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Research Article

Groundwater Quality Assessment Using Pollution Indices and Human Health Risks Through Exposure to Trace Elements in the City of Kara, Togo

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Abstract

This study assesses the concentrations of trace elements in groundwater from Kara, focusing on their implications for water quality and health risks. Groundwater samples were collected and analyzed during the dry and post-monsoon seasons for pH, TDS, and trace metals using standard methods and for calculating pollution indices and noncarcinogenic and carcinogenic risks. Groundwater was found to be fresh but more acidic during the dry season. Only As, Pb, Sb, Fe, and Mn exceeded acceptable limits in some samples, highlighting potential health risks. Based on the heavy metal pollution index, groundwater is unsuitable for domestic purposes for 16.67% and 4.17% of samples in dry and post-monsoon seasons, respectively. According to the degree of contamination, 37.5% in the dry season and 20.8% in post-monsoon fell in high pollution classes. Most samples presented a hazard index above the unity for the resident children and adults. Carcinogenic risk assessment scores exceeded 10 to 100-fold higher than the safe point of 10^{-6}. Adequate access to treated and safe drinking water and regular monitoring are essential to mitigate these risks in the Kara region.

Keywords

Arsenic, Health Risks, Lead, Pollution Indices, Togo, Urban Groundwater, Water Quality

1. Introduction

Groundwater quality may deteriorate due to trace chemical constituents. Even at relatively low concentrations, trace elements such as lead, mercury, thallium, arsenic, chromium, cadmium, and antimony have undesirable impacts on human health and the environment through their persistent accumulation and biomagnification to a poisonous concentration level

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[1, 2]. Their harmful effects on humans include cardiovascular toxicity, genotoxicity, reproductive and developmental toxicity, skin toxicity, immunological toxicity, hepatotoxicity, nephrotoxicity, carcinogenicity, and neurotoxicity [2, 3].

Trace elements in groundwater at higher concentrations compared to World Health Organization (WHO) [1] permissible limits for drinking water have been reported in different parts worldwide [3-5]. A global evaluation of heavy metals during the last three decades showed increasing concentrations with high heavy metal pollution indices in aquatic environments [6]. Pollution indices are semi-empirical approaches that evaluate overall water quality based on the concentrations of water parameters value compared to quality standards. It integrates individual elements in concentrations different from the allowable limit for a particular purpose and can be applied to water resources, soil, and sediments [4]. Several heavy metal pollution indices, such as Degree of Contamination (Cdi), Heavy Metal Pollution Index (HPI), and Heavy Metal Evaluation Index (HEI), have been applied to determine the pollution status of water ecosystems [4]. In addition, the carcinogenic and non-carcinogenic health risks can orientate decision-making regarding public health and water resource allocation [7].

In Togo, there is great interest in urban groundwater. However, previous studies have reported a substantial deterioration of urban groundwater water quality based on major ions, microbiological, and trace elements characterization [8-10]. Other studies in rural and mining areas showed the occurrence of heavy metals with potential health risks [11, 12]. This study focuses on heavy metal levels in groundwater and associated health risks in Kara, the second most urbanized city of Togo, under rapid urban expansion followed by intensive release of untreated effluents and pollution load without adequate sanitation systems [13]. Traffic and industrial emissions, vehicle workshops disposal, waste disposal or discharge, and agrochemicals-based urban agriculture are potential sources for releasing heavy metals in the city environment. The city is underlain by orthogneissic, mafic, and ultramafic bedrocks, which can also release trace elements in water resources. Consequently, reports concerning trace element concentrations in groundwater become necessary and may serve as a line to improve water resource allocation strategies in the city. In this context, this study was conducted in urban Kara with the following objectives: (i) to characterize heavy metals concentrations in the groundwater of Kara, (ii) to assess groundwater quality using metal pollution indices, and (iii) to evaluate potential carcinogenic and non-carcinogenic risks for children and adults through water ingestion and dermal exposure pathways.

2. Methods

2.1. Study Area

The study area encompassing the city of Kara covers an area of about 105 km^2 extending between 1°09′ to 1°15′ E longitudes and 9°30′ to 9°36′ N latitudes (Figure 1), with a population approximating 190 000 inhabitants [14]. The study area experiences a tropical sudanian climate controlled by the West African monsoon dynamics and characterized by a dry season lasting from November until March and a wet season lasting from April until October with an average annual rainfall of around 1300 mm and a mean annual temperature of around 28 ℃ [15, 16]. Kara River, sourced from the Atakora mountains in Benin, flows through the city following an irregular hydrological regime. With an altitude between 250 and 640 m asl, the study area is characterized by contrasting topography, ranging from flat to undulating, dotted with hills and irregular slopes. The diverse soils include ferralsols, acrisols, lixisols, leptosols, and fluviosols [15].

Metamorphic rocks, such as orthogneiss and granulites of the Pan-African Dahomeyide belt in North Togo, characterize the geology of the study area [17]. Groundwater is from a heterogeneous and low-productive basement aquifer type composed of a weathered layer acting as a storage component, a fissured layer whose permeability depends on the number and connectivity of the fissures, and a very low permeability unfissured basement. The weathered layer thickness is about 12 m bgl, and borehole depths are around 55 m bgl [16].

2.2. Sampling and Analyses

A total of twenty-four groundwater samples and two samples from Kara River were collected twice, during the dry season (February 2021) and post-monsoon (October 2023), for the measurement and analyses of 12 parameters (pH, EC, Pb, Cr, Cu, Co, Cd, As, Zn, Fe, Mn, Ni, Sb, Sr) using standard procedures [18]. The pH (±0.01) and electrical conductivity (EC ±2%, µS/cm), were measured *in situ* by calibrated portable pH and EC meters of HANNA® Instruments types. For the elemental analyses, samples were collected in 30 mL high-density polyethylene bottles, rinsed in distilled water, and rinsed again with the water to be sampled. Before analyses, water samples were filtered using a 0.45 µm membrane, preserved with 2 mL concentrated HNO_3 solution (trace metal grade acid), filled to the brim of the bottle, and sealed and labeled. Samples were packed and sent in chilled conditions to the laboratory. We determine heavy metals and trace element concentrations in acidified aliquots using an inductively coupled plasma-optical spectrometry (ICP-OES) technology device by coupling an inductively coupled argon plasma with a spectrometer. The analyses were performed at the GEGENAA laboratory, University of Reims Champagne-Ardenne, France. Each study was repeated three times before considering the mean concentration. The analytical precession was checked by verifying the standards as well as blanks. For all calculations, concentrations below the detection limits are fixed to 10^{-3} µg/L instead of nil.

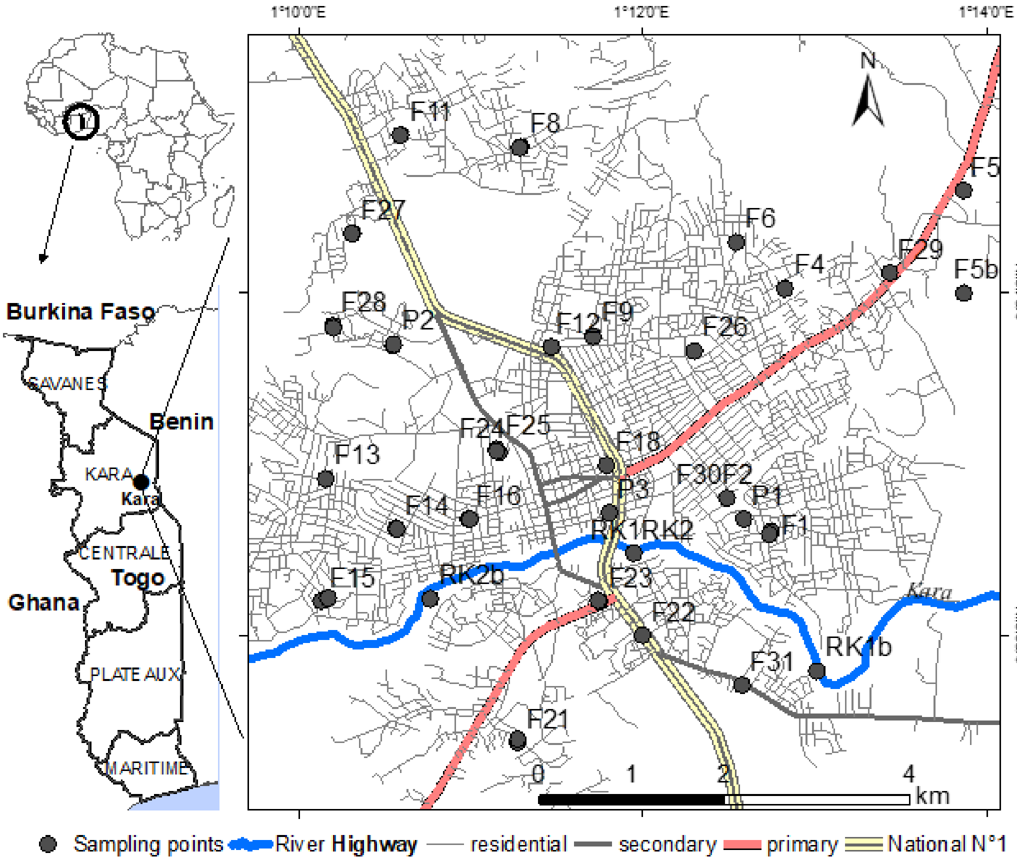

Figure 1. *Map showing the study area location, and sampling points.*

2.3. Pollution Indices

The indices applied in this water quality study, are namely the Heavy Metal Pollution Index (HPI) [19], the Heavy Metal Evaluation Index (HEI) [20], and the Degree of Contamination (Cdi) [21].

Heavy metal pollution index (HPI)

The HPI is calculated using Eqs 1, 2, and 3, where Wi represents the unit weight of the ith parameter, while Qi (Eq. 2) denotes the sub-index of the ith parameter. The term n signifies the number of parameters under consideration, with Mi denoting the heavy metal concentration. Ii represents the ideal value, the necessary value for essential metals, and the zero value for toxic metals of the ith parameter. Ii and Si values are obtained from the WHO guidelines for drinking water quality [1].

$$\mathrm{HPI}=\frac{\sum_{i=1}^{n} \mathrm{Wi}^{*}\mathrm{Qi}}{\sum_{i=1}^{n} \mathrm{Wi}} \qquad (1)$$

$$\mathrm{Qi}=\frac{|\mathrm{Mi}-\mathrm{Ii}|}{\mathrm{Si}-\mathrm{Ii}} {*}100 \qquad (2)$$

$$\mathrm{Wi}=\frac{1}{\mathrm{Si}} \qquad (3)$$

Heavy metals evaluation index (HEI)

In the HEI formula (Eq. 4), Hc represents the monitored value of the ith parameter. At the same time, Hmac denotes the maximum permissible concentration of the ith parameter following the WHO standard values.

$$\mathrm{HEI}=\sum_{i=1}^{n} \frac{\mathrm{Hc}}{\mathrm{Hmac}} \qquad (4)$$

Contamination degree index (Cdi)

The contamination index (Cdi) is calculated as the sum of all the contamination factors that exceed the maximum authorized values (Eq. 5). Ci represents the analytical values above the maximum permissible concentration (MACi).

$$\mathrm{Cdi}=\sum_{i=1}^{n} \left(\frac{\mathrm{Ci}}{\mathrm{MACi}}-1\right) \qquad (5)$$

The recommended standard (Si), permissible concentration MACi, and the ideal value Ii are presented in Table 1.

2.4. Noncarcinogenic Risk

This study conducted ingestion and dermal noncarcinogenic risk assessment following the methodologies outlined by the United States Environmental Protection Agency [22, 23]. To evaluate the non-carcinogenic risk linked with heavy metals, it's imperative to determine the Chronic Daily Intake (CDI) for each exposure pathway. Below are the parameters and equations used to calculate CDI (mg/kg-day) values (Eqs. 6 and 7).

Chronic daily intake (CDI) via ingestion and dermal absorption

$$CDI_{ingestion}=\frac{C*IR*ED*EF}{BW*ATnc} \quad (6)$$

$$CDI_{dermal}=\frac{C*SA*Kp*ET*ED*EF*CF}{BW*ATnc} \quad (7)$$

where:

- C represents the concentration of the element in each water source (mg/L),
- BW denotes the average body weight (70 kg for adults and 15 kg for children),
- IR stands for the ingestion rate (2.5 and 0.75 L/day for adults and children, respectively),
- EF signifies exposure frequency (365 days/year),
- ED indicates exposure duration (30 and 6 years for adults and children, respectively),
- ATnc is the average exposure time for assessing non-cancer risks. (ED × 365 days),
-ATc is the amount of time for chronic assessments (e.g., cancer), and potential lifetime average daily dose (70 years). This value replaces the ATnc in $CDI_{ingestion}$ the formula for carcinogenic purposes,
- SA denotes exposed skin surface area (18,000 cm^2 for adults and 6,600 cm^2 for children),
- ET signifies exposure duration (0.58 and 1 hour/day for adults and children, respectively),
- Kp is the skin water permeability coefficient (cm/h) presented in Table 1.
-CF Conversion factor of the concentration of the element in each water source (10^{-3} L/cm^3).

Table 1. *Standard values of Kp, RfD, and SF used to calculate health risks.*

Metals	**Kp (cm/ h)**	**$RfD_{ingestion}$ (mg/kg·day)**	**RfD_{dermal} (mg/kg·day)**	**$SF_{ingestion}$ (mg/kg·day)**	**Si/ MACi (μg/L)**	**I (μg/L)**
Pb	0.0001	0.0014	0.00042	0.0085	10	0
Cr	0.002	0.003	0.00012	0.5	50	0
Cu	0.001	0.04	0.000062	-	2000	50
Co	0.0004	0.0003	0.000006	-	50	25
Cd	0.001	0.0001	0.000062	0.38	3	0
As	0.001	0.0003	0.000062	1.5	10	0
Zn	0.0006	0.3	0.000037	-	3000	15000
Fe	0.001	0.7	-	-	300	2000
Mn	0.001	0.14	0.000062	-	80	50
Ni	0.0002	0.02	0.000012328	-	80	10
Sb	0.001	0.0004	0.000061643	-	20	3
Sr	-	0,6	-	-	-	-

Hazard coefficients (HQ)

The assessment of the non-carcinogenic hazard quotient (Eqs. 8 and 9) resulting from the ingestion and dermal absorption of groundwater for the i^{th} trace element was conducted as follows:

$$HQ^{i}_{ingestion}=\frac{CDI^{i}_{ingestion}}{RfD^{i}_{ingestion}} \quad (8)$$

$$HQ^{i}_{dermal}=\frac{CDI^{i}_{dermal}}{RfD^{i}_{dermal}} \quad (9)$$

where HQ is the hazard quotient, and RfD is the reference dose in Table 1.

Hazard index (HI)

The hazard index (HI) indicates the integrated non-carcinogenic risk calculated by summating the hazard quotients (HQs) associated with the examined trace elements (Eqs. 10 and 11).

$$HI_{ingestion} = \sum_{i=1}^{n} HQ^{i}_{ingestion} \quad (10)$$

$$HI_{dermal} = \sum_{i=1}^{n} HQ^{i}_{dermal} \quad (11)$$

2.5. Carcinogenic Risk

The carcinogenic potential was evaluated using the Excess Lifetime Cancer Risk (ELCR). In this study, As, Cd, Cr, and Pb were considered following the USEPA guidelines [24, 25]

$$ELCR=CDI_{ingestion}*SF_{ingestion} \quad (12)$$

With $SF_{ingestion}$ cancer slope factor (mg/kg day) presented in Table 1.

3. Results and Discussion

3.1. Trace Elements Concentrations in Groundwater

Table 2 presents the descriptive statistics of the measured parameters. The high coefficient of variation suggests high spatial variation during both seasons. Based on pH standards, groundwater tends to be more acidic in the dry season (16.67%) than in post-monsoon (3.8%). Generally, groundwater is more mineralized than river water sampled according to total dissolved solids (TDS). However, values lower than 1000 mg/L indicate freshwater types in the study area.

The elements Cr, Cu, Cd, Co, Zn, and Ni comply with the WHO standards for drinking water, probably due to a lesser impact of anthropogenic activities on the concentration of these ions or lesser leaching from solid phases in contact with water. Contrarily, for lead, all boreholes exceeded the acceptable limit in drinking water during the dry season against nearly 50% in the dry season. This suggests that Pb corrosion remains a worrying issue during both seasons. The most sensitive and vulnerable target for lead appears to be the nervous system, and exposure to lead in adults has been associated with hypertension, nephropathy, and anemia [2]. The elements As, Fe, and Mn concentrations exceed threshold values in the dry and post-monsoon seasons. In the dry season, the concentration of these trace metals is above WHO guidelines values of 20.8, 12.5, and 29.2-58.3%, against 25.0, 33.3, and 33.3-70.8% in the post-monsoon season, respectively. Prolonged exposure to arsenic groundwater, even at low concentrations, may cause complications in body organ systems such as integumentary, nervous, respiratory, cardiovascular, hematopoietic, immune, endocrine, hepatic, renal, reproductive, and developmental systems [26].

Table 2. *Descriptive statistics of in situ parameters and heavy metal concentrations in groundwater.*

		Dry season (*n* =24)							**Post-monsoon (*n* =24)**						
Parameters	**WHO guidelines**	**Mean**	**Min**	**Max**	**S.D**	**C.V (%)**	**Nb out of WHO guidelines**	**% out of WHO guidelines**	**Mean**	**Min**	**Max**	**S.D.**	**C.V (%)**	**Nb out of WHO guidelines**	**% out of WHO guidelines**
pH (-)	6.5 - 8.5	6.76	5.95	7.32	0.3	4.6	04	16.7	7.39	6.42	7.96	0.4	5.1	01	3.8
TDS (mg/L	1000	383	230	650	117.9	30.8	0	-	357	269	492	69.0	19.3	-	-
CE (µS/cm)	-	587	300	1170	236.5	40.3	-	0	592	420	910	143.1	24.2	-	-
Cd (µg/L)	3	-	<LD	<LD	-	-	0	0	<LD	<LD	<LD	-	-	0	0
Ni (µg/L)	80-70*	-	<LD	<LD	-	-	0	0.0	2.54	<LD	16.53	3.4	132.8	0	0
Co (µg/L)	50	0.37	<LD	8.86	1.81	488.6	0	0	0.06	<LD	1.52	0.3	482.3	0	0
As (µg/L)	10	5.68	<LD	40.92	10.79	190.1	5	20.8	7.10	<LD	48.25	10.5	147.7	6	25.0
Cr (µg/L)	50	1.48	<LD	12.82	2.99	202.3	0	0	0.13	<LD	3.08	0.6	486.1	0	0
Cu (µg/L)	2000	4.29	<LD	16.66	4.60	107.2	0	0	1.91	<LD	9.10	3.0	154.9	0	0
Fe_{total*} (µg/L)	No HV-300	131.86	9.92	488.65	144.64	109.7	3	12.5	301.26	13.90	1571.50	434.8	144.3	8	33.3
Mn* (µg/L)	80 - 20*	98.24	<LD	610.15	155.13	157.9	7-14*	29.2-58.3*	100.40	<LD	445.40	137.4	136.9	8-17*	33.3-70.8*
Pb (µg/L)	10	32.81	15.69	54.21	7.84	23.9	24	100	9.06	<LD	16.39	3.8	41.8	10	41.7
Sb (µg/L)	20	16.13	3.73	105.40	21.15	131.1	4	16.7	3.51	1.17	14.90	2.6	73.4	0	0

		Dry season (*n =24*)							Post-monsoon (*n =24*)						
Parameters	**WHO guidelines**	**Mean**	**Min**	**Max**	**S.D**	**C.V (%)**	**Nb out of WHO guidelines**	**% out of WHO guidelines**	**Mean**	**Min**	**Max**	**S.D.**	**C.V (%)**	**Nb out of WHO guidelines**	**% out of WHO guidelines**
Sr (µg/L)	-	264.56	70.04	555.80	132.44	50.1	-	-	282.43	77.79	667.20	129.1	45.7	-	-
Zn (µg/L)	3000 (NG)	8.52	0.39	33.50	8.62	101.2	0	0	9.99	1.41	30.64	8.4	84.2	0	0

*No health values (HV) for Iron, health value for Mn (80 µg/L) exceed threshold values (TV) of 20 µg/L

The relatively high contents of As, Ni, Co, Mn and Cr were linked to mining activities in Kano state, Nigeria [27], Singhbhum region, India [28] and Sabodala region, Senegal [5]. Besides, a similar increase of Fe in Kampala and Mbarara districts, Uganda, was attributed to the corrosion of iron or steel used for the wells [29]. Fe concentrations were significantly higher, with mean values of 1144.87 µg/L for groundwater and 115,548.15 µg/L for surface waters, due to mining wastes around Bangeli, Togo, [12].

Antimony, a pollutant of emerging concern often mixed with lead or other heavy metals, may cause symptoms of exposure, including headache, coughing, anorexia, troubled sleep, and vertigo [2, 30]. Sb was above the permissible limit only during the dry season for 16.7% of samples. High Sb was reported in Bangeli canton [12], whereas As, Cd, and Pb concentrations were found below their limits compared to this study. In general, Sr is not a health concern at drinking water levels. [1] Groundwater Sr ranged from 70.04 to 555.80 µg/L with a mean of 264.56 µg/L in dry season and from 77.79 to 667.20 with a mean of 282,43 µg/L in post-monsoon.

River water has a relatively high pH (means of 7.51 in the dry season and 8.11 in post-monsoon) than groundwater during both seasons. At the same time, mineralization was lower (means of 190 µS/cm in the dry season and 185 µS/cm in post-monsoon) than groundwater. The total iron concentration was significantly higher (1359 µg/L) in the post-monsoon season than in the dry season (54.9 µg/L), and one dry-season sample with a high Sb concentration (20.51 µg/L). All the parameters comply with WHO standards. The urban runoff may contribute to the higher concentrations of iron measured in the Kara River in post-monsoon.

3.2. Metal Pollution Indices

3.2.1. Heavy Metal Pollution Index (HPI)

The drinking water critical value for HPI is 100, and the groundwater quality can be classified into five categories, namely excellent (<25), good (25-50), poor (50-75), very poor (75-100), and unsuitable (>100) [31]. The HPI results (Figure 2) suggested that all surface water samples are of excellent quality concerning heavy metal contamination compared to values as high as 455.8, as reported by a study [32]. The HPI values in groundwater samples ranged from 41.4 to 143.0, with a mean value of 73.6 in the dry season, and from 10.8 to 117.6, with a mean value of 33.4 in post-monsoon. Only one sample (4.17%) is unsuitable post-monsoon against four (16.67%) in the dry season due to Fe, Mn, Pb, As, and Sb. High values of up to 470 were reported in other urban areas, such as Linares, Mexico [33].

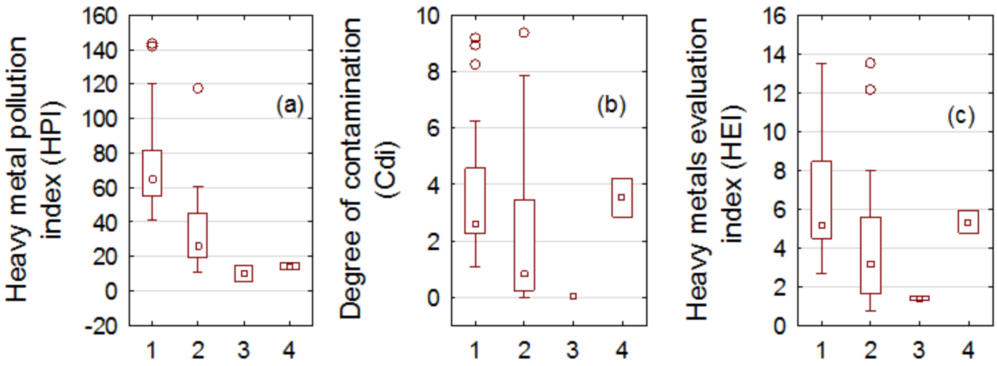

Figure 2. *Pollution indices for water quality evaluation (1 = GW Dry season; 2 = GW post-monsoon; 3= River dry season; 4 = River post-monsoon).*

The pollution level related to poor quality categories decreased in the wet season (12.5%) compared to the dry season (70.8%). Previous studies depicted the evolution of unsuitable groundwater samples decreasing in the post-monsoon season, as in the urban Delhi environs in India [34] and Wuhan City, China [35]. Although heavy metal contamination occurs, rapid infiltration of rainwater may diffuse into open conditions groundwater tables and dilute the metal concentrations contained therein [36]. In Kampala and Mbarara districts, Uganda, an increase in the percentage of samples under the excellent category was also observed in the wet season [29], supporting the dilution influence. Rupias et al., [37] found no seasonal variation of HPI values in the alluvial plain of Atibaia River-Campinas, Brazil. These variations suggest an influence of the sources, the extent, and the spatial variation of recharge and geochemical processes on the seasonal variation of heavy metal loads in urban groundwater environments.

3.2.2. Contamination Degree Index (Cdi)

The contamination index (Cdi) is calculated for As, Fe, Mn, Pb, and Sb. The critical value for Cdi is 3, and water deterioration can be categorized into three classes of pollution that are low (<1), moderate (1-3), and high (>3) [21]. The results (Figure 2) showed that all surface water samples fall in the low pollution class in the dry season, while moderate and high classes were found post-monsoon. Much higher values, ranging from 7.4 to 39.5, with a mean of 21.1 in surface water, were reported in locations of high-density settlements in the Lower Cross River Basin, southeastern Nigeria [20]. Higher values of 14.8 suggest a high pollution level was observed in the Buriganga River, Bangladesh [32]. The level of Kara River contamination presumes a low load of heavy metals in the water. However, further studies should consider a significant number of samples and sediments because of the potential sources of contamination, such as agrochemicals in vegetable gardening and discharge of domestic and industrial effluents. Heavy metals can accumulate in surface water sediments and pose environmental and human health risks, limiting the efficiency of freshwater management plans, as observed in the Olt River, Romania [38].

The groundwater values ranged from 0 to 9.2, with a mean value of 3.5 in the dry season, and from 0 to 9.2, with a mean value of 2.2 post-monsoon. In the dry season, 37.5% fall in the high pollution class, and the remaining 62.5% in the moderate pollution class. In post-monsoon, 20.8%, 12.5%, and 37.5% fall in high, moderate, and low pollution classes. Previous results reported a similar trend but with higher values in Shiraz City, Iran [39], Arang, Chhattisgarh, India, [31], and Kumasi, Ghana, [40]. Such results indicate that heavy metal pollution of water resources is a global concern, and constraining efforts are required to reduce human exposure.

3.2.3. Heavy Metals Evaluation Index (HEI)

The HEI varied for groundwater samples from 2.7 to 13.5 with a mean of 6.4 and from 0.7 to 13.5 with a mean of 4.1 in the dry season and post-monsoon, respectively. According to the critical value 400 [20], all water samples are at low risk of heavy metal pollution. Based on the multiple mean approaches, the computed mean was 5.0 for all collected samples, supposing that 29.17% in the dry season and 4.17% in post-monsoon fall in the high pollution category (HEI > 10).

Defining a global scale of groundwater pollution indices, particularly for HEI, appears difficult because of the significant differences in classes in different parts of the globe [36, 39, 41].

The overall results in this study suggest that the Cdi, HPI, and HEI are highly correlated, as observed in other studies [29, 31]. This may not happen, according to other studies [32, 40, 39]. However, samples fall into different pollution levels from one index to another, suggesting that integrated criteria should be considered for efficiently allocating water sources. Although heavy metal pollution indices are easy to calculate, their values vary worldwide, and the subjectiveness of the critical points appears as a fundamental limitation. Properly studying water resources and their quality evolution at a reconnaissance scale can help define these indexes' application rules. However, they remain undeniably sophisticated tools for water quality assessment and decision-making.

3.3. Health Risk Assessment

3.3.1. Chronic Daily Intake (CDI)

The mean CDI from groundwater is 2.8 10^{-2} mg/kg-day for children and 2.7 10^{-2} mg/kg-day for adults through ingestion during the dry season and 3.6 10^{-2} mg/kg-day for children and 2.6 10^{-2} mg/kg-day for adults during the post-monsoon (Table S1). Through the dermal route, the mean values are 6.0 10-5 mg/kg-day for children, 2.0 10-5 mg/kg-day for adults in the dry season, and 5.3 10-5 mg/kg-day for children, 1.8 10^{-5} mg/kg-day for adults in post-monsoon. These values are relatively lower for river water (Table S1).

Although ingestion CDI is substantially higher than dermal CDI, both ingestion and dermal CDI are lower for adults than children due to the difference in exposure conditions and anthropometric characteristics. This suggests more potential negative impact of metal exposure on children's health. The results also showed a seasonal variation of CDI as the seasonal variation of the elemental composition of water samples. The contribution order changed mostly for Zn, Pb, As, Sb, and Ni in groundwater. In river water, the contribution is highly variable for all elements except for Fe, Mn, and Sr, which are the top metal contributors to high CDI.

3.3.2. Hazard Quotient (HQ) and Hazard Index (HI)

Figure 3 and Table S2 present the descriptive statistics of HQ and HI for children and adults via ingestion and dermal routes.

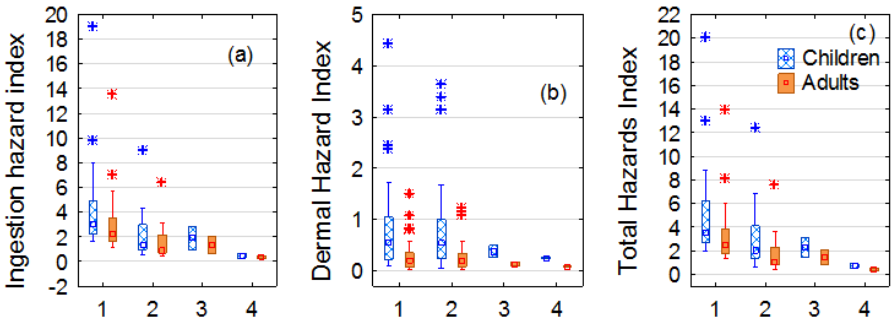

Figure 3. Results of (a) ingestion hazard index (b) dermal hazard index and (c) total hazard index (1 = GW Dry season; 2 = GW post-monsoon; 3= River dry season; 4 = River post-monsoon).

Hazard Quotient (HQ) values were above 1 in the dry season for Sb, Pb, As, and Co. Sb can harm the eyes, skin, lungs, heart, and stomach [2, 30]. A more stringent limit of 5 µg/L in drinking water similar to that of arsenic is set by some countries [42, 30]. These results suggest considering Sb, As, and Pb among pollutants of priority interest when elaborating and implementing water resources development programs in the Kara region to minimize exposure. During post-monsoon, the ingestion HQ is above 1 for only As and Sb for children and adults. Based on the dermal HQ model, Mn presented cases above 1, with children and adults during the dry season and post-monsoon.

Figure 3c shows that the corresponding hazard index (HI) was above 1 for all the collected groundwater samples in the dry season. The mean values of the HI through ingestion and dermal pathways and the total HI were 4.29, 0.97, and 5.26 for children and 3.07, 0.33, and 3.40 for adults. In post-monsoon, HI was above 1 for all the collected groundwater samples at 87.5% based on the children's model and 66.67% based on the adult model. The corresponding mean values of the HI through ingestion and dermal pathways and the total HI were 2.05, 0.89, and 2.95 for children, 1.47, 0.30, and 1.77 for adults. These results are indicative of the high level of non-carcinogenic health risk in the study area and also suggest that, on average, children are more exposed to a health risk.

Many other studies have been conducted to evaluate water quality using HI. Most of them found children among age groups as the most vulnerable populations to increased non-carcinogenic health risks reflected by higher HI metals [12, 35, 39]. The non-carcinogenic risks model indicated negligible health risks of metals in the surface water and groundwater of Isfahan, Iran [7]. Substantial, persistent non-carcinogenic risks due to Cd and Pb in urban groundwater were reported in Southeast Nigeria [43].

3.3.3. Cancer Risks to Human

The contents of As, Pb, Cr, and Cd possessing CSF values were considered to have the potential to induce cancer risks for humans in the study area through ingestion. The calculated excess lifetime cancer risk must be lower than the safe point of 10^{-6}, that is, 1 in 1,000,000 chance of acquiring cancer [44, 45]. The results (Table 3) showed that the calculated mean ELCR values exceed the safe point 10 to 100 times, irrespective of age groups, season, and water sources, corresponding to the chance of 2 to 20 cases per 200,000 inhabitants acquiring cancer. This suggests grim potential carcinogenic risks from ingesting groundwater and surface water in the study area.

Further, the risk could be higher due to the hot climatic conditions influencing the daily drinking water consumption rate, which can increase. Public efforts are required to supply affordable, safe drinking water for all in the city and surrounding areas. This requires extending the public treated water supply system to all and providing inexpensive treatment technologies for removing heavy metals.

Table 3. Cancer risk results.

	Mean	Min	Max	Mean	Min	Max
GW dry season. Children				GW post-monsoon. Children		
Cd	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09
As	3.6.E-05	6.4.E-09	2.6.E-04	4.6.E-05	6.4.E-09	3.1.E-04
Cr	3.2.E-06	2.1.E-09	2.7.E-05	2.8.E-07	2.1.E-09	6.6.E-06
Pb	1.2.E-06	5.7.E-07	2.0.E-06	3.3.E-07	3.6.E-11	6.0.E-07
ELCR	4.1.E-05	1.0.E-06	2.6.E-04	4.6.E-05	3.2.E-07	3.1.E-04

	Mean	Min	Max	Mean	Min	Max
GW dry season. Adults				GW post-monsoon. Adults		
Cd	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09
As	1.3.E-04	2.3.E-08	9.4.E-04	1.6.E-04	2.3.E-08	1.1.E-03
Cr	1.1.E-05	7.7.E-09	9.8.E-05	9.9.E-07	7.7.E-09	2.4.E-05
Pb	4.3.E-06	2.0.E-06	7.1.E-06	1.2.E-06	1.3.E-10	2.1.E-06
ELCR	1.5.E-04	3.6.E-06	9.4.E-04	1.7.E-04	1.2.E-06	1.1.E-03
River water dry season. Children				River water post-monsoon. Children		
Cd	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09	1.6.E-09
As	4.7.E-06	6.4.E-09	9.3.E-06	8.4.E-06	6.4.E-09	1.7.E-05
Cr	2.1.E-09	2.1.E-09	2.1.E-09	2.1.E-09	2.1.E-09	2.1.E-09
Pb	3.6.E-11	3.6.E-11	3.6.E-11	1.4.E-07	1.4.E-07	1.4.E-07
ELCR	4.7.E-06	1.0.E-08	9.3.E-06	8.5.E-06	1.5.E-07	1.7.E-05
River water dry season. Adults				River water post-monsoon. Adults		
Cd	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09	5.8.E-09
As	1.7.E-05	2.3.E-08	3.3.E-05	3.0.E-05	2.3.E-08	6.0.E-05
Cr	7.7.E-09	7.7.E-09	7.7.E-09	7.7.E-09	7.7.E-09	7.7.E-09
Pb	1.3.E-10	1.3.E-10	1.3.E-10	5.1.E-07	5.1.E-07	5.1.E-07
ELCR	1.7.E-05	3.7.E-08	3.3.E-05	3.0.E-05	5.5.E-07	6.0.E-05

Similar high carcinogenic risks were in mining areas in the south of the country [11], gold mining areas in Ghana [45], and Nigeria, but due to Cd and Pb [43]. In the Jamalpur Sadar area, Bangladesh, higher lifetime carcinogenic risks were also more significant from groundwater intake than surface water [46]. It was also seen elsewhere that children were more susceptible to non-carcinogenic health risks. In contrast, the carcinogenic risk was higher for adults in the urban and industrial region of southern Sonbhadra, Uttar Pradesh, India, [47], in the Monterrey Metropolitan Area, Mexico [48], and Târgoviște Plain, a densely populated area in Romania [49] where ELCR was extremely high as 10^{-3} to 10^{-2}. These regions' findings provide a comprehensive perspective on groundwater quality issues worldwide. Since it highlights common challenges faced by various communities, a global perspective for solution development can boost the urgent needs and action for effective mitigation strategies against heavy metals pollution of groundwater. The global synergy might contribute to the population's use of safely managed drinking water services to achieve target 6.2 of the sustainable development goal, which aims at universal and equitable access to safe and affordable drinking water for all.

Although heavy metal pollution and health risk assessment are significant, the results may suffer from uncertainties due to the parameters of the models, which may vary according to climatic region, culture, daily food, and occupational habits [12, 28, 41]. Despite these limits, the current study and findings are meaningful for orientation regarding water supply systems in Kara. The results also serve as a baseline database for water resources management since such studies have not yet been performed in the study area.

4. Conclusion

The findings of this study highlight significant seasonal variations in the concentration of trace elements with a dilution effect during the post-monsoon season. The groundwater and surface water are fresh and circumneutral. Elements like Cr, Cu, Cd, Co, Zn, and Ni generally complied with WHO standards for drinking water, while Pb, As, Fe, Mn, and Sb were above the permissible limits. The pollution indices indicate the unsuitability of groundwater for drinking and domestic purposes in some households. The health risk assessment highlighted both non-carcinogenic and carcinogenic risks associated with the ingestion and dermal exposure to contaminated groundwater. Children are more vulnerable to metal exposure than adults, emphasizing the need for protective measures for younger populations. The groundwater and surface water should be treated before drinking and domestic use. Despite some limitations, such as small river water samples, variability of critical values for pollution indexes classification, and uncertainties linked to health risk parameters, this study and its findings are meaningful for orientation regarding water quality in the city of Kara.

Abbreviations

CDI	Chronic Daily Intake
Cdi	Degree of Contamination
ELCR	Excess Lifetime Cancer Risk
HEI	Heavy Metal Evaluation Index
HI	Hazard Index
HPI	Heavy Metal Pollution Index
HQ	Hazard Quotient
WHO	World Health Organization

Supplementary Material

The supplementary material can be accessed at https://doi.org/10.11648/j.ajep.20241305.15

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Conflicts of Interest

The authors declare no conflicts of interest.

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