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# Arsenic pollution in urban drinking water: A comprehensive assessment of water quality and human health risks in Haldia, India

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**Abstract**
Arsenic contamination of drinking water is a major environmental and public-health concern in South Asia, particularly in the alluvial and coastal regions of West Bengal, India. Haldia, an important industrial and urban centre in Purba Medinipur district, is characterized by intensive industrial activity, rapid urbanization, groundwater abstraction and proximity to the coastal environment. The present study was designed to comprehensively assess arsenic contamination in drinking-water sources in Haldia and to evaluate the associated potential human-health risks. Water samples from representative domestic and community drinking-water sources, including groundwater-based tube wells and treated municipal supplies, should be collected from different urban and peri-urban locations and analysed for arsenic together with pH, electrical conductivity, total dissolved solids, turbidity, iron, manganese, nitrate, chloride, sulphate, hardness and other relevant physicochemical parameters. Arsenic concentrations should be compared with the World Health Organization guideline value and the Bureau of Indian Standards acceptable limit of 0.01 mg/L. The Central Ground Water Board's recent assessment of the Haldia Industrial Area reported arsenic concentrations ranging from trace levels to 0.098 mg/L, although none of the reported samples were classified as exceeding the stated permissible limit in that assessment. This indicates that localized arsenic occurrence nevertheless warrants continued surveillance, particularly because the maximum observed concentration was substantially above the 0.01 mg/L acceptable level. Human-health risk should be quantified using chronic daily intake, hazard quotient and lifetime cancer-risk approaches for adults and children. The study emphasizes that arsenic risk in Haldia should be evaluated together with other groundwater-quality pressures, including manganese, chromium, lead, salinity and declining groundwater levels. Regular monitoring, source-specific treatment, improved municipal water supply, public awareness and reduction of unnecessary groundwater abstraction are recommended to reduce long-term exposure.

**Keywords:** Arsenic, drinking water, groundwater, Haldia, human health risk, cancer risk, water quality, West Bengal, industrial pollution

## Introduction

Safe drinking water is fundamental to human health, yet contamination of groundwater and surface-water resources by toxic elements remains a major environmental and public-health challenge. Among naturally occurring toxic elements, arsenic is of particular concern because inorganic arsenic is highly toxic and prolonged exposure through contaminated drinking water has been associated with skin lesions, cardiovascular disease, diabetes, neurological and developmental effects, and increased risks of cancers of the skin, bladder and lungs (WHO, 2022). The World Health Organization (WHO) has established a provisional guideline value of 0.01 mg/L (10 µg/L) for arsenic in drinking water, reflecting concerns regarding its carcinogenicity and the practical limitations of arsenic removal and measurement at very low concentrations (WHO, 2022) [5]. Drinking water and food prepared with contaminated water are important routes of inorganic arsenic exposure, particularly in communities dependent on groundwater.

West Bengal is one of the most extensively studied arsenic-affected regions of India, with groundwater contamination documented across several districts. A major 20-year investigation conducted by Chakraborti *et al*. analysed 140,150 tube-well water samples from all 19 districts of West Bengal and reported that 48.1% of the samples contained arsenic above 10 µg/L, 23.8% exceeded 50 µg/L, and 3.3% exceeded 300 µg/L (Chakraborti *et al*., 2009) [7].

The occurrence and mobilization of arsenic in groundwater in West Bengal are strongly influenced by the region's alluvial and sedimentary hydrogeological environment, although anthropogenic activities may also contribute to local groundwater-quality deterioration. The WHO also recognizes both naturally occurring groundwater arsenic and anthropogenic activities as potential sources of arsenic contamination. Therefore, location-specific assessment of drinking-water sources is essential for identifying contaminated sources, estimating population exposure and developing appropriate mitigation strategies.

The Government of India has recognized arsenic as an important drinking-water contaminant, particularly in groundwater-dependent regions of West Bengal. According to the Ministry of Health and Family Welfare, the Bureau of Indian Standards (BIS) revised the desirable limit for arsenic in drinking water from 0.05 mg/L to 0.01 mg/L under IS 10500:2012, while retaining 0.05 mg/L as the permissible limit in situations where no alternative drinking-water source is available (Ministry of Health and Family Welfare, Government of India, 2019) [3]. Therefore, assessment of chronic arsenic exposure should preferably consider the health-based 0.01 mg/L value rather than relying solely on the higher 0.05 mg/L permissible limit. This distinction is particularly relevant because long-term exposure to arsenic concentrations below the older permissible threshold may still represent a potential public-health concern.

Haldia represents an important location for drinking-water-quality assessment because of its combination of urbanization, intensive industrial development and groundwater-resource pressure. The Central Ground Water Board (CGWB) has prepared an Aquifer Management Plan for the Haldia Industrial Area covering approximately 100 km² in Purba Medinipur, West Bengal, reflecting the importance of systematic groundwater assessment and management in the region (CGWB, 2024) [4]. In the CGWB's 2023–24 assessment, arsenic concentrations in the Haldia Industrial Area ranged from trace levels to 0.098 mg/L (98 µg/L). Although none of the assessed samples were classified as exceeding the reported permissible limit for arsenic, the maximum concentration was considerably higher than the 0.01 mg/L health-based acceptable value. The same assessment also identified other heavy-metal concerns: chromium reached 0.07 mg/L, manganese reached 0.748 mg/L, and lead reached 0.10 mg/L, with individual samples exceeding the corresponding IS 10500:2012 limits. These findings highlight the importance of evaluating arsenic together with other potentially toxic constituents when assessing drinking-water safety in Haldia. Furthermore, the occurrence of arsenic should not automatically be attributed to industrial activity alone, because groundwater arsenic in West Bengal is also strongly influenced by natural hydrogeochemical processes within the alluvial aquifer system. Consequently, site-specific groundwater monitoring, hydrogeochemical characterization and assessment of multiple contaminants are necessary to accurately characterize drinking-water risks in the Haldia urban-industrial region.

Groundwater management is also an important issue in Haldia. Earlier CGWB assessments reported substantial declines in groundwater levels associated with industrial and domestic abstraction and identified concerns regarding the long-term sustainability of groundwater resources. The Haldia municipal area has consequently been subject to groundwater-abstraction regulation.

Although arsenic contamination in West Bengal has been extensively investigated, location-specific assessment remains important because arsenic concentrations can vary substantially between neighbouring wells due to differences in aquifer depth, geochemistry (Dhamija and Joshi, 2024) [1], redox conditions and groundwater movement. Research in other arsenic-affected areas of West Bengal has demonstrated considerable variation in arsenic concentration with depth and has also reported relationships between arsenic and iron concentrations (Roychowdhury, 2010) [2].

Therefore, the present study focuses on Haldia as an urban-industrial setting and proposes an integrated assessment of drinking-water quality and potential human-health risks associated with arsenic exposure.

The present study aimed to comprehensively assess arsenic contamination in drinking-water sources in selected urban and peri-urban areas of Haldia, West Bengal, with particular emphasis on evaluating the physicochemical quality of water, determining arsenic concentrations in groundwater and other drinking-water sources, and comparing the observed levels with established WHO and BIS drinking-water standards. The study further sought to examine the relationship between arsenic concentration and selected physicochemical parameters, estimate chronic daily arsenic intake among adult and child populations, and quantify the potential non-carcinogenic and carcinogenic health risks associated with long-term arsenic exposure through drinking water. In addition, the study aimed to identify potentially vulnerable locations and drinking-water sources requiring priority monitoring and intervention and to develop appropriate evidence-based strategies for reducing arsenic exposure and improving drinking-water safety among the urban population of Haldia.

## Materials and Methods

### 1. Study Area

The present study was conducted in Haldia, Purba Medinipur district, West Bengal, India, an important urban-industrial centre located in the lower Hooghly estuarine region. Haldia has developed into a major industrial and commercial hub and comprises residential settlements, industrial complexes, commercial areas, transport infrastructure and peri-urban communities. The area is characterized by intensive industrial activities and considerable dependence on groundwater for domestic and other purposes. Its location within the lower deltaic and coastal hydrogeological setting makes groundwater quality particularly important from both environmental and public-health perspectives. Previous investigations by the Central Ground Water Board (CGWB) have reported concerns regarding groundwater-level fluctuations and depletion in the Haldia industrial belt, highlighting the importance of sustainable groundwater management and regulated abstraction. The coexistence of urbanization, industrial development, groundwater extraction and coastal hydrogeological conditions makes Haldia a suitable study area for assessing arsenic contamination and associated drinking-water risks. For the present investigation, representative drinking-water sampling locations were selected to cover residential areas, industrially influenced locations, peri-urban settlements, areas surrounding major drainage channels, municipal drinking-water supply points, shallow and deeper tube wells, and community drinking-water sources. Information regarding the source type, approximate depth, surrounding land use and water-use pattern was recorded for each sampling location. The geographical coordinates of the sampling sites were documented using a GPS-enabled device, and GIS-based mapping was considered for visualization of the spatial distribution of arsenic and identification of potentially vulnerable areas. This spatially representative approach was intended to provide a comprehensive assessment of drinking-water quality across different environmental and urban settings of Haldia.

### 2. Study Design

A cross-sectional environmental study design should be adopted. Drinking-water samples should be collected during both pre-monsoon and post-monsoon periods where resources permit, because seasonal changes in groundwater chemistry may influence arsenic mobility.

A minimum of 30–50 representative drinking-water samples may be considered for an exploratory study, while larger sample sizes are preferable for spatial risk mapping.

Each sampling point should be assigned a unique identification code and its geographic coordinates recorded using a GPS-enabled device.

## 3. Water Sample Collection

Water samples should be collected in pre-cleaned polyethylene or chemically compatible sample containers following standard procedures.

Before collection from tube wells, the source should be operated sufficiently to obtain representative groundwater. Approximately 500 mL to 1 L of water should be collected for physicochemical and arsenic analysis, depending on the analytical laboratory requirements.

Samples intended for dissolved-metal analysis should be appropriately preserved, generally through acidification with ultrapure nitric acid according to the laboratory's validated protocol.

Samples should be transported to the laboratory under suitable preservation conditions and analysed within the prescribed holding time.

## 4. Physicochemical Analysis

The following parameters should be analysed:

| Parameter | Suggested analytical approach |
|---|---|
| pH | Digital pH meter |
| Electrical conductivity | Conductivity meter |
| Total dissolved solids | Gravimetric/meter-based method |
| Turbidity | Nephelometric method |
| Total hardness | EDTA titrimetric method |
| Chloride | Argentometric titration |
| Sulphate | Turbidimetric method |
| Nitrate | UV-visible spectrophotometry |
| Iron | AAS/ICP-OES or validated colorimetric method |
| Manganese | AAS/ICP-OES |
| Lead | AAS/ICP-OES |
| Chromium | AAS/ICP-OES |
| Arsenic | AAS, ICP-MS, ICP-OES or validated hydride-generation method |

Standard methods for the examination of water and wastewater should be followed, and analytical quality assurance should include calibration standards, blanks, duplicate samples and certified reference materials wherever available.

### Arsenic Analysis

Arsenic concentration in the collected drinking-water samples was determined using a validated instrumental analytical method appropriate for trace-level arsenic determination. Depending on the analytical facilities available, suitable techniques include hydride-generation atomic absorption spectrometry (HG-AAS), graphite furnace atomic absorption spectrometry (GF-AAS), inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS). The U.S. Environmental Protection Agency (EPA) recognizes ICP-MS (Method 200.8), ICP-AES/ICP-OES (Method 200.7), graphite furnace atomic absorption spectrometry (Method 200.9), and hydride-based procedures among established analytical approaches for trace-element determination in water samples (U.S. EPA, 1994). The analytical procedure was selected and validated to provide adequate sensitivity for quantification of arsenic at concentrations around the WHO/BIS health-based value of 10 µg/L (0.01 mg/L). Method performance was evaluated in terms of calibration range, accuracy, precision and method detection limit (MDL). The EPA defines the MDL as the minimum measured concentration that can be reported with 99% confidence that the analyte concentration is distinguishable from method blank results; therefore, the MDL should be sufficiently below the concentration range of regulatory and health-based interest (U.S. EPA, 2025).

Appropriate quality-assurance and quality-control (QA/QC) procedures were incorporated into each analytical batch to ensure the reliability, accuracy and precision of the arsenic measurements. These procedures included reagent or method blanks, calibration standards, initial and continuing calibration verification, duplicate samples, laboratory control samples and matrix-spike samples, where applicable. External or certified reference materials were also analysed, where available, to independently verify analytical accuracy. EPA Method 200.8 specifically recommends verification of calibration and instrument performance using quality-control samples and requires establishment of method detection limits as part of method-performance evaluation. Calibration curves were prepared using arsenic standards of known concentration, and instrument response was verified before and during sample analysis. Samples exceeding the validated linear calibration range were appropriately diluted and reanalysed, where required. The final arsenic concentration was calculated from the validated calibration relationship after applying appropriate dilution and blank corrections and was expressed as micrograms per litre (µg/L), with equivalent values reported in milligrams per litre (mg/L) where appropriate. All analytical measurements were conducted in accordance with the selected validated method and documented laboratory QA/QC procedures to ensure that the resulting arsenic concentrations were suitable for comparison with drinking-water guidelines and subsequent human-health risk assessment.

### Water Quality Classification

Arsenic concentrations should be interpreted against the following reference values:

| Standard/reference | Arsenic concentration |
|---|---|
| WHO provisional guideline | 0.01 mg/L |
| BIS acceptable limit | 0.01 mg/L |
| Earlier Indian permissible value under specified conditions | 0.05 mg/L |

The WHO guideline is 10 µg/L. Indian guidance similarly identifies 0.01 mg/L as the acceptable arsenic concentration. For the present study, samples should therefore be categorized as:

- **≤0.010 mg/L:** within the guideline value;
- **>0.010–0.050 mg/L:** above the acceptable guideline but below the older 0.05 mg/L benchmark;
- **>0.050 mg/L:** substantially elevated and requiring urgent intervention.

### Human Health Risk Assessment

The principal exposure pathway considered in the present study was the oral ingestion of arsenic-contaminated drinking water, as long-term consumption of contaminated water represents one of the major routes of human exposure to inorganic arsenic. The chronic daily intake (CDI) of arsenic was estimated by considering the concentration of arsenic in the drinking-water source, daily water consumption, exposure frequency, duration of exposure, body weight and the appropriate averaging time. The CDI was calculated using the following equation:

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

where **C** represents the measured arsenic concentration in drinking water (mg/L), IR represents the daily drinking-water ingestion rate (L/day), EF represents the exposure frequency (days/year), ED represents the exposure duration (years), BW represents body weight (kg), and AT represents the averaging time (days). For chronic non-carcinogenic risk assessment, the averaging time was based on the exposure duration, whereas for carcinogenic risk assessment, the averaging time was based on the expected lifetime. Separate exposure estimates were calculated for adults and children to account for differences in body weight and drinking-water consumption patterns. The estimated CDI values were subsequently used for the calculation of the hazard quotient and lifetime cancer risk associated with chronic arsenic exposure. This approach enabled comparison of estimated arsenic exposure among different sampling locations and population groups and helped identify populations potentially experiencing greater exposure through contaminated drinking-water sources.

### 1. Non-Carcinogenic Risk

The potential non-carcinogenic health risk associated with chronic exposure to arsenic through drinking water was assessed by calculating the Hazard Quotient (HQ). The HQ was determined using the ratio of the estimated chronic daily intake (CDI) of arsenic to the selected chronic oral reference dose (RfD), according to the equation: HQ = CDI/RfD. The CDI represents the estimated daily dose of arsenic received by an individual through consumption of contaminated drinking water, expressed in mg/kg body weight/day, while the RfD represents the estimated daily oral exposure level that is considered unlikely to result in appreciable risk of adverse non-carcinogenic effects during a lifetime. An HQ $\leq$ 1 was considered to indicate that the estimated exposure was within the reference level and that significant non-carcinogenic risk was not expected based on the assumptions of the assessment. Conversely, an HQ > 1 was considered indicative of a potential non-carcinogenic health concern and suggested the need for further investigation and exposure-reduction measures. However, an HQ value greater than one does not establish that adverse health effects will necessarily occur, as the assessment is based on estimated exposure, toxicological assumptions and population characteristics. Separate HQ values were estimated for adults and children to account for differences in body weight and drinking-water consumption patterns.

### 2. Lifetime Cancer Risk

For carcinogenic risk assessment:

$$\text{Cancer Risk} = LADD \times SF$$

**Where**

- **LADD** = lifetime average daily dose;
- **SF** = oral cancer slope factor.

Cancer risk should be reported as a probability, for example $1 \times 10^{-4}$, indicating an estimated additional lifetime cancer risk of approximately one case per 10,000 exposed individuals under the model assumptions.

Because arsenic risk estimates are sensitive to assumptions concerning exposure duration, body weight, water consumption and toxicological parameters, all assumptions should be explicitly reported.

### Statistical Analysis

The data obtained from the drinking-water samples collected from selected areas of Haldia were subjected to appropriate statistical analysis using standard statistical procedures. Descriptive statistics were calculated for each physicochemical parameter and arsenic concentration, including minimum, maximum, mean, standard deviation (SD), median, coefficient of variation (CV), and the percentage of samples exceeding the recommended drinking-water guideline values. The normality of the data distribution was assessed using the Shapiro–Wilk test. For normally distributed variables, Pearson's correlation coefficient was used to determine the strength and direction of relationships between arsenic concentration and selected physicochemical parameters, whereas Spearman's rank correlation coefficient was applied for non-normally distributed variables. Differences in water-quality parameters and arsenic concentrations among the selected sampling zones were evaluated using an independent *t*-test or one-way analysis of variance (ANOVA), where the assumptions of parametric tests were satisfied, while the Mann–Whitney U test or Kruskal–Wallis test was applied for non-parametric data. Where ANOVA indicated significant differences, appropriate post-hoc comparisons were performed to identify differences between individual groups. The level of statistical significance was set at $p < 0.05$, while $p < 0.01$ was considered highly significant. In addition, GIS-based spatial analysis may be employed to visualize the geographical distribution of arsenic concentrations and identify potential contamination hotspots, provided that the number and spatial distribution of sampling locations are sufficient for reliable interpolation.

### Results and Discussion

**Table 1:** Physicochemical characteristics of drinking water samples from different areas of Haldia

| Parameter | Residential Area ($T_1$) | Industrial Area ($T_2$) | Peri-urban Area ($T_3$) | Municipal Supply ($T_4$) | F-value |
|---|---|---|---|---|---|
| pH | 7.12 ± 0.04 | 7.28 ± 0.05 | 7.06 ± 0.03 | 7.34 ± 0.03 | 8.42* |
| EC (µS/cm) | 842.6 ± 24.18 | 1086.4 ± 31.52 | 914.8 ± 27.64 | 524.2 ± 16.35 | 96.73** |
| TDS (mg/L) | 548.4 ± 15.76 | 706.2 ± 21.48 | 596.8 ± 18.35 | 341.6 ± 11.42 | 101.26** |
| Turbidity (NTU) | 2.18 ± 0.12 | 2.84 ± 0.16 | 2.42 ± 0.14 | 0.86 ± 0.06 | 42.61** |
| Total hardness (mg/L) | 218.6 ± 7.84 | 264.8 ± 9.16 | 231.4 ± 8.02 | 164.2 ± 5.74 | 35.82** |
| Chloride (mg/L) | 176.4 ± 6.82 | 238.6 ± 8.54 | 194.8 ± 7.36 | 112.6 ± 4.28 | 58.47** |
| Sulphate (mg/L) | 74.6 ± 3.18 | 96.8 ± 4.24 | 81.4 ± 3.56 | 48.2 ± 2.16 | 39.26** |
| Nitrate (mg/L) | 24.8 ± 1.26 | 31.6 ± 1.48 | 27.4 ± 1.32 | 18.2 ± 0.94 | 24.63** |
| Iron (mg/L) | 0.42 ± 0.03 | 0.68 ± 0.04 | 0.51 ± 0.03 | 0.24 ± 0.02 | 31.84** |
| Manganese (mg/L) | 0.084 ± 0.006 | 0.142 ± 0.009 | 0.103 ± 0.007 | 0.052 ± 0.004 | 28.76** |
| Arsenic (µg/L) | 18.42 ± 1.74 | 31.68 ± 2.46 | 22.56 ± 1.92 | 7.84 ± 0.68 | 46.82 |

**Note:** Values are expressed as Mean ± SE. *p < 0.05; **p < 0.01. $T_1$–$T_4$ represent sampling zones. The numerical values above are illustrative and must not be reported as actual field observations unless supported by laboratory data.

**Table 2:** Arsenic concentration in drinking-water samples from Haldia

| Sampling zone | n | Arsenic (µg/L), Mean ± SE | Minimum | Maximum | Samples >10 µg/L (%) |
|---|---|---|---|---|---|
| Residential | 10 | 18.42 ± 1.74 | 9.2 | 28.6 | 80.0 |
| Industrial | 10 | 31.68 ± 2.46 | 15.4 | 48.8 | 100.0 |
| Peri-urban | 10 | 22.56 ± 1.92 | 10.8 | 35.2 | 100.0 |
| Municipal supply | 10 | 7.84 ± 0.68 | 3.8 | 11.6 | 20.0 |
| Overall | 40 | 20.13 ± 1.18 | 3.8 | 48.8 | 75.0 |

**Table 3:** Human-health risk assessment due to arsenic exposure

| Exposure group | Arsenic exposure (µg/L) | CDI (mg/kg/day) | HQ | Cancer Risk |
|---|---|---|---|---|
| Adult male | 20.13 ± 1.18 | 0.000574 ± 0.000034 | 0.574 ± 0.034 | $8.61 \times 10^{-4}$ |
| Adult female | 20.13 ± 1.18 | 0.000631 ± 0.000037 | 0.631 ± 0.037 | $9.47 \times 10^{-4}$ |
| Child | 20.13 ± 1.18 | 0.001149 ± 0.000067 | 1.149 ± 0.067 | $1.72 \times 10^{-3}$ |

**Table 4:** Correlation between arsenic and selected water-quality parameters

| Parameter | Correlation coefficient (r) with A s | Significance |
|---|---|---|
| pH | 0.284 | NS |
| EC | 0.612 | ** |
| TDS | 0.594 | ** |
| Turbidity | 0.328 | * |
| Hardness | 0.476 | ** |
| Chloride | 0.521 | ** |
| Sulphate | 0.382 | * |
| Nitrate | 0.296 | NS |
| Iron | 0.684 | ** |
| Manganese | 0.641 | ** |

**NS:** Not significant; *p < 0.05; **p < 0.01.

**Table 5:** Classification of Haldia drinking-water samples according to arsenic concentration

| Arsenic category | Concentration | No. of samples | Percentage |
|---|---|---|---|
| Safe | ≤10 µg/L | 10 | 25.0 |
| Moderate concern | >10–25 µg/L | 15 | 37.5 |
| High | >25–50 µg/L | 15 | 37.5 |
| Very high | >50 µg/L | 0 | 0.0 |
| Total | — | 40 | 100.0 |

**Statistical note:** SE = SD/√n. If you send me the raw Haldia water-sample values, I can calculate the exact Mean ± SE, F-value, p-value, CD/LSD, CV%, correlation and health-risk values from your real data rather than using illustrative numbers.

The physicochemical characteristics of drinking-water samples showed clear differences among residential ($T_1$), industrial ($T_2$), peri-urban ($T_3$) and municipal-supply ($T_4$) sources in Haldia. The pH values ranged from 7.06 ± 0.03 in the peri-urban area to 7.34 ± 0.03 in municipal supply, indicating generally neutral to slightly alkaline conditions. The significant difference in pH among the sampling zones ($F = 8.42$, $p < 0.05$) suggests spatial variation in the chemical characteristics of the water sources. The industrial area showed the highest values of EC (1086.4 ± 31.52 µS/cm) and TDS (706.2 ± 21.48 mg/L), followed by the peri-urban and residential areas, whereas municipal water recorded the lowest values. The highly significant F-values for EC (96.73) and TDS (101.26) indicate substantial differences in dissolved ionic content among the water sources. The elevated EC and TDS in industrial and peri-urban groundwater may reflect greater mineral dissolution, groundwater–rock interaction and/or the influence of anthropogenic activities. Similar spatial differences were observed for turbidity, total hardness, chloride, sulphate and nitrate, with the industrial area consistently recording higher concentrations than the other sampling zones. The comparatively lower values in municipal supply indicate better control of water quality through treatment and distribution.

Iron and manganese also showed considerable variation between sampling zones. The highest concentrations of iron (0.68 ± 0.04 mg/L) and manganese (0.142 ± 0.009 mg/L) were recorded in the industrial area, while the lowest concentrations occurred in municipal water. The significant differences indicated by the F-values for iron (31.84, $p < 0.01$) and manganese (28.76, $p < 0.01$) demonstrate that these parameters varied substantially among the different sources. This pattern is particularly important because iron and manganese may be associated with groundwater geochemical conditions that also influence arsenic mobility. Thus, the simultaneous occurrence of elevated iron, manganese and arsenic in the industrial and peri-urban groundwater sources suggests that groundwater chemistry should be considered as an integrated system rather than evaluating arsenic in isolation. However, the present data alone cannot establish whether the observed enrichment is caused primarily by natural hydrogeochemical processes or anthropogenic inputs.

Arsenic exhibited marked spatial variation among the four water-source categories. The highest mean arsenic concentration was recorded in the industrial area (31.68 ± 2.46 µg/L), followed by the peri-urban area (22.56 ± 1.92 µg/L) and residential area (18.42 ± 1.74 µg/L), whereas municipal supply showed a substantially lower mean concentration of 7.84 ± 0.68 µg/L. The overall mean arsenic concentration was 20.13 ± 1.18 µg/L, with observed concentrations ranging from 3.8 to 48.8 µg/L. The F-value of 46.82 indicates a strong difference in arsenic concentration among the sampling zones. Importantly, the overall mean exceeds the WHO/BIS health-based value of 10 µg/L, indicating that arsenic exposure may be a concern for consumers dependent on untreated or inadequately treated groundwater. The relatively low arsenic concentration in municipal supply suggests that treated water can substantially reduce exposure compared with several groundwater sources.

The distribution of arsenic concentrations further demonstrates the extent of the problem. Among the 40 samples, 10 samples (25.0%) were within the ≤10 µg/L category, while 15 samples (37.5%) fell within the >10–25 µg/L category and another 15 samples (37.5%) were within the >25–50 µg/L category. Thus, 75% of the samples exceeded the 10 µg/L health-based guideline. Although no sample exceeded 50 µg/L in the presented dataset, the occurrence of concentrations approaching 50 µg/L remains a significant concern because prolonged consumption of

water containing arsenic above the health-based guideline can increase chronic exposure. The industrial and peri-urban zones were particularly important, as 100% of the samples from each of these zones exceeded 10 µg/L, compared with 80% of residential samples and 20% of municipal-supply samples. These findings identify industrial and peri-urban groundwater sources as priority areas for monitoring and intervention.

The correlation analysis provides additional insight into the relationship between arsenic and other water-quality parameters. Arsenic showed the strongest positive correlation with iron ($r = 0.684$, $p < 0.01$), followed by manganese ($r = 0.641$, $p < 0.01$), EC ($r = 0.612$, $p < 0.01$) and TDS ($r = 0.594$, $p < 0.01$). Significant positive relationships were also observed with hardness ($r = 0.476$), chloride ($r = 0.521$), turbidity ($r = 0.328$) and sulphate ($r = 0.382$). These relationships indicate that higher arsenic concentrations tended to occur in water having greater dissolved ionic content and higher concentrations of iron and manganese. The strong association with iron and manganese may indicate the importance of groundwater geochemical conditions in controlling arsenic occurrence. Nevertheless, correlation does not demonstrate causation, and additional hydrogeochemical and seasonal investigations would be necessary to identify the precise mechanisms controlling arsenic mobilization. The correlations with pH ($r = 0.284$) and nitrate ($r = 0.296$) were not statistically significant, suggesting that their variation was not strongly associated with arsenic concentration in the presented dataset.

The human-health risk assessment indicates that chronic arsenic exposure may be of greater concern for children than adults. The estimated chronic daily intake was 0.000574 mg/kg/day for adult males, 0.000631 mg/kg/day for adult females and 0.001149 mg/kg/day for children. The corresponding hazard quotients were 0.574, 0.631 and 1.149, respectively. The HQ values for adults were below one, whereas the value for children exceeded one, indicating a potential non-carcinogenic health concern for the child population under the assumptions used in the assessment. The estimated cancer risks were $8.61 \times 10^{-4}$ for adult males, $9.47 \times 10^{-4}$ for adult females and $1.72 \times 10^{-3}$ for children. These estimates indicate that the potential lifetime cancer risk associated with chronic arsenic exposure is higher for children than for adults in the presented assessment. Because cancer-risk estimates are model-dependent and sensitive to assumptions regarding water consumption, body weight, exposure duration and toxicological parameters, they should be interpreted as estimates of potential risk rather than predictions of actual cancer occurrence.

Overall, the results demonstrate substantial spatial variation in drinking-water quality across Haldia, with groundwater sources in industrial and peri-urban areas showing comparatively higher levels of arsenic and several other physicochemical parameters. The combination of elevated arsenic concentrations, significant associations with iron and manganese, and the estimated health-risk values indicates the need for continuous monitoring of groundwater sources and priority intervention at locations where arsenic exceeds 10 µg/L. Expansion and reliable maintenance of treated municipal water supplies, source-specific arsenic removal, regular testing of domestic tube wells, public awareness regarding contaminated sources and sustainable groundwater management would help reduce long-term exposure. Since the numerical values presented in the tables are explicitly identified as illustrative, these interpretations should be treated as applicable to the presented dataset and should be replaced or revised if laboratory-validated field observations become available.

## Conclusion

The present assessment indicates that arsenic contamination is an important drinking-water-quality concern in Haldia, particularly in groundwater-dependent residential, industrial and peri-urban areas. The reported values show that many samples exceeded the WHO/BIS health-based guideline of 0.01 mg/L, with comparatively higher arsenic levels in industrial and peri-urban sources, while municipal supply showed lower concentrations. The estimated health-risk indicators further suggest greater potential exposure among children, emphasizing the need for particular protection of vulnerable populations. The observed associations of arsenic with electrical conductivity, TDS, hardness, chloride, iron and manganese also indicate that arsenic contamination should be considered within the broader context of groundwater-quality changes. Therefore, regular source-specific monitoring, improved municipal drinking-water supply, appropriate arsenic treatment, public awareness and sustainable groundwater management are essential to reduce long-term exposure and protect public health in Haldia.

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