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Risk Assessment of Groundwater Contamination by Heavy Metals in the Gangetic plain: A Multivariate Statistical and Index-Based Study

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ABSTRACT

Groundwater in the Gangetic Plain of India is increasingly vulnerable to heavy metal contamination, raising serious public health concerns. This study analyzed 12 heavy metals (As, Cr, Ni, Mn, Fe, Zn, Pb, Cu, Se, Mo, Cd, and Co) in 30 groundwater samples using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Statistical evaluations included Shapiro-Wilk normalization, Pearson correlation (SPSS v25), and Principal Component Analysis (OriginLab v10.15). Heavy Metal Pollution Index (HPI), non-carcinogenic Health Risk Assessment (HI), and carcinogenic risk (CR) analysis were performed. Results showed that 70% of samples from Ballia exceeded the HPI threshold (>100), with the highest value at 328.77. Lead (Pb) and Arsenic (As) were the dominant contributors to non-carcinogenic risk, with HI values peaking at 28,334.8.

Carcinogenic risk values for As and Ni exceeded acceptable limits in all districts, with Prayagraj and Ballia showing total CR values of 2.17 and 3.00, respectively. Strong correlations among metals (e.g., Cd–Mn, r = 0.80) suggest anthropogenic origins, particularly from industrial and agricultural sources. These findings highlight the urgent need for routine monitoring, point-source control, and localized treatment to ensure groundwater safety.

INTRODUCTION

Globally, the occurrence of heavy metals in groundwater poses a significant concern. These metals, even at low concentrations can be toxic to humanhealth and aquatic organisms (Mahato et al., 2023; Ayazi et al., 2010).Nowadays, heavy metal pollution has become a critical environmental concern, especially in developing countries like India, where industrialization, urbanization, and agricultural practices greatly contribute to rising their levels (Badar et al., 2024; Saw et al., 2023b). Hence, it is essential to keep their levels below acceptable thresholds limit in drinking water as it is associated with significant health risksand can accumulate in the human body over time, leading to chronic toxicity (Mahato et al., 2023). Moreover, due to their non-biodegradable nature, these metals also accumulate in sediments, and living organisms, making it essential to assess the environmental distribution (Kumar et al., 2019).These elements like arsenic (As), chromium (Cr), cadmium (Cd), nickel (Ni), lead (Pb), manganese (Mn), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), selenium (Se), and molybdenum (Mo) are frequently detected in the groundwater and possesses both carcinogenic and non-carcinogenic nature to human (Saw et al., 2023a; Mahato et al., 2017). These metals may be associated with cardiovascular disease, lung and bladder cancer, and damage to the kidneys, liver, and nervous system (USEPA, 2005; Kumar et al., 2020). According to the World Health Organization (WHO), approximately 20% of cases of global cancer are attributed to the consumption of unsafe water (WHO, 2019). Hence, to evaluate the degree of water pollution by heavy metals for drinking purposes heavy metal pollution index (HPI) is one of the most effective methods. Health risk assessment is a valuable tool for determining the level of risk for both cancerous and non-cancerous diseases, utilizing measures such as the Hazard Quotient (HQ) and Cancer Risk (CR) (Chorol and Gupta, 2023; Wagh et al., 2018).Many studies were conducted separately in India for HPI and human health risk assessment (HRA) in drinking water (Matta et al., 2023; Wagh et al., 2018; Botle et al., 2023). However, no research integrated the simultaneous investigation of HPI, Pearson correlation (PCC), Principal Component Analysis (PCA), and human health risk assessment with special reference to the drinking water of the

Gangetic Plain region in India. At this time, a holistic view of heavy metal contamination and its implications for public health and environmental policy is needed for this region.

Despite various studies on heavy metal contamination in India, an integrated assessment combining multivariate statistical analysis, pollution indexing, and comprehensive health risk evaluation remains scarce, particularly in the Gangetic Plain region. This area, characterized by intense agricultural and industrial activities, faces growing pressure on groundwater resources, yet lacks detailed region-specific investigations. The present study addresses this gap by applying an integrated approach using Principal Component Analysis (PCA), Pearson correlation, Heavy Metal Pollution Index (HPI), and both non-carcinogenic and carcinogenic risk assessments (HQ, HI, and CR). By evaluating groundwater samples from three districts—Ballia, Lakhimpur, and Prayagraj—this research provides a holistic understanding of pollution levels, source identification, and associated health risks. The findings aim to support evidence-based groundwater management and inform mitigation strategies in one of India's most densely populated and ecologically sensitive regions.

2.0 Material and Methods

2.1 Study region and Sampling

The Gangetic Plain is located in the north-central part of India, where the Uttar Pradesh state covers the maximum part of this region.This region, lying along the Ganges Riveris marked by diverse hydrogeological conditions, along with extensive agricultural and industrial activities, which can substantially impact groundwater quality.For this study, 30 groundwater samples were collected from the three districts, Prayagraj, Lakhimpur, and Ballia, which lie in the Central Plain Zone of this region. The geographical coordinate of these districts is depicted in Table 1. All the samples were collected in 500 mL high-density polyethylene (HDPE) bottles that were pre-cleaned and acid-washed with 10% nitric acid to prevent metal contamination. After collection, each sample was promptly sealed, stored at 4°C, and transported to the laboratory for analysis within 48 hours, following the standard sampling protocols of the Bureau of Indian Standards (BIS) (BIS 2015). The Sampling location map of the study area is illustrated in Fig. 1.

Table 1 Description of the study area

SlNo.	Name of Districtzzz	Geographical Coordinate	Source water	Population (Lakh) (Census 2011)
1.	Prayagraj	25.4358° N 81.8463° E	Groundwater	59.54
2.	Lakhimpur Kheri	27.9450° N 80.7821° E	Groundwater	40.21
3.	Ballia	25.8307° N, 84.1857° E	Groundwater	32.39

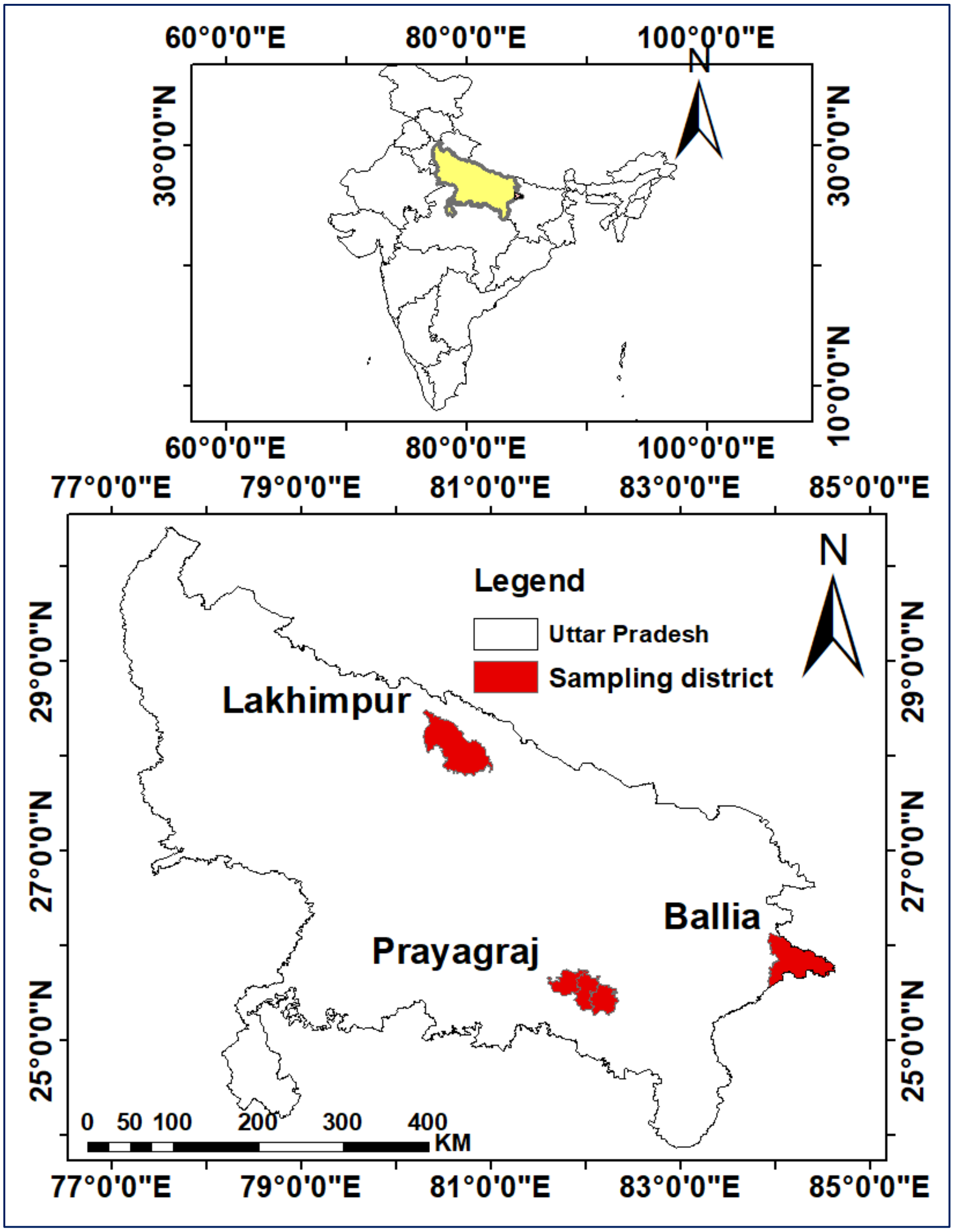

Fig 1 Sampling Location map.

2.2 Heavy Metals Selection and theirMultivariate Graphical Analysis

Based on frequent detection of elements in the groundwater of this region 12 heavy metals viz. As, Cr, Cd, Ni, Pb, Mn, Fe, Co, Cu, Zn, Se, and Mo were selected for the quality monitoring analysis. The concentration of these heavy metals was quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS following the standard operating procedures of APHA (APHA, 2012). To examine the inter-metal correlations and identify potential sources of contamination, the Pearson correlation coefficient (PCC) was established using SPSS (version 25). Before using SPSS all the data were normalized with the Shapiro-Wilk test to ensure suitability for parametric correlation.Multivariate statistical techniques like Principal Component Analysis (PCA) were employed using Origin Lab software (Version 9.6.5.) to identify underlying factors contributing to heavy metal distribution across the study area.Moreover, the Box plot technique was used for graphical representation and enhanced the understanding of data trends and distribution.

2.3 Heavy Metal Pollution Index (HPI)

To assess the overall quality of water, the Heavy Metal Pollution Index (HPI) is used. This method uses a weighted arithmetic mean, which involves two steps: (1) assigning a rating to each parameter with an appropriate weight, and (2) identifying the parameters contributing to pollution for inclusion in the index. The rating scale ranges from 0 to 1. For each parameter in the HPI calculation (Table 2), the unit weight (Wi) is inversely proportional to the recommended standard (Si). HPI can be expressed mathematically as Eq. (1) (Mohan et al., 1996).

$$\text{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \qquad (1)$$

Where 'Qi' represents the sub-index of the i^{th} parameter, 'Wi' denotes the unit weight of the i^{th} parameter, and 'n' is the total number of parameters included in the analysis. The sub-index (Qi) for each parameter is calculated using Eq. (2):

$$\text{Qi} = \sum_{i=1}^{n} \frac{\{Mi - Ii\}}{(Si - Ii)} \times 100 \qquad (2)$$

Here, Mi, Ii, and Si represent the monitored, ideal, and standard permissible values of the i^{th} parameter, respectively. A critical HPI value of 100 is considered the threshold for drinking water safety. In this study, a modified classification scale is adopted, categorizing HPI values into four levels: low, medium, high, and very high, as detailed in Table 3.

Table 2Sub Index calculation of avg of Heavy Metal

Heavy Metals	Mean Concentration (Ci) (μg/L)	Max. Permissible Value (BIS 2012)	Unit weightage (Wi)	Sub Index (SI)

As	12.1262	10	0.16	0.19
Cr	1.1475	50	0.13	0.002984
Cd	2.4855	3	0.13	0.11
Ni	6.821833	20	0.09	0.030698
Pb	28.1305	10	0.16	0.45
Mn	370.3008	100	0.03	0.11
Fe	1498.373	300	0.02	0.10
Co	0.429	100	0.06	0.00
Cu	21.29517	50	0.06	0.03
Zn	574.2563	5000	0.05	0.01
Se	1.166	10	0.08	0.01
Mo	1.108167	70	0.05	0.00
			HPI = $\sum SI$	104.3

Table 3HPI value for drinking water used in this study

Category	**HPI Range**
Low	<40
Medium	40-70
High	70-100
Very High	>100

2.4 Health Risk Assessment Framework

The assessment of health risks from metal pollutants in groundwater includes a consideration of both non-carcinogenic and carcinogenic risks. The risk was quantified following the United States Environmental Protection Agency (USEPA) guidelines for human health risk assessment (USEPA, 2005). The average daily intake (ADI) of metals via. Oral ingestion and dermal pathway were estimated using Eq. (3) and (4), respectively.

$$ADI_{ingestion} = \frac{C \times IR \times EF \times ED}{BW \times AT} \times CF \quad (3)$$

$$ADI_{dermal} = \frac{C \times SA \times SAF \times DAF \times ED \times EF}{BW \times AT \times PEF} \times CF \quad (4)$$

The Average Daily Intake (ADI) represents the daily exposure to heavy metals, expressed in mg/kg/day, and is calculated using parameters shown in Table 4.

Table 4 Exposure Parameter used in Health Risk Assessment

Parameter	**Description**	**Value**	**Unit**	**Reference**
C	Concertation of Heavy Metal	-	mg	-
IR	Ingestion Rate	3.0	L/day	ICMR, 2009
EF	exposure frequency	365	Days/year	ICMR, 2009
ED	Exposure duration	30	Years	ICMR, 2009
BW	Body Weight	57.5	Kg	-
AT	Average time	10,950	Days	ED*365
CF	Conversion Factor	10^{-6}	Kg/mg	-

Potential non-carcinogenic risks are evaluated through Hazard Quotient (HQ)(Eq .5), which is the ratio of the exposure level of a specific element to its reference dose (RfD) as defined by USEPA (2011) (Table 4) (Saw et al., 2023a). The Hazard Index (HI), which accounts for multiple substances under a single exposure pathway, is determined as the sum of the HQs for all analyzed metals (Eq. 6).

$$\mathrm{HQ} = \frac{ADI}{RfD} \qquad (5)$$

$$\mathrm{HI} = \sum HQ \qquad (6)$$

The carcinogenic risk (CR) whichwas calculated by the product of oral slope factor (Sf) and exposure level (ADI) (Eq.7). The Sf value shown in Table 5.The acceptable range of CR or CR_{total} was defined as 1×10^{-6} to 1×10^{-4}(USEPA 2009).CR or $CR_{total} < 1x\ 10^{-6}$showed negligible carcinogenic risk; CRor $CR_{total} > 1\times10^{-4}$ showed unacceptable carcinogenic risks (USEPA, 2001).

$$\mathrm{CR} = \mathrm{ADI\ x\ Sf} \qquad (7)$$

Table 5 Oral reference dose and oral slope factor value (Shekoohiyan et al., 2021, USEPA 2009)

Heavy metals	**Rf (mg/kg/day)**	**Sf $(mg/kg/day)^{-1}$**
As	0.0003	1.5
Cd	0.001	6.3
Cr	0.003	0.5
Ni	0.02	0.91

Pb	0.0035	0.0085
Mn	0.14	-
Fe	0.7	-
Zn	0.3	-
Cu	0.04	-
Co	0.0003	-
Se	0.005	-
Mo	0.005	-

2.5 Quality assurance and quality control (QA/QC)

All the samples were handled carefully to avoid contamination and ensure the results' reliability. Instrument calibration was performed before analysis and the analysis accuracy was checked by analyzing the reference standard of water (NIST 1640a and NIST 1643b). Analytical precision was verified by calculating relative standard deviations, which remained within acceptable limits (<5%) for all elements.

3.0 Results and Discussion

3.1 Graphical representation of heavy metals

The box plot representation of all 12 targeted heavy metals was illustrated in Fig. 2a-l. Out of all these 12 elements, As, Cr, Cd, Ni, and Pb are carcinogenic, while the remaining 7 (Mn, Fe, Co, Cu, Zn, Se, and Mo) are non-carcinogenic to human health (Mahato et al., 2017; Saw et al., 2023a). The concentration of Fe (1498.07±975.6 µg/L) in the groundwater of collected water sample exceeded the guideline value (300 µg/L) set by WHO and BIS (Fig. 2a). While the concentration of Cu and Zn (Fig. 2b-c) are well within acceptable limits with an averages value of 21.29±14.9 µg/L and 574.25±1106.4 µg/L, respectively. Coand Mo (Fig. 2d-e) were detected at minimal concentrations, indicating no immediate concern. Se showed a high value of 11.345 µg/L exceeding the BIS guideline (10 µg/L) (Fig. 2f). Cd value ranged from 0.03 to 9.73 µg/L, with an average of 2.48±2.7 µg/L, approaching the 3µg/L specified by both BIS and WHO (Fig. 2g).Arsenic (As) levels were considerably elevated, reaching a maximum of 102.6 µg/L with an average of 12.12±21.2 µg/L, surpassing the 10 µg/L threshold recommended by both standards, indicating a potential health risk(Fig. 2h).The elevated concentrations of heavy metals such as arsenic, lead, and chromium in the groundwater of districts like Ballia and Lakhimpur may be attributed to both natural geogenic sources and anthropogenic influences, particularly agricultural runoff (e.g., phosphate fertilizers, pesticides) and industrial discharges from activities such as sugar processing and small-scale manufacturing (Sharma et al., 2019; Singh & Singh, 2021).Cr (Fig. 2i) and Ni(Fig. 2k) were below their respective BIS limits of 50 µg/L, with an averaging value with 1.14±1.4 µg/L and 6.82±3.8 µg/L, respectively.Pb (Fig. 2j), showed alarmingly high values, peaking at 118.3 µg/L with an average of 28.13±29.2 µg/L, far exceeding both the BIS and WHO permissible limits, underscoring severe contamination risks. Mn (Fig. 2l) levels were also markedly high, ranging from 7.7 to 1167 µg/L, averaging 370.30±360.8 µg/L, surpassing the BIS limit of 100 µg/L (Table 6).

Table 6 Percentage of sample exceeding BIS limits for Heavy Metals

Heavy metal	BIS Limits (µg/L)	% of sample
Arsenic (As)	10	47
Lead (Pb)	10	37
Chromium (Cr)	50	30
Cadmium (Cd)	3	23
Nickel (Ni)	20	27
Iron (Fe)	300	17
Manganese (Mn)	100	13.3
Zinc (Zn)	5000	0
Copper (Cu)	50	0
Selenium (Se)	10	0
Cobalt (Co)	Not specified	0
Molybdenum (Mo)	Not specified	0

The variation in the concentration range of these targeted heavy metals in this region is attributed to the competing influences of the Ganga river basin's diagenesis, physicochemical weathering, sediment texture, geology, and geochemistry of individual metals (Kumar et al., 2019; Singh et al., 2006; Ukah et al., 2019). Moreover, the leachable ions from the soils and the lithogenic origin of minerals in groundwater may also vary the quality of water in this region (Khan and Rai, 2023).

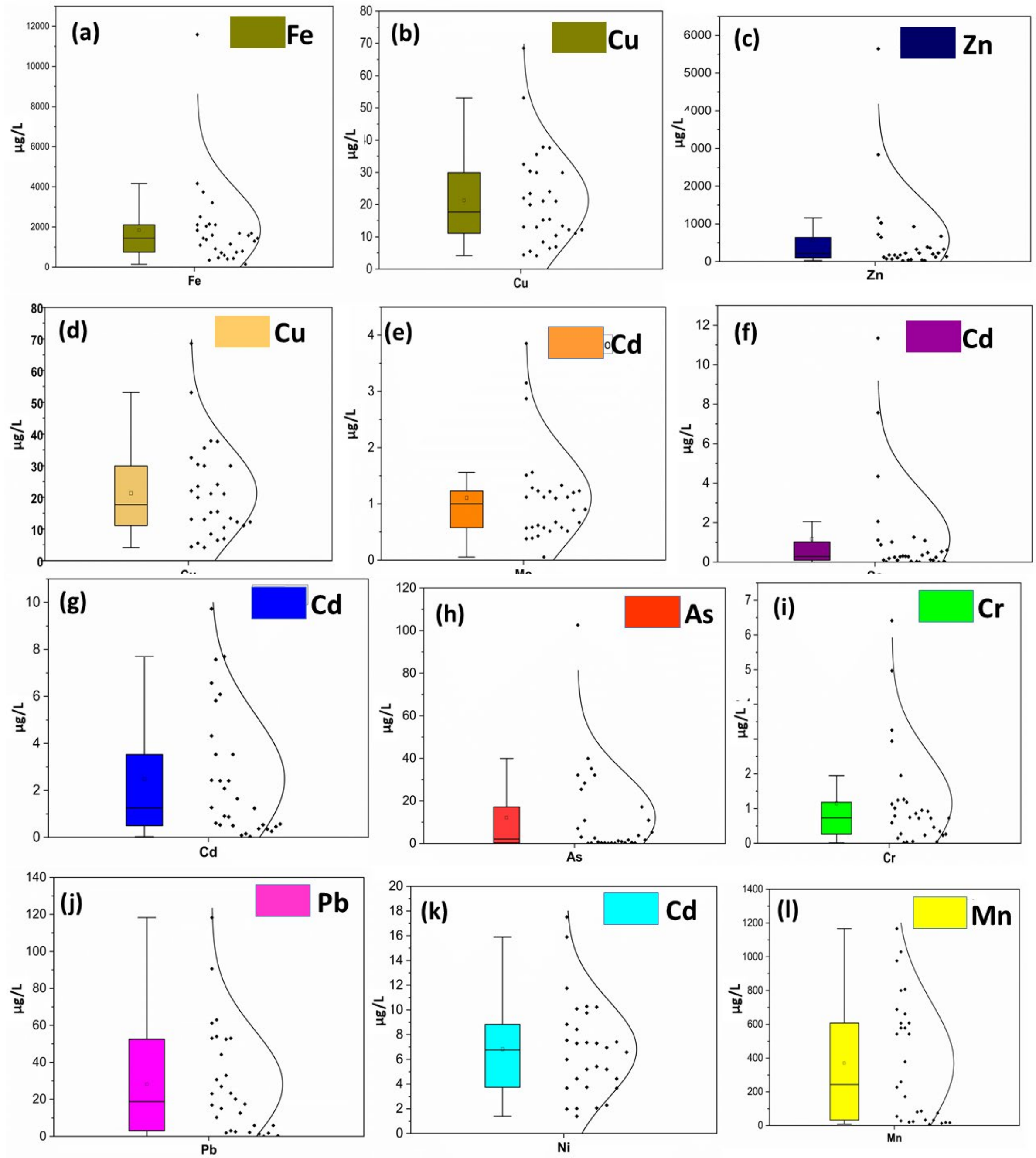

Fig. 2 Box plot diagramwith kernel density estimate of heavy metals (a) Fe, (b) Cu, (c) Zn, (d) Co, (e) Mo, (f) Se, (g) Cd, (h) As, (i) Cr, (j) Pb, (k) Ni, and (l) Mn

3.2 Pearson Correlation Matrix

The Pearson correlation matrix among the heavy metal content in the groundwater of the study area is shown inFig. 3. To better interpret the relationships among heavy metals, correlation coefficients were grouped by strength: strong (r > 0.7), moderate (0.5 ≤ r ≤ 0.7), and weak (r < 0.5). Strong correlations were observed between Cd–Mn (r = 0.80), Fe–Co (r = 0.79), and Pb–As (r = 0.75), suggesting common anthropogenic sources such as industrial discharge or agrochemical runoff (Mahato et al., 2023). Moderate correlations were seen between Cr–Ni and Zn–Cu, which may indicate shared transport or geogenic pathways (Singaraja et al., 2015). Weak correlations were noted for pairs like Mo–Zn, implying dissimilar origins or independent mobility in groundwater. Conversely, cobalt (Co) exhibited negative correlations with elements like arsenic (As) (r = -0.17) and lead (Pb) (r = -0.13), indicating potential differences in their sources or environmental interactions (Saw et al., 2023a). Overall this correlation matrix revealed potential metal sources and interactions in water samples, aiding in identifying contamination origins and assessing environmental risks.

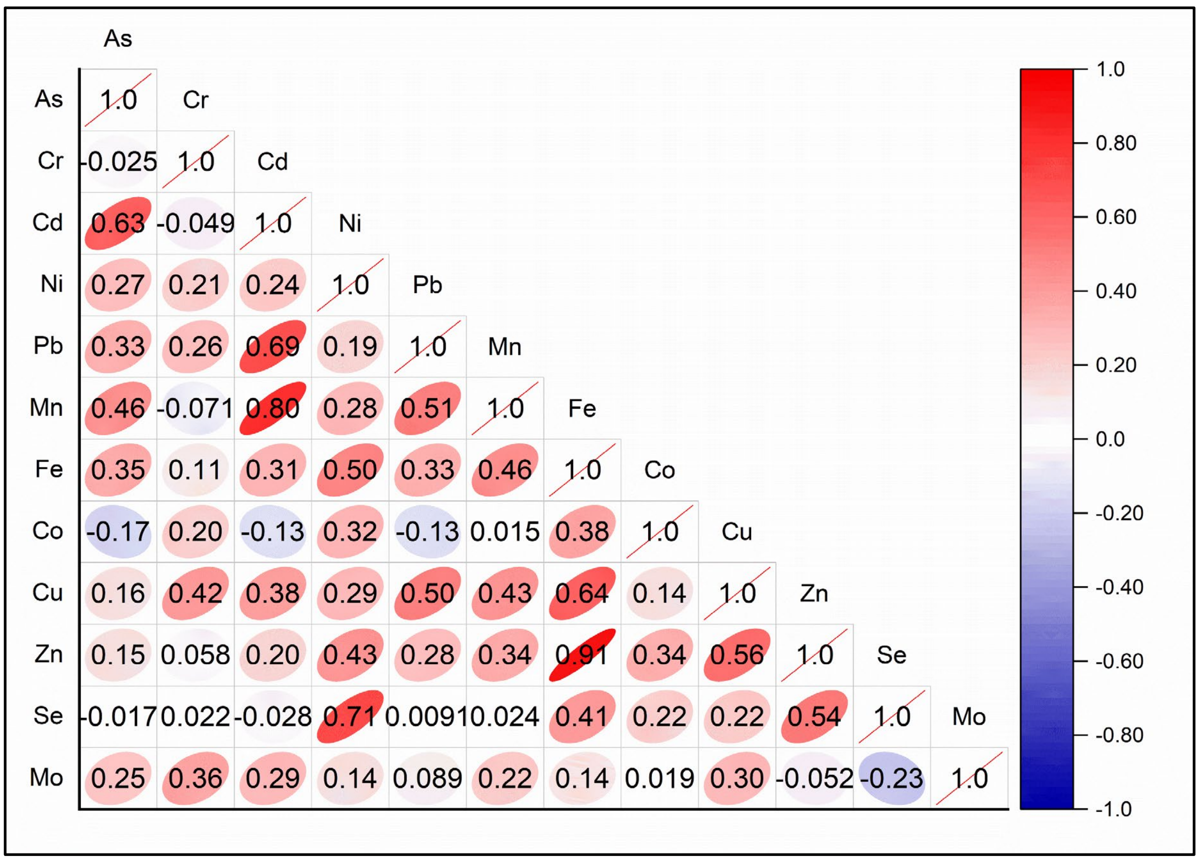

Fig. 3Pearson correlation matrix among the heavy metal content

3.3 Principal Component Analysis (PCA)

The PCA plot in Fig. 4 depicted theheavy metal correlations and concentration distribution across the study area using two principal components PC1 and PC2 which varied 35.6% and 19.3%, respectively. Data points for each district are color-coded (Ballia-Black, LakhimpurKheri-Red,and Prayagraj-Green) with 95% confidence ellipses. Moreover, the blue arrows signified the contribution of each heavy metal to the principal components. The elements like Se, Co, Ni, and Cu contributed significantly to PC1, this pattern suggests a common anthropogenic origin, as these elements are often associated with industrial effluents, electroplating waste, alloy manufacturing, and phosphate-based fertilizers**.**While Cr, Mo, and As are more strongly associated with PC2. The deviation in the distribution is attributed to the regional variations in heavy metal concentrations driven by environmental or human factors (Mishra et al., 2018). PC1, with an eigenvalue of 4.27, indicating its strong representation of key factors influencing heavy metal distribution. Moreover, PC2 has an eigenvalue of 2.31, bringing the cumulative variance explained to 54.9% (Table 7).PC1 and PC2 capture over half of the data's variability, with heavy metals (Se, Co, Ni, Cu, Cr, Mo, As) strongly contributing to these components, indicating regional sources or environmental impacts (Shakeri et al., 2021). The first four components explain 75.9% of the variance, defining the heavy metal pollution profiles for Ballia, Lakhimpur, and Prayagraj.

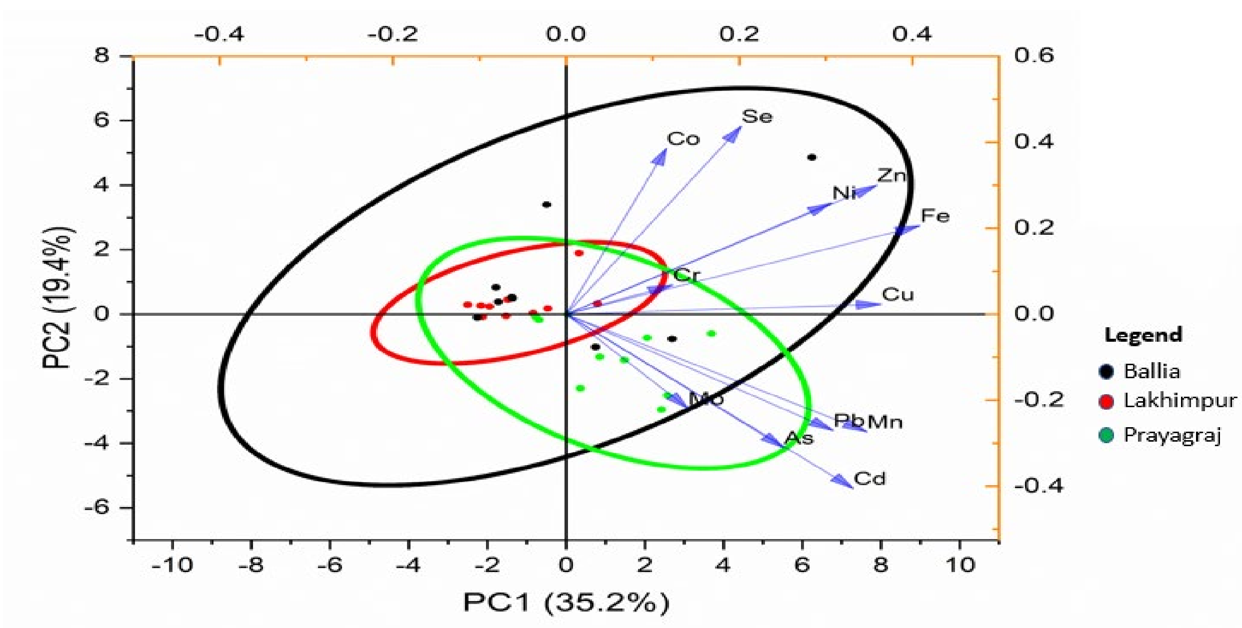

Fig. 4 PCA plot of heavy metal concentrations in Ballia, Lakhimpur, and Prayagrajdistricts of Uttar Pradesh

Table 7 Eigenvalue and percentage of variance of PCA

Principal Component Number	Eigenvalue	Percentage of Variance (%)	Cumulative (%)
1	4.26	35.58	35.58
2	2.31	19.28	54.86
3	1.53	12.78	67.64
4	0.99	8.30	75.95
5	0.85	7.11	83.07
6	0.61	5.13	88.21
7	0.49	4.13	92.35
8	0.29	2.43	94.79
9	0.24	2.06	96.85
10	0.16	1.39	98.25
11	0.13	1.09	99.35
12	0.07	0.64	100

3.4 Heavy Metal Pollution Index (HPI)

Table 5 presents the HPI values and their corresponding pollution categories for water samples collected from three districts: Lakhimpur, Prayagraj, and Ballia. HPI values were categorized into four groups: Low (HPI < 50), Medium (50 ≤ HPI < 75), High (75 ≤ HPI < 100), and Very High (HPI ≥ 100).

In Lakhimpur, four samples (40%) were classified as Low with HPI values ranging from 11.07 to 27.27, two samples (20%) as Medium (48.39–59.28), two samples (20%) as High (70.61 and 70.71), and two samples (20%) as Very High (126.27 and 144.44) shown in Fig 5. While in Prayagraj, five samples (50%) fell under the Low category (14.14–43.69), two samples (20%) as Medium (55.22–59.42), and three samples (30%) as Very High (156.24–188.16). In Ballia, all 10 samples exhibited severe contamination, with three samples (30%) falling under the Medium category (55.22–62.46) and seven samples (70%) classified as Very High (130.38–328.77). The highest HPI value (328.77) was recorded in Ballia (Sample 26), while the lowest (11.07) was observed in Lakhimpur (Sample 8). The data showed that the Ballia district has the highest frequency of Very High pollution levels, emphasizing the need for targeted interventions to address the critical pollution levels in this district. Lakhimpur displayed a mix of categories, while Prayagraj presented moderate to high pollution levels, indicating the need for sustained monitoring and remedial actions.

Table 8 HPI Value and its category of all samples

Locations	Sample no.	HPI value	Category L-Low, M-Medium, H-High, VH-Very High
Lakihimpur	1	144.4383	VH
	2	48.39563	M
	3	70.61014	H
	4	126.2699	VH
	5	27.27457	L
	6	59.27744	M
	7	70.71346	H
	8	11.07056	L
	9	16.49459	L
	10	21.73648	L
Prayagraj	11	34.24993	L
	12	43.69198	M
	13	21.3887	L
	14	59.424	M
	15	188.1626	VH
	16	175.9942	VH
	17	55.22373	M
	18	14.13937	L
	19	156.2387	VH
	20	20.865	L
Ballia	21	287.1517	VH
	22	152.6187	VH
	23	130.384	VH
	24	313.7766	VH
	25	172.1715	VH
	26	328.7666	VH
	27	55.22373	M
	28	58.15205	M
	29	188.0822	VH
	30	62.462	M

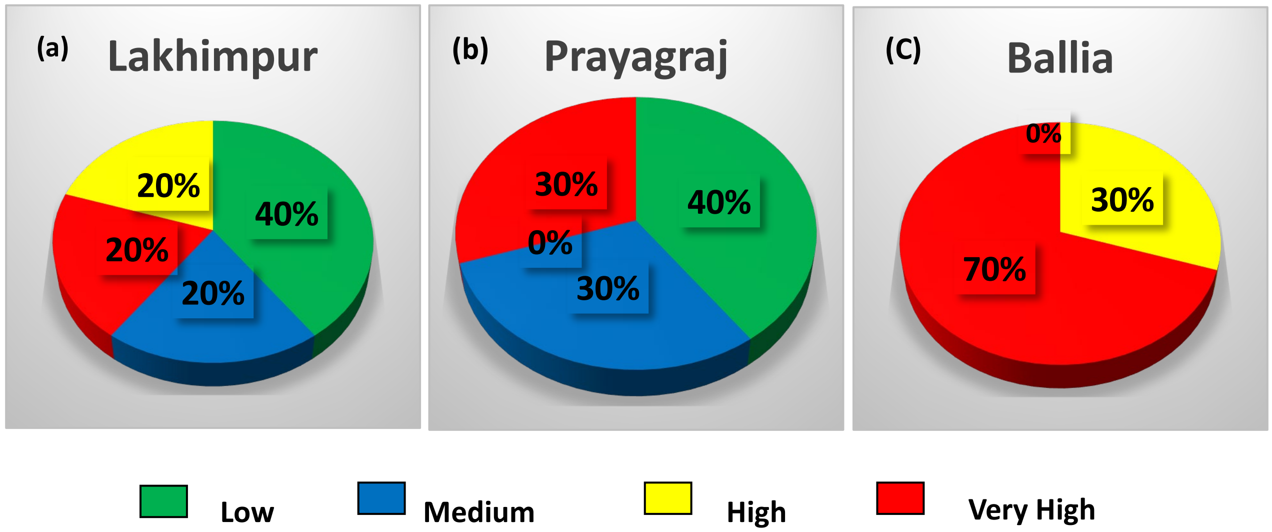

Fig.5 Pie chart diagram of HPI of a) Lakhimpur, b) Prayagraj, and c) Ballia

3.5 Health Risk Assessment

3.5.1 Non-carcinogenic risksof heavy metals

The potentiality of non-carcinogenic risksof heavy metals via oral ingestion was evaluated using the indices HQ and HI. The calculated values of the same were tabulated in Table 9. For non-carcinogenic risk, an HQ value exceeding 1 indicates potential adverse effects, while a value less than 1 is considered safe for drinking.The results showed substantial variation in metal concentrations across samples and districts. In particular, Ballia exhibited alarmingly high concentrations of Fe, Pb, Cd, and As, with HQ values indicating potential health risks. For instance, sample 21 from Ballia reported an HI of 22,664.90, suggesting a severe pollution level. Pb, As, Fe, and Cd are the primary contributors to HQ, with their extremely high values pushing the HI to a higher value.In terms of contributions to non-carcinogenic risk, Pb and As were the dominant contributors in Ballia and Prayagraj, with HI values far exceeding safe thresholds. In Lakhimpur, Cd and Mn were the primary contributors. These patterns suggest that contamination sources and exposure risks vary geographically and require location-specific mitigation strategies.

3.5.2 Carcinogenic risks of heavy metals

The total carcinogenic risk (CR_{Total}) ranged from 0.714 in Lakhimpur to 3.004 in Ballia, with Prayagraj showing the highest individual risk for Arsenic (2.166) shown in Table 10. These values are significantly higher than the USEPA acceptable limit (1×10^{-4}), indicating elevated cancer risk due to prolonged exposure. Among all elements, Arsenic and Nickel were the primary contributors to the total carcinogenic risk.

Table9HQ and HI value of non-carcinogenic health risk of Heavy metals.

Location	**Sample No.**	**HQ**												**HI**
		Mn	Fe	Zn	Cu	Se	Mo	Co	Pb	Cd	As	Ni	Cr	
Lakhimpur	1	84.50	136.77	125.22	42.40	11.63	11.69	0.63	10643.48	132.52	1228.70	19.67	0.22	12437.42
	2	20.11	81.73	111.48	17.06	9.13	5.95	0.54	2946.09	63.13	524.35	9.59	0.04	3789.18
	3	10.50	107.70	20.37	26.01	1.10	6.10	0.56	4006.09	55.30	1876.52	5.26	0.02	6115.52
	4	63.84	102.30	12.30	16.97	0.16	6.47	0.57	10956.52	94.43	6.26	30.67	0.03	11290.51
	5	7.54	25.88	30.32	19.85	1.93	6.00	0.64	1781.74	90.78	27.83	9.77	0.01	2002.29
	6	96.61	118.88	11.63	39.61	10.64	13.41	2.70	2619.13	52.17	441.74	26.30	0.17	3433.00
	7	8.96	68.16	29.80	28.74	2.56	15.76	0.64	5330.43	171.65	113.04	19.03	0.04	5788.82
	8	29.98	34.81	17.75	5.72	0.99	3.97	0.66	335.65	8.87	36.52	5.37	0.01	480.30
	9	31.90	53.40	29.96	20.14	2.87	4.07	0.52	532.17	16.17	43.48	5.15	0.00	739.84
	10	140.94	44.12	4.58	13.58	3.23	5.37	0.47	436.52	3.13	9.57	3.63	0.00	665.15
Prayagraj	11	12.35	30.35	39.10	7.18	3.08	7.04	0.59	2190.43	129.39	34.78	19.20	0.03	2473.53
	12	2.87	85.64	7.21	30.55	2.87	6.05	0.58	3038.26	38.61	10.43	15.61	0.04	3238.74
	13	11.89	32.28	9.37	5.40	0.37	5.37	0.64	373.04	254.09	204.35	5.97	0.00	902.77
	14	27.63	55.45	161.30	17.45	13.15	4.49	0.55	4686.09	55.83	146.96	9.53	0.03	5178.45

	15	202.02	157.42	57.01	39.03	0.31	12.83	1.17	9222.61	368.35	5589.57	11.56	0.03	15661.89
	16	363.80	187.23	201.57	89.41	21.50	9.29	0.43	9389.57	685.57	50.43	19.04	0.03	11017.87
	17	215.52	125.66	39.63	15.94	0.00	11.69	1.10	1022.61	251.48	280.00	13.54	0.01	1977.17
	18	4.98	59.69	7.66	10.96	3.65	12.73	1.43	231.30	36.52	66.09	14.14	0.03	449.18
	19	256.47	86.38	981.74	69.27	78.99	6.99	2.68	5725.22	217.04	4415.65	41.48	0.03	11881.95
	20	6.84	10.87	5.05	8.38	118.38	0.57	0.64	0.00	27.13	33.91	45.69	0.02	257.49
Ballia	21	298.17	279.06	493.39	46.41	45.29	9.39	0.17	15754.78	789.91	4925.22	23.03	0.07	22664.90
	22	225.99	310.36	178.26	49.33	11.37	32.87	0.24	7688.70	450.78	650.43	21.99	0.10	9620.43
	23	246.63	117.84	67.06	14.49	5.01	29.95	0.92	300.87	635.48	6940.87	26.82	0.00	8385.94
	24	434.91	152.05	62.64	27.55	1.25	11.48	1.34	20573.91	1015.30	2977.39	18.13	0.01	25275.97
	25	383.85	159.80	34.66	31.37	0.94	13.88	0.66	4055.65	607.30	6113.04	26.69	0.04	11427.89
	26	226.40	239.33	20.94	27.47	2.50	16.28	0.05	9130.43	802.43	17843.48	25.46	0.04	28334.82
	27	215.52	125.66	39.63	15.94	0.00	11.69	1.10	1022.61	251.48	280.00	13.54	0.01	1977.17
	28	300.86	96.82	116.54	9.03	5.53	12.52	0.33	46.96	48.00	1893.91	19.33	0.01	2549.83
	29	202.02	157.42	57.01	39.03	0.31	12.83	1.17	9222.61	368.35	5589.57	11.56	0.03	15661.89
	30	6.40	107.33	22.94	49.04	6.26	40.17	0.99	3504.35	59.48	913.04	17.14	0.11	4727.26

Table 10CR value of Carcinogenic risk of heavy metals

	CR(Avg)					CR_{total}
Locations	**Pb**	**Cd**	**AS**	**Ni**	**Cr**	
lakhimpur	0.010	0.013	0.194	0.457	0.040	0.714
Prayagraj	0.018	0.096	2.166	0.693	0.032	1.219
Ballia	0.009	0.039	0.487	0.666	0.018	3.004

4. Conclusion

This study highlights the serious extent of heavy metal contamination in the groundwater of the Gangetic Plain, particularly in Ballia district, where 70% of samples exhibited very high HPI values and the highest recorded HPI was 328.77. Among the 12 metals analyzed, Pb, As, Fe, Cd, and Mn frequently exceeded BIS permissible limits. Health risk assessments revealed that Pb and As were the most hazardous, with Hazard Index (HI) values reaching up to 28,334.8 in Ballia, indicating severe non-carcinogenic health risks. In addition, carcinogenic risk (CR) values for Pb, Cd, As, Ni, and Cr were evaluated. The total carcinogenic risk exceeded the acceptable limit of 1×10^{-4} in all three districts, with Prayagraj showing the highest CR due to elevated Arsenic (2.166) and Ballia reaching a total CR of 3.004, highlighting significant long-term health risks from chronic exposure. Particularly Ballia, immediate interventions such as point-source identification, regular monitoring, and installation of localized treatment systems. However, this study is limited by a small sample size and single-time sampling, which may not capture seasonal variations. Future research should include large sample set, multi-seasonal monitoring, expanded spatial coverage, and integration of hydrogeochemical modeling and source apportionment techniques to better understand pollutant dynamics and inform targeted mitigation strategies.

Data Availability

The data used and analyzed in this study are accessible upon request from the corresponding author.

Authors' Contributions

NP was responsiblefor investigation, writing, and formal analysis. SS reviewed the manuscript.AS and GG were responsible for supervision and editing the manuscript.

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