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Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 3, September 2026 issue

Type of the Paper (Original Research)

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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Key Words	Index-Based Evaluation (IBE), Geospatial Mapping, IDW interpolation, Kernel Density Estimation (KDE), Heavy metals, Groundwater
DOI	https://doi.org/10.46488/NEPT.2026.v25i03.B4387 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Chutia, D., Kataki, S. and Kataki, A.S., 2026. Index-based evaluation (IBE) and geospatial mapping of heavy metal contamination in groundwater of an industrially influenced peri-urban area of Guwahati, Assam, India. *Nature Environment and Pollution Technology*, 25(3), B4387. https://doi.org/10.46488/NEPT.2026.v25i03.B4387

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 analysed 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), Cd (0.011 mg/L), Ni (0.049 mg/L), and Mn (1.983 mg/L) 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 as 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 (H. 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 severe impact on environment due to their 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 and 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 management of industrial waste emissions and routine water quality monitoring.

2. MATERIALS AND METHODS

Study Area

The study-area holds geographical significance as it is one of the fastest-developing peri-urban area of Guwahati Metropolitan city, Assam as well as a part of Meghalaya state, India (Figure 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 (Figure 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 and 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 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 is poorly understood due to limited comprehensive assessments. Studies rarely use integrated index-based and geospatial approaches, and seasonal or temporal variations are often overlooked. This gap highlights the need for systematic, multidimensional evaluation to ensure sustainable groundwater management in the region. Therefore, a comprehensive study was undertaken to evaluate the Index-Based Evaluation (IBE) and spatial distribution of heavy metals in groundwater and to assess their impact on groundwater quality for domestic use. Notably, this represents the first detailed investigation in the region employing IBE and geospatial analysis, as no prior groundwater studies integrating Metal Index (MI) and Heavy Metal Pollution Index (HPI) assessments have been conducted here.

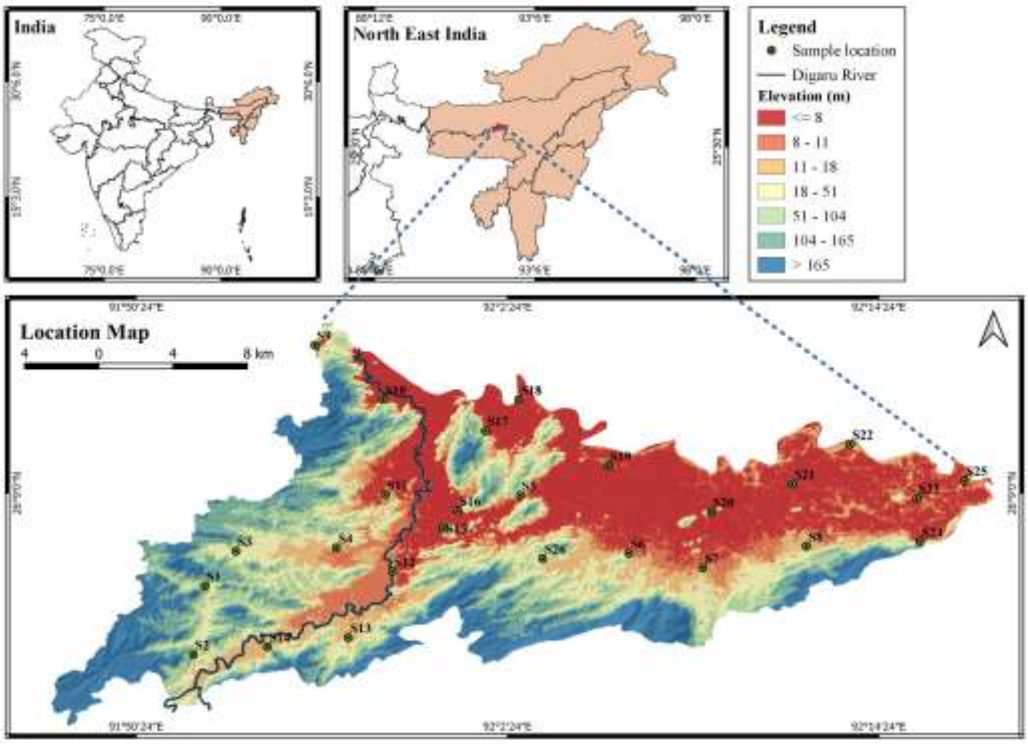

Fig.1: Map depicting the areal extent of the study area and heavy metals sampling locations.

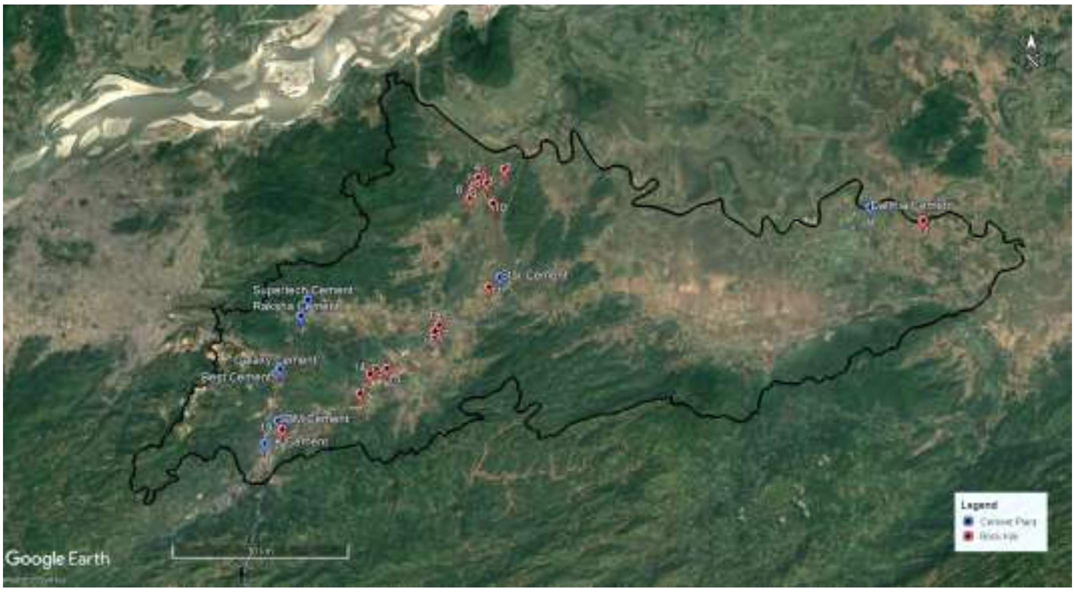

Fig. 2: Locations of cement manufacturing plants and Brick kilns in the study area

Sample Collection

Groundwater samples were collected from dug wells (DW) and deep tube wells (DTW) during both the pre- and post-monsoon periods, following standard procedures outlined by APHA (2023). Sampling sites were selected from twenty-six grid cells out of a total of thirty-five covering the study area, based on factors such as accessibility, settlement distribution, and demographic considerations. A total of 53 groundwater samples were collected from depths ranging between 1.84 m (gneissic rocks) and 182 m (unconsolidated sediments) and subsequently analysed. Samples were preserved in an acidic medium (pH < 2) by adding HNO_3, and transported to the laboratory within 48 hours of collection. Prior to analysis, all samples were filtered in accordance with APHA (2023) protocols. Quality assurance and quality control (QA/QC) measures included the analysis of field duplicates and field blanks. Field duplicates were collected at regular intervals to assess sampling and analytical precision, while field blanks were used to detect any potential contamination during sample collection, transport, and analysis. The groundwater samples were analysed for major cations and anions, pH, electrical conductivity (EC), total dissolved solids (TDS), and heavy metals.

Heavy Metal Analysis

The collected groundwater samples were analysed to determine the presence and 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). Index-based Evaluation (IBE) method was used to quantify and interpret the overall impact of heavy metals present in groundwater in the study area The indices help to assess the water quality in terms of pollution status and potential health risks. Several authors including Tiwari & Singh (2014), 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.

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 con centration 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 analysed

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 and Bose (2001), but the concept and foundational methodology were earlier elaborated by Horton (1965) and later modified by the 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, W_i is the unit weight of the i^{th} parameter, n is the number of heavy metals considered and Q_i is the sub-index value of the i^{th} parameter.

The unit weight, W_i, is calculated by - $W_i = K/S_i$

Where, K is the proportionality constant =1;

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

Q_i is calculated as -

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

Where, M_i is the monitored value; I_i is the ideal value of 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.

Geospatial Mapping of Heavy Metals

Geospatial mapping refers to the spatial and temporal analysis of data over a geographical area and a specific period of time. Spatial analysis involves the plotting the data on maps using the Geospatial interpolation techniques to identify hotspots and spatial trends of contaminations. Temporal analysis examines how the concentration of heavy metals changes over different times -such as seasonal (pre-monsoon vs post-monsoon), annual or multi-year intervals. While applied to environmental studies, particularly groundwater contamination, it helps in visualizing how pollutant levels very across locations and change seasonally or annually. In this context, geo-temporal mapping of heavy metals in groundwater is a vital tool for understanding contamination patterns, identifying pollution sources, and implementing mitigation strategies.

The geospatial distribution maps of nine heavy metals—Cd, Cr, As, Cu, Pb, Mn, Ni, Zn, and Fe, were generated for both pre- and post-monsoon seasons using the Spatial Analyst toolbox in ESRI ArcGIS 10.8.2. The Resolution of interpolated raster images: 90m. The Inverse Distance Weighting (IDW) interpolation method was employed to create these maps, utilizing heavy metal concentration data to model the geospatial distribution across the entire study area. As the sample size is less than 50, IDW interpolation 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 size < 50, the variograms derived are often erratic with little or no evident spatial structure (Webster and Oliver, 2001; 2007). The permissible limits for drinking water are taken from the both WHO and BIS.

3. RESULTS

The heavy metals analysed 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 presents the number of sampling locations where the concentrations of the respective heavy metals exceed the permissible limits prescribed by WHO and BIS for domestic use. It was observed that a significant number of groundwater samples in the study area contain elevated concentrations of Pb and Cd, during both pre- and post-monsoon seasons; Ni in pre-monsoon and Mn in post-monsoon season. Cadmium (Cd) exceeded permissible limits at 14 locations during the pre-monsoon period, while only one location showed exceedance in the post-monsoon season. Similarly, elevated Nickel (Ni) concentrations were observed at eight locations in the pre-monsoon period, with no exceedances reported post-monsoon. Manganese (Mn) exceeded the permissible limit at two locations during the post-monsoon season. Lead (Pb) contamination was the most widespread, with concentrations surpassing the maximum allowable limit of 0.01 mg/L at 24 out of 26 locations in the pre-monsoon and at 22 locations in the post-monsoon period (Table 1).

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

Heavy Metals	Permissible Standards (BIS) (mg/L)	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

The box plots (Figure 3) generated using RStudio (version 2024.04.2+764), are illustrating the seasonal variation (pre-monsoon vs post-monsoon) in the concentrations of four heavy metals—Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb)—in groundwater. The y-axis is presented on a logarithmic scale to accommodate the wide range of concentration values and to enhance visualization, particularly in the presence of outliers. During the pre-monsoon period, Manganese (Mn) exhibits higher variability, a broader interquartile range (IQR), and several outliers, indicating spatial heterogeneity and potential localized contamination. In contrast, post-monsoon Mn concentrations appear more consistent (narrower IQR), although the median concentration is slightly elevated, possibly due to leaching or recharge effects during the monsoon. Cadmium (Cd) concentrations are higher and more variable in the pre-monsoon season, with several elevated outliers, while the post-monsoon season shows markedly reduced concentrations and variability, suggesting dilution effects. Lead (Pb) demonstrates a wide distribution and numerous outliers in the pre-monsoon period, indicating substantial spatial variability and possible site-specific contamination. Post-monsoon Pb levels are comparatively lower and less variable. Nickel (Ni) displays a broad distribution and multiple outliers in the pre-monsoon season, with a slightly higher median compared to the post-monsoon period. The narrow concentration range and reduced levels observed in the post-monsoon season may be attributed to rainfall-induced dilution or a decline in industrial inputs.

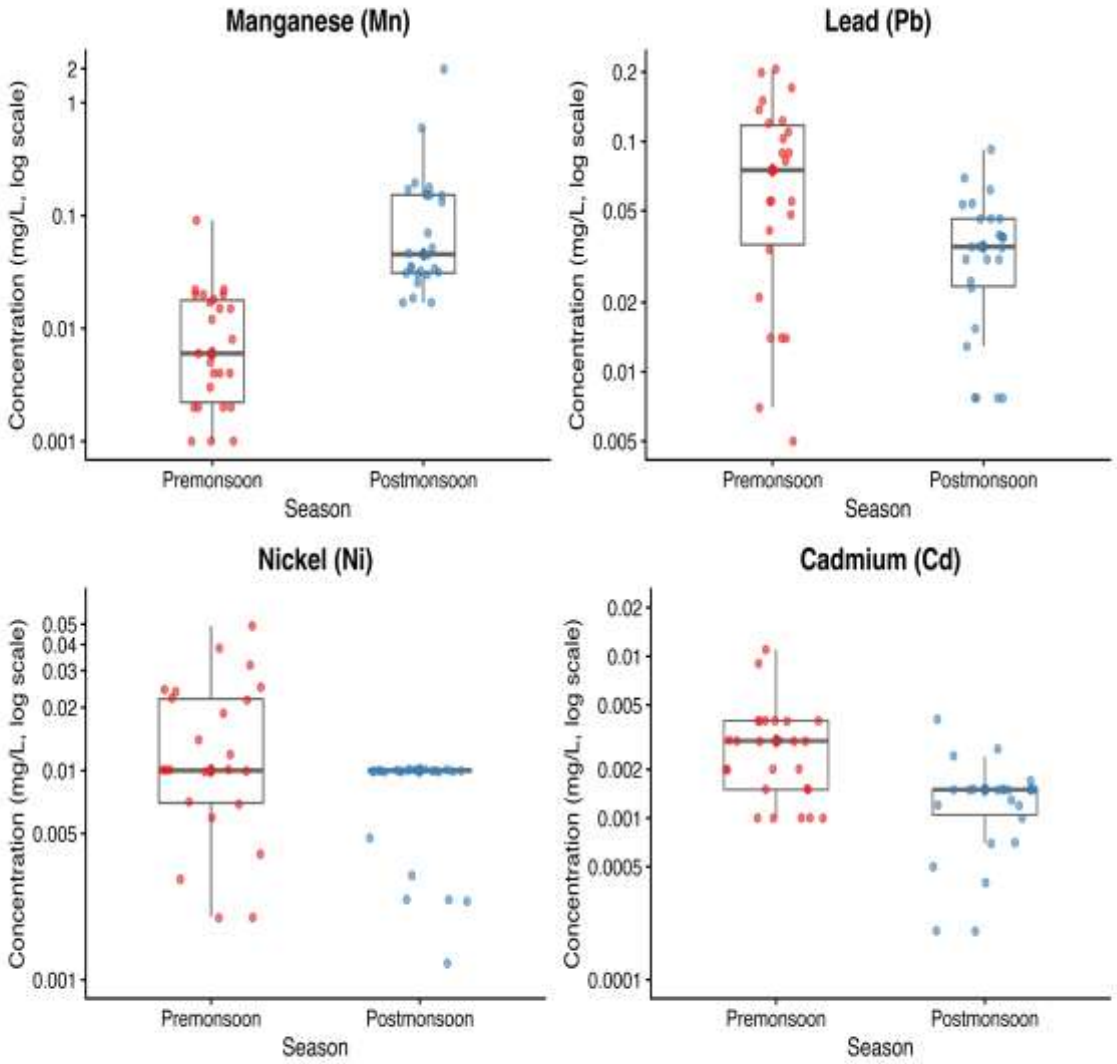

Fig. 3: Box plots showing the concentrations of heavy metals, Manganese (Mn), Nickel (Ni), Lead (Pb), and Cadmium (Cd) that exceed the Bureau of Indian Standards (BIS) permissible limits for domestic use in the study area (all concentrations are in mg/L).

The highest recorded concentration of lead in the study area was 0.206 mg/L during the pre-monsoon season and 0.092 mg/L 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 and 0.0041 mg/L 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 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 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 (Figure 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.

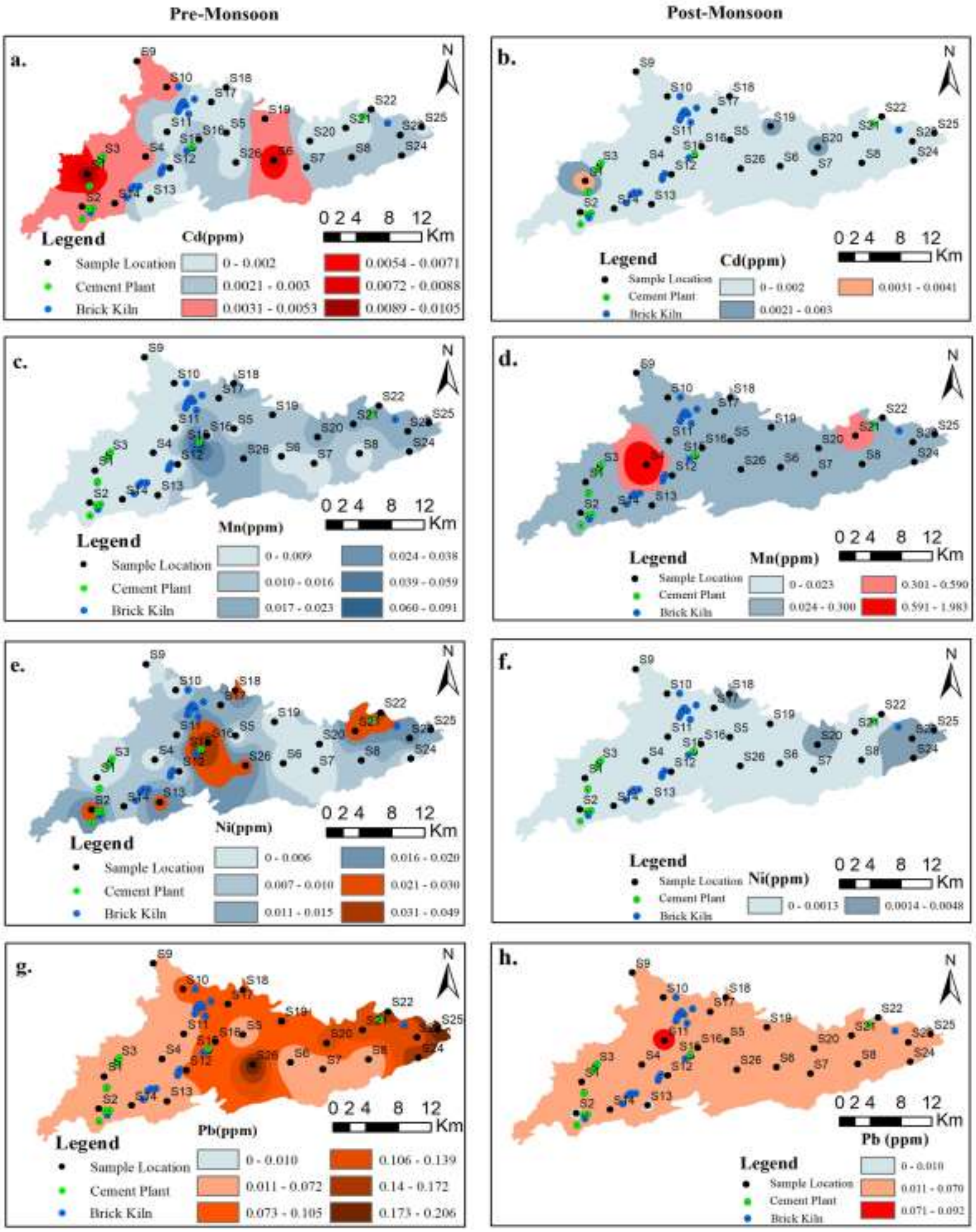

Fig. 4: The geospatial distribution maps illustrate the spatial and seasonal variation in the concentrations of heavy metals- Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb)- across the study area during both pre- and post-monsoon seasons (all concentrations are in ppm).

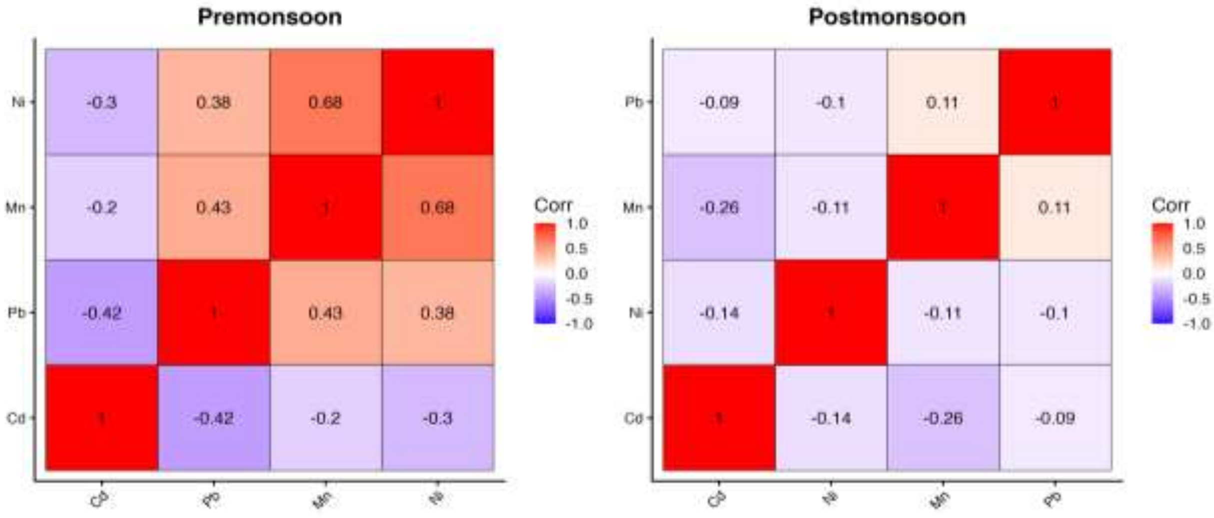

Fig. 5: Seasonal correlation matrices of heavy metals (Mn, Pb, Ni, and Cd) in groundwater samples during pre-monsoon and post-monsoon seasons, generated using RStudio (version 2024.04.2+764).

The colour scale represents Pearson's correlation coefficients (r) ranging from –1 (strong negative correlation, blue) to +1 (strong positive correlation, red). During the pre-monsoon season, the metals (Mn-Ni, Cd-Pb) exhibit moderate to strong positive correlations, suggesting common anthropogenic or geogenic sources. In contrast, weaker and more variable correlations in the post-monsoon season indicate dilution, leaching, or differential mobilization of metals following rainfall.

The interpretations of the Metal Index (MI) and Heavy Metal Pollution Index (HPI) values for the analysed heavy metals are presented in Tables 2 & 3, respectively. In both pre- and post-monsoon seasons, four locations recorded MI values between 2 and 4, indicating moderate contamination. During the post-monsoon period, 12 locations exhibited MI values between 4 and 6, classifying them as strongly affected. Notably, 21 locations in the pre-monsoon season and 7 locations in the post-monsoon season recorded MI values equal to or greater than 6, suggesting serious levels of heavy metal contamination. HPI results further revealed that 22 locations during the pre-monsoon season and 20 during the post-monsoon season exceeded the critical threshold value, placing them in the high pollution category. These findings indicate that groundwater in these areas is unsafe for drinking purposes without appropriate treatment. The statistical summary of Metal Index (MI and Heavy metal Pollution Index (HPI) has been presented in Table 4

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)

The KDE plot (Figure 6) clearly illustrates the seasonal dynamics of heavy metal pollution in groundwater. It shows that groundwater quality improves post-monsoon, with lower metal contamination levels, as reflected by the shift and reduction in both MI and HPI distributions. The significantly higher HPI values in the pre-monsoon season indicate greater pollution, whereas the lower post-monsoon values suggest improvement due to natural dilution processes. These findings highlight the importance of seasonal monitoring for accurate assessment of heavy metal pollution trends and underscore the need for effective water quality management and mitigation strategies.

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

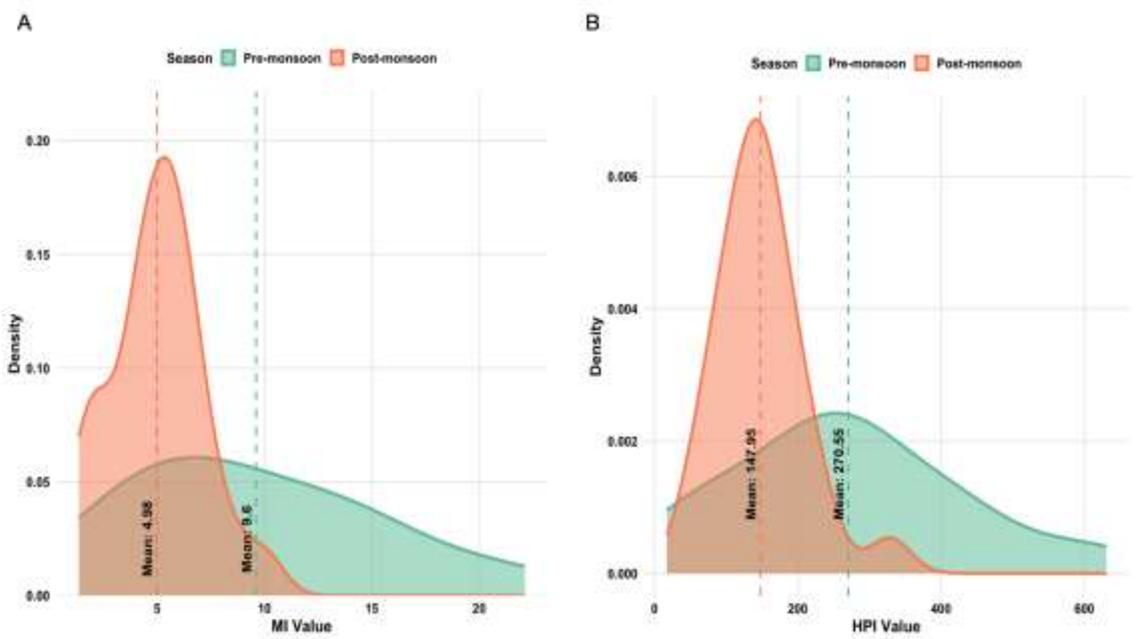

Fig 6: Kernel Density Estimation (KDE) plot using RStudio (version 2024.04.2+764) for [A] Metal Index (MI) values and [B] Heavy Metal Pollution Index (HPI) values in groundwater samples (n=26), comparing pre- and post-monsoon seasons [Dashed Vertical Lines indicate the mean MI values for each season].

The GIS-based geospatial maps of the Metal Index (MI) and Heavy Metal Pollution Index (HPI) [Figure 7] for groundwater in the study area clearly illustrate the temporal variation in heavy metal contamination. The pre-monsoon period is characterized by widespread and serious pollution levels, indicating a higher degree of heavy metal accumulation. In contrast, the post-monsoon maps show localized improvements in groundwater quality, particularly in areas such as S2 and S14 (Figure6), reflecting the dilution and flushing effects of monsoonal rainfall. These spatial patterns align with the statistical results and underscore the importance of seasonal monitoring. Furthermore, the findings highlight the need for spatially targeted mitigation and remediation strategies to effectively manage and reduce heavy metal pollution in groundwater resources. The results of spatial interpolation of Metal Index (Table 5) unravel that the area may be classified into four classes in both the seasons. During pre-monsoon most of the area (78%) came under seriously affected class, whereas strongly affected (69%) class was most dominant in post monsoon. Similarly based on Heavy Metal Pollution Index the area may be classified into high and low pollution zones (Table 6). From pre monsoon data 97% area was showing high pollution, similarly interpolation of post monsoon data resulted 95% of the area coming under high pollution class.

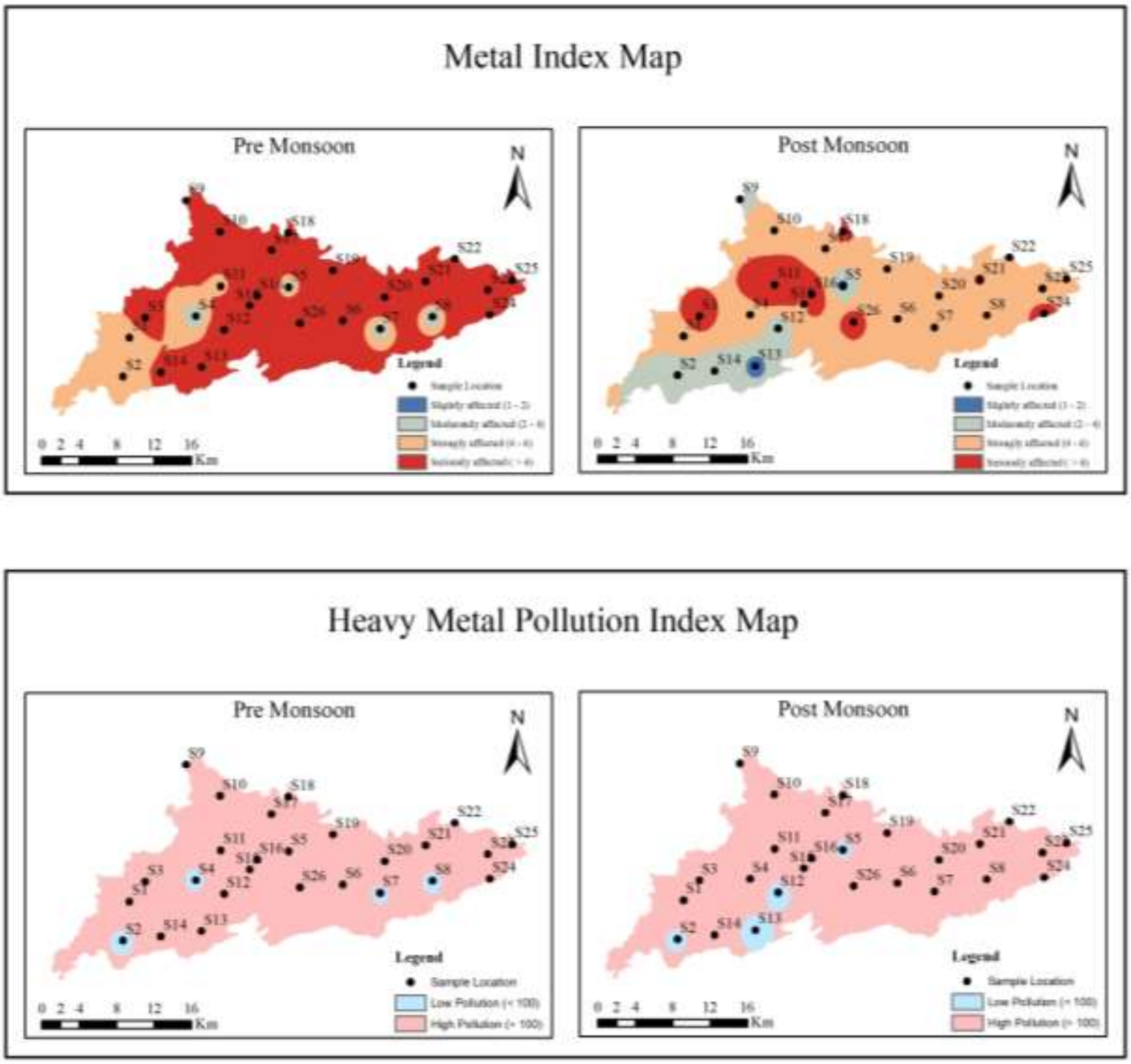

Fig 7: Geospatial distribution of Metal Index (MI) and Heavy Metal Pollution Index (HPI) of groundwater within the study area for the pre-monsoon and post-monsoon periods

Table 5: Spatial distribution of Metal Index

Class	Pre Monsoon Area (Sq. Km)	Pre Monsoon Percentage	Post Monsoon Area (Sq. Km)	Post Monsoon 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 Area (Sq. Km)	Pre Monsoon Percentage	Post Monsoon Area (Sq. Km)	Post Monsoon Percentage
Low Pollution	16.70	3.14	25.38	4.77
High Pollution	515.75	96.86	507.07	95.23

4. 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 & Jackson, 1991; Nies, 1999, 2003). Short term exposure to high levels of cadmium in drinking water may cause vomiting and diarrhoea. (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, tyres, and certain slags (WBCSD, 2014). Acute cadmium ingestion can cause renal dysfunctions, hepatic injury, osteomalacia, pulmonary edema, gastrointestinal tract erosion, depending on the route of poisoning (Baselt RC, 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 and Alabi, 2005; Achternbosch, M. et al., 2003; Centre for Disease Control and prevention, Atlanta, 2001; ATSDR, 2020). Lead compounds cause kidney tumours 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) 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 precipitate 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 condition (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 dependant; 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, clay-rich and low-permeability formations act as sinks, while coarse, permeable, or fractured lithologies serve as pathways for heavy metal transport, especially under the prevailing near-neutral pH conditions. Cement manufacturing plants in the study area may release cadmium, lead, and nickel into the environment. These toxic metals occur naturally in raw materials such as limestone, clay, and shale used for cement production. During the high-temperature process (~1450°C) in rotary kilns, these metals can volatilize and disperse into the air, later settling on soil, surface water, and groundwater. Additional sources include the use of additives, fuels, and waste materials (e.g., used tires, industrial waste) in both cement and brick kilns. Improper disposal of cement kiln dust, fly ash, bottom ash, and fuel residues further contributes to 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.

5. CONCLUSIONS

This study demonstrates that the combined application of Index-Based Evaluation (MI and HPI) and GIS-based geospatial mapping provides a robust and integrative approach to assessing cumulative heavy metal contamination in groundwater. In the study area, lead (Pb) concentrations exceeded permissible limits in 92% of pre-monsoon and 85% of post-monsoon samples, while cadmium (Cd) exceeded limits in 54% of pre-monsoon and 4% of post-monsoon samples. A total of 21 sites during the pre-monsoon and 7 locations during the post-monsoon seasons were found to be seriously affected (MI ≥ 6), and Heavy Metal Pollution Index (HPI) values greater than 100 were observed at 22 and 20 sites, respectively. These findings indicate that Pb and Cd contamination is both spatially widespread and seasonally persistent, with higher exceedances during the pre-monsoon period. Nickel (Ni) and manganese (Mn) also pose localized risks, suggesting complex interactions between seasonal variations and geogenic-anthropogenic influences. The dominance of high MI and HPI values in the pre-monsoon season reflects pollutant accumulation from industrial emissions, while the post-monsoon decline highlights the partial dilution and flushing effects of monsoonal recharge. The spatial pattern in the geospatial maps aligns closely with the distribution of these industrial units. While minor geogenic inputs cannot be entirely ruled out. A multi-barrier approach combining advanced treatment technologies (adsorption and ion exchange, permeable reactive barriers, electrocoagulation, membrane filtration, etc.), pollution source reduction (effluent segregation, industrial process modification, stormwater management, and strict regulatory enforcement), and institutional strengthening (long-term monitoring, community engagement, and capacity building) is recommended for effective mitigation of heavy metal contamination in the industrial clusters of the study area.

The methodological framework and outcomes of this study offer a transferable model for industrially stressed aquifers, enabling early detection, spatial prioritization, and timely remediation of heavy metal contamination. The implications of these results extend beyond the immediate study area. At the regional scale**,** these approaches can guide policymakers and water managers in Assam and similar peri-urban industrial zones across India to implement targeted monitoring, enforce stricter industrial discharge regulations, and design location-specific mitigation strategies. At the global scale**,** the integration of index-based evaluation (IBE) with geospatial mapping provides a replicable tool for assessing groundwater vulnerability in rapidly industrializing regions worldwide, where similar pressures from cement manufacturing, brick kilns, and other heavy industries threaten water security. Proactive management based on such integrated approaches is vital to safeguarding groundwater resources, protecting public health, and ensuring the sustainable growth of both regional and international peri-urban and industrial landscapes. Ultimately, our findings contribute valuable insights to environmental monitoring, industrial impact assessment, and groundwater safety for domestic use, offering a strategic template for both developing and developed nations confronting the dual challenge of economic growth and water resource protection.

AUTHOR CONTRIBUTIONS

D.C.: Writing- Original draft, Methodology, Software, Visualization, Formal Analysis. **S.J.K.:** Conceptualization, Supervision, Writing-Original draft, Methodology, Software, Formal Analysis, Data Analysis, Visualization, Reviewing and Editing. **A.S.K.:** Data Analysis, Software, Visualization, Formal Analysis, Reviewing and Editing.

FUNDING: This research received no external funding.

ACKNOWLEDGMENTS: The authors express their sincere gratitude to ICAR-NBSS & LUP, Regional Centre, Jorhat, and State Public Health Laboratory, Commissionerate of food safety, Assam, for their valuable support in facilitating the sample analysis.

CONFLICTS OF INTEREST: “The authors declare no conflicts of interest.”

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