



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) analyses were performed. The results showed that 70% of the samples from Ballia exceeded the HPI threshold (>100), with the highest value being 328.77. Lead (Pb) and Arsenic (As) were the dominant contributors to non-carcinogenic risk, with HI values peaked at 28,334.8. The carcinogenic risk values for As and Ni exceeded the 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

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. This area, characterized by intense agricultural and industrial activities, faces growing pressure on groundwater resources but lacks detailed, region-specific investigations. This 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 study provides a comprehensive 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, the Indo-Gangetic Plain (IGP).

MATERIALS AND METHODS

Study Region and Sampling

The Gangetic Plain is located in the north-central part of India, where the state of Uttar Pradesh covers the largest part. This region, lying along the Ganges River, is marked by diverse hydrogeological conditions and extensive agricultural

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and industrial activities that can substantially impact groundwater quality. In this study, 30 groundwater samples were collected from three districts, Prayagraj, Lakhimpur, and Ballia, in the Central Plain Zone of this region. The geographical coordinates of the districts are listed in Table 1. All 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 h, following the standard sampling protocols of the Bureau of Indian Standards (BIS) (BIS 2015).

The sampling location map of the study area is shown in Fig. 1.

Heavy Metals Selection and their Multivariate Graphical Analysis

Based on the 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 quality monitoring analysis. The concentrations of these heavy metals were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), following the standard operating procedures of the APHA (APHA 2012).

Table 1: Description of the study area.

| Sl.No. | Name of the District | 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 |

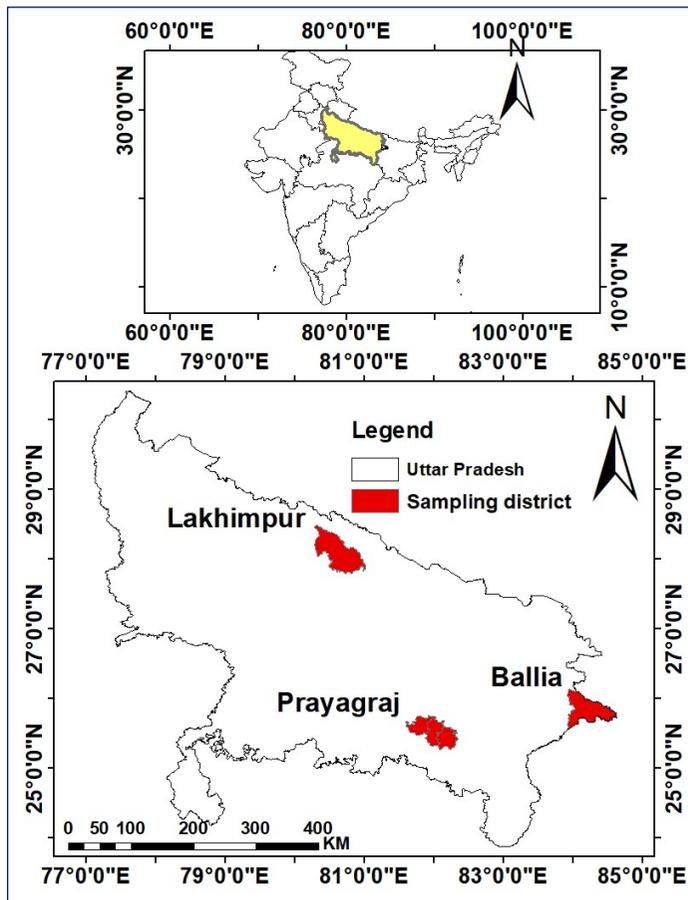


Fig. 1: Sampling Location map.

Table 2: Sub-Index calculation of the average of Heavy metals.

| Heavy Metals | Mean Concentration (Ci) [$\mu\text{g.L}^{-1}$] | 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 |

To examine inter-metal correlations and identify potential sources of contamination, the Pearson correlation coefficient (PCC) was calculated using the SPSS software (version 25). Before using SPSS, all data were normalized using the Shapiro-Wilk test to ensure their suitability for parametric correlation. Multivariate statistical techniques, such as Principal Component Analysis (PCA), were employed using OriginLab software (version 9.6.5) to identify the underlying factors contributing to heavy metal distribution across the study area. Moreover, the Box plot technique was used for graphical representation and to enhance the understanding of data trends and distribution.

Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) was used to assess the overall water quality. 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 ranged from 0 to 1. For each parameter in the HPI calculation (Table 2), the unit weight (W_i) was inversely proportional to the recommended standard (S_i). HPI can be expressed mathematically as follows: (1) (Mohan et al. 1996).

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

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):

$$Q_i = \sum_{i=1}^n \frac{\{M_i - I_i\}}{(S_i - I_i)} \times 100 \quad \dots(2)$$

Where M_i , I_i , and S_i 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 safe drinking water. In this study, a modified classification scale was adopted, categorizing HPI values into four levels: low, medium, high, and very high, as detailed in Table 3.

Health Risk Assessment Framework

The assessment of health risks from metal pollutants in groundwater includes consideration of both non-carcinogenic and carcinogenic risks. The risk was quantified according to 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 pathways was estimated using Equations (3) and (4), respectively.

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

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

The Average Daily Intake (ADI) represents the daily exposure to heavy metals, expressed in $\text{mg.kg}^{-1}.\text{day}^{-1}$, and is calculated using the parameters shown in Table 4.

Potential non-carcinogenic risks are evaluated through the Hazard Quotient (HQ) (Eq. 5), which is the ratio of the

Table 3: HPI value for drinking water used in this study.

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

Table 4: Exposure Parameter used in Health Risk Assessment.

| Parameter | Description | Value | Unit | Reference |
|-----------|------------------------------|------------------|-----------|-----------|
| C | Concentration 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 | - |

exposure level of a specific element to its reference dose (RfD), as defined by the 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).

$$HQ = \frac{ADI}{RfD} \quad \dots(5)$$

$$HI = \sum HQ \quad \dots(6)$$

The carcinogenic risk (CR) was calculated by multiplying the oral slope factor (Sf) by the exposure level (ADI) (Eq. 7), which is an important measure in risk assessment. The Sf values are listed in Table 5. The acceptable range for CR or CR_{total} is defined as 1×10⁻⁶ to 4×10⁻¹ (USEPA 2009). A CR or CR_{total} less than 1×10⁻⁶ indicates a negligible carcinogenic risk, whereas a CR or CR_{total} greater than 1×10⁻⁴ signifies an unacceptable carcinogenic risk (USEPA 2001).

$$CR = ADI \times Sf \quad \dots(7)$$

Quality Assurance and Quality Control (QA/QC)

All samples were handled carefully to avoid contamination and ensure reliability. Instrument calibration was performed before analysis, and the accuracy of the analysis was verified

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 ⁻¹ .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 | - |

by analyzing the reference standard of water (NIST 1640a and NIST 1643b). The analytical precision was verified by calculating the relative standard deviations, which remained within acceptable limits (<5%) for all elements.

RESULTS AND DISCUSSION

Graphical Representation of Heavy Metals

The box plot representation of all 12 targeted heavy metals is shown in Fig. 2a-l, of these 12 elements, As, Cr, Cd, Ni, and Pb are carcinogenic, whereas the remaining seven (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⁻¹) in the groundwater of the collected water sample exceeded the guideline value (300 µg.L⁻¹) set by the WHO and BIS (Fig. 2a). The concentrations of Cu and Zn (Fig. 2b-c) were well within the acceptable limits, with average values of 21.29±14.9 µg.L⁻¹ and 574.25±1106.4 µg.L⁻¹, respectively. Co and Mo (Fig. 2d-e) were detected at minimal concentrations, indicating that there was no immediate concern. Se showed a high value of 11.345 µg.L⁻¹, exceeding the BIS guideline (10 µg.L⁻¹) (Fig. 2f). Cd value ranged from 0.03 to 9.73 µg.L⁻¹, with an average of 2.48±2.7 µg.L⁻¹, approaching the 3µg.L⁻¹ specified by both BIS and WHO (Fig. 2g). Arsenic (As) levels were considerably elevated, reaching a maximum of 102.6 µg.L⁻¹, with an average of 12.12±21.2 µg.L⁻¹, surpassing the 10 µg.L⁻¹ 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 such as Ballia and Lakhimpur may be attributed to both natural geogenic sources and anthropogenic influences, particularly agricultural runoff (e.g., phosphate fertilizers and 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⁻¹, with average values of 1.14±1.4 µg.L⁻¹ and 6.82±3.8 µg.L⁻¹, respectively. Pb (Fig. 2j) showed alarmingly high

Table 6: Percentage of sample exceeding BIS limits for Heavy Metals.

| Heavy metal | BIS Limits [$\mu\text{g.L}^{-1}$] | % 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 |

values, peaking at $118.3 \mu\text{g.L}^{-1}$ with an average of $28.13 \pm 29.2 \mu\text{g.L}^{-1}$, far exceeding both the BIS and WHO permissible limits, underscoring severe contamination risk. Mn (Fig. 2l) levels were also markedly high, ranging from 7.7 to $1167 \mu\text{g.L}^{-1}$, averaging $370.30 \pm 360.8 \mu\text{g.L}^{-1}$, surpassing the BIS limit of $100 \mu\text{g.L}^{-1}$ (Table 6).

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

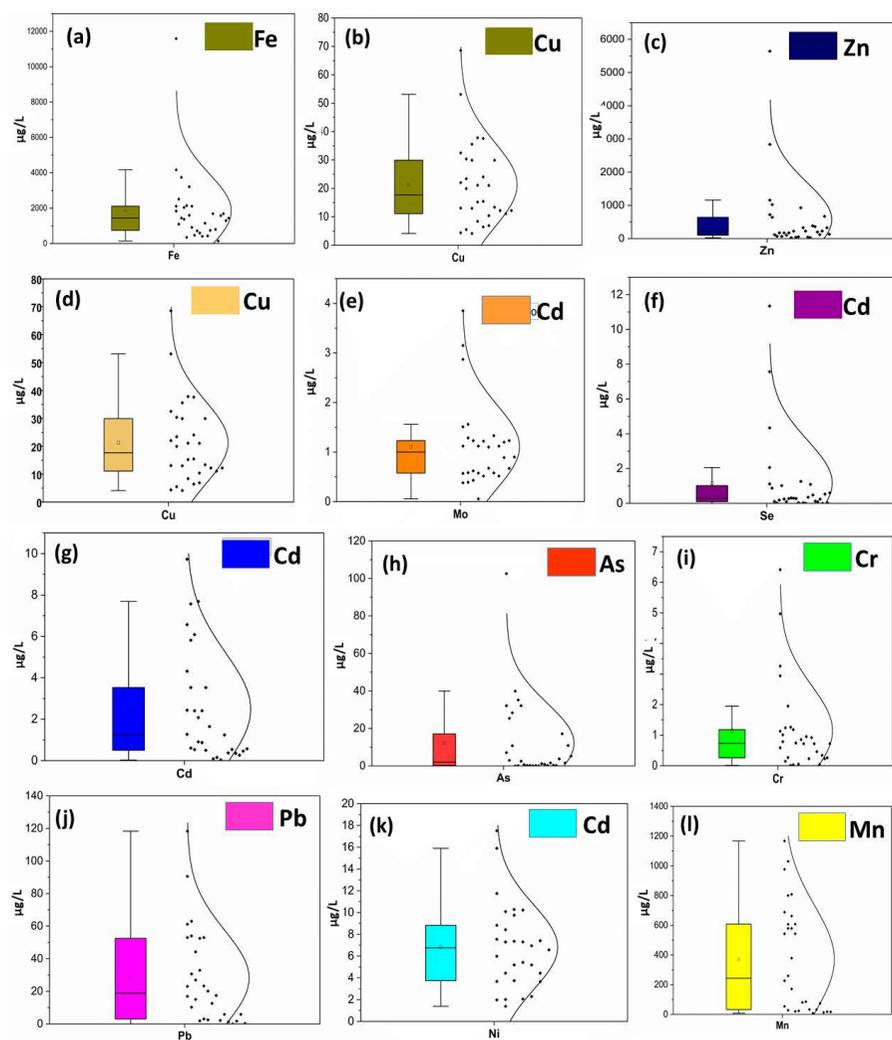


Fig. 2: Box plot diagram with kernel density estimate of heavy metals (a) Fe, (b) Cu, (c) Zn, (d) Co, (e) Mo, (f) Se, (g) Cd, (h) As, (i) Cr, (j) Pb, (k) Ni, and (l) Mn.

Pearson Correlation Matrix

The Pearson correlation matrix of the heavy metal content in the groundwater of the study area is shown in Fig. 3. To better interpret the relationships among heavy metals, correlation coefficients were grouped by strength: strong ($r > 0.7$), moderate ($0.5 \leq r \leq 0.7$), and weak ($r < 0.5$). Strong correlations were observed between Cd and Mn ($r = 0.80$), Fe and Co ($r = 0.79$), and Pb and As ($r = 0.75$), suggesting common anthropogenic sources such as industrial discharge or agrochemical runoff (Mahato et al. 2023). Moderate correlations were observed between Cr and Ni and Zn–Cu, which may indicate shared transport or geogenic pathways (Singaraja et al. 2015). Weak correlations were noted for pairs such as Mo–Zn, implying dissimilar origins or independent mobility in groundwater. Conversely, cobalt (Co) exhibited negative correlations with elements such as 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 the identification of contamination origins and assessment of environmental risks.

Principal Component Analysis (PCA)

The PCA plot in Fig. 4 depicts the heavy metal correlations and concentration distribution across the study area using two principal components, PC1 and PC2, which varied by 35.6% and 19.3%, respectively. Data points for each district are color-coded (Ballia-Black, Lakhimpur-Kheri- Red, and Prayagraj-Green) with 95% confidence ellipses. The blue arrows signify 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 was attributed to regional variations in heavy metal concentrations driven by environmental or human factors (Mishra et al. 2018). PC1, with an eigenvalue of 4.27, strongly represented the key factors influencing heavy metal distribution. Moreover, PC2 had an eigenvalue of 2.31, bringing the cumulative variance explained to 54.9% (Table 7). PC1 and PC2 captured over half of the data variability, with heavy metals (Se, Co, Ni, Cu,

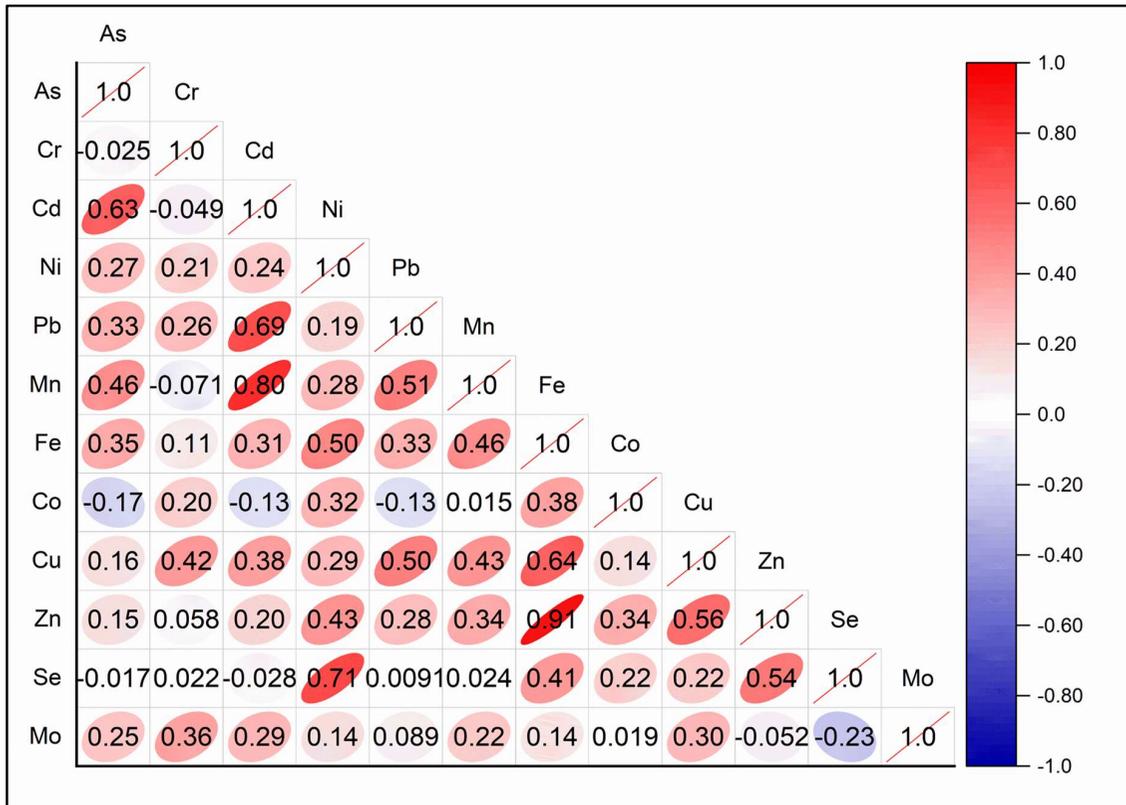


Fig. 3: Pearson correlation matrix among the heavy metal content.

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 |

Cr, Mo, and As) strongly contributing to these components, indicating regional sources or environmental impacts (Shakeri et al. 2021). The first four components explained 75.9% of the variance, defining the heavy metal pollution profiles for Ballia, Lakhimpur, and Prayagraj.

Heavy Metal Pollution Index (HPI)

Table 8 presents the HPI values and their corresponding pollution categories for the water samples collected from the three districts: Lakhimpur, Prayagraj, and Ballia. HPI values were categorized into four groups: low (HPI < 50), medium ($50 \leq \text{HPI} < 75$), high ($75 \leq \text{HPI} < 100$), 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%) under the Medium category (55.22–59.42), and three samples (30%) under the Very High category (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.

Health Risk Assessment

Non-carcinogenic risks of heavy metals: The potentiality of non-carcinogenic risks of 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

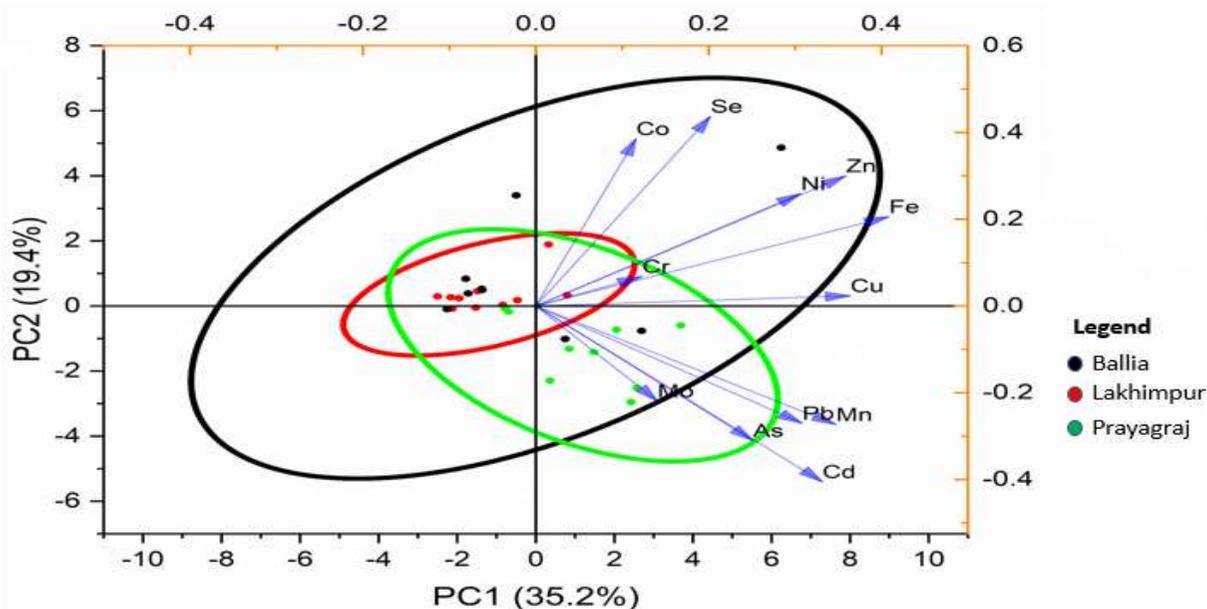


Fig. 4: PCA plot of heavy metal concentrations in Ballia, Lakhimpur, and Prayagraj districts of Uttar Pradesh.

Table 8: HPI Value and its category for all samples.

| Locations | Sample No. | HPI value | Category L-Low, M-Medium, H-High, VH-Very High |
|-----------|------------|-----------|--|
| Lakhimpur | 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 |

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.

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), as shown in Table 10. These values are significantly higher than the USEPA acceptable limit (1×10^{-4}), indicating an elevated cancer risk due to prolonged exposure. Among all elements, As and Ni were the primary contributors to the total carcinogenic risk.

CONCLUSIONS

This study highlights the serious extent of heavy metal contamination in the groundwater of the Gangetic Plain, particularly in the Ballia district, where 70% of the samples exhibited very high HPI values, with the highest recorded HPI being 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

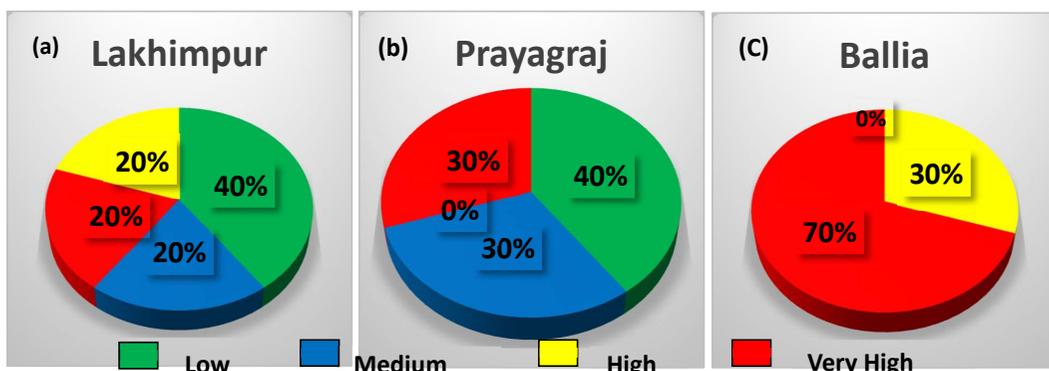


Fig. 5: Pie chart diagram of HPI of a) Lakhimpur, b) Prayagraj, and c) Ballia.

Table 9: HQ and HI values 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 10: CR value of Carcinogenic risk of heavy metals.

| Locations | CR(Avg) | | | | | CR _{total} |
|-----------|---------|-------|-------|-------|-------|---------------------|
| | 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 |

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 a 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.

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