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Article

Assessment of groundwater quality and trace elements toxicity in southern Brahmaputra floodplains: A health risk study

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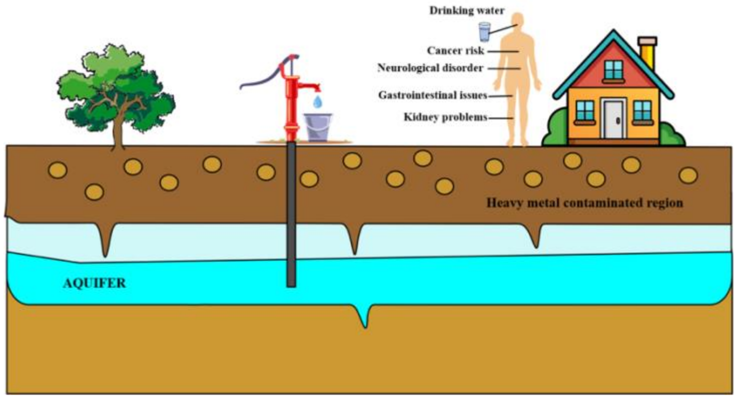

Highlights

- *Hydrochemical facies indicates slow recharge and pollution from sewage and agricultural runoff.*
- *Occurrence of higher Fe, Mn, and Pb concentrations in the aquifer.*
- *The degree of contamination index indicates variable pollution levels.*
- *Non-carcinogenic and carcinogenic health risk occurring in female, male and children.*

Abstract

Groundwater, which is a freshwater reserve, is becoming a global concern due to its high extraction and contamination. This study investigated the contamination of heavy metals in groundwater, the potential health hazards it causes, and the essential role of monitoring and mitigating environmentally induced influences on water resources in southern Brahmaputra floodplains, India. The parameters: pH, TDS (total dissolved solids), EC (electrical conductivity), Hardness, HCO_3^-, SO_4^{2-}, Na^+, Ca^{2+}, Cl^-, Mg^{2+}, F^-, K^+, NO_3^- including heavy metals such as As (arsenic), Cu (copper), Pb (lead), Mn (manganese), Fe (iron), Zn (zinc) and Cd (cadmium) were analyzed. In Sivasagar district, the groundwater and surface water are slightly alkaline, with hardness, EC and TDS all within permissible limits. Na^+ followed by Ca^{2+} are the cations predominant in the region, with HCO_3^- being the dominant anion. A high level of NO_3^- in some samples indicates contamination from anthropogenic sources like agricultural runoff and domestic waste. Silicate weathering and rock-water interaction influence the groundwater quality. Groundwater composition changes through natural processes, as well as industrial and agricultural activities, are further highlighted by principal component analysis (PCA). Heavy metal analysis revealed that Fe (88%), Pb (92%), and As (14%) exceeded permissible limits, with notably high Fe and Pb concentrations due to both anthropogenic and natural processes. Concentrations of Mn (92%) and Cd (12%) were also found to exceed the permissible limits. Heavy metal contamination

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indices indicate a high level of pollution, particularly for Cd. Carcinogenic risk (CR) is shown for children, females, and males due to exposure to As, Cd, and Pb, despite the major ions being within the permissible limit.

1 Introduction

Groundwater, often considered as a critical source of fresh water, provides world's 50% of potable water, supports agriculture, and is of key importance in industrial processes (Lall et al., 2020). It is particularly significant in regions where there is limited (arid and semi-arid regions) or contaminated surface water. Currently, millions of people are dependent on it for food security, economic stability and their well-being. However, numerous threats are being faced by this crucial resource. Intensive extraction, contamination, and improper management practices are leading to depletion and pollution of the aquifers (Alao et al., 2024).

Long-term health issues may occur to communities that rely on contaminated water sources for consumption and irrigation (Rahman et al., 2009). High level of As causes health problems like cancer, hyperkeratosis, ulceration and also effects lungs, kidney, heart and liver (Mahanta et al., 2015; WHO, 2020). Excess Fe concentration can cause hemochromatosis that causes damage to the liver, heart, and pancreas. In contrast, higher concentration of Mn can cause damage to the nervous system (Rushdi et al., 2023) and increase rate of infant mortality. The International Agency for Research on Cancer (IARC) categorizes Cd, a group I carcinogenic metal for human supported by substantial evidence from studies in human and experimental animals (Jarup, 2003). Another issue is Pb contamination from sources like paint, batteries, pipes which can cause effects in the nervous system, bones, reproductive system, haematological system, and renal cancer (Collin et al., 2022). Agricultural runoff, waste disposal, treated or untreated industrial waste are some anthropogenic activities that causes high concentration of nitrate (NO_3^-) whereas weathering of minerals, evaporation are some natural sources contributing to high concentration of fluoride (F^-) (Gad et al., 2024).

Heavy metals being one of the most dangerous contaminants of groundwater accumulate over time, threatening human health (Latif et al., 2024). The trace elements As, Pb, Cd, and Hg are persistent, stable in the environment and are harmful even at low levels. However heavy metals like Cu, Mn, and Zn are also important to human body in small amounts. Particularly in developing countries, the presence and contamination of heavy metal is of great concern as it may cause potential health risks. There are various techniques to analyze the heavy metals for evaluating their toxicity, source and health risk. Heavy metal pollution index (HPI), heavy metal evaluation index (HEI), contamination degree (C_d), and water quality index (WQI) are widely used to access the extent of heavy metal enrichment and its health impacts to exposed communities (Choudhury et al., 2024).

In India, groundwater is heavily contaminated with As, F^- and other toxic metals (Bhowmick et al., 2018). Arsenic contamination, one of the most alarming issues, particularly in Bangladesh and West Bengal (Chakraborti et al., 2002). In the Ganga-Meghna-Brahmaputra (GMB) basin more than 10 million people, i.e., about 92% of the population, consume As contaminated water above permissible limit (10 ppb) (Kumar et al., 2021). Furthermore, 40% of the population in India, live in regions with elevated F^- concentration (Choudhury et al., 2024). Additionally, Pb contamination in many parts of India, especially in urban industrial areas like Delhi (Alsubih et al., 2021).

Northeast India abounds in water resources. However, groundwater contamination remains a major concern for the state despite being water rich. In Assam, several districts are contaminated with heavy metals, particularly in areas near the Brahmaputra River and its tributaries (Goswami et al., 2022; Nath et al., 2022). Jorhat, Darrang, Majuli, Nagaon, and Morigaon districts are highly contaminated with heavy metals in the region. The main source of drinking water of the people of Sivasagar district is groundwater but there is limited information available regarding its quality. This study shows how the heavy metal contamination in groundwater over the post-monsoon season effects the carcinogenic and non-carcinogenic health risk of the local population. An Environmental Impact Assessment (EIA) study revealed that every parameter examined fell below the permissible limits, encouraging our interest in understanding the overall quality of water in addition to heavy metal contamination and its health impact in the district.

The objectives of the research are to examine spatial and temporal variations of groundwater chemistry using various geochemical parameters, evaluating heavy metal distribution in the study area and assessing health risk for adults and children exposed to heavy metal contamination.

2. Materials and methods

2.1 Description of the study area

Sivasagar district, Assam is situated approximately between latitudes 26.4° N and 27.0° N, and longitudes 94.2° E and

94.6° E. To the North, the district is bounded by the Brahmaputra River, to the East is the Disang River, to the South is the Naga Patkai Hill range and to the west is the Jhanji River (**Fig. 1**). Disang, Dikhow, Jhanji, are the rivers of the district originating from the Naga Patkai Hill range. The district has a humid and a sub-tropical climate with minimum temperature (3.4°C to 11°C) in winter, maximum temperature (27°C to 38°C) in summer and high humidity from June to September (CGWB, 2013). Abundant rainfall is experienced in the region with an annual average of 2,504 mm, July being the wettest during the monsoon season.

Hydrogeologically, the water table depth is 4 m below the surface with groundwater occurring under both in confined and unconfined conditions. The transmissivity ranges from 263.40 m^2/day to 3,390 m^2/day and the discharge rate ranges from 37.8 m^3/hr to 428.94 m^3/hr (CGWB, 2013). Geomorphologically, the study area is divided into active floodplains (silty clay to clay loam), recent floodplains (loam to silty clay loam) and lower floodplains (fine loamy and medium acidic).

2.2 Groundwater monitoring and evaluation

A total of 39 groundwater and 11 surface water samples were collected from specified locations determined by the GPS (Global Positioning System), GARMIN etrex10 device, in the post-monsoon (December) season of 2023. Groundwater samples were collected using clean, sterilized 500 ml and 1 L HDPE bottles from tubewells that has been regularly used for water extraction. Before collecting the samples, to remove the stagnant water, the well was pumped for several minutes so that the sample represents the fresh groundwater. Surface water samples of Brahmaputra, Dikhow, Disang and Jhanji rivers were collected from mid depths, avoiding any impurities and bottom sediments by holding the bottle facing downstream. The pH, EC (electrical conductivity), TDS (total dissolved solids) and temp (temperature) were measured on-field using Hanna instrument (HI98129 pH/conductivity/TDS tester). Ca^{2+}, Cl^-, hardness, and HCO_3^- are measured through titrimetric method; SO_4^{2-}, NO_3^-, and F^- concentrations were analyzed using a spectrophotometer and Na^+ (sodium) and K^+ (potassium) were quantified with a flame emission spectrophotometer.

To determine trace element concentrations, HCl (hydrochloric) and HNO_3 (nitric) acids had been used as preservatives for water samples which were further analyzed using Atomic Absorption Spectroscopy (AAS) with wavelengths 193.70 nm for As, 248.33 nm for Fe, 228.80 nm for Cd, 324.75 nm for Cu, 213.86 nm for Zn, 279.48 nm for Mn and 283.31 nm for Pb. Flame absorption technique was used for As, Fe, Cu, Zn, Mn whereas graphite furnace was used for Cd and Pb. The LOD (limit of detection) values established for the elements are: 1.0 µg/L for As, 10.0 µg/L for Fe, 0.5 µg/L for Cd, 1.0 µg/L for Cu, 2.0 µg/L for Zn, 2.0 µg/L for Mn and 0.5 µg/L for Pb which was calculated as 3 × standard deviation by repeatedly measuring the solution. The LOQ (limit of quantification) values were calculated as 10 ×

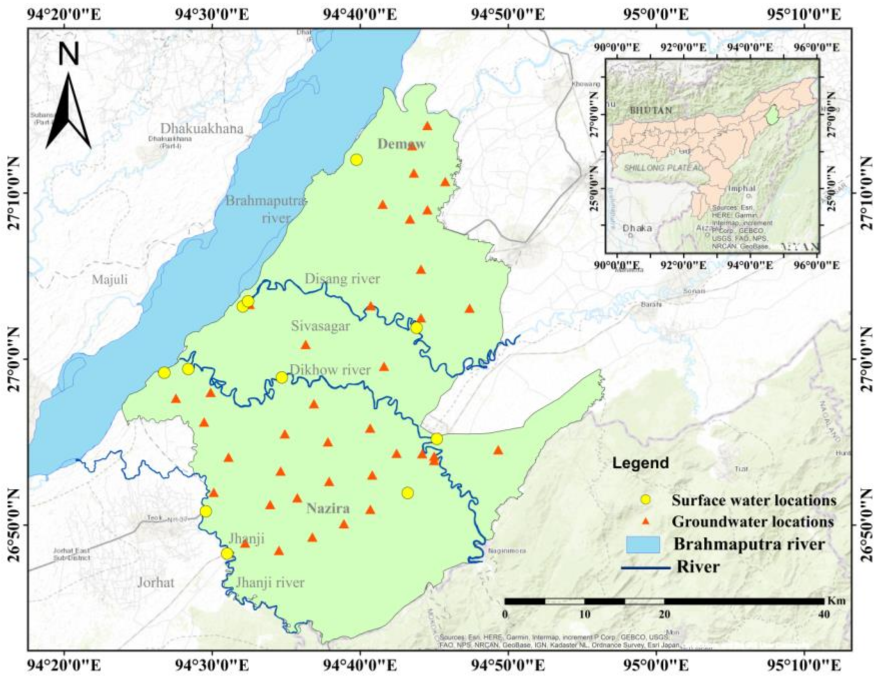

Figure 1. Map showing the sampling locations from where groundwater and surface water was collected.

standard deviation of blanks. The certified reference material (CRM) is sourced from NIST SRM 1643f Trace Elements. All the RSD values are below 5% maintaining the element's precision and reliability. For digestion, HNO_3 is used with calibration standards prepared from stock solutions of 1,000 mg/L for As, Fe, Pb, Cd, Cu, Zi and Mn diluted in 2% HNO_3.

Using ArcGIS 10.8.2, software, geospatial distribution mapping for heavy metals and heavy metal index was created. Statistical analysis was calculated using SPSS (Statistical Package for the Social Sciences) 26.0. A health survey was conducted to identify the health hazards associated with contaminated drinking water.

2.3 Heavy metal indices

It is a technique used to calculate the high level of heavy metal concentration in the groundwater. The calculation of HPI, HEI and C_d was considered for 7 metals, viz. As, Pb, Mn, Cd, Fe, Cu and Zn, which were further compared with the standards given by World Health Organization (WHO) and Bureau of Indian Standards (BIS). The proposed HPI by Mohan et al. (1996) is given by:

$$\text{HPI} = \frac{\sum_{i=1}^{n} W_i\, Q_i}{\sum_{i=1}^{n} W_i} \qquad (1)$$

In the above equation, W_i is the unit weightage of the ith sample and Q_i is the subordinate value for the ith parameter whereas n denotes total number of parameters taken into consideration. Q_i for all parameters is computed by the equation:

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

Where, M_i represents metal concentration for the ith parameter, l_i is the ideal concentration of the ith sample, S_i is the standard permissible limit values given by WHO and BIS. The equation used to calculate HMEI (Edet and Offiong, 2002) is given as:

$$\text{HMEI} = \sum_{i=1}^{n} \frac{H_c}{H_{max}} \qquad (3)$$

Where, Hc denotes the analyzed concentration of the ith variable, H_{max} is the maximum acceptable concentration for the ith variable. The formula for C_d (contamination index) is given by the equation:

$$C_d = \sum C_{fi}\,,\; C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \qquad (4)$$

In the above equations, C_{fi} is taken as fit index for the ith factor, C_{Ai} is the measured concentration and C_{Ni} is the maximum acceptable concentration for the ith factor (Mukanyandwi et al., 2019).

The HPI is categorized into low pollution (<100) and high pollution (>100), the HEI is categorized into low (<8), medium (8-15), and high pollution (>15) category and C_d was categorized into low pollution (<1), medium (1-3), and high (>3) pollution category.

2.4 Statistical analysis

PCA commonly used tool to assess groundwater quality. It transforms related large dimension variables to unrelated smaller dimension variables. The first factor of PCA explains the dataset that has highest variability in contrast to the successive factors. The accuracy of the data is determined by KMO (Kaiser-Meyer-Olkin) and Bartlett's test. The correlation data is considered acceptable with KMO value between 0.5 and 0.8 (Gad et al., 2024).

2.5 Health risk assessment

The health risk of both carcinogenic and non-carcinogenic health concerns from heavy metal in drinking water was assessed for adults and children based on USEPA (US Environment Protection Agency) 1989 guidelines. A survey of 54 people was considered from the heavy metal contaminated regions of which 18 were male and 18 were female and children, respectively for both oral ingestion and dermal exposure. The non-carcinogenic risk was calculated from the hazard quotient (HQ) by the formula:

$$HQ_{oral} = CDI_{oral} \,/\, RfD_{oral} \qquad (5)$$

$$HQ_{dermal} = CDI_{dermal} \,/\, RfD_{dermal} \qquad (6)$$

Where, CDI is the chronic daily intake, and RfD is the absorption reference.

The CDI for both ingestion and dermal exposure (Stanton et al., 2002; Rapant and Krěmová, 2007; Wu et al., 2011) was calculated following the equations given below:

$$CDI_{oral}\ \text{mg/kg/day} = (CW \times IR \times EF \times ED) \,/\, (BW \times AT) \qquad (7)$$

Where, CW is denoted as concentration of heavy metals in drinking water sample, IR is the ingestion rate, EF is the exposure frequency, ED is the exposure duration, BW is the body weight and AT is the average time.

$$CDI_{dermal}\ \text{mg/kg/day} = (CW \times SA \times EF \times ED \times CF \times ET \times Kp) \,/\, (BW \times AT) \qquad (8)$$

Where, SA is the skin area, CF is the conversion factor, ET is the exposure time and Kp is the permeability coefficient.

The probable health risk from various heavy metals is calculated by hazard index (HI) given by the formula:

$$HI = HQ1 + HQ2 + HQ3 + HQ4 \ldots\ldots\ldots\ldots + HQn \quad (9)$$

Where, HI > 1 indicates potential health risk and HI < 1 indicates minimal or no health risk.

The carcinogenic risk (CR) was calculated using the formula given below:

$$CR_{oral} = ADD \times SF \quad (10)$$

$$CD_{dermal} = DAD \times SF \quad (11)$$

$$CI = CR_{oral} + CD_{dermal} \quad (12)$$

Where, ADD is the average daily dose, DAD is the dermal absorbed dose, and CI is the cancer index.

According to USEPA (1999), carcinogenic risk is negligible for $CR < 1 \times 10^{-6}$, acceptable for CR between 1×10^{-6} to 1×10^{-4} and high for $CR > 1 \times 10^{-4}$.

3. Results and discussion

3.1 Groundwater geochemistry

The groundwater physical and chemical parameters and its comparison with WHO (2020) and BIS (2012) are depicted in **Table 1**. The pH varies from 7.13 to 8.28, with a mean value of 7.67, indicating that it is weakly basic in condition and is within the permissible limit of WHO and BIS. The EC indicates the ease of flowing electric current. It ranges from 133 to 222 µs/cm, with a mean value of 169.84 µs/cm. The EC values of all the samples are within the acceptable limits set by the WHO and BIS. Furthermore, the groundwater hardness, primarily caused by dissolved Ca^{2+} and Mg^{2+} ions, varies from 30 to 245 mg/L, with a mean value of 104.7 mg/L. The TDS, which is the result of rock-water interaction as groundwater infiltrates to recharge an aquifer (Asomaning et al., 2023), ranges from 60 to 112 mg/L, mean 84.86 mg/L. The Na^{+}, Ca^{2+}, Mg^{2+}, and K^{+} concentrations ranges from 46.34 to 590.82 mg/L (mean 160.59 mg/L), 6 to 64.05 mg/L (mean 18.01 mg/L), 3.63 to 26.69 mg/L (mean 14.48 mg/L) and 4.15 to 58.66 mg/L (mean 14.78 mg/L), respectively. The abundance of cations follows the order $Na^{+} > Ca^{2+} > K^{+} > Mg^{2+}$. The concentration of the samples of the entire study area is found below the permissible limit set by the WHO and BIS.

The HCO_3^{-} is the major anion in the study area, with concentrations ranging from 5 to 245.20 mg/L (mean 86.14 mg/L). The concentrations of Cl^{-}, SO_4^{2-}, NO_3^{-} and F^{-} ranges from 14.18 to 81.54 mg/L (mean 22.10 mg/L), 0.05 to 49.45 mg/L (mean 11.20 mg/L), 0.2 to 45.9 mg/L (mean 6.22 mg/L) and below detection limit (BDL) to 0.49 mg/L (mean 0.20 mg/L), respectively. All the major ions are within the allowable limit set by the WHO and BIS ensuring the water to be chemically safe for human consumption.

Table 1. *Groundwater quality parameters (n = 50) and comparison with WHO (2020) and BIS (2012) drinking water standards.*

Parameter	Min	Max	Mean	WHO/BIS (Permissible limit)	No of samples above permissible limit
pH	7.13	8.28	7.67	6.5–8.5	None
EC (µs/cm)	133	222	169.84	400	None
Hardness (mg/L)	30	245	104.7	600	None
TDS (mg/L)	60	112	84.86	2,000	None
HCO_3^{-} (mg/L)	5	245.20	86.14	300	None
Na^{+} (mg/L)	46.34	590.82	160.59	Not available	None
SO_4^{2-} (mg/L)	0.05	49.45	11.20	400	None
Ca^{2+} (mg/L)	6	64.05	18.01	200	None
Cl^{-} (mg/L)	14.18	81.54	22.10	1,000	None
Mg^{2+} (mg/L)	3.63	26.69	14.48	100	None
K^{+} (mg/L)	4.15	58.66	14.78	Not available	None
F^{-} (mg/L)	BDL	0.49	0.20	1.5	None
NO_3^{-} (mg/L)	0.2	45.9	6.22	45	1
As (mg/L)	BDL	0.017	0.004	0.01	7
Pb (mg/L)	0.002	0.21	0.02	0.01	22
Mn (mg/L)	0.18	2.08	0.74	0.3	46
Fe (mg/L)	0.43	115.13	21.57	1	44
Zn (mg/L)	BDL	10.24	0.48	15	None
Cu (mg/L)	BDL	0.1	0.02	1.5	None
Cd (mg/L)	BDL	0.009	0.001	0.003	6

Note: BDL – Below detection limit.

3.1.1 Hydrogeological evolution of groundwater

Piper diagram is used to analyze the groundwater dynamics contributing to groundwater evolution by classifying the collected data into distinct hydrochemical facies (Piper, 1944). The piper diagram identifies that the primary hydrochemical facies is Na-K-HCO_3 and NaCl for groundwater and surface water respectively (**Fig. 2**). Few samples fall under the mixed water type (16% for groundwater and 9.5% for surface water). The trilinear diagram suggested the dominant role of alkaline nature and both weak and strong acids in regulating the chemical composition of groundwater of the study area. The Na^+ and Cl^- dominance may be due to various anthropogenic activities such as use of fertilizers, sewage disposal and contamination of groundwater by leaching (Nath et al., 2007; Choudhury et al., 2024).

The evolution of water chemistry is explained by Gibbs diagram governed by rock-water interaction, precipitation and evaporation dominance (Marandi and Shand, 2018). $Na^+/(Na^+ + Ca^{2+})$ versus TDS and $Cl^- / (Cl^- + HCO_3^-)$ versus TDS diagrams, were plotted to understand the chemistry of the groundwater (**Fig. 3**). Most of the groundwater as well as the surface water samples fall within the precipitation zone while some samples are within the domain of rock-water interaction. Precipitation dominance is the result of saturation of water with respect to specific minerals (Gibbs, 1970), whereas rock-water interaction takes place when dissolution of minerals, alterations in the chemical composition of water as well as exchange of ions takes place due to the interaction of the surrounding rocks with the water present in the aquifer (Stumm and Morgan, 1996). Moreover, the position of the samples in the plots are towards high Na^+ and low HCO_3^- region, indicating that silicate weathering is dominant in the study area (Marandi and Shand, 2018).

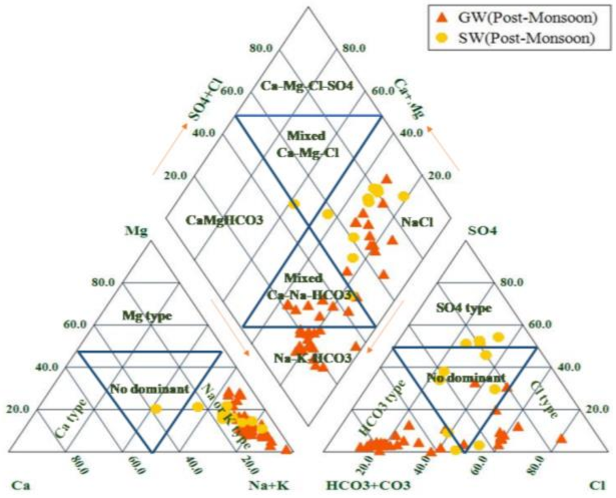

Figure 2. *Piper diagram showing the hydrochemical composition of groundwater (GW) and surface water (SW) samples in the study area.*

3.1.2 Trace element concentrations

Arsenic concentrations show elevated levels in 14% of the samples especially across the northern zone and certain pockets of the southern area of the study area (**Fig. 4a**). The release mechanism of As may vary with location, hydrogeochemical profile, chemical ions and sediments which are controlled by multiple complex processes (Goswami et al., 2020). High As doses leads to cancer, including skin cancer and lung, bladder, kidney illness (Kapaj et al., 2006; Wasserman et al., 2014), hyperkeratosis, ulceration and effects lungs, kidney, heart and liver (Mahanta et al., 2015). As exposure can be seen most vulnerable in children than in adults (Dauphiné et al., 2011).

Fe concentration in the study area exhibits 88% of the samples exceeding the permissible limit (1 mg/L) set by BIS. High concentration of Fe is recorded around the entire study

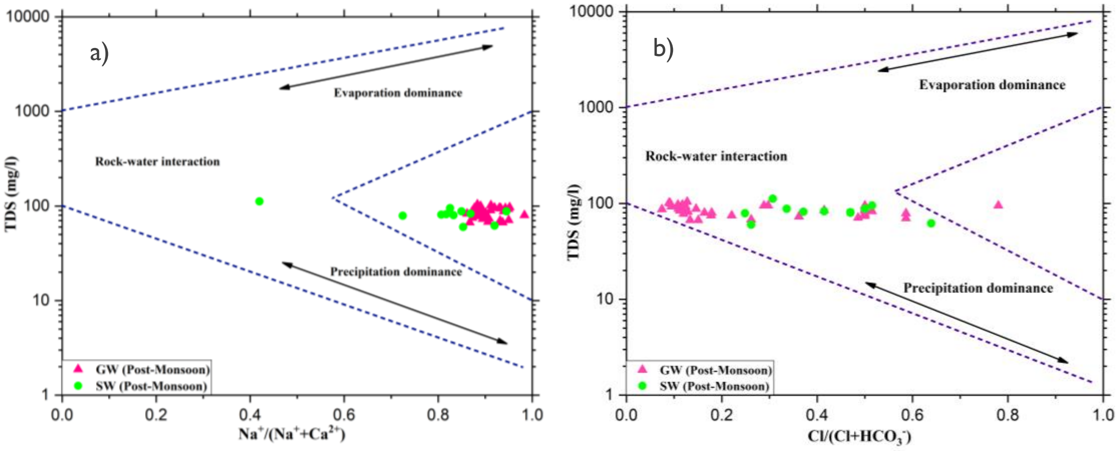

Figure 3. *Gibbs plot of groundwater (GW) and surface water (SW) samples in the study area; a) $Na^+ / (Na^+ + Ca^{2+})$ vs. TDS, and b) $Cl^- / (Cl^- + HCO_3^-)$.*

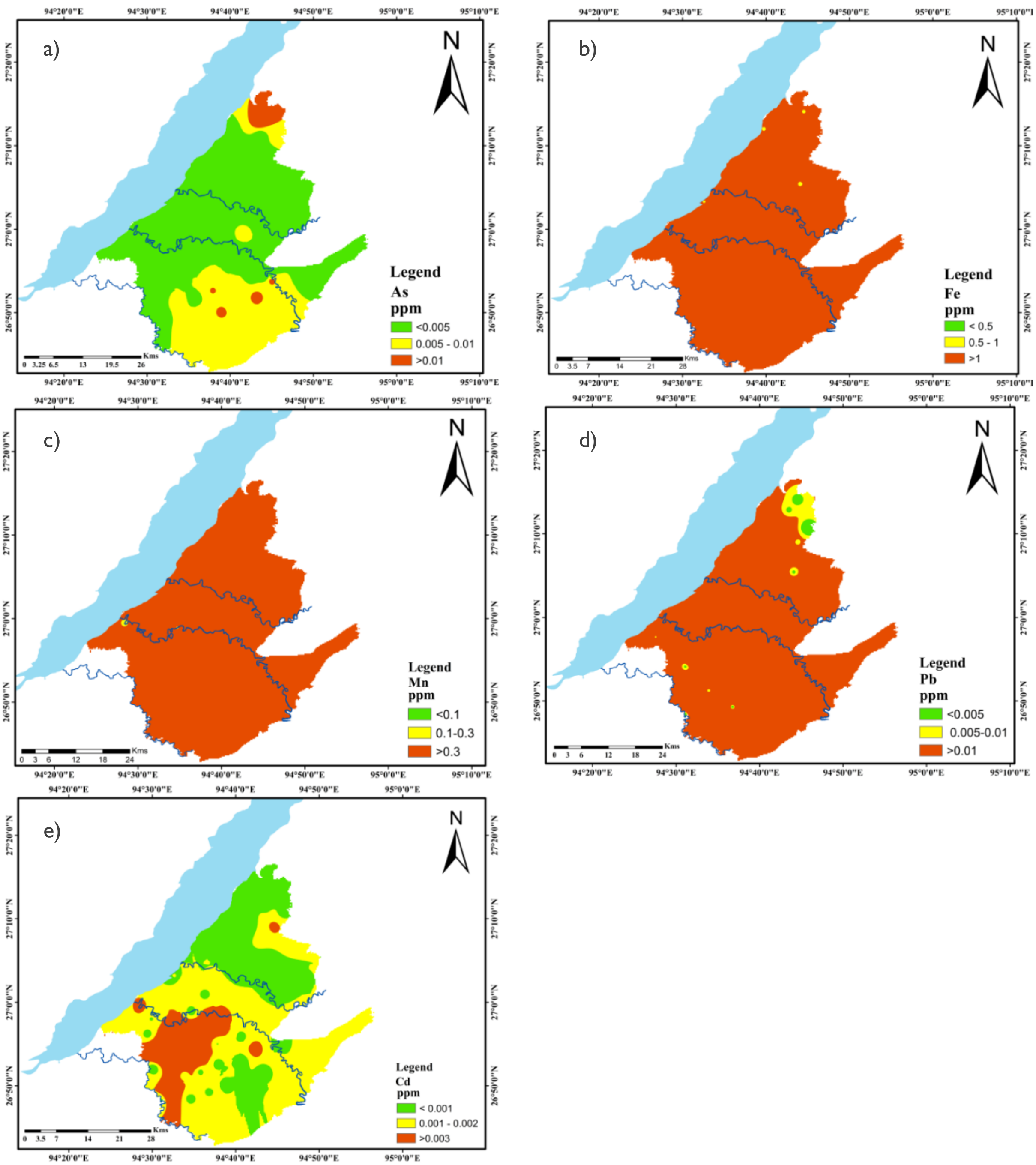

Figure 4. *Spatial distribution of a) As, b) Fe, c) Mn, d) Pb, and e) Cd concentrations (mg/L) in the study area.*

area except in some few pockets (**Fig. 4b**). People who have access to this water may cause diseases like hemochromatosis that causes damage to the liver, heart, and pancreas. However, removal of Fe from groundwater can be done by microfiltration and oxidation (Laonamsai et al., 2023).

The values of Mn concentration show that about 92% of the water samples exceed the permissible limit (**Fig. 4c**). Mn is a naturally occurring element and one of the most abundant metals in the Earth's surface. It can enter groundwater from the dissolution of Mn-containing minerals (Vinnarasi et al., 2022). Higher concentration of Mn in body can lead to neurological problems (Rushdi et al., 2023).

Pb concentration in the study area shows 44% of the samples exceeds the permissible limit (0.01 mg/L) except for the northern region and few areas to the south (**Fig. 4d**).

The elevated Pb levels in these regions may be due to both natural and anthropogenic factors, particularly due to industrial waste and use of fertilizers and pesticides containing Pb in agricultural practices, which contribute significantly to groundwater contamination (Brown et al., 2012). Over time, Pb can leach from the soil into the groundwater, leading to higher concentrations in the groundwater (Atafar et al., 2010). The health implications that can be faced due to excess Pb are anemia, development disorders, and brain and kidney damage (Shalhevet, 1994).

The high level of Cd in 12% of the samples mainly in the south-west region (**Fig. 4e**) may result from oxidation and acidification caused by groundwater pumping, as well as excessive nitrate infiltration from agricultural fertilizers (Badeenezhad et al., 2023). Reports have also highlighted a link of Cd exposure with kidney and lung cancer (Jarup, 2003). Zn and Cu concentrations are in BDL that meet the drinking water quality guidelines established by the WHO and BIS.

3.1.3 Evaluation of heavy metal indices

The HPI, HEI and C_d values are calculated for As, Pb, Fe, Mn, Cd, Cu and Zn. For HPI, 22% show high pollution (>100), for HEI, 58% are classified as high pollution (>15) and for C_d 68% show high pollution (>3). To explore further, scatter plots comparing HPI, HEI and C_d with each other have been created (**Fig. S1**). There is a strong correlation between HEI and C_d ($R^2 = 0.99$) and a poor correlation between HPI and HEI ($R^2 = 0.18$), as well as between C_d and HPI ($R^2 = 0.18$). This suggests that using either HEI or C_d, or both together, could be a more effective method for classifying water samples (Chaturvedi et al., 2018). Thematic maps were created based on HEI and C_d to visually represent the geospatial distribution of pollutant levels across the study region. The map illustrates the groundwater to be safe in the middle portion and a small area in the northern region of the study area (**Fig. 5**). Similar research is done for evaluating heavy metal pollution indices in Northeast India. Kshetriya et al. (2021) observed high HPI values, particularly for Cd, Cr and Cu, linked to high anthropogenic pollution. Choudhury et al. (2024) found variability in HPI values emphasizing the critical need for pollution control in the area. Barman et al. (2022) found considerable degree of contamination due to radioactivity of uranium in Nagaon district, Assam.

3.1.4 Principal component analysis (PCA)

The PCA results in 6 principal components with eigenvalue exceeding 1, constituting 85% of the total variance. In this statistical analysis 6 components are taken from which the factors > 0.5 are used to correlate with the parameters (**Table 2**). PC1 describes 32.66% of water quality variation with high loadings in EC (.765), TDS (.763), Ca^{2+} (.866), Mg^{2+} (.693) and K^+ (.819). Hardness, Ca^{2+} and Mg^{2+} are closely related. EC is directly controlled by TDS which depend on the concentration of Ca^{2+} and Mg^{2+} (Rapant et al., 2017). Presence of K^+ may be due to dissolution of plagioclase and feldspar minerals or different agricultural activities in the study area. PC2 accounts for 13.58% of the total variance and shows strong positive loadings for HCO_3^- (.825) and Na^+ (.825) which may be due to the use of $NaHCO_3$ salts and other Na^+ based compounds in irrigation practices. Hardness (.893) and Mg^{2+} (.682) show high loadings on PC3 with a total variance of 12.53%. Mg^{2+} is a contributor to hardness, and it may be added to groundwater through leaching of soil (Tiwari and Bajpai, 2012). PC4 contributed for 9.70% of variation with, pH (.819) and SO_4^{2-} (.795) as high loadings that results from areas impacted by industrial runoff which increases the SO_4^{2-} levels and can raise groundwater pH due to the buffering effect of CO_3 minerals

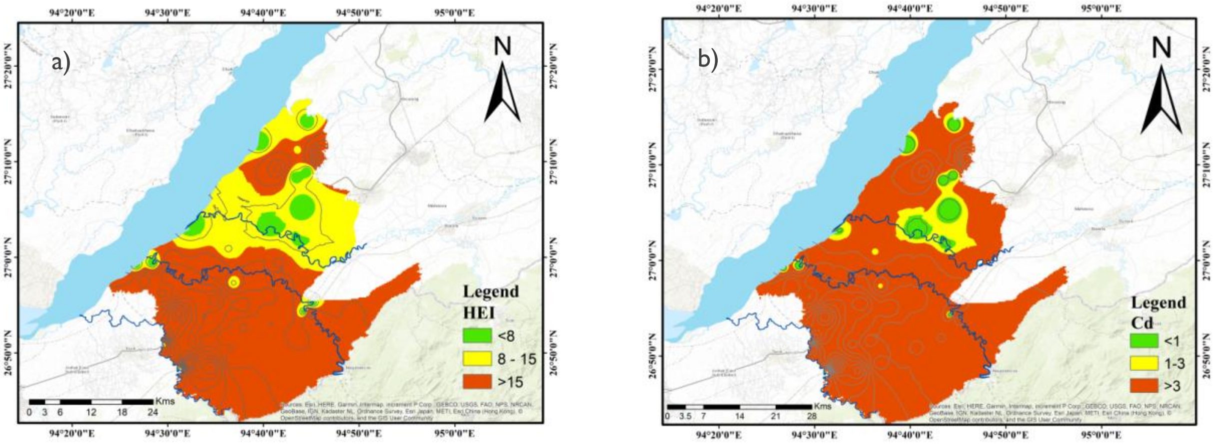

Figure 5. *Spatial variation of a) HEI, and b) Cd in the study area.*

Table 2. *Factor loadings of groundwater quality parameters in the study area.*

Variables	PC1	PC2	PC3	PC4	PC5	PC6
pH	-.157	.098	.067	.819	.317	-.054
EC	. 765	.401	.221	-.145	.076	.319
TDS	.763	.410	.231	-.140	.038	.317
HCO_3^-	.048	.825	.368	-.035	-.038	-.151
Cl^-	.131	.162	-.205	-.161	-.817	.069
Ca^{2+}	.866	.072	.173	.173	-.182	-.151
Hardness	.246	.021	.893	-.090	.006	.131
Mg^{2+}	.693	.059	.682	.049	-.108	-.009
SO_4^{2-}	.004	-.321	-.164	.795	-.185	.123
F^-	.075	.138	-.248	-.053	.808	.128
Na^+	.122	.825	-.274	-.099	.007	.103
K^+	.819	-.220	-.018	-.302	.059	-.098
NO_3^-	.008	-.024	.082	.057	.039	.947

like $CaCO_3$ (R. C. 1983). PC5 and 6 reported variations of 8.80% and 8.12% respectively, with strong positive correlation in F^- (.808) and NO_3^- (.947) which may be due to anthropogenic activities agricultural runoff, waste disposal and industries (Wu et al., 2019).

3.2 Evaluation of potential health risk

In Sivasagar district, carcinogenic and non-carcinogenic effects are evaluated to analyze the harmful health risks caused when contact with trace elements through water consumption. The primary exposure routes of contaminated drinking water are by ingestion and dermal contact with ingestion being the dominant route. The potential health impacts for non-carcinogenic risks are evaluated based on the concentration of metals in water and their impacts on the human body. Carcinogenic risks are determined by the presence of specific metals that are linked to long-term cancer development. To calculate the probability of adverse health effects from exposure to these trace metals, the total health risk is quantified using reference doses and cancer slope factors.

3.2.1 Non-carcinogenic health risk

The non-carcinogenic risk of heavy metals in drinking water was evaluated using both deterministic and probabilistic approaches. The risk assessment focused on the chronic daily intake (CDI) and hazard quotient (HQ) values for various heavy metals, including As, Mn and Fe. These values were calculated for three distinct exposure groups: children, males, and females representing the distribution of non-carcinogenic risks for these metals. The non-carcinogenic health risk is generally low (HQ < 1) from heavy metals across Sivasagar, Nazira, Demow, and Amguri regions implying low health impact to the people. The non-carcinogenic risk in the region for oral exposure exhibits in the following order: male > children > female, while the dermal exposure is less than 1 for children, females, and males (**Table 3**).

In Amguri, the HQ of Fe is 1.36 for children, 1.8 for females, 1.7 for males and the HQ of Mn is 1.38 for children, 1.8 for females and 1.8 for males. For dermal exposure the HQ of Cd is higher in the region with a value of 0.22 in females. This is followed by Sivasagar with HQ values for Mn of 1.37 for children, 1.32 for females, 1.74 for males, and HQ values for Fe of 1.43 for children, 1.3 for females, and 1.7 for males through oral route of exposure, whereas the value for dermal exposure is low. The HQ of Fe and Mn are highest in both the regions through oral exposure (**Fig. 6a**). In Nazira, the HQ for Fe through oral route is 1.38 in children, 0.6 in females, 1.6 in males and for Mn it is 1.39 in children, 0.7 in females, and 1.6 in male. In Demow, the HQ for Fe is the lowest, having 1.21 in children, 1.2 in females, 1.3 in males and for Mn it is 1.21 in children, 1.19 in females and 1.34 in males, through oral routes. The health risk for dermal exposure in Nazira and Demow is minimal (**Fig. 6b**). The

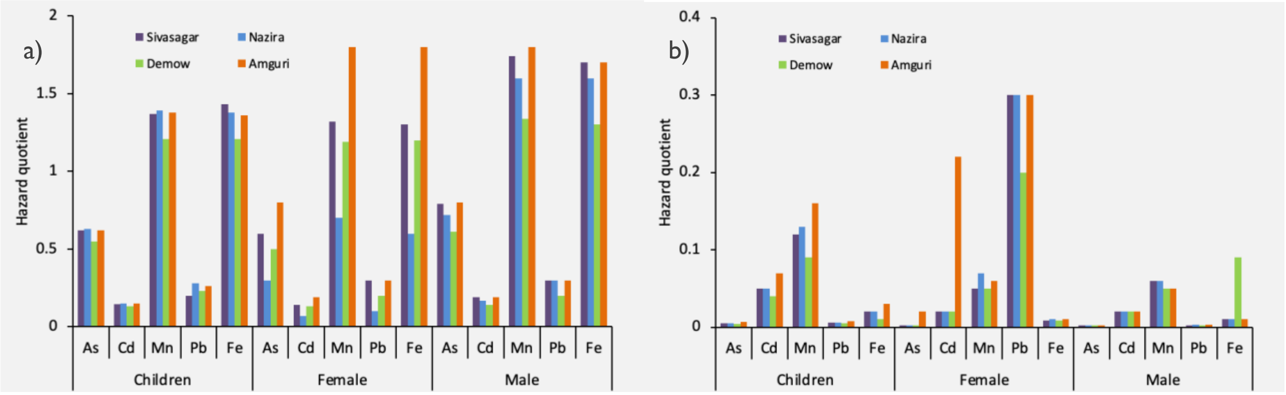

Figure 6. *Non-carcinogenic hazard quotient (HQ) through a) oral, and b) dermal exposure route in children, males and females.*

Table 3. *Calculated hazard quotient for both oral and dermal exposure to heavy metals in children, female and male.*

Category	Metals	Sivasagar		Nazira		Demow		Amguri	
		Oral	*Dermal*	*Oral*	*Dermal*	*Oral*	*Dermal*	*Oral*	*Dermal*
Children	As	0.62	0.005	0.63	0.005	0.55	0.004	0.62	0.007
	Cd	0.145	0.05	0.15	0.05	0.13	0.04	0.15	0.07
	Mn	**1.37**	0.12	**1.39**	0.13	**1.21**	0.09	**1.38**	0.16
	Pb	0.2	0.006	0.28	0.006	0.23	0.005	0.26	0.008
	Fe	**1.43**	0.02	**1.38**	0.02	**1.21**	0.01	**1.36**	0.03
Female	As	0.6	0.002	0.3	0.002	0.5	0.002	0.8	0.02
	Cd	0.14	0.02	0.07	0.02	0.13	0.02	0.19	0.22
	Mn	**1.32**	0.05	0.7	0.07	**1.19**	0.05	**1.8**	0.06
	Pb	0.3	0.3	0.1	0.3	0.2	0.2	0.3	0.3
	Fe	**1.3**	0.009	0.6	0.01	**1.2**	0.009	**1.8**	0.01
Male	As	0.79	0.002	0.72	0.002	0.61	0.002	0.80	0.002
	Cd	0.19	0.02	0.17	0.02	0.14	0.02	0.19	0.02
	Mn	**1.74**	0.06	**1.6**	0.06	**1.34**	0.05	**1.8**	0.05
	Pb	0.3	0.002	0.3	0.003	0.2	0.002	0.3	0.003
	Fe	**1.7**	0.01	**1.6**	0.01	**1.3**	0.09	**1.7**	0.01

Note: Bold values indicate exposure levels that may pose a non-carcinogenic health risk.

HQ values of As (0.5–0.8) and Pb (0.2–0.3) are low with primary concern of health risk mainly from Fe and Mn exposure. For oral exposure, the HI values exceed the threshold of 1 across the studied region blocks, whereas through the dermal exposure are negligible (< 0.7) (**Fig. 4**). This result indicates that the possibility for detrimental health effects from such exposure is minimal or unlikely based on the current data and risk assessment methodology.

3.2.2 Carcinogenic health risk

Carcinogenic risk assessment for As, Cd, and Pb in the drinking groundwater across children, males, and females is summarized in **Table 4**. The potential to develop cancer due to exposure to these metals is estimated based on cancer risk parameters. The cancer slope factor (CSF) is taken for each metal, to calculate the cancer risk which helps to quantify the probability of occurring cancer when prolonged exposure (Oni et al., 2022).

The calculated risks for oral exposure of children for As ranged from 2.4E-4 to 2.8E-4, for Cd from 9.6E-4 to 1.1E-3, and for Pb from 6.94E-6 to 7.95E-6. The oral values are above the USEPA's acceptable range, indicating a higher potential for cancer risk, particularly for As and Cd, which show values significantly exceeding the threshold of 10E-4. For females the carcinogenic risks through oral exposure ranged as follows: for As, it varied from 1.4E-4 to 3.6E-4; for Cd, it ranged from 9.4E-4 to 1.0E-3; and for Pb, it ranged from 7.56E-6 to 1.01E-5. The calculated oral values indicate a high potential risk of cancer, particularly from Cd exposure, where the values significantly exceed the USEPA's

Table 4. *Calculated cancer risk for both oral and dermal exposure to heavy metals in children, female and male.*

Category	Metals	Sivasagar		Nazira		Demow		Amguri	
		Oral	*Dermal*	*Oral*	*Dermal*	*Oral*	*Dermal*	*Oral*	*Dermal*
Children	As	2.8E-4	2.4E-6	2.8E-4	2.5E-6	2.4E-4	1.8E-6	2.8E-4	3.2E-6
	Cd	1.0E-3		1.1E-3		9.6E-4		1.0E-3	
	Pb	7.83E-6	5.03E-6	7.95E-6	5.07E-6	6.94E-6	3.83E-6	7.86E-6	6.52E-6
Male	As	3.58E-4	1.1E-6	3.2E-4	1.2E-6	2.7E-4	9.5E-6	3.5E-4	1.7E-6
	Cd	1.3E-3		1.2E-3		1.0E-3		1.3E-3	
	Pb	1.0E-5	2.2E-6	9.15E-6	2.5E-6	7.68E-6	1.93E-6	1.0E-6	2.17E-6
Female	As	2.7E-4	9.7E-6	1.4E-4	1.3E-6	2.4E-4	9.4E-6	3.6E-4	1.1E-6
	Cd	1.0E-3		5.4E-4		9.4E-4		1.3E-3	
	Pb	7.56E-6	1.97E-6	3.96E-6	2.66E-6	6.79E-6	1.9E-6	1.01E-6	2.26E-6

acceptable risk range. The carcinogenic risk through oral exposure for male was observed as follows: As risk varied from 2.7E-4 to 3.58E-4, Cd ranged from 1.0E-3 to 1.3E-3, and Pb risk spanned from 9.15E-6 to 1.0E-5. The cancer risk from dermal route of exposure remains minimal.

The mean cancer indices (CI) value for men is 3.07E-4, for women is 2.42E-4, and for children is 2.6E-4. Men exhibit the highest mean CI. The highest risk for cancer was observed in both children and adults via ingestion, especially due to Cd exposure. The International Agency for Research on Cancer (IARC) categorizes Cd to be a group I carcinogen for human and research animals supported by substantial evidence (Jarup, 2003). Reports have also highlighted a link between Cd exposure associated with kidney cancer, while some studies have suggested an association with lung cancer among individuals exposed to Cd (Jarup, 2003).

4 Conclusion

Groundwater and surface water quality of Sivasagar district has been evaluated. The spatial distribution of trace metals, its pollution indices and health risk assessment are examined. The major ions are found to be within the acceptable limits, indicating that the groundwater meets the required quality standards. Piper diagram reveals the facies as Na-K-HCO_3 and NaCl type, for both groundwater and surface water suggesting slow recharge, extended contact with geological materials and anthropogenic influence from sewage and agricultural runoff respectively. In terms of trace element contamination, Fe (0.43 to 115.13 mg/L) and Pb (2.09 to 214.52 mg/L) are the highest in the groundwater, with concentrations exceeding permissible limits in several samples. Other metals such as As (14%), Cd (12%) and Mn (92%) also exceed the permissible limits. The degree of contamination was evaluated in which for HPI, the level of pollution was low for 78% of the samples, while 68% had high pollution levels based on the C_d index. The potential health risk evaluation indicated that both non-cancer and cancer health risks exist, particularly from trace elements like As, Pb and Cd. The risk of non-cancerous issues was higher for females especially in region of Amguri compared to children and males. In the study, HI exceeds 1 suggesting potential risk of non-carcinogenic health issues in the study area, emphasizing proper need for water quality management to mitigate these risks. The carcinogenic risk in both children and adults is found to be high primarily due to Cd exposure, which may be due to the higher metabolic rates of children and repeated exposure in adults leading to faster absorption and processing of toxins.

5 Data availability statement

The supplementary data is provided. Raw data used in the analysis can be accessed upon request from the corresponding author.

6 Ethical statements

Ethical approval was not required for this research. However, informed consent was obtained during the survey, which included both adults and children. When, necessary, parents were provided with consent forms for children's participation in the survey.

7 Conflict of interest

No conflict of interest is declared by the authors related to this study.

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9 Author contributions

Lisha Borgohain: Investigation, formal analysis, and writing – original draft. Runti Choudhury: Conceptualization, supervision, writing – review & editing. The final version of the manuscript was approved by both the authors.

10 Copyright statement

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