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Index-Based Evaluation (IBE) and Geospatial Mapping of Heavy Metal Contamination in Groundwater of an Industrially Influenced Peri-Urban Area of Guwahati, Assam, India

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ABSTRACT

This study evaluates the geospatial variability of heavy metal contamination in groundwater within an industrially influenced peri-urban area spanning parts of Guwahati, Assam, and Meghalaya, India. A total of 26 samples were analyzed for nine heavy metals, As, Cd, Cr, Cu, Mn, Ni, Pb, Zn, and Fe, using Atomic Absorption Spectroscopy (AAS) during both pre- and post-monsoon seasons. Index-Based Evaluation (IBE) was employed to assess cumulative contamination levels. Results revealed maximum concentrations of Pb (0.206 mg.L^{-1}), Cd (0.011 mg.L^{-1}), Ni (0.049 mg.L^{-1}), and Mn (1.983 mg.L^{-1}) in the groundwater samples. Metal Index (MI) values ≥ 6 at 21 (pre-monsoon) and 7 (post-monsoon) sites indicated serious contamination, while Heavy Metal Pollution Index (HPI) values > 100 at 22 and 20 sites, respectively, classified the water as unsuitable for drinking. Kernel Density Estimation (KDE) and box plots further supported the temporal patterns of contamination. Geospatial mapping of MI using the Inverse Distance Weighting (IDW) technique revealed that 78% (pre-monsoon) and 69% (post-monsoon) of the area were seriously or strongly affected, while HPI interpolation indicated 97% and 95% of the area under high-pollution zones, respectively. The findings underscore the strong anthropogenic impact of cement and brick industries on groundwater quality, emphasizing the need for continuous monitoring and effluent control. The adopted framework provides a transferable model for early detection, spatial prioritization, and remediation of heavy metal contamination in industrially stressed aquifers globally.

1. INTRODUCTION

Groundwater is generally considered less prone to contamination than surface water due to its concealed nature and limited direct exposure. However, it remains vulnerable to threats such as chemical leaching, industrial discharge, over-extraction, and inadequate monitoring. So, while it may appear safer, sustainable use and proper testing are crucial to truly ensure its safety. Groundwater quality exhibits spatial variability influenced by geographic location, anthropogenic pollution sources, and prevailing ecological conditions. Heavy metal pollution is a global environmental concern due to its toxicity, bioaccumulation, and persistence (Ali et al. 2019). Even slight increases in concentrations beyond acceptable limits, from natural or anthropogenic sources, can cause serious environmental and health risks (Yahaya et al. 2009, Prasad et al. 2014, Jazza et al. 2022). Although heavy metals are naturally occurring elements distributed throughout the Earth's crust, environmental contamination and human exposure are predominantly the result of anthropogenic activities. In groundwater, the primary sources of heavy metal pollution include geogenic processes, such as rock – water interactions, and human-induced inputs (Bradl 2002). Among the various human-induced sources, industrial pollution has a severe impact on the environment due to its emissions of various contaminants, including heavy metals, into the atmosphere. Heavy metal pollutions in groundwater can result from these contaminants moving vertically through the soil profile. The extent to which these metals dissolve in soil and groundwater is largely determined by the pH range of 6-8, the concentration of the metals, and the cation exchange capacity (Martinez & Motto 2000). Heavy metals such as Arsenic (As), Cadmium (Cd), Chromium (Cr), Mercury (Hg), Lead (Pb), Nickel (Ni), Manganese (Mn) are found in groundwater due to both natural geological processes and anthropogenic activities like industrial discharge, mining, use of agrochemicals, and improper waste disposal. These metals are toxic even at low concentrations and pose serious health risks to humans and ecosystems. The International Agency for Research on Cancer (IARC) has classified the heavy metals and the compounds of arsenic, cadmium, chromium, and nickel in group 1 (carcinogenic to humans) and lead and the inorganic lead compounds (2A), cobalt in metallic form and its compounds (as possibly carcinogenic to humans. The United States Environmental Protection Agency (US-EPA) categorizes these substances as known or probable human carcinogens based on both epidemiological and toxicological studies. These classifications highlight the significant public health risks associated with long-term exposure to contaminated water sources. Even at the modest exposure levels, these metallic elements are known to cause numerous organ damage and are regarded as systemic toxicants. Anthropogenically, these heavy metals can be discharged into the air and soil during the production of cement and bricks. Through food chain transfer and drinking water contamination, these pollutants can bioaccumulate in crops produced close to the sites and endanger the long-term health of the surrounding people. The groundwater-dependent ecosystem may suffer if the anthropogenic release of heavy metals into the atmosphere is not managed appropriately. The impact of heavy metal contamination on the environment can be reduced by the management of industrial waste emissions and routine water quality monitoring.

2. MATERIALS AND METHODS

2.1. Study Area

The study area holds geographical significance as it is one of the fastest-developing peri-urban areas of Guwahati Metropolitan city, Assam, as well as a part of Meghalaya state, India (Fig. 1). The peri-urban fringes of Guwahati have undergone rapid industrial expansion in recent decades, driven by urban congestion, rising land costs, and infrastructural development within the metropolitan core. This shift has attracted numerous cement plants, brick kilns, and small-scale industries to the outskirts, transforming rural landscapes into mixed industrial-residential zones. Consequently, the region faces increasing environmental stress, particularly on groundwater resources, due to unregulated industrial discharges, waste disposal, and over-extraction. Geologically, the area represents the northeasterly extension of the Assam-Meghalaya Plateau underlain by a basement gneissic complex predominantly composed of quartz-feldspathic gneiss. This basement is overlain by unconsolidated alluvial sediments consisting of clay and sand of varying grades, deposited during the Quaternary period. Groundwater serves as the sole source for drinking, industrial and agricultural use in this area, as the River Lower-Digaru depends heavily on upstream rainfall in Meghalaya. This dependency makes surface water availability highly variable and unreliable, further emphasizing the critical role of groundwater in sustaining the area's water demands.

The area under study is also significant from an industrial perspective, with seven cement manufacturing plants and nineteen brick kilns presently operational in the area (Fig. 2). The area also previously housed a paper industry, which is no longer in existence, and is presently being repurposed for the establishment of a semiconductor manufacturing facility. Heavy metals such as cadmium and lead are found in trace quantities in the raw materials, particularly in limestone, shale and clay, which are the principal constituents in cement manufacture (European Commission 2010). The high temperatures used in the cement manufacturing process can volatilize the heavy metals, such as cadmium, lead, mercury, etc., present in the raw materials, which can then be emitted into the air and settle onto the ground, surface water, and groundwater. Furthermore, the use of chemical additives in the cement manufacturing process and during pulping and bleaching in the paper manufacturing process, can also contribute to the release of heavy metals. The use of waste fuels such as used tires or industrial waste in brick kilns can release heavy metals into the air. In addition, the disposal of cement kiln dust, a by-product of the cement manufacturing process, can release these heavy metals into the environment, particularly if not handled properly. A number of studies have demonstrated that cement plants and brick kilns significantly raise the concentrations of heavy metals in nearby soils and water bodies (Singh et al. 2010, Mehta & Mehta 2012, Mohapatra et al. 2014). Borgohain et al. (2024) investigated heavy metal contamination and associated health risks in groundwater at the Byrnihat Industrial Area near the Guwahati–Shillong Highway (Meghalaya) and reported that concentrations of Cr, Cd, and Pb exceeded the permissible limits prescribed by WHO and BIS. Arunakumari et al. (2023) examined the persistence of heavy metals and associated human health risks in an industrial area of Telangana, South India, and reported significant soil contamination (based on geo-accumulation and contamination factor indices) along with elevated health risks through groundwater exposure.

Yerraguntla in Andhra Pradesh, India, an area with multiple cement industries and a thermal power plant, showed elevated concentrations of mercury, lead, cadmium, chromium and arsenic in groundwater (Kalpana et al. 2023). Similarly, in the Roper Wetland region of Punjab, elevated levels of cadmium and zinc in groundwater were attributed to nearby cement and other industrial activities (Kaur et al. 2019). Soil and dust studies in Ghana and Jordan have further confirmed the presence of heavy metals such as Pb, Cd, Cr and Ni, indicating atmospheric deposition and leaching as potential pathways for groundwater contamination (Awuah et

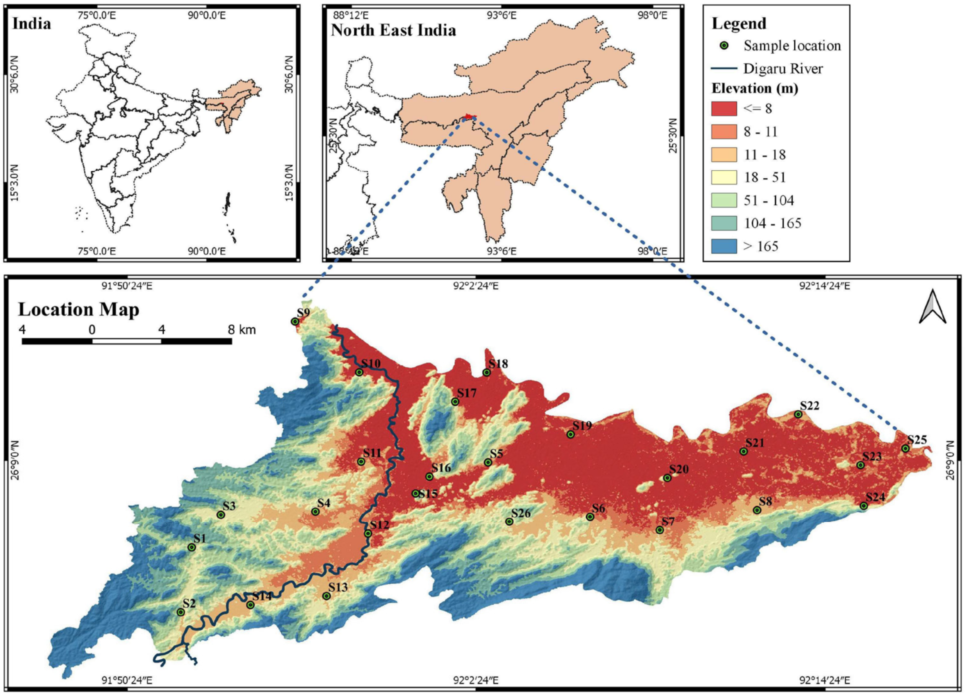


Fig. 1: Map depicting the areal extent of the study area and heavy metals sampling locations.

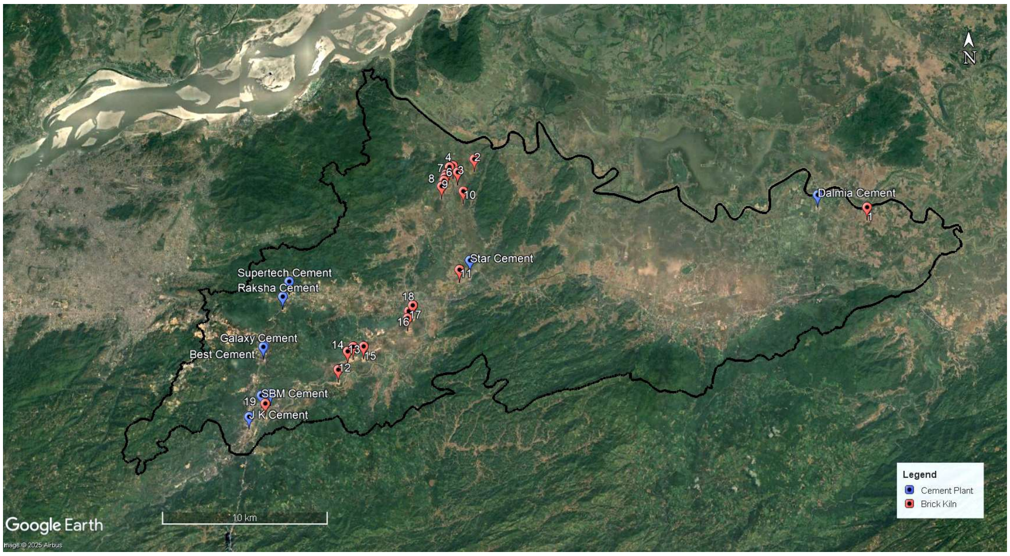


Fig. 2: Locations of cement manufacturing plants and Brick kilns in the study area.

al. 2022, Al-Khashman & Shawabkeh 2005). These findings suggest that the cement manufacturing process, through emissions, raw material handling, and waste disposal, can contribute significantly to heavy metal enrichment in the surrounding environment, including groundwater systems.

Groundwater quality in industrial peri-urban areas of Northeast India remains poorly understood due to limited comprehensive assessments. Studies rarely employ integrated index-based and geospatial approaches, and seasonal or temporal variations are often overlooked. This gap underscores the need for systematic, multidimensional evaluation to ensure sustainable groundwater management in the region. Accordingly, a comprehensive study was undertaken to evaluate the Index-Based Evaluation (IBE) and the spatial distribution of heavy metals in groundwater, and to assess their impact on groundwater quality for domestic use. Notably, this is the first detailed investigation in the region to employ IBE and geospatial analysis, as no prior groundwater studies have integrated Metal Index (MI) and Heavy Metal Pollution Index (HPI) assessments here.

2.2. Sample Collection

Groundwater samples were gathered from dug wells (DW) and deep tube wells (DTW) during both pre- and post-monsoon periods, adhering to standard procedures outlined by APHA (2023). Selection of sampling sites was based on accessibility, settlement patterns, and demographic factors, covering twenty-six of thirty-five grid cells within the study area. A total of 53 samples were collected from depths ranging from 1.84 meters in gneissic rocks to 182 meters in unconsolidated sediments and were subsequently analyzed. Samples were preserved in an acidic medium (pH < 2) with HNO_3 and transported to the laboratory within 48 hours. Before analysis, all samples were filtered following APHA (2023) guidelines. QA/QC measures included the analysis of field duplicates, collected periodically to evaluate sampling and analytical consistency, and field blanks to detect any contamination during collection, transport, or analysis. The samples were analyzed for major cations and anions, pH, electrical conductivity (EC), total dissolved solids (TDS), and heavy metals.

2.3. Heavy Metal Analysis

The groundwater samples collected were analyzed to identify and measure the concentrations of heavy metals, including Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Manganese (Mn), Lead (Pb), Zinc (Zn), and Iron (Fe), using Graphite Furnace Atomic Absorption Spectroscopy (GFAAS, Shimadzu AA6300 model). An index-based evaluation (IBE) method was employed to assess and interpret the overall impact of these heavy metals on groundwater quality in the study area. These indices facilitate the evaluation of water pollution levels and potential health risks. Several authors, including Reza and Singh (2010), Mohan et. al. (1996), and Backman et al. (1998), effectively demonstrated the practical application of indexing techniques for identifying contamination hotspots.

2.4. Metal Index (MI) Calculation

The Metal Index (MI) method is a widely used approach for assessing and quantifying the presence and severity of heavy metal contamination in groundwater. It consolidates complex heavy metal concentration data into a single numerical value, providing an overall indication of water quality with respect to metal content. The Metal Index (MI) was first proposed by Caeiro et al. (2005). The following formula is used to calculate the Metal Index:

$$MI = \sum_{i=1}^{n} (C_i \div MAC_i)$$

Where, Ci = concentration of the i^{th} metal in the water sample, MAC_i = Maximum admissible concentration of the i^{th} metal (as per WHO, BIS), *n*= total number of metals analyzed

2.5. Heavy Metal Pollution Index (HPI) Calculation

The Heavy Metal Pollution Index (HPI) is a measure of the heavy metals present in a particular environment and is a widely used method to evaluate the cumulative effect of multiple heavy metals on groundwater quality. It is an empirical evaluation system designed to assess the overall impact of specific metals on water quality (Dheeraj et al. 2022). This method was first developed by Prasad & Bose (2001), but the concept and foundational methodology were earlier elaborated by Horton (1965) and later modified by researchers like Mohan et. al. (1996) and Backman et al. (1998) for groundwater pollution studies. Unlike the Metal Index (MI), the HPI gives a weighted score, considering both the concentration and the significance (weight) of each metal. It is typically calculated by measuring the concentration of a number of different heavy metals in the environment and combining these measurements into a single index value. The Heavy Metal Pollution Index (HPI) of groundwater in the study area was calculated to assess the extent of contamination with nine heavy metals (As, Cd, Cr, Cu, Mn, Ni, Pb, Zn and Fe) using the following formula in MS-Excel -

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$$

Where, Wi is the unit weight of the i^{th} parameter, n is the number of heavy metals considered and Qi is the sub-index value of the i^{th} parameter.

The unit weight, Wi, is calculated by - Wi = K/Si

Where, K is the proportionality constant =1,

Si is the standard permissible limit value of the 'i'th parameter.

Q_i is calculated as -

$$Q_i = \sum_{i=1}^{n} \frac{(M_i\,(-)\,I_i)}{(S_i - I_i)}\ x\ 100$$

Where M_i is the monitored value, I_i is the ideal value of the heavy metal of the i^{th} parameter.

The relative weights (w_i) assigned to each water quality parameter were normalized to ensure that their sum equals unity ($\sum W_i = 1$), following the standard formulation.

2.6. Geospatial Mapping of Heavy Metals

Geospatial mapping involves analyzing data across geographic areas over specific time periods. Spatial analysis visualizes data on maps through geospatial interpolation techniques to identify contamination hotspots and spatial trends. Temporal analysis tracks changes in heavy metal concentrations over different times, such as seasonal (pre-monsoon versus post-monsoon), annual, or multi-year periods. While primarily used in environmental studies, especially groundwater contamination, it aids in visualizing how pollutant levels vary across locations and fluctuate seasonally or yearly. In this context, geo-temporal mapping of heavy metals in groundwater is an essential tool for understanding contamination patterns, pinpointing pollution sources, and guiding mitigation efforts.

Geospatial distribution maps of nine heavy metals, Cd, Cr, As, Cu, Pb, Mn, Ni, Zn, and Fe, were generated for both the pre- and post-monsoon seasons using the Spatial Analyst toolbox in ESRI ArcGIS 10.8.2. The resolution of the interpolated raster images was 90 m. Inverse Distance Weighting (IDW) was used as the interpolation method to model the geospatial distribution of heavy metals across the entire study area. Because the sample size was less than 50, IDW was adopted to map the distribution of heavy metals. IDW performs better than kriging when the sample size is small (Li & Heap 2011). For sample sizes < 50, the derived variograms are often erratic and show little or no evident spatial structure (Webster & Oliver 2001, 2007). The permissible limits for drinking water are taken from both the WHO and the BIS.

3. RESULTS AND DISCUSSION

The heavy metals examined in this study include Cadmium (Cd), Chromium (Cr), Arsenic (As), Copper (Cu), Lead (Pb), Nickel (Ni), Manganese (Mn), Zinc (Zn), and Iron (Fe). Table 1 shows the number of sampling sites where heavy metal concentrations exceeded the limits set by WHO and BIS for domestic water use. It was found that many groundwater samples in the area had elevated levels of Pb and Cd during both pre- and post-monsoon seasons, with Ni elevated in pre-monsoon and Mn in post-monsoon. Specifically, Cadmium (Cd) exceeded safe levels at 14 locations during pre-monsoon, but only once post-monsoon. Nickel (Ni) was above permissible limits at eight locations pre-monsoon, with no exceedances after the monsoon. Manganese (Mn) surpassed the limit at two sites in the post-monsoon season. Lead (Pb) contamination was the most widespread, exceeding 0.01 mg.L^{-1} at 24 of 26 locations pre-monsoon and at 22 locations post-monsoon (see Table 1).

The box plots (Fig. 3), generated using RStudio (version 2024.04.2+764), illustrate the seasonal variation, pre-monsoon versus post-monsoon, in the concentrations of four heavy metals: Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb), in groundwater. The y-axis is on a logarithmic scale to accommodate the wide range of values and improve visualization, especially for outliers. During the pre-monsoon period, manganese (Mn) shows greater variability, a wider interquartile range (IQR), and several outliers, indicating spatial heterogeneity and potential localized contamination. In contrast, post-monsoon Mn concentrations are more consistent, with a narrower IQR, although the median is slightly higher, possibly due to leaching or recharge during the monsoon. Cadmium (Cd) levels are higher and more

Table 1: Number of sampling locations in the study area exceeding the BIS permissible limits (mg.L^{-1}) for pre- and post-monsoon seasons.

Heavy Metals	Permissible Standards (BIS) [mg.L^{-1}]	No. of samples exceeding the permissible standards/ Total no of samples	
		Pre-monsoon	Post-Monsoon
Arsenic (As)	0.05	0.05	0/26
Cadmium (Cd)	0.003	14/26	01/26
Chromium (Cr)	0.05	0/26	0/26
Copper (Cu)	1.5	0/26	0/26
Manganese(Mn)	0.3	0/26	2/26
Nickel (Ni)	0.02	08/26	0/26
Lead (Pb)	0.01	24/26	22/26
Zinc (Zn)	15	0/26	0/26
Iron (Fe)	1	0/26	0/26

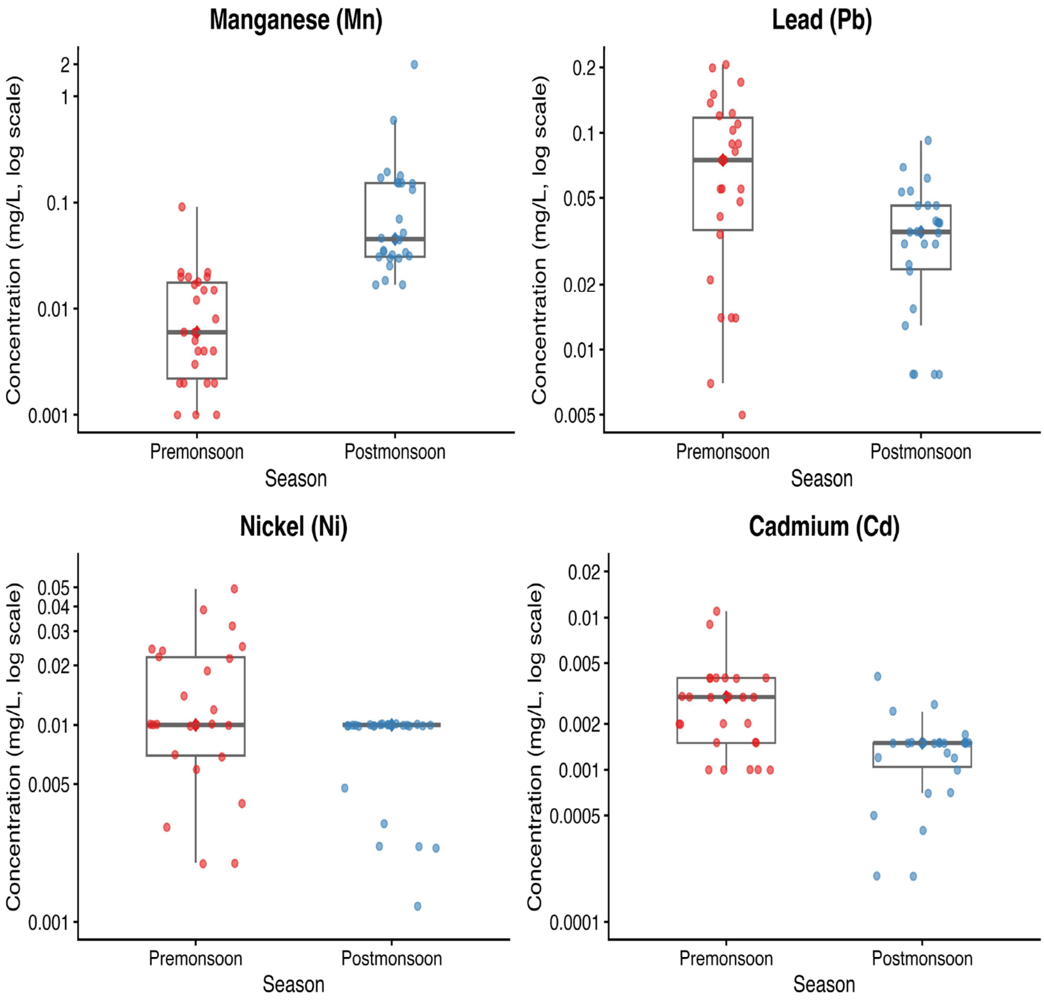


Fig. 3: Box plots showing the concentrations of heavy metals, Manganese (Mn), Nickel (Ni), Lead (Pb), and Cadmium (Cd) that exceed the Bureau of Indian Standards (BIS) permissible limits for domestic use in the study area (all concentrations are in mg.L^{-1}).

variable pre-monsoon, with several elevated outliers, while post-monsoon levels decrease markedly, suggesting dilution. Lead (Pb) exhibits a broad distribution and numerous outliers pre-monsoon, reflecting significant spatial variability and potential site-specific pollution, whereas post-monsoon levels are lower and less variable. Nickel (Ni) shows a wide distribution and multiple outliers pre-monsoon, with a median slightly higher than post-monsoon; the reduced levels in the latter may be due to rainfall-induced dilution or decreased industrial inputs.Bottom of Form

The highest recorded concentration of lead in the study area was 0.206 mg.L^{-1} during the pre-monsoon season and 0.092 mg.L^{-1} in the post-monsoon season, both observed in Sample No. S26 (Nalgedra area, near the Star Cement Plant). Cadmium concentrations were 0.011 mg.L^{-1} and 0.0041 mg.L^{-1} in the pre- and post-monsoon seasons, respectively, recorded in Sample No. S1 (Jorabat, near the Raksha Cement Plant). Manganese reached its maximum concentration of 1.983 mg.L^{-1} during the post-monsoon period in Sample No. S4 (Nazirakhat, near Raksha and Star Cement Plants), while pre-monsoon levels remained below the permissible limit. The highest concentration of nickel was 0.049 mg.L^{-1} in the pre-monsoon season, observed in Sample No. S15 (Samota Pathar, near the Star Cement Plant), with post-monsoon levels falling below the permissible threshold (Fig. 4). The concentrations of Chromium (Cr), Arsenic (As), Copper (Cu), Zinc (Zn), and Iron (Fe) were found to be within the prescribed permissible limits during both seasons.

The color scale (Fig. 5) depicts Pearson’s correlation coefficients (r) ranging from –1, indicating a strong negative correlation (blue), to +1, indicating a strong positive correlation (red). During the pre-monsoon season, metals

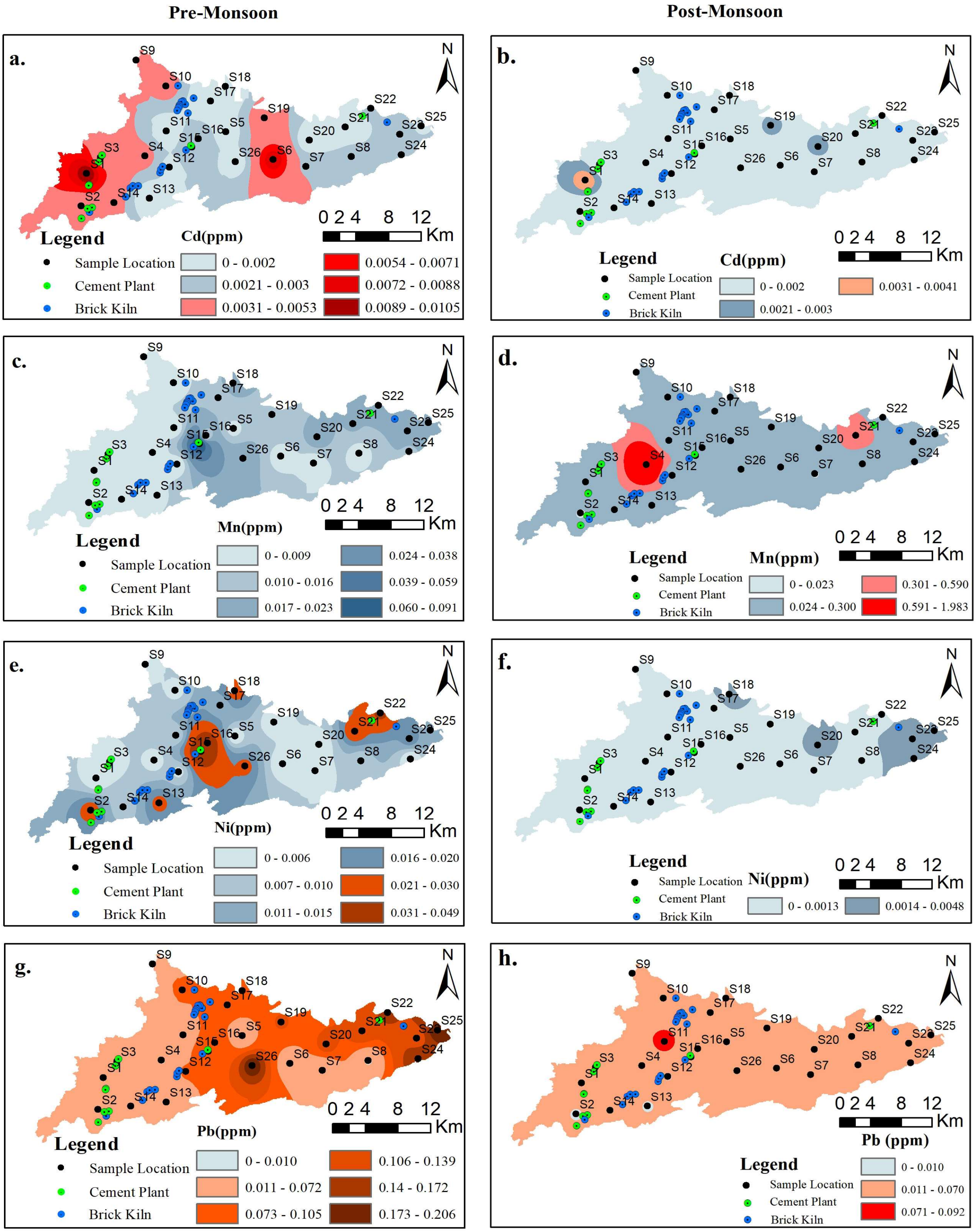


Fig. 4: The geospatial distribution maps illustrate the spatial and seasonal variation in the concentrations of heavy metals- Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb)- across the study area during both pre- and post-monsoon seasons (all concentrations are in ppm).

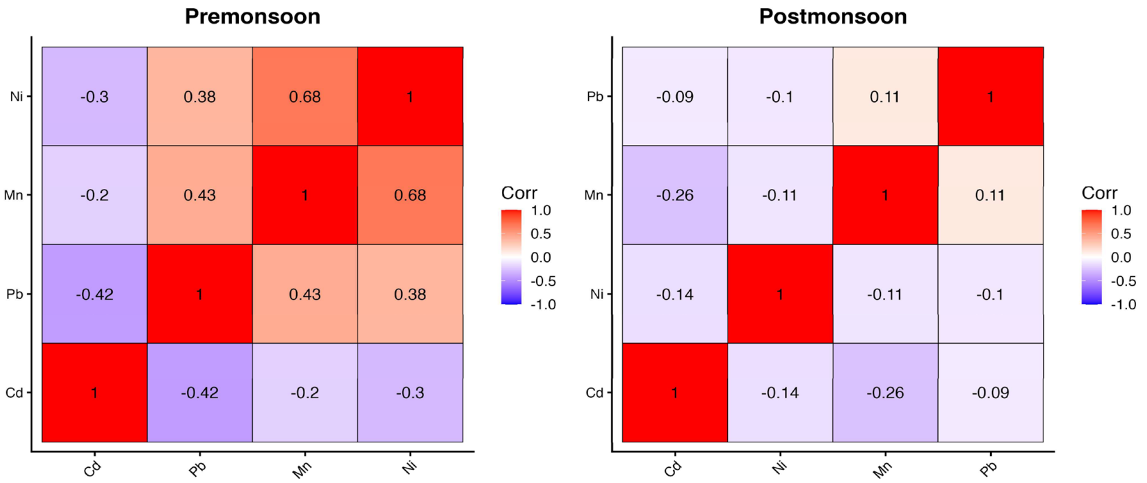


Fig. 5: Seasonal correlation matrices of heavy metals (Mn, Pb, Ni, and Cd) in groundwater samples during pre-monsoon and post-monsoon seasons, generated using RStudio (version 2024.04.2+764).

Table 2: Interpretation of Metal Index (MI) value of the heavy metals analysed.

Metal Index (MI) Range	No. of locations affected (Pre-Monsoon)	No. of locations affected (Post-Monsoon)	Water Quality Status
MI < 1	Nil	Nil	Good (no significant pollution)
1 ≤ MI < 2	01	03	Slightly affected
2 ≤ MI < 4	04	04	Moderately affected
4 ≤ Mi < 6	Nil	12	Strongly affected
Mi ≥ 6	21	07	Seriously affected

Table 3: Interpretation of Heavy Metal Pollution Index (HPI) value (Horton 1965).

(HPI) Range	No. of locations affected (Pre-Monsoon)	No. of locations affected (Post-Monsoon)	Water Quality Status
HPI< 100	04	06	Low/no pollution (safe for drinking)
HPI >100	22	20	High pollution (unsafe for drinking)

such as Mn-Ni and Cd-Pb exhibit moderate to strong positive correlations, implying common anthropogenic or geogenic sources. In contrast, the post-monsoon season shows weaker and more variable correlations, likely due to dilution, leaching, or differential mobilization of metals after rainfall.

The interpretations of the Metal Index (MI) and Heavy Metal Pollution Index (HPI) for the analyzed heavy metals are detailed in Tables 2 and 3. Throughout both seasons, four sites showed MI values ranging from 2 to 4, indicating moderate contamination. In the post-monsoon period, 12 sites exhibited MI values between 4 and 6, categorizing them as significantly affected. Notably, 21 sites in the pre-monsoon season and 7 in the post-monsoon season had MI values of 6 or higher, indicating severe heavy metal contamination. The HPI results revealed that 22 sites in the pre-monsoon season and 20 during the post-monsoon season surpassed the critical threshold, placing them in the high pollution category. These results suggest that the groundwater in these areas is unsafe for drinking without proper treatment.

A statistical summary of the Metal Index (MI) and Heavy Metal Pollution Index (HPI) is provided in Table 4.

The KDE plot (Fig. 6) effectively depicts the seasonal variations in heavy metal contamination of groundwater. It reveals an improvement in water quality after the monsoon, evidenced by decreases in metal levels and shifts in both MI and HPI distributions. The higher HPI values observed before the monsoon indicate increased pollution, while the lower post-monsoon values suggest natural dilution has reduced contamination. These results emphasize the importance of seasonal monitoring for precise evaluation of heavy metal pollution trends and highlight the necessity of implementing robust water quality management and mitigation measures.

Table 4: Statistical summary of Metal Index (MI and Heavy Metal Pollution Index (HPI).

Season	Sample Size (N)	MI_mean	MI_median	MI_mode	MI_sd	MI_se	MI_ci_lower	MI_ci_upper
Post-monsoon	26	4.97	5.14	5.51	2.12	0.42	4.11	5.83
Pre-monsoon	26	9.6	8.69	5.14	5.74	1.12	7.28	11.92
Season	Sample Size (N)	HPI_mean	HPI_median	HPI_mode	HPI_sd	HPI_se	HPI_ci_lower	HPI_ci_upper
Post-monsoon	26	147.94	147.73	141.17	59.97	11.76	123.72	172.17
Pre-monsoon	26	270.54	258.03	264.91	158.75	31.13	206.42	334.66

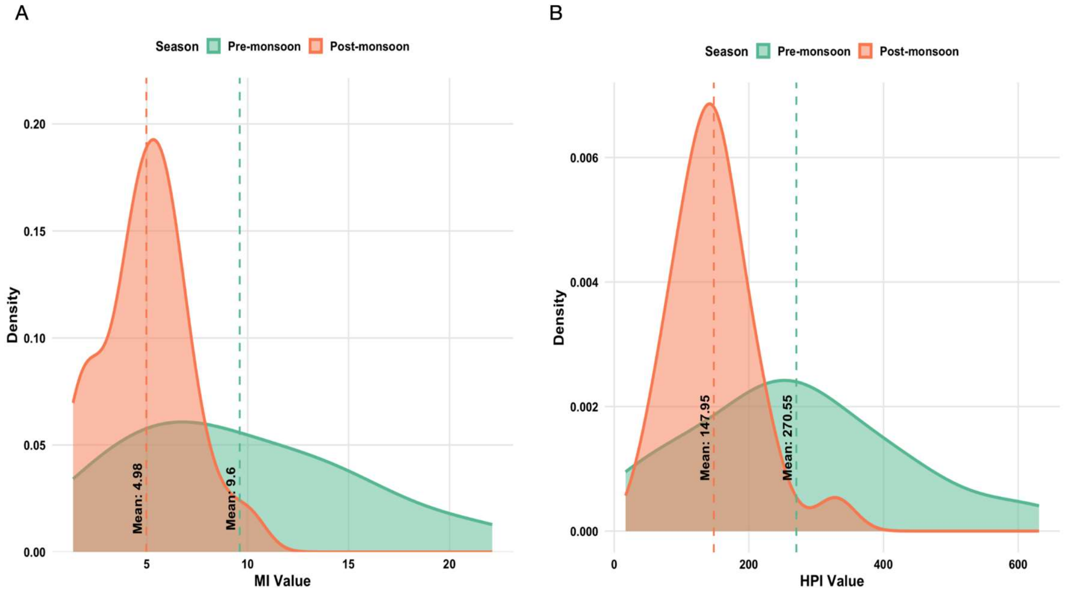
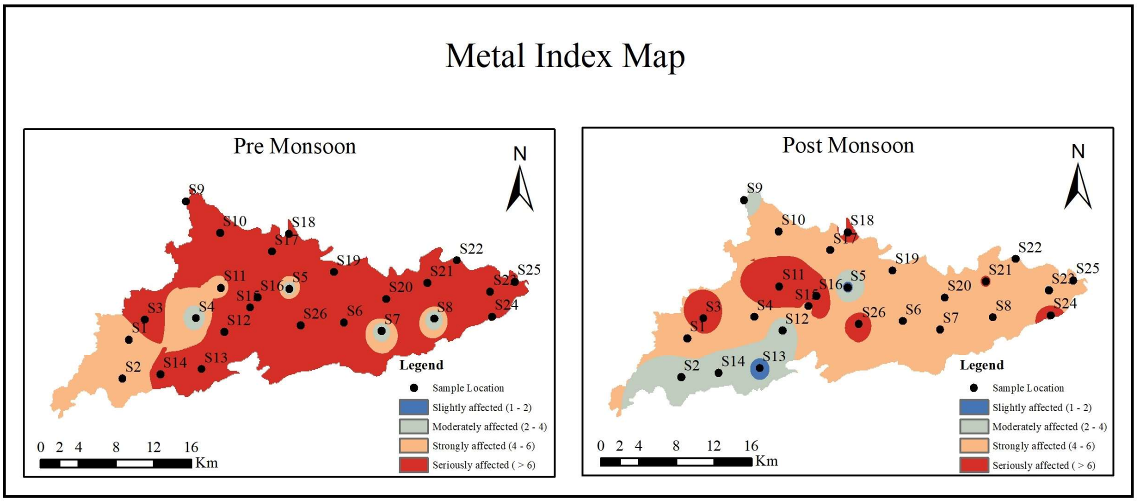


Fig 6: Kernel Density Estimation (KDE) plot using RStudio (version 2024.04.2+764) for [A] Metal Index (MI) values and [B] Heavy Metal Pollution Index (HPI) values in groundwater samples (n=26), comparing pre- and post-monsoon seasons [Dashed Vertical Lines indicate the mean MI values for each season].

The GIS-based geospatial maps illustrating the Metal Index (MI) and Heavy Metal Pollution Index (HPI) in groundwater within the study area clearly depict seasonal variations in heavy metal contamination (Fig. 7). The pre-monsoon period exhibits widespread and severe pollution, indicating substantial heavy metal accumulation. Conversely, post-monsoon maps reveal localized improvements in groundwater quality, particularly in areas such as S2 and S14, due to dilution and flushing effects of rainfall. These spatial patterns are consistent with the statistical findings and emphasize the importance of seasonal monitoring. Additionally, the results underscore the need for spatially targeted mitigation and remediation strategies to effectively address and reduce heavy metal pollution in groundwater sources. Spatial interpolation of the Metal Index (Table 5) indicates that the area can be classified into four categories in both seasons. During pre-monsoon, approximately 78% of the area falls into the seriously affected class, while in the post-monsoon, the strongly affected class dominates at 69%. Similarly, based on the Heavy Metal Pollution Index (Table 6), the area can be divided into high and low pollution zones, with 97% of the pre-monsoon region showing high pollution levels, and 95% of the post-monsoon region also falling under high pollution.

3.1. Discussion

In the study area, cadmium and lead concentrations exceeding permissible limits are of particular concern due to their potential to cause severe health effects, especially in children and pregnant women. Cadmium (Cd) is classified as a Group 1 carcinogen (WHO 2017), and among the most hazardous and highly mobile elements in the environment (Alloway & Jackson1991, Nies 1999, 2003). Short-term exposure to high levels of cadmium in drinking water may cause vomiting and diarrhea. (US EPA 2023). The use of wastes as alternative fuels or raw materials in cement kilns introduces additional trace elements such as cadmium, lead, etc. into the system, especially from sources like sewage sludge, tires, and certain slags (WBCSD 2014). Acute cadmium ingestion can cause renal dysfunctions, hepatic



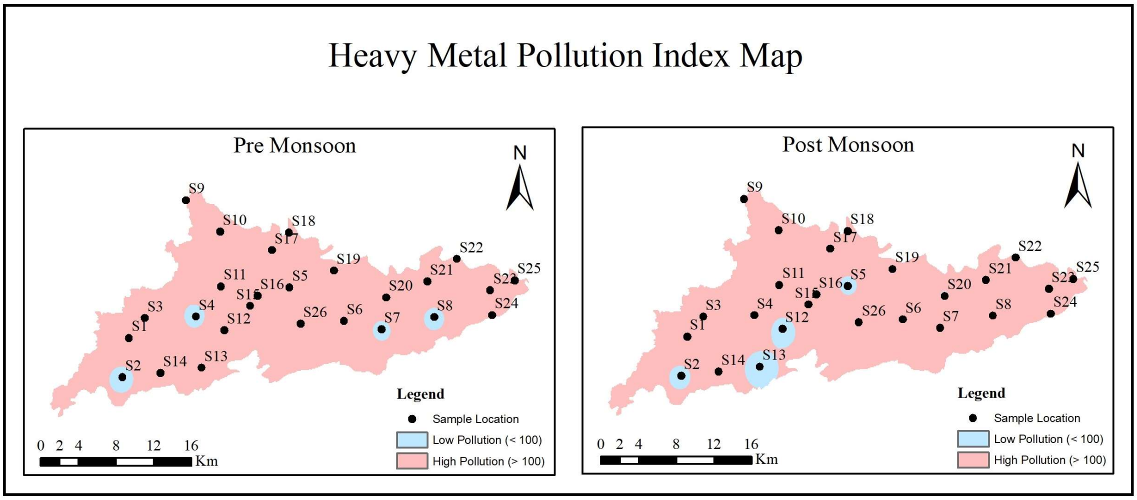


Fig 7: Geospatial distribution of Metal Index (MI) and Heavy Metal Pollution Index (HPI) of groundwater within the study area for the pre-monsoon and post-monsoon periods.

Table 5: Spatial distribution of Metal Index.

Class	Pre Monsoon		Post Monsoon	
	Area [Sq. km]	Percentage	Area [Sq. km]	Percentage
Slightly affected	0.16	0.03	4.69	0.88
Moderately affected	12.24	2.30	86.98	16.34
Strongly affected	105.96	19.90	369.38	69.37
Seriously affected	414.10	77.77	71.39	13.41

Table 6: Spatial distribution of Heavy Metal Pollution Index.

Class	Pre Monsoon		Post Monsoon	
	Area [Sq. km]	Percentage	Area [Sq. km]	Percentage
Low Pollution	16.70	3.14	25.38	4.77
High Pollution	515.75	96.86	507.07	95.23

injury, osteomalacia, pulmonary edema, and gastrointestinal tract erosion, depending on the route of poisoning (Baselt 2000). In the human body, cadmium mainly builds up in the kidneys, with a biological half-life ranging from 10 to 35 years. Lead (Group 2A) has been considered for centuries as a cumulative metabolic poison and neurotoxic (ATSDR 2020, WHO 2017, Adepoju-Bello & Alabi 2005, Achternbosch et al. 2003, Center for Disease Control and Prevention, Atlanta 2001, ATSDR 2020). Lead compounds cause kidney tumors and other cancers in experimental animals (IARC 2006 & 2012). Nickel is classified as a Group 2B carcinogen by the IARC. Prolonged exposure to elevated levels can cause dermatitis (skin irritation), respiratory issues, kidney and cardiovascular problems, and it has potential carcinogenic effects at high doses. Though an essential nutrient, excessive Mn (>0.3 $mg.L^{-1}$) can lead to neurological problems, especially in children (WHO 2017). Manganese is found as Mn^{2+} in groundwater under reducing conditions. Mn^{2+} is highly soluble and mobile in reducing low pH environments. Under oxidizing conditions, e.g., at the water table, Mn oxidizes to Mn^{4+} or Mn^{3+} and precipitates as oxides, resulting increasing risk of contamination. In reducing conditions, Mn^{2+} may exceed permissible limits in groundwater, requiring treatment before consumption.

In the study area, pH in groundwater varies from slightly acidic to alkaline conditions (5.22–7.23). Lead in groundwater is commonly found as Pb^{+2} at low to neutral pH, at higher pH (≥ 8), lead precipitates as Pb $(OH)_2$, reducing its solubility. Cadmium (Cd) remains in aqueous solution primarily in the form of Cd^{+2} ions, and its solubility is strongly pH-dependent, at a pH of less than 6.5 and under oxygenated conditions (Kubier et al. 2019). The distribution of Cd and Pb in groundwater serves as a tracer for anthropogenic impact, particularly in industrial or urbanized regions. Their behaviour reflects the integrated effects of lithology, hydrology, and land-use patterns, making them important indicators in hydrogeochemical and environmental assessments. Moreover, industrial effluents, agricultural runoff, and waste disposal can alter natural hydrogeochemical conditions, enhancing the metal contamination. The lithology of the study area strongly influences heavy metal retention and migration. Fine-grained units such as sand, silt, pebble, and clay, along with gneiss, exhibit higher adsorption capacity, promoting retention of metals like Pb, Cd, Ni, and Mn through binding to clay minerals and oxides. In contrast, loamy sand and weathered porphyritic granite have higher permeability and lower adsorption potential, facilitating greater metal mobility in groundwater.

Overall, formations rich in clay and with low permeability act as sinks, while coarse, permeable, or fractured lithologies function as pathways for heavy metal transport, particularly under near-neutral pH conditions. Cement manufacturing facilities in the area may release cadmium, lead, and nickel into the environment. These toxic metals are naturally present in raw materials such as limestone, clay, and shale used for cement production. During the high-temperature processing (~1450°C) in rotary kilns, these metals can volatilize and become airborne, eventually settling on soil, surface water, and groundwater. Additional contamination sources include additives, fuels, and waste materials—such as used tires and industrial waste—in both cement and brick kilns. Improper disposal of cement kiln dust, fly ash, bottom ash, and fuel residues further exacerbates heavy metal contamination through leaching into nearby soil and shallow groundwater.

High contamination is not uniform across the aquifer but concentrated near industrial clusters, indicating point-source or localized anthropogenic inputs rather than widespread geogenic leaching. The measured pH in groundwater in the study area (6.30–7.49) further reduces the likelihood of dominant geogenic origins, as the gneissic basement and overlying alluvial sediments are not typically significant sources of Pb or Cd under near-neutral conditions (Martinez & Motto 2000, Alloway & Jackson 1991). Under such pH ranges, the solubility and mobility of Pb^{2+} and Cd^{2+} from natural lithological sources are generally low, making anthropogenic inputs the more plausible primary contributors to the observed contamination. Regular groundwater monitoring and stricter regulation of waste fuels in kilns are vital for protecting the environment and public health. Continuous monitoring helps detect contamination early, guide remediation, and support evidence-based policies. At the same time, enforcing strict controls on waste fuel use—through permits, emission limits, quality standards, and mandatory EIAs ensures sustainable industrial practices that minimize pollution and safeguard natural resources.

4. CONCLUSIONS

This study demonstrates that utilizing both Index-Based Evaluation (MI and HPI) and GIS-based geospatial mapping offers a comprehensive approach to assessing cumulative heavy metal contamination in groundwater. In the study area, lead (Pb) levels surpassed permissible limits in 92% of pre-monsoon samples and 85% of post-monsoon samples, while cadmium (Cd) exceeded limits in 54% of pre-monsoon samples and 4% of post-monsoon samples. A total of 21 sites during pre-monsoon and 7 sites during post-monsoon were identified as seriously affected (MI ≥ 6), with Heavy Metal Pollution Index (HPI) values over 100 at 22 and 20 sites, respectively. These results indicate that Pb and Cd contamination is widespread and persistent across seasons, with higher exceedances before the monsoon. Nickel (Ni) and manganese (Mn) also pose localized risks, highlighting complex interactions between seasonal changes and both natural and human influences. The high MI and HPI values in the pre-monsoon season suggest pollutant buildup from industrial emissions, whereas the decrease after monsoon reflects dilution and flushing due to monsoonal recharge. The spatial distribution observed in geospatial maps closely corresponds with the locations of industrial units, though minor natural sources cannot be completely excluded. A multi-barrier mitigation strategy, including advanced treatment methods (adsorption, ion exchange, permeable reactive barriers, electrocoagulation, membrane filtration), pollution source control (effluent segregation, process modifications, stormwater management, strict regulation), and institutional support (long-term monitoring, community involvement, capacity building), is recommended to effectively reduce heavy metal contamination in the industrialized regions of the study area.

The methodological framework and results of this study present a transferable model for managing industrially stressed aquifers, facilitating early detection, spatial prioritization, and prompt remediation of heavy metal contamination. These findings have implications beyond the immediate study area. Regionally, they can assist policymakers and water authorities in Assam and similar peri-urban industrial zones across India to implement targeted monitoring, strengthen regulations on industrial discharges, and develop location-specific mitigation strategies. Globally, combining index-based evaluation (IBE) with geospatial mapping offers a replicable tool for assessing groundwater vulnerability in rapidly industrializing regions worldwide, where industries like cement manufacturing and brick kilns pose similar threats to water security. Proactive management, supported by such integrated approaches, is essential to protect groundwater resources, safeguard public health, and promote sustainable growth in urban and industrial areas both locally and internationally. Ultimately, our findings provide valuable insights for environmental monitoring, industrial impact assessment, and groundwater safety, serving as a strategic template for countries at different stages of development facing the challenge of balancing economic growth with water resource conservation.

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6. REFERENCES

Achternbosch, M., Richers, U. and Stemmermann, P., 2003. Heavy metals in cement and concrete resulting from the co-incineration of wastes in cement kilns with regard to the legitimacy of waste utilisation. German Federal Environmental Agency (UBA). Retrieved February 10, 2026, from https://www.umweltbundesamt.de

Adepoju Bello, A.A. and Alabi, O.M., 2005. Heavy metals: A review. *The Nigerian Journal of Pharmacy*, 37(1), pp.41-45.

Agency for Toxic Substances and Disease Registry (ATSDR), 2020. *Toxicological Profile for Lead*. U.S. Department of Health and Human Services, Public Health Service, Atlanta, pp.250.

Al-Khashman, O.A. and Shawabkeh, R.A., 2005. Metal distribution in soils around a cement factory in southern Jordan. *Environmental Geochemistry and Health*, 27(4), pp.331-340. [DOI]

Alloway, B.J. and Jackson, A.P., 1991. The behaviour of heavy metals in sewage sludge-amended soils. *Science of the Total Environment*, 100, pp.151-176. [DOI]

American Public Health Association (APHA), 2023. *Standard Methods for the Examination of Water and Wastewater, 24th Ed*. APHA Press, Washington, DC, pp.1500.

Arunakumari, K., Begum, F., Surinaidu, L., Umamaheswari, A. et al., 2023. Persistence of heavy metals and human health risk assessment in the South Indian industrial area. *AQUA - Water Infrastructure, Ecosystems and Society*, 72(6), pp.898-913. [DOI]

Awuah, G.B., Gyasi, R.M., Addae, M.K. and Darko, E.O., 2022. Health risk associated with heavy metals in dust from cement factories in Ghana. *Journal of Environmental and Public Health*, 2022(1), pp.1-10. [DOI]

Backman, B., Bodis, D., Lahermo, P., Rapant, S. and Tarvainen, T., 1998. Application of a groundwater contamination index in Finland and Slovakia. *Environmental Geology*, 36(1-2), pp.55-64. [DOI]

Baselt, R.C., 2000. *Disposition of Toxic Drugs and Chemicals in Men, 5th Ed*. Chemical Toxicology Institute, Foster City, CA, pp.1200.

Borgohain, D., Lanong, S. and Jaishi, H.P., 2024. Heavy metal contamination and health risks in groundwater at Byrnihat industrial area: urgent need for remediation and public health safeguards. *Proceedings of the Indian National Science Academy*, 90, pp.931-942.

Bradl, H., 2002. *Heavy Metals in the Environment: Origin, Interaction and Remediation (Volume 6)*. Academic Press, London, pp.400.

Caeiro, S., Costa, M.H., Ramos, T.B., Fernandes, F., Silveria, N., Coimbra, A. and Painho, M., 2005. Assessing heavy metal contamination in Sado Estuary sediment: an index analysis approach. *Ecological Indicators*, 5(2), pp.151-169. [DOI]

Centre for Disease Control and Prevention (CDCP), 2001. *Managing Elevated Blood and Lead Levels Among Young Children: Recommendations from the Advisory Committee on Childhood Lead Poisoning Prevention*. CDC, Atlanta, pp.100.

Dheeraj, V.P., Singh, C.S., Kishore, N. and Sonkar, A.K., 2022. Groundwater quality assessment in Korba Coalfield region, India: an integrated approach of GIS and heavy metal pollution index (HPI) model. *Nature Environment and Pollution Technology*, 22(1), pp.369-382. [DOI]

European Commission, 2010. *Reference Document on Best Available Techniques (BREF) for the Production of Cement, Lime and Magnesium Oxide*. Integrated Pollution Prevention and Control (IPPC), p.278.

Jazza, S.H., Najim, S.S. and Adnan, M.A., 2022. Using heavy metals pollution index (HPI) for assessment quality of drinking water in Maysan Province in Southern East in Iraq. *Egyptian Journal of Chemistry*, 65(2), pp.703. [DOI]

Kalpana, A., Puppala, R.K. and Maheswaramma, K.S., 2023. An assessment of ground water contamination due to heavy metals and fly ash around Yerraguntla Town, Kadapa District, Andhra Pradesh, India. *Journal of Pollution Effects & Control*, 11(1), pp.1-10. [DOI]

Kaur, M., Kaur, R. and Bhardwaj, R., 2019. Appraisal of heavy metal contents in groundwater and associated health hazards posed to human population of Ropar Wetland, Punjab. *Chemosphere*, 237, pp.124470. [DOI]

Kubier, A., Wilkin, R.T. and Pichler, T., 2019. Cadmium in soils and groundwater: a review. *Applied Geochemistry*, 108, pp.104388.

Ali, H., Khan, E. and Ilahi, I., 2019. Heavy metals in the environment: sources and toxicity. *Journal of Chemistry*, 2019, article 6730305. [DOI]

Horton, R.K., 1965. An index number system for rating water quality. *Journal of the Water Pollution Control Federation*, 37(3), pp.300-306.

International Agency for Research on Cancer (IARC), 2006. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 87: Inorganic and Organic Lead Compounds*. World Health Organization, IARC, Lyon, France, pp.500.

International Agency for Research on Cancer (IARC), 2012. *Arsenic, Metals, Fibres and Dusts. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100 C*. IARC, Lyon, France, pp.300.

Li, J. and Heap, A.D., 2011. A review of comparative studies of spatial interpolation methods in environmental sciences: performance and impact factors. *Ecological Informatics*, 6(3-4), pp.228-241. [DOI]

Martinez, C.E. and Motto, H.L., 2000. Solubility of lead, zinc and copper added to mineral soils. *Environmental Pollution*, 107(1), pp.153-158.

Mehta, R.K. and Mehta, D., 2012. Heavy metal contamination near brick kiln industries in Varanasi, India. *International Journal of Environmental Sciences*, 3(1), pp.293-300.

Mohapatra, M. et al., 2014. Environmental impact of cement production on groundwater quality in India. *Journal of Environmental Science and Engineering*, 56(3), pp.211-218.

Mohan, S.V., Nithila, P. and Reddy, S.J., 1996. Estimation of heavy metal pollution index for groundwater using weighted arithmetic mean method in industrial area of Andhra Pradesh, India. *Environmental Monitoring and Assessment*, 42(1), pp.39-54. [DOI]

Nies, D.H., 2003. Efflux-mediated heavy metal resistance in prokaryotes. *FEMS Microbiology Reviews*, 27(2-3), pp.313-339. [DOI]

Nies, D.H., 1999. Microbial heavy-metal resistance. *Applied Microbiology and Biotechnology*, 51(6), pp.730-750. [DOI]

Prasad, B., Kumari, P., Bano, S. and Kumari, S., 2014. Ground water quality evaluation near mining area and development of heavy metal pollution index. *Applied Water Science*, 4(1), pp.11-17. [DOI]

Prasad, B. and Bose, J., 2001. Evaluation of heavy metal pollution index for groundwater around coal mining area, Yellandu, Khammam district, Andhra Pradesh, India. *Environmental Geology*, 41(1-2), pp.1-9. [DOI]

Reza, R. and Singh, G., 2010. Heavy metal contamination and its indexing approach for groundwater of Sumbal area, Kashmir, India. *Environmental Earth Sciences*, 63(7), pp.1349-1360.

Singh, G. et al., 2010. Assessment of heavy metal contamination in soil around brick kilns in northern India. *Environmental Monitoring and Assessment*, 168(1-4), pp.365-371.

U.S. Environmental Protection Agency (US EPA), 2023. Guidelines for Carcinogen Risk Assessment (EPA/630/P-03/001F). Retrieved February 10, 2026, from https://www.epa.gov/sites/default/files/2013-09/documents/cancer_guidelines_final_3-25-05.pdf

Webster, R. and Oliver, M.A., 2001. *Geostatistics for Environmental Scientists (1st ed.)*. John Wiley & Sons, Chichester, pp.400.

Webster, R. and Oliver, M.A., 2007. *Geostatistics for Environmental Scientists (2nd ed.)*. John Wiley & Sons, Chichester, pp.300. [DOI]

World Business Council for Sustainable Development (WBCSD), Cement Sustainability Initiative, 2014. *Guidelines for Co-processing Fuels and Raw Materials in Cement Manufacturing*. WBCSD, pp.100.

World Health Organization (WHO) and International Agency for Research on Cancer (IARC), 2017. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: List of Classifications, Volumes 1–120*. IARC, Lyon, France. Retrieved February 10, 2026, from https://monographs.iarc.who.int/list-of-classifications

Yahaya, M.I., Mohammad, S. and Abdullahi, B.K., 2009. Seasonal variations of heavy metals concentration in Abattoir dumping site in Nigeria. *Journal of Applied Sciences and Environmental Management*, 13(4), pp.9-13.