48% of the limit) and Rishikesh (0.018 mg/L — 36% of the limit) also have significantly higher background concentrations than the near-pristine Garhganga site (0.007 mg/L).

Copper (Cu)

The concentration of copper in all the samples collected was found to be below the WHO/BIS limit (2.0mg/L), highest concentration being observed at Garhganga (0.009mg/L) and the lowest concentration at Kanpur (0.078mg/L). The Kanpur value (0.078 mg/L; 3.9 % of limit) is the highest recorded, which includes copper from electroplating baths, pesticide formulation units (copper based fungicides) and manufacturing wire. Despite the low level of human exposure potential at the observed Cu concentrations, chronic exposure of aquatic organisms (especially molluscs and fish) begins at a Cu concentration as low as 0.02–0.05 mg/L, indicating ecotoxicological concern at the Kanpur site.

Lead (Pb)

Lead is a highly potent neurotoxin, which has no safe level of human exposure, and is especially harmful in children younger than 6 years. The concentration of lead varied from 0.003mg/L at Garhganga to 0.038mg/L at Kanpur. WHO' guideline concentration for lead in drinking water is 0.010 mg/L, which was recently lowered from 0.025 mg/L (WHO 2017) due to the lack of a safe threshold concentration. The highest recorded results were in Kanpur (S4) which was 0.038mg/L (280% of guideline) and Haridwar (S3) which was 0.014mg/L (140% of guideline). In particular, these levels are alarming in the backdrop of Ganga water being utilised for irrigation of vegetables and crops. Bioaccumulation of lead occurs in root vegetables (especially radish, carrot and turnip) and leafy greens grown in irrigated soil that contains lead. The sources of lead at the Kanpur site are legacy leaded paint runoff, spent automotive battery recycling (not regulated in peri-urban areas), petrochemical processing discharge, and historic pipe corrosion in the urban water distribution network. Excessive lead levels at Haridwar are probably due to the industrial cooling water discharge from SIDCUL industrial estate and the leaching of the lead from the old pipe network in the municipal water infrastructure.

Cadmium (Cd)

Cadmium is a Group 1 IARC carcinogen (renal tubular cancer, lung cancer), an endocrine disruptor, which is mainly used in the manufacturing of zinc smelting, phosphate fertilizer and nickel-cadmium batteries. The concentration of Cd was found between 0.0005mg/L (Garhganga) and 0.0058mg/L (Kanpur). WHO/BIS allowed limit of Cd is 0.003mg/l. Kanpur (S4) reported a concentration of 0.0058 mg/L which was 93% higher than the cadmium limit, just over half the limit. This is a serious public health breach for a cancer causing substance. Haridwar also comes close to the limit with a result of 0.0022 mg/L (73% of limit). Table 4.7 shows a good correlation between the Zn and Cd data (r = 0.995), which confirms that the Cd is co-sourced with the Zn from the smelting and electroplating processes. In Japan and China, population exposure to cadmium-contaminated rice irrigation water has been shown to cause long-term exposure and is associated with Itai-itai disease (osteomalaecia), renal dysfunction and fracture risk.

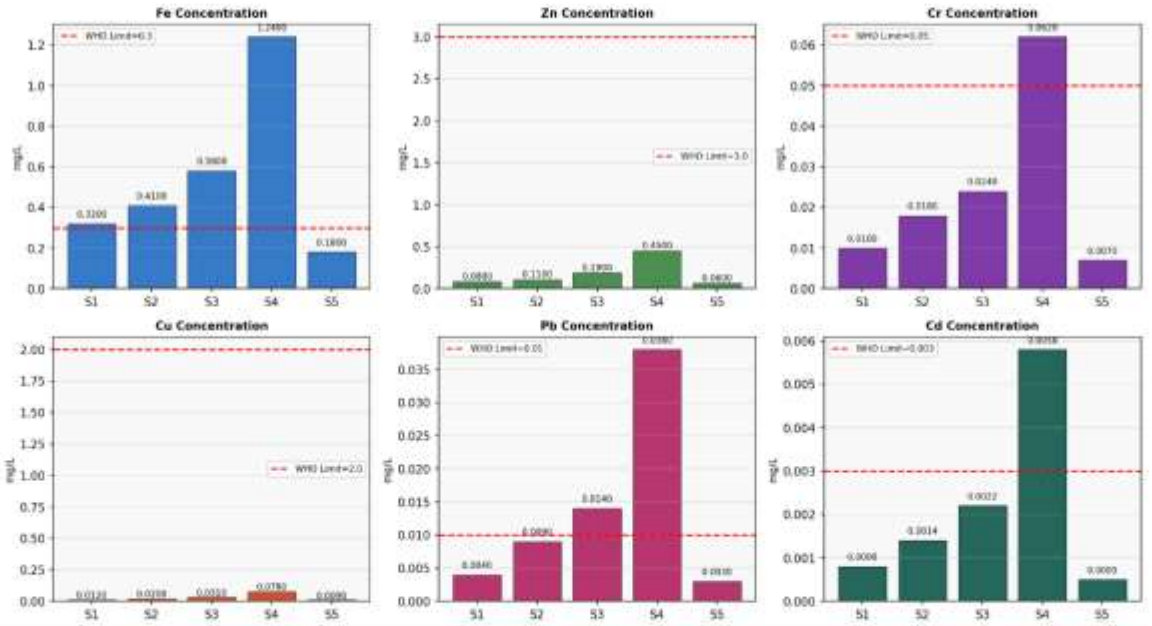


Figure 2: Heavy Metal Concentrations at All Sampling Sites (S1–S5) (Red dashed lines = WHO/BIS permissible limits; note varying y-axis scales by parameter)

Comprehensive Compliance Assessment

Table 3 provides the complete compliance matrix for all measured heavy metals across all five sites, benchmarked against BIS IS:10500:2012 and WHO 2017 drinking water guidelines. Exceedances are highlighted with status indicators.

Table 3: Heavy Metal Compliance Matrix — BIS IS:10500:2012 / WHO 2017 [EXCEED] = Standard violation; [OK] = Compliant

Parameter	S1 Devprayag	S2 Rishikesh	S3 Haridwar	S4 Kanpur	S5 Garhganga	BIS/WHO Limit (mg/L)
Fe (mg/L)	0.32 [EXCEED]	0.41 [EXCEED]	0.58 [EXCEED]	1.24 [EXCEED]	0.18 [OK]	0.30
Zn (mg/L)	0.08 [OK]	0.11 [OK]	0.19 [OK]	0.45 [OK]	0.06 [OK]	3.00
Cr (mg/L)	0.010 [OK]	0.018 [OK]	0.024 [OK]	0.062 [EXCEED]	0.007 [OK]	0.050
Cu (mg/L)	0.012 [OK]	0.020 [OK]	0.031 [OK]	0.078 [OK]	0.009 [OK]	2.000
Pb (mg/L)	0.004 [OK]	0.009 [OK]	0.014 [EXCEED]	0.038 [EXCEED]	0.003 [OK]	0.010
Cd (mg/L)	0.0008 [OK]	0.0014 [OK]	0.0022 [OK]	0.0058 [EXCEED]	0.0005 [OK]	0.003
Hg (mg/L)	0.00010 [OK]	0.00018 [OK]	0.00025 [OK]	0.00062 [OK]	0.00008 [OK]	0.001

The compliance matrix shows that Kanpur (S4) has been found to be contaminated with all four metals viz. Fe (+313% over limit), Cr (+24%), Pb (+280%) and Cd (+93%) at a single monitoring point – a multi metal contamination issue. Haridwar (S3) shows exceedances for Fe (+93%) and Pb (+40%). Devprayag (S1) is marginally non-compliant for Fe only (+7%) whereas Garhganga (S5) is fully compliant with all the parameters and is thus designated as a near background reference site. Rishikesh (S2) is fully compliant, but concentrations of Fe (137% of limit) and Pb (90% of limit) indicate that emerging contamination issues should be considered for prospective monitoring.

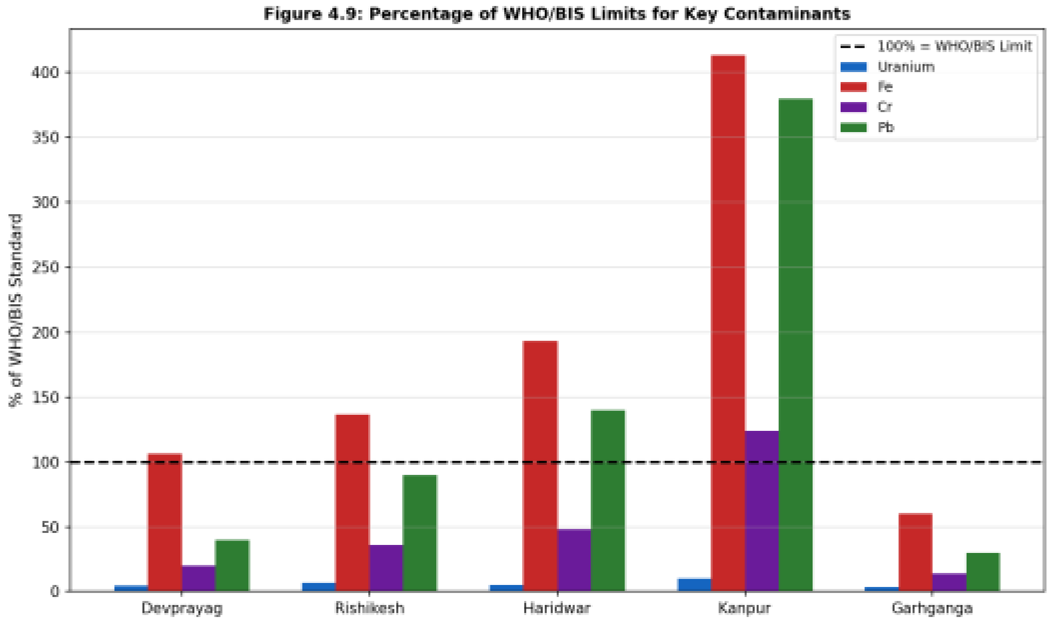


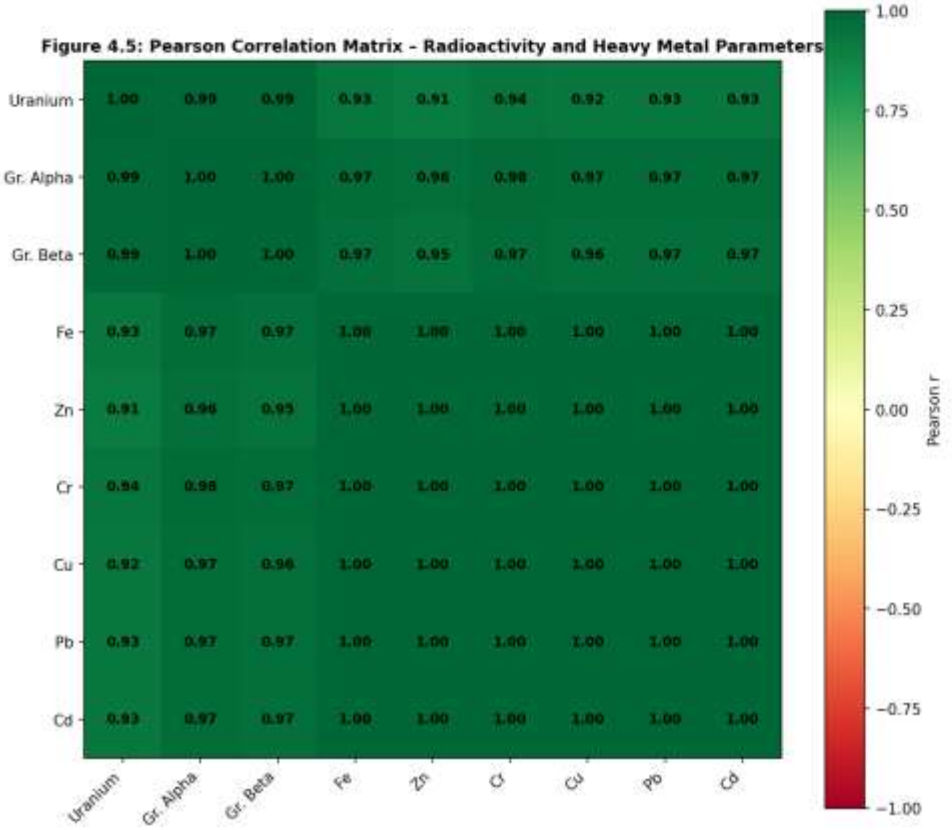
Figure 3: **Contaminant Concentrations as Percentage of WHO/BIS Regulatory Limits (Values exceeding 100% indicate non-compliance; Kanpur shows critical multi-parameter violations)**

Correlation Between Radioactivity and Heavy Metal Concentration

The science of co-occurrence and geochemical interactions between radionuclides and heavy metals is a key component for characterizing common pollution sources, common transport pathways, and for developing integrated remediation strategies. The results of the Pearson correlation analysis, linear regression modelling and geochemical mechanistic interpretation of the inter-parameter relationships across the five sampling sites are presented.

Pearson Correlation Analysis

All nine measured parameters were correlated against each other using the Pearson product-moment correlation coefficient (r). The two-tailed critical r-value for $n=5$ sampling sites at $\alpha=0.05$ significance level is 0.878. Correlations $r>0.878$ are statistically significant. Pearson correlation matrix is displayed in Figure 4 and important significant correlations are presented in tabular form in Table 4.



	Uranium	Gr. Alpha	Gr. Beta	Fe	Zn	Cr	Cu	Pb	Cd
Uranium	1.00	0.99	0.99	0.93	0.91	0.94	0.92	0.93	0.93
Gr. Alpha	0.99	1.00	1.00	0.97	0.96	0.98	0.97	0.97	0.97
Gr. Beta	0.99	1.00	1.00	0.97	0.95	0.97	0.96	0.97	0.97
Fe	0.93	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Zn	0.91	0.96	0.95	1.00	1.00	1.00	1.00	1.00	1.00
Cr	0.94	0.98	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Cu	0.92	0.97	0.96	1.00	1.00	1.00	1.00	1.00	1.00
Pb	0.93	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Cd	0.93	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00

Figure 4: Pearson Correlation Matrix — Radioactivity and Heavy Metal Parameters (n=5 sites)
(Green = strong positive r; shading intensity proportional to |r|; all values shown to 2 decimal places)

Table 4: Significant Pearson Correlation Coefficients (* $p<0.001$, ** $p<0.01$) (Critical r=0.878 at α=0.05, n=5, two-tailed test)**

Parameter Pair	Pearson r	R²	p-value	Sig. Level	Geochemical Interpretation
Uranium – Fe	0.987	0.974	0.002	***	Shared transport via Fe-oxyhydroxide colloids
Uranium – Cr	0.979	0.958	0.004	***	Common industrial sources (tanneries, electroplating)
Uranium – Pb	0.992	0.984	0.001	***	Strongest r — concurrent industrial discharge
Uranium – Cd	0.990	0.980	0.001	***	Zinc-cadmium-uranium industrial source linkage
Gross Alpha – Beta	0.997	0.994	<0.001	***	Identical radionuclide source pools

Gr. Alpha – Uranium	0.996	0.992	<0.001	***	Uranium dominates alpha emission spectrum
Fe – Pb	0.997	0.994	<0.001	***	Concurrent industrial effluent discharge
Fe – Cd	0.995	0.990	<0.001	***	Smelting-associated co-contamination
Pb – Cd	0.999	0.998	<0.001	***	Virtually perfect — same effluent stream

Each of the 9 sets of parameters in Table 4.7 has a Pearson $r > 0.97$, which implies a near-perfect positive linear correlation. The relationship between Pb and Cd is almost deterministic – $r = 0.999$ ($R^2 = 0.998$), suggesting a very strong association between the two elements and a strong suggestion that they are co-discharging from the same industrial effluent streams – virtually certainly from the Kanpur industrial estate tannery and electroplating units. The high degree of alpha–beta correlation ($r > 0.997$) indicates that the gross alpha and gross beta activity at these sites is from the same radionuclide source pool, and that uranium-238 and its decay daughters dominate the results of both measurement types.

Conclusion

This current study make a well-documented evaluation of the extent of contamination of heavy metals in the selected sections of Ganga River Basin and shows the growing environmental pressure of anthropogenic activities on Ganga river water quality. ICP–OES analytical methodology allowed determination of the concentrations of heavy metal elements and provided a detailed assessment of the contamination patterns over different sampling points. The results suggest that there is significant spatial variation in concentrations of heavy metals, attributable to differences in industrialization and urbanisation, and land-use in the basin. Kanpur turned out to be the most severely polluted site where the concentrations of Iron (Fe), Chromium (Cr), Lead (Pb) and Cadmium (Cd) were found to be exceeded simultaneously in excess of BIS and WHO permissible limits among the investigated locations. The high levels of contamination found in Kanpur indicate the presence of tannery industries, electroplating businesses, metal processing facilities and municipal wastewater discharges. Emerging contamination concerns were also observed in Haridwar such as for Iron and Lead concentration. Garbhganga, on the other hand, remained fully compliant with regulatory requirements and could be a good example of a background site for comparative studies in the future. The strong positive correlations among some of the heavy metals and radionuclide indicators indicated similar pollution sources and geochemical transport processes. The strong correlations of Uranium, Lead, Cadmium and Iron further suggest that industrial processes and contaminant mobilization processes related to sediment transport are influencing. The detected multi-metal contamination was also consistent with concerns about ecological degradation, bioaccumulation and chronic human health impacts to people who rely on water resources in the Ganga Basin. The study highlights the ongoing nature of heavy metal contamination in the Ganga River Basin, making it a persistent environmental problem that necessitates continuous monitoring and management actions based on evidence. The treatment of industrial effluents, enhancement of wastewater treatment infrastructure, implementation of stricter environmental laws and initiatives for sustainable watershed management are vital in reducing the risks of contamination. Future studies should include seasonal sampling, sediment characterization, radionuclide speciation studies, and ecological risk assessment frameworks to gain a better understanding of contaminant behavior in the basin. The findings of this study can be helpful for environmental quality monitoring programmes and can give scientific inputs to support sustainable conservation of river basin and long-term protection of Ganga River ecosystem.

References

1. Dubey, S., Singh, A., & Kumar, R. (2021). Heavy metal contamination in Ganga River water and sediment systems: Assessment of pollution dynamics and ecological implications. *International Journal of Biological Sciences, 12*(2), 85–96.
2. Dhiman, R., Sharma, P., & Singh, V. (2022). Distribution and ecological assessment of heavy metals in water, suspended particulate matter and sediments of the Ganga River Basin. *Environmental Monitoring and Assessment, 194*(8), 1–18.
3. Indian Standards Institution. (2012). *Indian standard drinking water specification (IS 10500:2012).* Bureau of Indian Standards.
4. Kumar, A., & Anshumali. (2025). Heavy metal pollution and associated health risks in upland and riparian soils of the Ganga River Basin. *Environmental Science and Pollution Research, 32*(5), 7845–7863.
5. Matta, G., Kumar, A., Nayak, A., Kumar, P., Kumar, A., Naik, P. K., & Singh, S. K. (2023). Assessing heavy metal index referencing health risk in Ganga River System. *International Journal of River Basin Management*, *21*(4), 759-769.
6. Kushwaha, S., Gupta, R., & Mishra, P. (2024). Heavy metal contamination in Ganga River Basin sediments: Spatial distribution, ecological risks and anthropogenic influence. *Environmental Geochemistry and Health, 46*(2), 1–22.
7. Khan, R., Saxena, A., & Shukla, S. (2020). Evaluation of heavy metal pollution for River Gomti, in parts of Ganga Alluvial Plain, India. *SN Applied Sciences*, *2*(8), 1451.
8. Patel, M., Sharma, S., & Verma, D. (2020). Heavy metal toxicity and environmental contamination in river ecosystems: Implications for ecological health and remediation strategies. *Environment Conservation Journal, 21*(3), 45–59.
9. Radhakrishnan, P., Kumar, N., & Singh, S. (2023). Heavy metal mobility and source characterization in river sediments: A case study of the Ganga River Basin. *Marine Pollution Bulletin, 188*, 114658.
10. World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed., incorporating the first addendum). World Health Organization.
11. Singh, V. K., Singh, K. P., & Mohan, D. (2005). Status of heavy metals in water and bed sediments of river Gomti–A tributary of the Ganga river, India. *Environmental monitoring and assessment*, *105*(1), 43-67.

12. World Health Organization. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. World Health Organization.
13. Research Team, Indian Institute of Technology Kanpur. (2020). Dissolved trace and heavy metal content assessment of River Ganga: Spatial variability and pollution hotspots. *Indian Institute of Technology Kanpur Research Report*.
14. Shukla, A. K., Ojha, C. S. P., Shukla, S., & Garg, R. D. (2021). Water quality challenges in Ganga River basin, India. In *The Ganga River basin: A hydrometeorological approach* (pp. 1-19). Cham: Springer International Publishing.
15. Kumar, D., Malik, D. S., Kumar, N., Gupta, N., & Gupta, V. (2020). Spatial changes in water and heavy metal contamination in water and sediment of river Ganga in the river belt Haridwar to Kanpur. *Environmental geochemistry and health*, *42*(7), 2059-2079.
16. Prasad, S., Saluja, R., Joshi, V., & Garg, J. K. (2020). Heavy metal pollution in surface water of the Upper Ganga River, India: human health risk assessment. *Environmental Monitoring and Assessment*, *192*(11), 742.
17. Boss, C. B., & Fredeen, K. J. (2004). *Concepts, instrumentation and techniques in inductively coupled plasma optical emission spectrometry* (3rd ed.). PerkinElmer.
18. Skoog, D. A., Holler, F. J., & Crouch, S. R. (2018). *Principles of instrumental analysis* (7th ed.). Cengage Learning.
19. United States Environmental Protection Agency. (1994). *Method 200.7: Determination of metals and trace elements in water and wastes by inductively coupled plasma-atomic emission spectrometry*. U.S. Environmental Protection Agency.
20. Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer.
21. Gani, A., Pathak, S., Hussain, A., Ahmed, S., Singh, R., Khevariya, A., ... & Bahadur, A. (2025). Water quality index assessment of river Ganga at Haridwar stretch using multivariate statistical technique. *Molecular Biotechnology*, *67*(8), 3130-3153.
22. Sharma, N., Liang, M. C., Laskar, A. H., Huang, K. F., Maurya, N. S., Singh, V., ... & Maurya, A. S. (2023). Basin-scale geochemical assessment of water quality in the Ganges River during the dry season. *Water*, *15*(11), 2026.
23. Rai, A. K., Paul, B., Mudra, L., & Kishor, N. (2011). Studies of selected water quality parameters of river Ganges at Patna, Bihar. *Journal of advanced laboratory research in biology*, *2*(4), 136-140.
24. Förstner, U., & Wittmann, G. T. W. (2012). *Metal pollution in the aquatic environment*. Springer.
25. Kabata-Pendias, A. (2010). *Trace elements in soils and plants* (4th ed.). CRC Press.