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Pollution metrics and health implications of heavy metals in coastal groundwater systems in Bangladesh

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ABSTRACT

Groundwater is a vital resource for both agricultural and drinking water needs in emerging nations like Bangladesh. However, increasing heavy metal contamination has raised concerns about its safety. This study examines the degree of heavy metal contamination at 50 groundwater sampling sites in the Kuakata region of Kalapara Upazila, Patuakhali District, *Bangladesh*, with a focus on manganese (Mn), nickel (Ni), and iron (Fe). These metals were selected due to both natural factors, such as their presence in the local geological formations, and anthropogenic sources, including agricultural runoff, industrial discharges, and leaching from outdated plumbing systems. Concentrations of Mn, Ni, and Fe were measured using a Perkin Elmer Atomic Absorption Spectrophotometer (AAS, Model 3110). To evaluate contamination and human health risks, six groundwater quality indices, including *HEI*, *NPI*, *PLI*, C_d, and *WQI*, as well as a non-carcinogenic risk model based on United States Environmental Protection Agency (USEPA) guidelines, were applied. Results showed that 42% of groundwater samples were categorized as unsuitable by the *HEI*, while other indices indicated low to moderate pollution levels across most sites. Importantly, health risk assessment revealed no significant non-carcinogenic risk from oral exposure to Mn, Ni, and Fe for different age groups. These findings suggest that although localized contamination is evident, the overall groundwater in the region does not pose a substantial non-carcinogenic health threat. The analysis emphasizes the need for continuous monitoring and sustainable water resource management strategies to mitigate potential risks.

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1. Introduction

Groundwater is vital for drinking, irrigation, and industrial activities, particularly in developing countries like Bangladesh, where surface water contamination is a significant concern (Tariq SR et al., 2008). Globally, approximately 66% of the population relies on groundwater for daily needs, and in regions like Southeast Asia, over 60% of rural and 66% of urban households depend on this resource (Danso SY and Ma Y, 2023; Monira U et al., 2024). This growing dependence, driven by population expansion and agricultural intensification, has heightened the risks of over-extraction and contamination, making water quality monitoring a critical concern.

In Bangladesh, the reliance on shallow aquifers is particularly pronounced due to their lower susceptibility to surface-level contamination. However, rapid urbanization and industrialization have introduced a variety of contaminants into these groundwater sources, posing a threat to their safety and purity. Among these, heavy metals are of significant concern due to their toxicity, persistence, and bioaccumulative nature. They originate from natural geological processes and anthropogenic activities such as industrial discharge, agricultural runoff, and improper waste disposal. Inadequate regulation and poor waste management systems exacerbate heavy metal accumulation in groundwater, posing long-term

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threats to both human and environmental health (Fu Z et al., 2020; Wu YF et al., 2008). Heavy metals such as manganese (Mn), nickel (Ni), and iron (Fe) are of particular concern due to their toxicity even at low concentrations and their non-biodegradable nature (WHO, 2017). These elements can have severe health implications, including kidney dysfunction, bone damage, and neurological disorders when exposure is chronic.

In coastal areas like Kuakata, groundwater contamination presents unique challenges. Among various heavy metals, manganese, nickel, and iron were selected due to their frequent detection in coastal aquifers, association with both natural and anthropogenic sources, and documented relevance to human health in prior studies in Bangladesh (Fig. 1). The region is influenced by natural processes, such as saline water intrusion and anthropogenic pressures, including unregulated tourism and poor waste disposal practices (Mia MA et al., 2015). Studies have highlighted the presence of manganese (Mn), nickel (Ni), and iron (Fe) in coastal aquifers, which pose varying risks to human health and environmental sustainability. The absence of stringent groundwater quality regulations in such areas exacerbates these risks, allowing contamination to continue without adequate mitigation.

Recent advances in environmental assessment methodologies, such as the Heavy Metal Pollution Index (HPI), the Heavy Metal Evaluation Index (HEI), and the Nemerow Pollution Index (NPI), offer comprehensive tools for evaluating groundwater quality. However, their application requires continuous field data and contextual validation, which remains limited in Bangladesh's coastal regions.

Although previous studies have utilized indices such as HPI, HEI, and NPI, this research builds upon them by incorporating continuous field validation and focusing specifically on manganese (Mn), nickel (Ni), and iron (Fe) in coastal aquifers. By combining advanced pollution indices with real-time data and geospatial methods, this study offers a more detailed and accurate assessment of groundwater contamination, addressing gaps in earlier research and improving water security for coastal communities.

Therefore, this study aims to (1) determine the concentrations of Mn, Ni, and Fe in the groundwater of Kuakata; (2) assess the associated human health and environmental risks using advanced pollution indices (HPI, HEI, and NPI); and (3) employ geospatial and statistical methods to map contamination patterns. Although several studies in Bangladesh have investigated trace metal contamination (Hossain MJ et al., 2024; Nahar N et al., 2025), the present work advances this knowledge by focusing on a coastal aquifer system and integrating multiple pollution indices with geospatial analysis to deliver a comprehensive assessment of groundwater quality and associated risks. It is

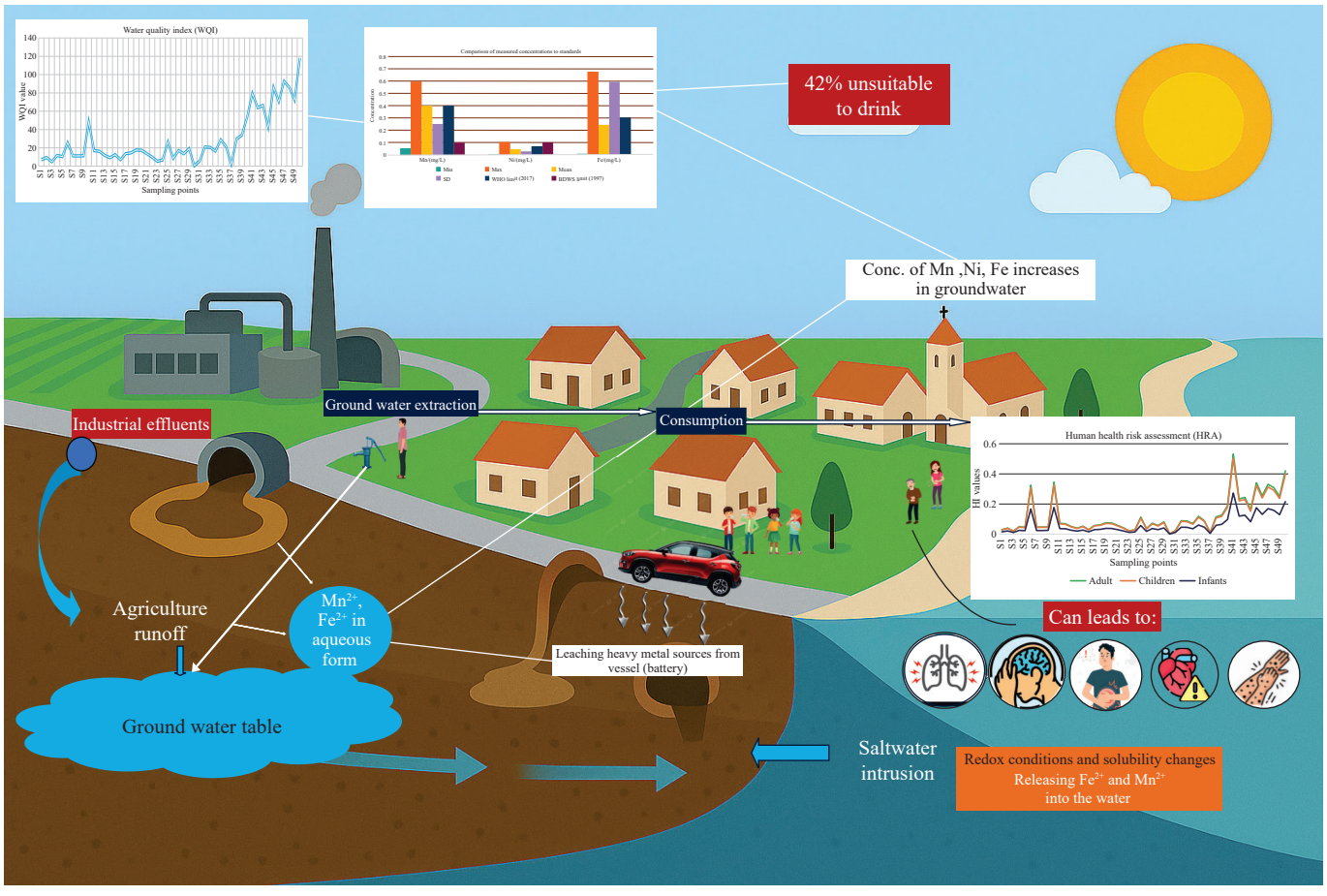


Fig. 1. Pathways of groundwater contamination and health risks from elevated Mn, Ni, and Fe due to industrial and agricultural sources.

hypothesized that groundwater quality in Kuakata is shaped by the combined influence of natural geological factors and anthropogenic activities, producing spatially heterogeneous contamination patterns and health risks that necessitate targeted, site-specific management strategies.

2. Materials and methods

2.1. Study area

The study area is located in Kuakata, Bangladesh, specifically in Kalapara Upazila within the Patuakhali District. Kuakata is situated in the Latachapli Union and features an 18 km long sandy beach along the Bay of Bengal, making it a vital coastal region (Banik P et al., 2022). The area, officially designated in May 2011 (Mahfjur M et al., 2015), is approximately 7 m above sea level, situated between the Galachipa and Andharmanik rivers and roughly 65 km south of Patuakhali town.

The region is characterized by a flat coastal terrain and is shaped by tidal deposits, creeks, and channels (Banik P et al., 2022). Kuakata experiences a tropical monsoon climate, with an average annual temperature of 25.9°C and a mean sea surface temperature of 27.3°C (Mobassher A et al., 2016). Seasonal temperature variations range from a January high of 25.1°C to an April peak of 33.8°C, while the annual rainfall averages 2580 mm, with 90% of precipitation occurring between June and September (Bangladesh Meteorological Department, 2024).

In terms of hydrogeology, the region is supported by loose tidal and alluvial deposits that provide shallow aquifers that are normally tapped between 30 m and 90 m below the surface. Tidal dynamics and river-aquifer interactions have a significant impact on groundwater flow, which makes these aquifers extremely susceptible to saline intrusion and trace metal mobilization. Groundwater pollution is more likely under such circumstances, especially in areas with heavy pumping and inadequate waste management (Mahfjur M et al., 2015).

The area is highly vulnerable to tropical cyclones, storm surges, tidal flooding, and saline water intrusion, particularly from May to November (Uddin Ahmed A, 2016). Frequent land erosion and accretion due to strong tidal forces intensify environmental instability, affecting groundwater quality and availability. Given these challenges, the study strategically selected sampling sites based on areas with the highest tube well usage, primarily for drinking and household purposes, to effectively assess the risks of groundwater contamination.

2.2. Sample collection

To ensure sample integrity, 50 groundwater samples were collected from public and private wells across Kuakata using high-density polypropylene (HDPP) bottles (Fig. 2). To prevent contamination, all bottles were pre-treated by soaking in 50% nitric acid (HNO_3) for 24 hours, followed by thorough rinsing with distilled water and air-drying before use. Before sampling, wells were allowed to run for 15–20 minutes to ensure the collection of fresh groundwater and to eliminate stagnant water within the system.

Sampling was conducted only during the monsoon season (June–August), which may influence metal concentrations due to dilution or recharge effects. Therefore, seasonal variation is a potential limitation of this study. Each sample was

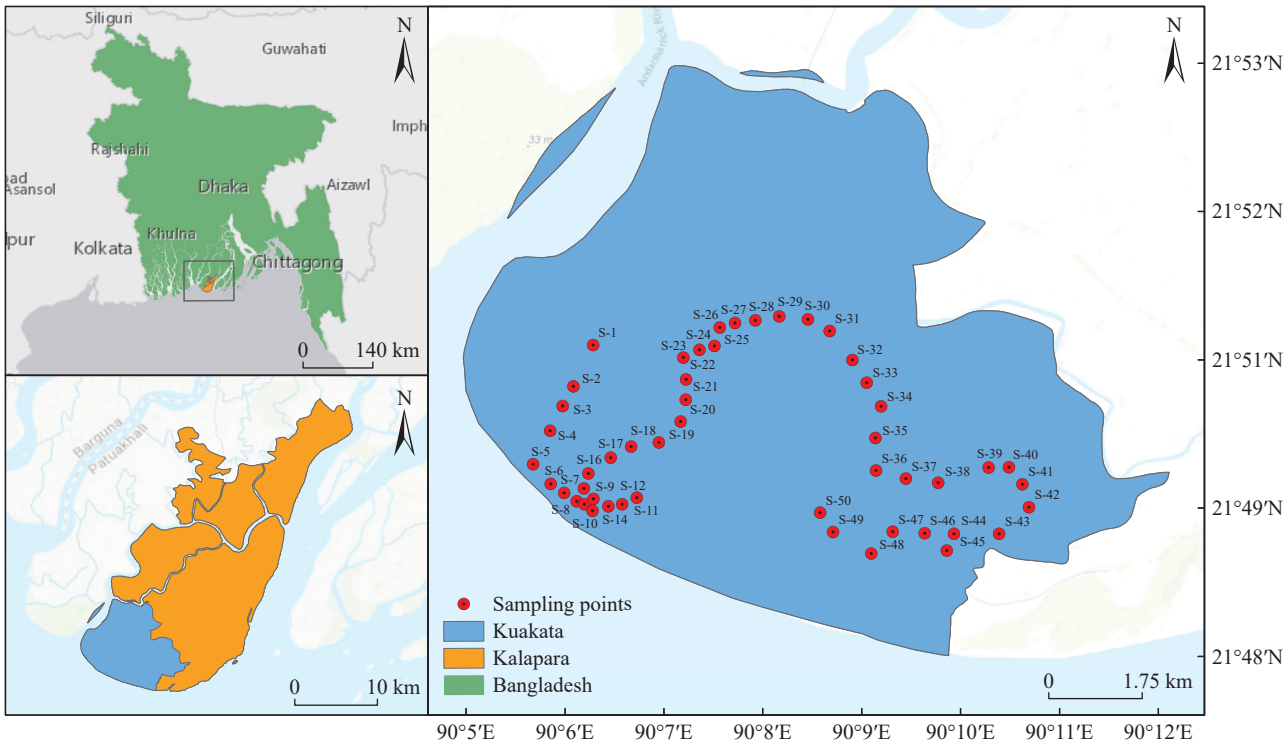


Fig. 2. Location map exhibiting the sampling site containing the sampling stations of the study region.

immediately filtered using a 0.45 μm membrane filter to remove suspended particles and debris (APHA, 1998). To ensure the stability of the samples, 2 mL of concentrated HNO_3 was added to each sample for the analysis of heavy metals. The sampling locations were precisely documented using Global Positioning System (GPS) coordinates to support spatial analysis. The collection process occurred between June and August, coinciding with the monsoon season when groundwater levels fluctuated due to increased precipitation.

2.3. Sample preparation and chemical analysis

The samples were maintained at a stable temperature of 4°C. Heavy metals, including manganese (Mn), nickel (Ni), and iron (Fe), were quantitatively analyzed using the Perkin-Elmer Atomic Absorption Spectrophotometer (AAS, Model 3110), a well-established method for this type of measurement. The analysis adhered strictly to the US-APHA protocols (Standard Methods for the Examination of Water and Wastewater, 1999) at every stage of the analytical process. The procedure followed comprehensive instruction manuals and precise methods to ensure the highest quality of the metal analyses. To ensure data accuracy, field blanks and standard reference materials were used, and recoveries ranged from 94% to 105%. All measurements were conducted in triplicate. Detection limits for Mn, Ni, and Fe were 0.001 mg/L, 0.002 mg/L, and 0.005 mg/L, respectively. Calibration curves for all elements consistently achieved R^2 values above 0.999, confirming excellent linearity. Laboratory duplicates were analyzed to verify precision, showing relative standard deviations (RSD) below 5% (Chen HY and Chen C, 2022). The instrument was recalibrated after every ten samples to maintain accuracy. A metal standard solution was utilized to calibrate the instrument for each element. All analytical procedures were performed under strict quality control to ensure reliable and reproducible results. The samples were promptly sent to the Bangladesh Council of Scientific and Industrial Research (BCSIR) laboratory in Dhaka for further chemical and spectroscopic examination.

2.4. Groundwater integrated pollution indices

2.4.1. Heavy Metal Pollution Index (HPI)

The *HPI* is a rating system that considers the combined impact of all heavy metals on groundwater quality. As a result, researchers have widely embraced the *HPI* as a comprehensive method for assessing the overall water quality based on heavy metals (Bhavan M et al., 2012; Herojeet R et al., 2015; Tavassoli Sand Mohammadi F, 2017; Vasant W et al., 2016). The World Health Organization water standards were used to compute the HPI for each chemical characteristic in milligrams per liter, shown in Equs. 1 (WHO, 2017).

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

Where n– represents the number of heavy metals; W_i– denotes their unit weightage; and Q_i – indicates their subindex. The unit weight, W_i, is calculated by

$$Wi = \frac{K}{S_i}$$

where S_i – is the standard allowable limit for the i^{th} heavy metal; and K– is the proportionality constant.

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{S_i}}$$

$$\sum_{i=1}^{n} = \frac{1}{S1} + \frac{1}{S2} + \cdots \frac{1}{Sn}$$

where standards for various heavy industries are represented by S1, S2, S3, etc. Qi, the sub-index, is determined by

$$Qi = \sum_{i=1}^{n} \frac{|M_i - I_i|}{(S_i - I_i)} \times 100$$

Where M_i – measured the i^{th} heavy metal's value; I_i – determined the i^{th} heavy metal's ideal value *HPI* is classified into three classes, including Low (<15), Medium (15–30), and High (>30), based on its pollution. According to the established threshold, water with an *HPI* above 30 is considered highly polluted and unsuitable for human consumption (Singh Y and Kaur L, 2017).

2.4.2. Heavy Metal Evaluation Index (HEI)

The *HEI* approach yields an overall water quality regarding heavy metal content consistent with the *HPI* (Edet AE and Offiong OE, 2002; Prasanna MV et al., 2012). This indicator is commonly used to evaluate groundwater quality. The HEI is determined in this manner, as shown in Equs. 2.

$$HEI = \sum_{i=1}^{n} \frac{M_i}{S_i} \quad (2)$$

Here, S_i – represents the maximum acceptable concentration (MAC) of the i^{th} parameter; while M_i – denotes the monitored value of the i^{th} parameter. If the concentration of heavy metals exceeds the S_i value, the water quality is considered poor. Based on the established threshold, any *HEI* exceeding 2 indicates severe contamination, making the water unsuitable for drinking (Prasad Band Bose JM, 2001).

2.4.3. Contamination Degree (C_d)

From low to high, the contamination degree (C_d) represents the level of pollution caused by each contaminant or water quality indicator (Islam SMD et al., 2015). It is determined for each water sample by adding up the factors for individual constituents that exceed allowed limits. C_d provides a summary of the combined impacts of various quality factors that could harm household water. The contamination index, which can be computed using Equs. 3 below, has been

calculated for this study based on all available data (Backman B et al., 1998).

$$C_d = \sum_{n=1}^{n} C_{fi} \quad (3)$$

The factor of contamination for the i^{th} component is C_{fi}. The parameter's contamination factor (C_{fi}) is computed using

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1$$

C_{Ai} – represents the analytical value for the ith element. N– signifies the normative value; while C_{Ni} – stands for the upper allowable concentration of the i^{th} component.

2.4.4. Nemerow Pollution Index (NPI)

The Nemerow Pollution Index (*NPI*) is used to assess the extent of groundwater contamination by heavy metals at various sampling locations. This index gives priority to highly polluting substances and considers the maximum and average values of the Single Factor Pollution Index, as shown in Equs. 4.

$$NPI = \sqrt{\frac{\left[\frac{1}{n}\sum\left(\frac{Ci}{Si}\right)^2\right]^2 + \left[\mathrm{Max}\left(\frac{Ci}{Si}\right)\right]^2}{2}} \quad (4)$$

C_i – represents the measured concentration of heavy metal; S_i – represents the standard value; and *n*– represents the number of indices. Groundwater contamination by heavy metals is categorized into six groups: No pollution: ⩽ 0.5, Clean: 0.5–0.7, Warm: 0.7–1.0, Polluted: 1.0–2.0, Medium: 2.0–3.0, and Severe: > 3.0. According to the established *NPI* threshold, water with an *NPI* greater than 1.0 is considered unsuitable for human consumption (Zhong S et al., 2015).

2.4.5. Pollution Load Index (PLI)

The Pollution Load Index (*PLI*) for a specific site was determined using the method presented by (Tomlinson DL et al., 1980). *PLI* can be calculated in Equs. 5.

$$PLI = (\mathrm{CF1} \times \mathrm{CF2} \times \mathrm{CF3} \times \cdots \mathrm{CF}_n)^{\frac{1}{n}} \quad (5)$$

Where CF– represents the contamination factor and *n* stands for the number of metals. The contamination factor can be calculated using the following relationship:

$$\mathrm{CF} = \frac{C_{Ai}}{C_{Ni}} - 1$$

Where, CF – Contamination Factor; C_{Ai} – Represents the analytical value for the i^{th} element; N– Signifies the normative value, while C_{Ni} stands for the upper allowable concentration of the i^{th} component; C_{Ni} – The maximum acceptable concentration in this case is denoted.

2.4.6. Water Quality Index (WQI)

WQI was initially introduced by (Brown RM et al., 2013) and modified by (Backman B et al., 1998). The World Health Organization (WHO) recommends using the World Quality Index (*WQI)* as a tool to assess the impact of water quality indicators on drinking water quality (WHO, 2017). The index comes with some uncertainty. This study utilized the *WQI* calculation process based on Horton's reference approach to simulate water quality parameters using a Monte-Carlo simulation (Abbasnia A et al., 2019; Amiri V et al., 2014; Backman B et al., 1998; Gorgij AD et al., 2017; Machiwal D et al., 2018) shown in Equs. 6.

$$WQI = \sum_{n=1}^{n} Q_n W_n \quad (6)$$

W_n – represents the relative weight of Q_n, and Q_n – stands for the quality score of the n^{th} water quality parameter. Each chemical parameter's weight adds up to one. The definition of the quality rating is

$$Q_n = \frac{C_n}{S_n} \times 100$$

S_n – represents the standard acceptable value for each water quality parameter; while C_n – denotes the parameter's actual value.

2.5. Risk assessment

2.5.1. Human health risk assessment (HRA)

HRA was classified as either non-carcinogenic or carcinogenic based on the level of exposure to metals or metalloids. In this study, the hazard index (*HI*), hazard quotient (*HQ*), and chronic daily intake (*CDI*) of contaminants through drinking water were measured according to USEPA recommendations.

2.5.2. Hazard Quotient (HQ)

When non-carcinogenic pollutants are exposed, the non-CR is measured using *HQ*. Manganese and nickel are deemed non-carcinogenic pollutants by the USEPA Toxicants Division. To compute *HQ*, use the following Equs. 7:

$$HQ = \frac{CDI}{RfD} \quad (7)$$

The reference dose, also known as *RfD* (mg/kg/day), is 0.14 mg/kg/day for manganese (USEPA, 1989). The chronic daily intake, or *CDI* (mg/kg/day), is calculated using the following Equs. 8:

$$CDI = \frac{\mathrm{C} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \quad (8)$$

Where IR– represents the ingestion rate in liters per day for adults (3.53 liters per day); and C– stands for the concentration of heavy metals (mg/L) (Milton AH et al., 2003), 1.0 L per day for kids (USEPA, 1989), as well as 0.25 L/day for infants (Brindha K et al., 2016); ED– represents the duration of exposure (six years for children and seventy years for adults) (Final I,1989), and 1 year for infants (Brindha K et

al., 2016); EF– is the exposure frequency in days/year (365 days for adults, children, and infants (Final, 1989); BW– is the average body weight in kg (50 kg for adults, 15 kg for children, and 6.9 kg for infants (Dhaka A and Measure Dhs, B., 2013; USEPA, 1989); and AT– is the average time[AT = (365× ED(d)]. This study focuses exclusively on oral exposure to heavy metals through drinking water. Oral ingestion is considered the primary route of exposure because it leads to the highest internal dose. Dermal contact was not included since skin absorption of heavy metals is minimal and contributes little to overall exposure.

2.5.3. Hazard Index (HI)

HI is calculated using the following Equs. 9, and is defined as the sum of the *HQ* of the parameters under study:

$$HI = HQ_1 + HQ_2 + HQ_3 + ... + HQ_n \quad (9)$$

HQ values show no substantial non-carcinogenic health impacts when *HQ* is less than 1 and greater than 1, respectively. A non-cancer health risk is indicated when HI is less than 1, while a considerable non-cancer health risk is indicated when HI is greater than 1. The following categories apply to the chronic risk (*HQ* or *HI*): Minimal (⩽ 0.1), Low (⩾ 0.1 and < 1), Medium (⩾ 1 and < 4), and High (⩾ 4), in that order (Kamara SM, 2019).

3. Results and discussion

3.1. Heavy metal concentration in groundwater

The concentrations of manganese (Mn), nickel (Ni), and iron (Fe) in groundwater samples from Kuakata, Bangladesh, showed considerable variation, with Mn concentrations ranging from 0.0553 mg/L to 0.5956 mg/L, with two samples exceeding the WHO limit of 0.4 mg/L. The mean Mn concentration of 0.4011 mg/L surpassed both the WHO and Bangladesh Drinking Water Standards (BDWS) limits, indicating significant contamination that could pose health risks, potentially linked to geogenic sources, as Mn is naturally occurring in soil and rocks or anthropogenic activities such as local industrial operations or improper waste disposal. The analysis, as presented in Table 1 and Fig. 3, shows that given that Mn toxicity has been associated with neurological effects, its elevated levels in groundwater demand immediate public health attention. Nickel was detected in 15 samples, ranging from 0.0040 mg/L to 0.1043 mg/L, with an average concentration of 0.0470 mg/L. Although most Ni values were below the BDWS limit, four samples exceeded the WHO guideline of 0.07 mg/L, suggesting localized contamination potentially from agricultural runoff, industrial effluents, or mining activities. Considering Ni's carcinogenic properties, these spikes underscore the need for focused investigation and monitoring. Iron concentrations ranged from 0.0081 mg/L to 0.6700 mg/L, with 14 samples exceeding the WHO limit of 0.3 mg/L and a maximum recorded concentration of 4.2957 mg/L, indicating severe contamination in specific areas, potentially due to both geogenic and anthropogenic sources. Iron concentrations varied from 0.0081 mg/L to 4.2957 mg/L, with 14 samples surpassing the WHO limit of 0.3 mg/L. The mean Fe concentration of 0.3165 mg/L slightly exceeds the WHO guideline, but the exceptionally high maximum values indicate severe contamination in specific areas. The ranking of mean concentrations (Mn > Fe > Ni) highlights Mn as the most concerning contaminant. The repeated exceedance of Mn and Fe thresholds emphasizes the necessity for both

Table 1. Concentrations of Mn, Ni, and Fe in groundwater samples from Kuakata, Bangladesh.

Parameter	Min/(mg/L)	Max/(mg/L)	Mean/(mg/L)	SD	WHO Limit/(mg/L)	BDWS Limit/(mg/L)	No. of Samples Exceeding WHO Limit
Mn	0.0553	0.5956	0.4011	0.2520	0.4	0.1	2
Ni	0.0040	0.1043	0.0470	0.0289	0.07	0.1	4
Fe	0.0081	0.6700	0.2425	0.5901	0.3	0.3–1	14

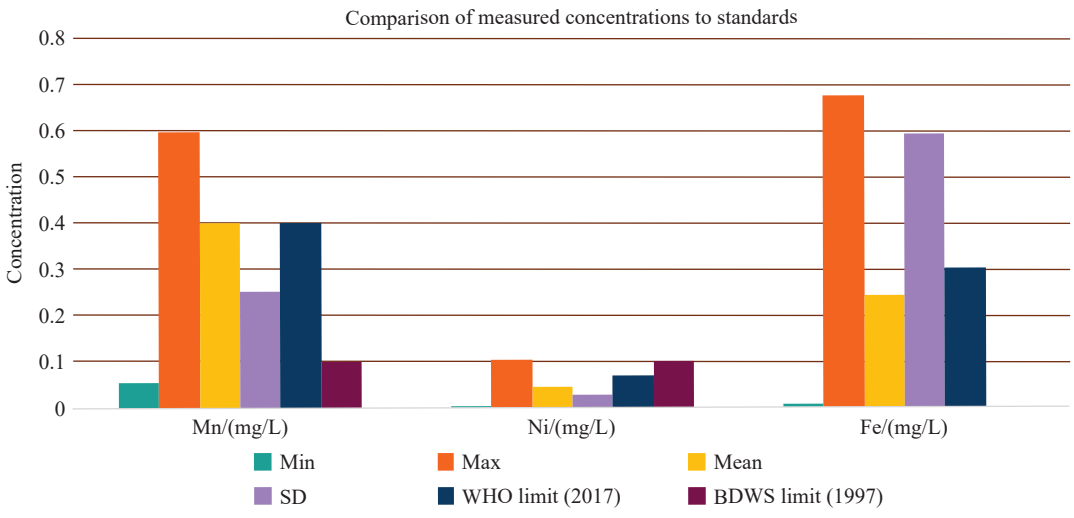


Fig. 3. Comparison of measured concentrations to standards.

continuous monitoring and targeted remediation strategies, particularly in areas with dense industrial, agricultural, or residential activity.

3.2. Groundwater integrated pollution indices

3.2.1. Heavy Metal Pollution Index (HPI)

The calculated Heavy Metal Pollution Index (*HPI*) values ranged from 2.7 to 312.52, with a mean *HPI* of 102.72, based on the concentrations of three heavy metals in 50 groundwater samples. As illustrated in Fig. 4, two samples (SP-30, SP-37) were categorized as excellent, while six samples (SP-1, SP-3, SP-16, SP-23, SP-24, SP-31) were classified as good (Prasad B and Bose JM, 2001) (Table 2). The threshold for the *HPI* is 100, above which the water is considered unsuitable for human consumption (Prasad B and Bose JM, 2001). The *HPI* values for other samples exceeded the critical *HPI* limit, indicating significant contamination, particularly in sampling points SP-7, SP-12, SP-19, and SP-47, which showed *HPI* values surpassing 200. This underscores the urgent need for targeted interventions to address the high concentrations of heavy metals in these areas and restore groundwater quality to ensure it is safe for human consumption. Further in-depth analysis of the sources of contamination and their potential health implications should be considered, particularly regarding the localized contamination observed at specific sampling points. The results underscore the importance of continuous monitoring and effective treatment measures.

3.2.2. Heavy Metal Evaluation Index (HEI)

The Heavy Metal Evaluation Index (*HEI*) results in Fig. 5 reveal substantial spatial variation across the 50 sampling points, with *HEI* values ranging from 0.027 to 3.46 and a mean of 1.07. Categorizing the samples by pollution level (Prasad Band Bose JM, 2001), 54% fall into the low-risk category ($HEI < 1$), 40% are medium-risk ($1 \leqslant HEI \leqslant 2$), and 6% specifically SP-10, SP-41, and SP-50, indicate high pollution ($HEI > 2$), suggesting severe contamination in these areas. The graphical representation in Fig. 5 highlights high-risk points that exceed the red demarcated threshold, indicating unsafe water *quality for human use* (Prasad B and Bose JM, 2001). These elevated Health Environmental Index (*HEI*) values may be linked to localized pollution sources, such as industrial effluents, agricultural runoff, or improper waste disposal. In contrast, the remaining 94% of the samples reflect *HEI* levels within safe or moderate bounds, emphasizing the overall suitability of the water for domestic purposes. This uneven distribution underscores the need for targeted interventions and ongoing monitoring at identified hotspots to avert health risks and promote sustainable water resource management (Chowdhury AN et al., 2024; Prasad B and Bose JM, 2001).

3.2.3. Degree of contamination (C_d)

To determine the extent of metal pollution at the sampling sites, the degree of contamination (C_d) was calculated, with the lowest C_d value being 1.348 and the highest C_d value being 2.973, resulting in a mean concentration of 2.159. These results indicate that all sampling areas are moderately polluted, making the groundwater unsuitable for human consumption, aquatic life, or any other uses (Backman B et al., 1998). The bar chart in Fig. 6 visually illustrates the degree of contamination across the sampling sites, further highlighting the moderate level of pollution in the study area. This underscores the need for effective water treatment and pollution management strategies to ensure the safety and usability of groundwater in the region.

3.2.4. Nemerow Pollution Index (NPI)

The Nemerow Pollution Index (*NPI*) values from the groundwater samples analyzed in this study ranged from 0.00000038184 to 1.054, with an average of 0.1898, indicating varying levels of contamination across the sampling sites. Notably, three samples (SP-47, 48, 49) fell within the “warm” to “pollution” range, while three others (SP-6, 41, 50) were categorized as polluted (Zhong S et al., 2015). These results suggest that while most (88%) of the groundwater samples met the safe threshold set by the (WHO,

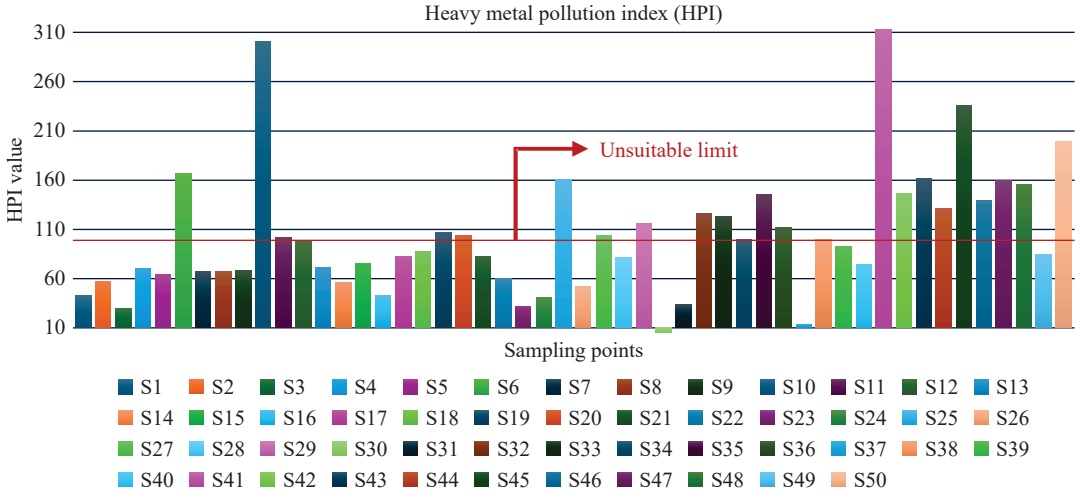


Fig. 4. Heavy Metal Pollution Index (HPI)of the selected heavy metals.

2022), there were specific localized hotspots of contamination. These findings underscore the necessity for ongoing monitoring and targeted remediation strategies to mitigate the elevated pollution levels in specific areas. Further research should focus on identifying potential sources of contamination in polluted and warm sites to mitigate risks associated with heavy metal exposure. The analysis is visually represented in Fig. 7, which shows the distribution of *NPI* values across the sampling points. Additional detailed data is provided in Table 2.

Table 2. Values of various pollution indices.

Index	Degree of Pollution	Ranges	Sample ID	Number of Samples	Samples/%
HPI	Excellent	<25	S30, S37	2	4
	Good	26–50	S1, S3, S16, S23, S24, S31	6	12
	Poor	51–75	S2, S4, S5, S7, S8, S9, S14, S22, S26, S40	10	20
	Very Poor	76–100	S12, S13, S15, S17, S18, S21, S28, S34, S38, S39, S49	11	22
	Unsuitable	>100	S6, S10, S11, S19, S20, S25, S27, S29, S32, S33, S35, S36, S41, S42, S43, S44, S45, S46, S47, S48, S50	21	42
HEI	Low	<1	S1, S2, S3, S4, S5, S7, S8, S9, S12, S13, S14, S15, S16, S17, S18, S21, S22, S23, S24, S26, S28, S30, S31, S34, S37, S39, S40	27	54
	Medium	1–2	S6, S11, S19, S20, S25, S27, S29, S32, S33, S35, S36, S38, S42, S43, S44, S45, S46, S47, S48, S49	20	40
	High	>2	S10, S41, S50	3	6
WQI	Excellent	0–25	S1, S2, S3, S4, S5, S7, S8, S9, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S26, S27, S28, S29, S30, S31, S32, S33, S34, S36, S37	33	66
	Good	25–50	S6, S10, S25, S35, S38, S39, S44	7	14
	Poor	50–75	S40, S42, S43, S46, S49	5	10
	Very Poor	75–100	S41, S45, S47, S48	4	8
	Unsuitable	>100	S50	1	2
NPI	No Pollution	<0.5	S1, S2, S3, S4, S5, S7, S8, S9, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S27, S28, S29, S30, S31, S32, S33, S34, S35, S36, S37, S38, S39, S42, S43, S44	40	80
	Clean	0.5–0.7	S10, S40, S45, S46	4	8
	Warm	0.7–1.0	S47, S48, S49	3	6
	Polluted	1.0–2.0	S6, S41, S50	3	6
	Medium Pollution	2.0–3.0	–	0	0
	Severe Pollution	>3.0	–	0	0
PLI	No Pollution	<1	S1-S50	50	100
	Polluted	1<	–	0	0
C_d	Low	<1	–	0	0
	Medium	1–3	S1-S50	50	100
	High	>3	–	0	0

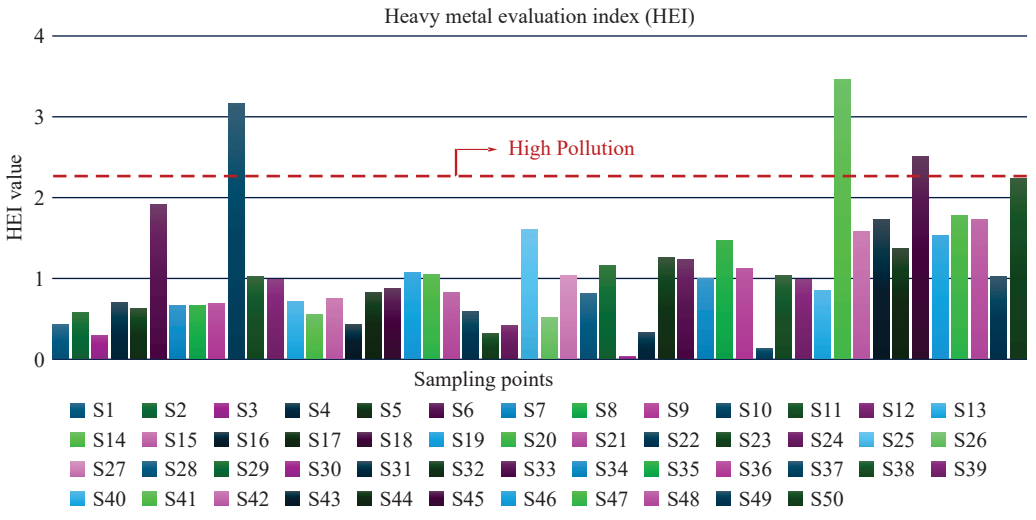


Fig. 5. Heavy Metal Evaluation Index (*HEI*) of the selected heavy metals.

3.2.5. Pollution Load Index (PLI)

PLI reflects the ratio of heavy metals accounted for in groundwater to the respective background value for each, providing a clear indication of the level of pernicious heavy metals in Kuakata's groundwater. It offers a clear evaluation of groundwater pollution levels in Kuakata and highlights specific contamination hotspots. The *PLI* methodology, initially outlined by Hakanson (Benarabi A et al., 2021), considers both the sum of contamination factor values and the geometric mean or arithmetic average of the studied contaminants (Mmolawa K et al., 2011). According to the *PLI* study, the mean *PLI* value within the bounds of 50 groundwater samples was 0.577. As for the categories of pollution, the *PLI* limit > 1 is evaluated as polluted, while the *PLI* limit < 1 is declared as no pollution (Ahmed S et al., 2019). As illustrated in Fig. 8, none of the samples exceeded the critical threshold of 1, suggesting that Kuakata's groundwater is not significantly impacted by heavy metal

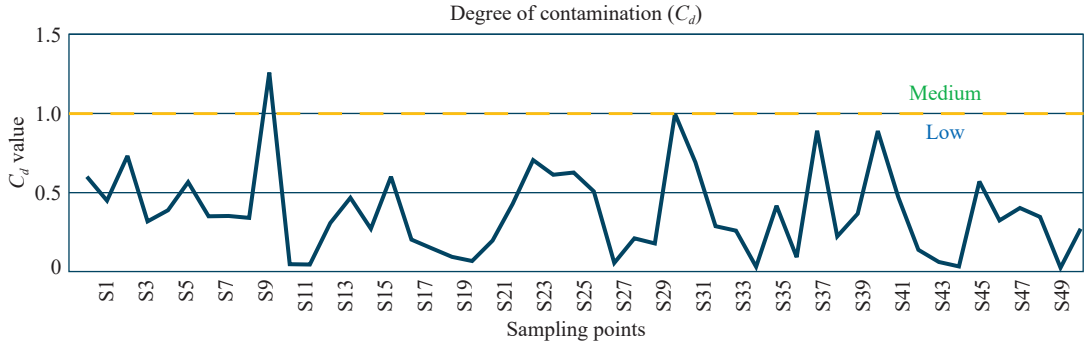


Fig. 6. Degree of contamination (C_d) of the selected heavy metals.

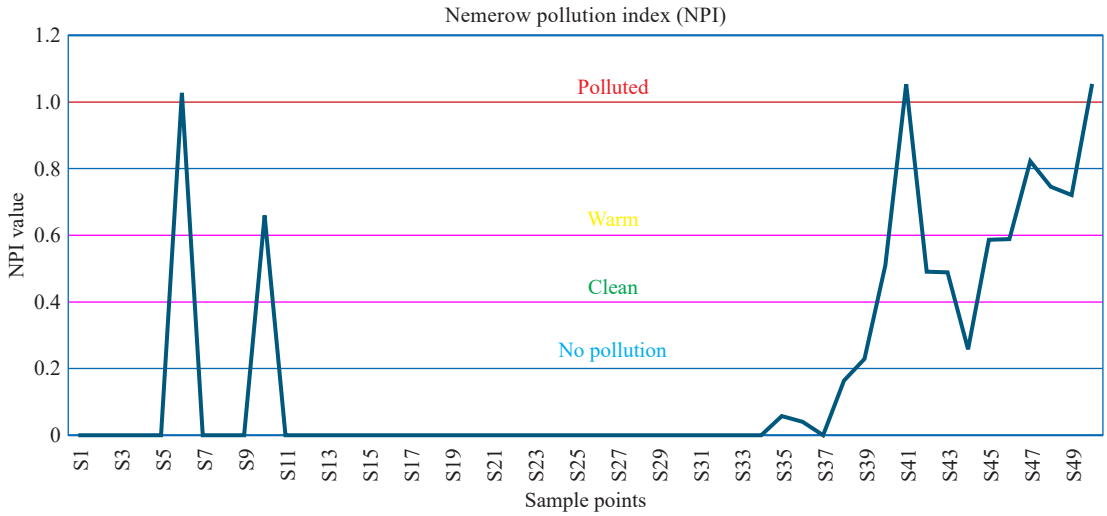


Fig. 7. Nemerow Pollution Index (*NPI*) of the selected heavy metals.

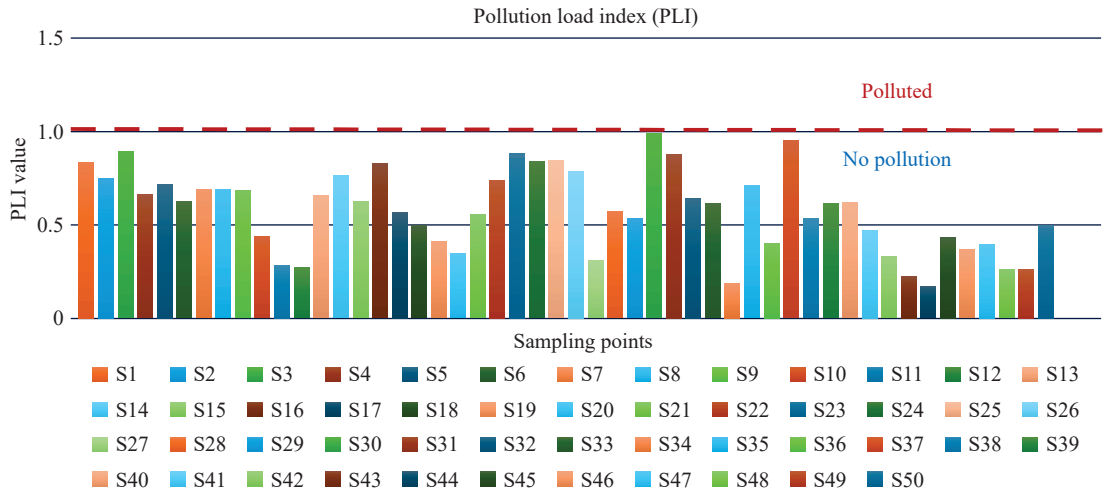


Fig. 8. Pollution Load Index (*PLI*) of the selected heavy metals metals.

contamination. However, localized variations in heavy metal concentrations necessitate ongoing monitoring to prevent potential future contamination.

3.2.6. Water Quality Index (WQI)

The Water Quality Index (*WQI*) was used to evaluate the overall groundwater quality in Kuakata by analyzing the concentration of heavy metals. The *WQI* values ranged from 0.447 to 118.2697, with a mean value of 28.4233 across 50 groundwater samples. A column chart is provided to compare all the findings of the WQI for each sample. By *WQI*, water quality status is categorized into the following values: Excellent (0–25); Good (25–50); Poor (50–75); Very Poor (75–100); and Unsuitable for consumption (greater than 100) (Yogendra K and Puttaiah ET, 2008) (Table 1). To conclude, four samples (SP-41, 45, 47, 48) are considered to be very poor, five samples (SP-40, 42, 43, 46, 49) are in the poor category, 14% (SP-6, 10, 25, 35, 38, 39, 44) are considered to be good, and 66% are considered to be excellent. The line chart in Fig. 9 illustrates the distribution of *WQI* values across the sampled locations. Although most samples fall within safe limits, continuous monitoring and remediation efforts are necessary to ensure sustainable groundwater quality in Kuakata.

3.2.7. Comparison among pollution indices by classification category

Based on the data presented in Table 2, pollution levels were systematically categorized into three distinct groups: The best category, comprising the lowest pollution classes such as Excellent, Low, and No Pollution; the intermediate category, encompassing moderate pollution levels including Poor, Medium, and Clean–Warm; and the worst category, consisting of the highest pollution classes such as Unsuitable, High, Polluted, Very Poor, and Severe Pollution. The evaluation of groundwater samples from Kuakata, Bangladesh, using multiple pollution indices reveals both convergence and divergence in contamination assessment. The *HPI* and Degree of Contamination (C_d) highlight a predominance of moderate to high pollution, with 42% of samples classified as unsuitable by *HPI* and all samples identified as moderately polluted by C_d. Conversely, the Heavy Metal Evaluation Index (*HEI*) offers a comparatively favorable assessment, placing 54% of samples in the low-risk category and only 6% in the high-risk group. Similarly, the Water Quality Index (*WQI*) indicates predominantly good groundwater quality, with 66% of samples rated excellent and 14% good, albeit with isolated sites categorized as very poor or unsuitable. In contrast, the Nemerow Pollution Index (*NPI*) and Pollution Load Index (*PLI*) exhibit lower sensitivity to localized pollution spikes, with *NPI* reporting 88% of samples as unpolluted and *PLI* finding no samples exceeding pollution thresholds. These variations are visually illustrated in Fig. 10, which presents a comparative overview of pollution categories across all indices, reinforcing the observed trends. Despite methodological differences, all indices consistently identify specific contamination hotspots, most notably at sampling points SP-41, SP-47, and SP-50, primarily associated with elevated manganese and iron concentrations. These findings collectively emphasize the critical need for targeted remediation strategies and continuous groundwater quality monitoring.

3.3. Human health risk assessment (HRA)

Since groundwater in the study area contains elevated concentrations of Mn, Ni, and Fe, it is crucial to assess the long-term health risks associated with its ingestion. This study focuses on assessing non-carcinogenic health risks using the Hazard Quotient (*HQ*) and Hazard Index (*HI*), with a specific examination of the oral ingestion pathway for infants, children, and adults. The HQ values show that the order of risk is Ni > Mn > Fe across all age groups, with Mn and Ni having *HQ* values below 1 (*HQ* < 1), in Table 3**,** indicating minimal toxic effects even with prolonged exposure. In terms of the Hazard Index (*HI*), none of the 50 groundwater samples exceeded the USEPA-approved threshold of *HI* > 1, suggesting that there is no significant non-carcinogenic health risk for infants, children, or adults from consuming groundwater in the study area **(**Fig. 11**)**. Despite the elevated concentrations of these metals, the *HQ* and *HI* values indicate that there are no immediate health concerns. However, continuous monitoring is crucial to ensure that safe drinking water standards are maintained in the region over time.

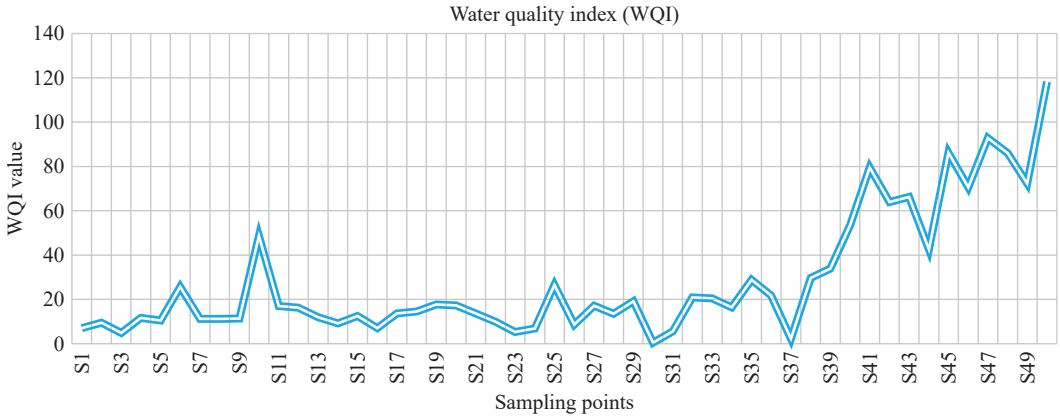


Fig. 9. Water Quality Index (*WQI*) of the designated heavy metals.

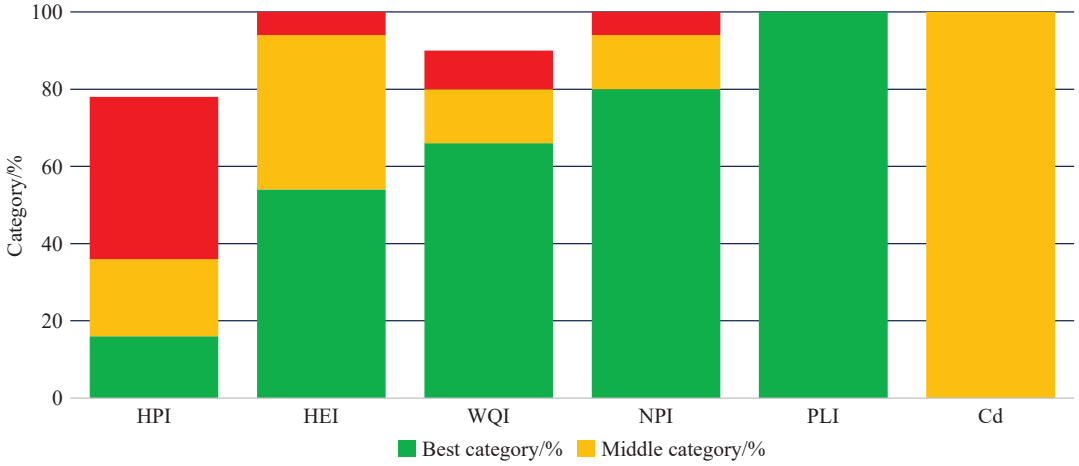


Fig. 10. Comparison of groundwater pollution levels and indices.

Table 3. Hazard Index (*HI*) values for adults, children, and infants.

Sample ID	*HI* (Adults)	*HI* (Children)	*HI* (Infants)	Sample ID	*HI* (Adults)	*HI* (Children)	*HI* (Infants)
S1	0.0300	0.0283	0.0154	S26	0.0365	0.0345	0.0187
S2	0.0406	0.0384	0.0209	S27	0.0727	0.0687	0.0373
S3	0.0207	0.0195	0.0106	S28	0.0574	0.0542	0.0295
S4	0.0498	0.0471	0.0256	S29	0.0815	0.0770	0.0418
S5	0.0449	0.0424	0.0231	S30	0.0019	0.0018	0.0010
S6	0.3253	0.3071	0.1669	S31	0.0235	0.0222	0.0121
S7	0.0476	0.0449	0.0244	S32	0.0892	0.0842	0.0458
S8	0.0475	0.0448	0.0244	S33	0.0872	0.0823	0.0447
S9	0.0483	0.0456	0.0248	S34	0.0701	0.0662	0.0360
S10	0.3456	0.3264	0.1774	S35	0.1184	0.1118	0.0607
S11	0.0722	0.0682	0.0371	S36	0.0895	0.0845	0.0459
S12	0.0692	0.0653	0.0355	S37	0.0094	0.0089	0.0048
S13	0.0506	0.0478	0.0260	S38	0.1138	0.1075	0.0584
S14	0.0393	0.0371	0.0202	S39	0.1263	0.1193	0.0648
S15	0.0531	0.0502	0.0273	S40	0.1879	0.1774	0.0964
S16	0.0300	0.0283	0.0154	S41	0.5317	0.5021	0.2729
S17	0.0580	0.0547	0.0297	S42	0.2338	0.2207	0.1200
S18	0.0618	0.0584	0.0317	S43	0.2438	0.2302	0.1251
S19	0.0755	0.0713	0.0388	S44	0.1612	0.1522	0.0827
S20	0.0736	0.0695	0.0378	S45	0.3418	0.3227	0.1754
S21	0.0585	0.0552	0.0300	S46	0.2549	0.2407	0.1308
S22	0.0421	0.0398	0.0216	S47	0.3312	0.3127	0.1700
S23	0.0225	0.0212	0.0115	S48	0.3084	0.2912	0.1583
S24	0.0291	0.0274	0.0149	S49	0.2517	0.2377	0.1292
S25	0.1131	0.1068	0.0580	S50	0.4213	0.3978	0.2162

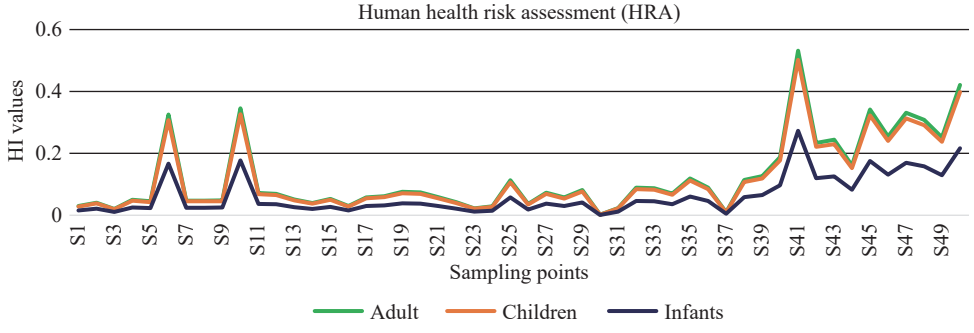


Fig. 11. Hazard index (*HI*) of the selected metals from the groundwater.

4. Conclusions

In developing countries like Bangladesh, groundwater plays a vital role in both agricultural production and drinking water supplies. However, the present study revealed growing concerns about heavy metal contamination in Kuakata's groundwater. The key findings can be summarized as follows:

(i) Approximately 42% of the groundwater samples exceeded the WHO safety thresholds, with the *HPI* indicating unsuitability for consumption in these cases.

(ii) The *HEI* index showed that only 6% of samples had high pollution levels, while the C_d pollution scale revealed a moderate degree of contamination across all sampling sites.

(iii) The *WQI* analysis indicated fluctuating trends, with 2% of samples being unsuitable for consumption and an additional 18% classified as bad or very poor quality.

(iv) Health risk assessment clarifying that the risk assessment shows no significant non-carcinogenic oral exposure risk from Mn, Ni, and Fe.

This study's innovation lies in the integrated use of multiple pollution indices (*HPI*, *HEI*, *Cd*, and *WQI*) with health risk assessment, offering a comprehensive view of groundwater quality in a coastal aquifer. It also provides baseline data for Kuakata and shows the effectiveness of a multi-index approach in identifying spatial contamination patterns.

Overall, the findings highlight a notable level of heavy metal contamination that could potentially affect human health and the local ecosystem. Therefore, further studies should focus on identifying additional contaminants and examining their interactions with biotic and abiotic factors, as well as their impacts on plants, animals, and sediment.

CRediT authorship contribution statement

Jubairul Hassan: Investigation, visualization, formal analysis, methodology, writing – original draft. Md. Raisul Hasan: Methodology, formal analysis, writing – review & editing. Ali Newaz Chowdhury: Formal analysis, investigation, data curation. Thomas S. Varner: Resources, validation, writing – review & editing. Md. Nur Alam Likhon: Investigation, data curation, methodology. Md. Hasan Tareq: Visualization, software, writing – review & editing. Parvin Sultana: Visualization, validation. Tanha Dewan Apon: Project administration, resources, writing – review & editing. Md Mesbah Uddin Bhuiyan: Conceptuaization, funding acquisition, project administration, supervision, writing – review & editing. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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