Physicochemical parameters, heavy metal pollution and health risk assessment of water bodies in Kolokuma/Opokuma Local Government Area of Bayelsa State

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Water bodies in Bayelsa state are affected by pollution, which makes them unfit to drink and seriously disturbs aquatic life and ecosystems. This study examined physicochemical parameters and health risk assessment of heavy metals in the drinking water sources in Odi and Kaiama of Kolokuma/Opokuma Local Government Area (KOLGA) of Bayelsa State, Nigeria. Four (4) water samples were obtained from underground (borehole), River, Agbayai Lake, and dug-well. The samples were analysed using standard laboratory methods. The possible harmful health effects of exposure to heavy metals content in the water samples were also estimated using reliable tools of health risk assessment indices. The physicochemical parameters showed that the range values of pH, temperature, total dissolved solids, dissolved oxygen, biological oxygen demand, chloride, sulphate, nitrate, and phosphate were within the standards of the United States Environmental Protection Agency (USEPA), Nigerian Industrial Standard (NIS), and WHO permissible limits ($P<0.05$). Compared to lead detected in underground (0.023 mg/mL) and dug-well (0.033 mg/mL) water and iron detected in River water (0.738 mg/mL), which were above the permissible limits, cadmium, chromium, zinc, copper, and manganese were below the allowable limit. The health risk assessment results showed that children are more vulnerable to health risks. The average exposure dose through ingestion (LADDing) for all the metals in the water samples was above the acceptable limit, while the dermal exposure dose (LADDderm) for all the metals revealed in the water samples was within the USEPA acceptable range of $1x10^{-6}$ to $1x10^{-4}$. The oral and dermal accumulative carcinogenic risk (Rtotal) values for Cd, Cr, and Pb highlighted long-term risks. From the present study, it is important to track the exposure levels and consistently revise risk assessments to ensure the safety of water resources in the Niger Delta environment and to protect the health of the population.
Keywords: Physiochemical, carcinogenic, assessment, Cadmium, Chromium, Lead

Introduction

The significance of water for the survival of humans, plants, and animals cannot be overstated. This is because safe, high-quality water is essential for sustaining good health, and living without water is as unfeasible as living without food (Stevanovic *et al*., 2010). In recent years, the increasing demand for quality drinking water has become more difficult and seemingly unfeasible due to pollution (Stevanovic *et al*., 2010; Kamgba *et al*., 2023). Common sources of drinking water include springs, streams, hand-dug wells, and boreholes, most are often untreated, which leads to significant agricultural productivity issues and health risks, including disease outbreaks (Lutterodt *et al*., 2018). Furthermore, these polluted water sources are unsuitable for household use, worsening communities' difficulties in obtaining safe and clean water. Over half of the 700 million people worldwide who lack access to a secure water supply live in sub-Saharan Africa (Agensi *et al*., 2019). As the World Health Organization reported, 1.4 million individuals succumb each year due to a lack of adequate drinking water, sanitation, and hygiene. The overwhelming majority of these fatalities occur in low- and middle-income nations (WHO, 2024). Furthermore, UNICEF indicates that limited access to quality water sources in Nigeria significantly contributes to increased morbidity and mortality rates among children under five years old. Additionally, UNICEF found that just 26.5% of Nigeria's population relies on improved drinking water sources (UNICEF, 2021).

During crude oil spills, environmental samples and crude oil often contain heavy metals that are classified as carcinogens by the Agency for Toxic Substances and Disease Registry. These metals include lead (Pd), nickel (Ni), vanadium (V), zinc (Zn), chromium (Cr), arsenic (As), and cadmium (Cd) (ATSDR, 2013; Fu *et al*., 2014; Igwe *et al*., 2021). It has been claimed that drilling mud, storage pits, ponds, diesel emissions, flaring, venting, and stimulation fluids have contaminated many aspects of the Niger Delta environment. In addition to being widely distributed throughout the Niger Delta, these heavy metals are also a major cause of systemic toxicity and have been connected to the emergence of cancer (Anyanwu *et al*., 2023). Water bodies are impacted by this pollution, which makes them unfit to drink and seriously disturbs aquatic life and ecosystems. However, many rural populations in the Niger Delta environment of Nigeria use this polluted water for household and drinking purposes since they have no other options (Oyeyemi *et al*., 2024). Therefore, the major environmental pollution that causes degraded water bodies, disturbed aquatic life, and a damaged ecosystem is partly the cause of the civil unrest and violent protests against the Nigerian state that are coming from the Niger Delta region. Fish, goat, chicken, and cow meat from this environment are among the aquatic and terrestrial food sources that are primarily contaminated with heavy metals (Okoye *et al*., 2021; Okoye *et al*., 2022b). Numerous *in-situ* and *ex-situ* investigations have indicated that exposure to environmental contaminants by humans has a major role in the bioaccumulation of harmful substances in the body (Owonikoko *et al*., 2021; Owonikoko *et al*., 2022; Okoye *et al*., 2022b).

Health risk assessments for both carcinogenic and non-carcinogenic substances have become essential components of toxicological evaluations (Oyeyemi *et al*., 2024). Given that invasive research is not ethically acceptable for studies involving human participants, the establishment of toxicity estimation models has emerged as an approved approach in the field of toxicology. These risk assessments have proven to be practical and reliable tools for understanding the risks related to environmental exposure to xenobiotics, especially toxic metals (Rubio *et al*., 2022; Yang *et al*., 2022). The Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) has identified over 1300 hazardous substances, including volatile organic compounds, heavy metals, polycyclic aromatic hydrocarbons (PAHs), particulate matter, and others, which pose potential health risks to vulnerable populations (European Scientific Committee on Health, 2018). Research by Thomas *et al*. (2021), detected notable contamination by heavy metal in the water sources of the Niger Delta region, even after remediation attempts. This finding aligns with an earlier study that analytically examined the quality of groundwater, the health risks connected with heavy metal pollution, and total hydrocarbons in Delta State, Nigeria, revealing serious carcinogenic risks, especially among adults and children due to crude oil contamination (Ajeh *et al*., 2022). More recent evidence has indicated that heavy metal pollution in the Niger Delta causes serum and neuropathological alterations through bioaccumulation of heavy metals and oxidative stress in African giant rats (Olopade *et al*., 2023). Consequently, this has led to the need for an assessment of physicochemical parameters and heavy metal pollution in water bodies within KOLGA of Bayelsa State (Niger Delta) using indices related to human health risks. The study aimed to utilize specific indices to evaluate the health risks the local inhabitants may face. Furthermore, the research proposed participatory strategies to enhance and sustain water quality in the examined regions.

Research Methodology

Study sites

The research was conducted in KOLGA of Bayelsa State, Nigeria, the headquarters is in the community of Kaiama. This area covers 361 km² and had a population of 77,292 according to the 2006 census (NBS, 2007). In 2016, the projected population for the LGA was 105,900 (Wikipedia, 2020). Spanning 361 km², it comprises 20 communities that belong to two clans, situated between latitudes 08´ North and longitude 06´18 East within the equatorial rainforest. The region experiences two seasonal variations: a dry season from November to February and a rainy season from March to October. The average temperature ranges from 27 °C to 30 °C, accompanied by high humidity levels of 90 mm and an annual rainfall total of 2,400 mm. The two clans represented are Kolokuma and Opokuma, respectively (Manpower Nigeria, 2020). For this research, four water sources were chosen from the two primary towns, Kaiama and Odi, located in KOLGA, Bayelsa State, Nigeria (Figure 1). The main reason for selecting these study sites was their unique water bodies, which share the same river that traverses state boundaries and connects to the Atlantic, indicating potential similarities in metal contaminants. These water sources serve as the primary supply for drinking and various domestic purposes.

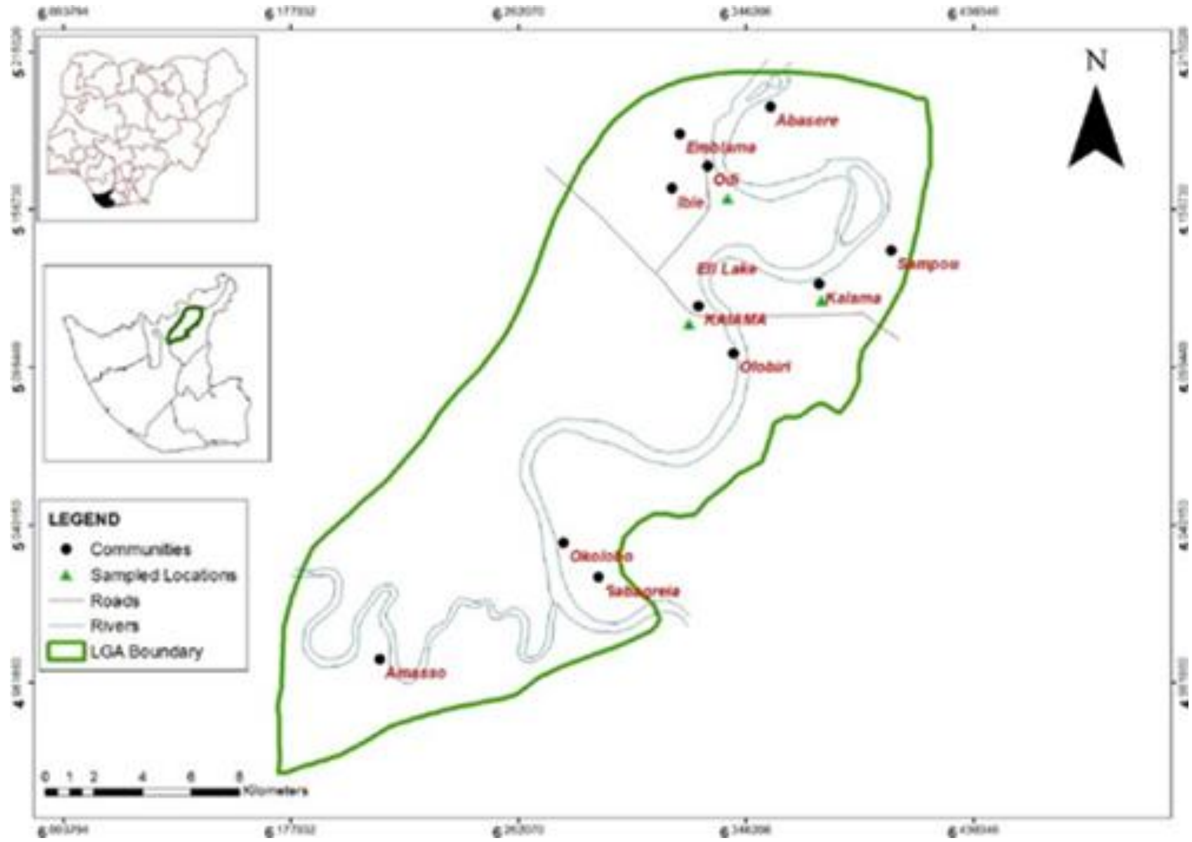

Figure 1: Map Showing the Study Locations adapted from Nwankwoala *et al*., 2016

Sample collection and preparation

The collection of water samples was done at intervals for two months between January and February 2024. The water sources include underground (borehole), River, Agbayai Lake, and dug-well. Samples were taken using 2-litre plastic containers and 200 cm^3 reagent bottles that had been thoroughly rinsed with deionised water before use. The collection process involved carefully immersing the sample containers in the flowing water and using aseptic techniques for the still water sources. The containers were sealed with snug-fitting corks and stoppers to prevent air bubbles from forming after collection. The samples were then placed in a refrigerator at 4 °C until analysis could be performed.

Physicochemical analysis

Physico-chemical assessments of pH, conductivity, temperature and turbidity were performed to identify factors that could influence the results obtained from the research. The method outlined by the American Public Health Association for the preparation and analysis of water samples was utilized for evaluating the physicochemical parameters in this investigation (APHA, 1998). The pH of the water samples was assessed alongside the temperature using a calibrated pH meter. Conductivity and total dissolved solids (TDS) were evaluated using a calibrated Hanna (4-in-1) conductivity meter. The turbidity of the water samples was measured with a Hach turbidimeter (Model 800). The biological oxygen demand (BOD) was assessed using the dilution method as per APHA 5210 B. The quantity of oxygen used over a specified duration (typically five days) corresponds to the level of organic matter in the original sample. The dissolved oxygen (DO) levels were initially measured using the Winkler Method, followed by incubation of the samples for five days at 20 °C. After five days, DO was measured again, and the BOD in mg/L was calculated.

Anions including sulphate, nitrate and phosphate were analysed using the Colorimetric technique with the UV-visible spectrophotometer (Hach DR 5000) at 420 nm, 410 nm and 680 nm respectively. Standard solutions and blanks were routinely processed to identify potential errors in the analytical methods. From the calibration graph, the corresponding concentration (in mg/L) was calculated

Digestion and heavy metals analysis in water

Heavy metals that were analysed are cadmium, lead, chromium, zinc, iron, copper, and manganese. The wet oxidation technique was employed to extract heavy metals from samples via digestion. A 5`0 mL aliquot of a thoroughly mixed water sample was measured into a

150 mL beaker. Thereafter, 5 mL of concentrated HNO_3 was added. The solution was heated on a hot plate until it nearly evaporated to dryness and allowed to cool. Another 5 mL of concentrated HNO_3 was added to the beaker, which was immediately covered with a watch glass. The heating continued with additional HNO_3 until light-coloured residue was obtained indicating that digestion was complete. A final addition of 1-2 mL of concentrated HNO_3 was made to the residue, which was then washed with distilled water. The mixture was filtered into a 100-mL volumetric flask to eliminate silicate and other insoluble materials. The solution was brought up to the mark with distilled water. It was stored in a 125-The solution was stored in a 125-mL polypropylene bottle for analysis with the Atomic Absorption Spectrophotometer (AAS) (Varian 220), which was used to detect various heavy metals in the samples with different heavy metal cathode lamps. To ensure the analytical method's reliability during digestion and sample preparation, quality control (QC) and blank samples were digested simultaneously with each set of samples and analyzed for appropriate elements using the same procedure (Gregg, 1989). Reference standards for this analysis were also sourced from established guidelines (WHO, 2009; NIS, 2015; USEPA, 2016).

Assessment of human health risk

The evaluation of health risks utilizes a framework suggested by the USEPA (Hadzi et al., 2015). Health risk evaluation includes examining how environmental pollutants affect health. These risks can be categorized into two types: Carcinogenic (CR) and non-carcinogenic (NCR) (USEPA, 2004). CR evaluate the probability of developing cancer due to long-term exposure to a pollutant or a mixture of pollutants. Conversely, NCR mainly addresses exposure and encompasses genetic and teratogenic impacts (Habib *et al*., 2020; Gade *et al*., 2021). The four water sources evaluated in this research serve as potential water sources for the local community, hence, heavy metals present in these sources mainly enter the body through ingestion and skin exposure. These are the key pathways for risk evaluation since residents drink the water and sometimes swim in the river, bathe, or are used for agricultural and other domestic purposes, thus increasing their risk of encountering toxic metals (Naveedullah *et al*., 2014). Thus, this research performs health risk assessments based on direct consumption and skin contact, which can be represented in Eqs. 1 and 2 with minor adjustments.

Equation 1

$$ADDing = \frac{(Cs \times IngR \times EF \times ED)}{(BW \times AT)}$$

Where ADDing refers to the average daily dosage taken via ingestion per kilogram of body weight (USEPA, 2011; Hadzi *et al*., 2015). Cs represents the concentration of harmful metals in drinking water (mg/L), InR denotes the ingestion rate over a specific period (L/day), ED indicates the exposure duration (years), which corresponds to the life expectancy of a typical Nigerian resident, EF signifies the exposure frequency (days/year), BW is the average body weight (kg), and AT is the averaging time calculated as ED x EF. To convert years into days, a factor of 365 days was applied. Consequently, the average daily dose for dermal exposure was computed using Equation 2.

Equation 2

$$ADDderm = (Cs \times SA \times SL \times ABS \times EF \times ED) / (BW \times AT)$$

Where ADDderm represents the typical daily dose received via dermal exposure, SA denotes the surface area of the skin that is exposed (cm^2), SL is the factor for water adherence to skin ($mg.cm^2$.event-1), ABS indicates the rate of dermal absorption, CF is the conversion factor for the volume for water (1 L/1000 cm^3), EF signifies the frequency of exposure (days/years), ED stand is the exposure duration (years), and BW is body weight (kg). AT is calculated by multiplying ED by EF.

Hazard quotient

The hazard assessment was conducted by assessing the calculated contaminant dose from ingestion and dermal exposure pathways and comparing them to the reference dose (RfD) to derive the hazard quotient (HQ) using Equation 3 provided below. The purpose of the hazard assessment is to determine if a substance presents an NCR to humans and to identify the conditions under which the identified risk may manifest (USEPA, 2003).

Equation 3

$$HQ = ADD/RfD$$

HQ = hazard quotient via ingestion or dermal contact and RfD = oral/dermal reference dose (mg/L/day).

Hazard index

The Hazard Index is calculated using Equation 4.

Equation 4

$$HI = \Sigma HQ$$

$$\Sigma ADD/RfD$$

Carcinogenic risks

The CR of the metal was calculated using Equation 5.

The Carcinogenic risk is determined based on lifetime exposure and represents the additional likelihood of a person developing cancer throughout their life due to total exposure to possible carcinogens. The lifetime daily exposure dose is computed using the equation below;

Equation 5

$$LADD = \frac{C \times EF}{AT} \times \left(\frac{CRchild \times EDchild}{BWchild} + \frac{CRadult \times EDadult}{BWadult}\right)$$

where; LADD= total average exposure dose through various pathways over a lifetime (mg/kg/d); average duration of exposure; EF = Frequency of exposure; CR = rate of intake (for oral and ingestion pathways; CR = InhR; for dermal contact pathways, CR = SA.SL.ABS); C represents concentration of heavy metal in water, while body weight for adults and children is 61.8 and 15 kg, respectively.

Equation 6

Rtotal= ΣR but

R= LADD x RF; therefore,

R= ΣLADD x SF

Where; Rtotal = total cancer risk, R = excess lifetime cancer risk; LADD = lifetime daily exposure dose; SF = slope factor.

Where LADDing and LADDderm signify the cancer risk associated with ingestion and skin contact routes, correspondingly, SF denotes the slope factor (mg/kg)/day. To illustrate the long-term cancer risk that the local community might face, the LADD values were computed for all seven metals.

Also, R is the excess cancer risk; Rtotal is the total cancer risk, which is the accumulative carcinogenic risk. It is expressed by multiplying the dose by the corresponding SF. Both R and Rtotal were calculated for Pb, Cr and Cd for the oral ingestion; Pb and Cr were calculated for the dermal exposures. SF for other contaminants is not available in the literature at the time of this write-up.

Data analysis

GraphPad Prism version 6.0 was utilized to perform the statistical evaluation of the data gathered from the study. The results were presented as Mean ± standard error. For the data derived from the analysis of the physicochemical parameters, a one-way analysis of variance was conducted at $P< 0.05$, and the Tukey HSD Test was applied to identify the source of the observed differences.

Table 1: Reference Values for Assessing Exposure to Heavy Metals in Water Samples (RAGS, 2004; Adesiyan *et al*., 2018)

Exposure factors		Values	
Symbols	**Definition (units)**	**Child**	**Adult**
IngR	Ingestion rate (mg/day)	200	100
EF	Exposure frequency (d/y)	350	350
ED	Exposure duration child (years)	6	24
BW	Body weight child (kg)	15	61.8
AT	Average time (days)	EDx365	EDx365
PEF	Particulate Emission Factor (m^3/kg)	$1.316x\ 10^9$	$1.316x\ 10^9$
InhR	Inhalation rate child(cm^3/day)	7.63	12.80
SA	Exposed surface area (cm^2/day)	2800	5700
SL	Skin Adherence factor ($(mgcm^2/day)^{-1}$)	0.2	0.07
ABS	Skin Absorption factor	0.001	0.001

Results

Physicochemical analysis

Table 2 presents the physicochemical characteristics of the analysed water samples including Underground, River, Agbayai Lake, and dug-well water in Odi and Kaiama communities situated in the Niger-Delta environment following the US EPA, WHO, and Nigerian Industrial standards. The pH of the samples was within the range of 7.2 to 7.8, signifying water conditions that range from neutral to alkaline which are within the standards of USEPA, NIS and WHO permissible limits. However, there is a significant difference between River water and the other water samples ($P<0.05$). The temperatures of the water samples ranged between 27.2 °C and 27.7 °C with no significant differences ($P=0.05$). TDS levels varied from 30.7 to 260 mg/L, with substantial differences underground, River, Agbayai, and dug-well water ($P<0.05$). The temperature and TDS levels were lower than the WHO standard. The conductivity level was highest in well water with 517 µS/cm while the least was found in underground water (61.2 µS/cm) with significant differences (P<0.05). The conductivity level of only the dug-well water was higher than the WHO standard but lower than the NIS. The turbidity of the studied water samples ranged from 5.15 NTU to 52.5 NTU which were higher than the WHO and Nigerian Industrial permissible standard. The dissolved oxygen (DO) level was in the range of 6.6 mg/mL in Agbayai Lake water to 8.3 mg/mL in River while the BOD level ranged from 0.94 mg/mL in Well water to 2.1 mg/mL in Agbayai Lake water with significant differences (P<0.05). The range for the chloride concentration in the study sites was between 42.2 and 5.14 mg/L with a significant difference (P<0.05) among the water samples. The concentration was 5.14 mg/L in underground water and 6.54, 10.3 and 42.2 mg/mL in River, Agbayai and dug-well water, respectively. The sulphate concentration level in underground water was 0.013 mg/L, Odi River water, 0.015 mg/L, Agbayai Lake water, 0.084 mg/L and dug-well water with 0.264 mg/L respectively with significant differences (P<0.05). The nitrate concentration ranged from 0.005 mg/mL in underground water to 0.019 mg/mL in dug-well water. While the phosphate concentration in underground water was less than 0.001 mg/mL, others ranged between 0.001 and 0.007 mg/L with significant differences (P<0.05). These values however were generally less than the WHO and Nigerian Industrial standard limit.

Heavy metals

Table 3 presents the average concentrations of heavy metals detected in the studied water samples. The average concentration of Fe in the Underground, Agbayai Lake, and dug-well water samples had similar values of <0.001 mg/mL while River water had 0.738 mg/mL average concentration which exceeded the standard limit set by USEPA and NIS but lower than the standard limit of WHO. The concentrations of Zn in the water samples had similar concentration levels of <0.001 mg/mL. The concentrations of Cu in River and Agbayai Lake water were similar, with <0.001 mg/mL. Cu concentration in underground water was 0.033 mg/mL while in dug-well water was 0.045 mg/mL. They were lower than the NIS, USEPA, and WHO standard limits. The average concentration of Cr in River water was highest at 0.008 mg/mL followed by 0.002 mg/mL in Agbayai Lake water while the underground and dug-well water had the same concentration level of <0.001 mg/mL. The concentrations in Pb are ranked in ascending order as follows: Agbayai Lake, <0.001 mg/mL > River, 0.016 mg/mL> Underground, 0.023 mg/mL> dug-Well water, 0.033 mg/mL. Notably, the average concentration of Pb in Underground, River, and dug-Well water surpassed the standard limits set by NIS, USEPA and WHO. The concentrations of Cd in the water samples had similar concentration levels of <0.001 mg/mL, lower than the standard limit set by USEPA, NIS, and WHO. Mn had a concentration of 0.047 mg/mL in dug-well water while the other water samples had the same concentration of >0.001 mg/mL, lower than the standard limit set by USEPA and NIS.

Table 2: Physicochemical Parameters for Water Samples from Different Sources

	Sample (Mean ± SEM)				Permissible limit		
Parameters	**Underground**	**River**	**Agbayai Lake**	**Dug-well**	**USEPA**	**WHO**	**NIS**
pH	7.40±0.07^{a}	7.8±0.02^{b}	7.20±0.04^{ac}	7.4±0.03^{a}	6.5-8.5	6.5-8.5	6.5-8.5
Temperature (ºC)	27.7±0.12^{a}	27.2±0.15^{a}	27.6±0.12^{a}	27.2±0.11^{a}	-	29	-
TDS (mg/L)	30.7±0.02^{a}	39.6±0.01^{b}	60.5±0.02^{c}	260±0.22^{d}	-	500	500
Conductivity (µS/cm)	61.2±0.02^{a}	78.4±0.01^{b}	121±0.06^{c}	517±0.01^{d}	-	500	1000
Turbidity (NTU)	18.3±0.01^{b}	52.5±0.01^{c}	18.3±0.01^{b}	5.15±0.01^{a}	-	5	5
DO (mg/L)	7.90±0.03^{b}	8.3±0.02^{c}	6.6±0.01^{a}	8.5±0.03^{d}	-	-	-
BOD (mg/L)	1.70±0.01^{c}	1.3±0.00^{b}	2.1±0.01^{d}	0.94±0.01^{a}	-	<5.0	-
Chloride (mg/L)	5.14±0.01^{a}	6.54±0.02^{b}	10.3±0.01^{c}	42.2±0.01^{d}	250	200	250
Sulphate (mg/L)	0.013±0.0^{a}	0.015±00^{b}	0.084±00^{c}	0.264±00^{d}	-	400	100

Nitrate (mg/L)	0.005±00[a]	0.006±00[a]	0.011±00[b]	0.019±00[c]	-	10	50
Phosphate (mg/L)	<0.001[a]	0.001±00[a]	0.004±00[b]	0.007±00[c]	-	1.00	-

Each value is expressed as mean ± standard error (n = 3). Different letters in each row indicate significant differences at P<0.05 according to the Tukey HSD Test.

Table 3: Levels (mg/L) of heavy metals in water samples collected from four distinct sources

	Sample				**Permissible limit**			**Dermal Permeability Coefficient (cm/h)**
Metal	**Underground**	**River**	**Agbayai Lake**	**Dug-well**	**USEPA**	**WHO**	**NIS**	
Fe	<0.001	0.738	<0.001	<0.001	0.30	1.00	0.30	1×10^{-3}
Zn	<0.001	<0.001	<0.001	<0.001	5.00	5.00	3.00	6×10^{-4}
Cu	0.033	<0.001	<0.001	0.045	1.00	2.00	1.00	1×10^{-3}
Cr	<0.001	0.008	0.002	<0.001	0.100	0.05	0.05	2×10^{-3}
Pb	0.023	0.016	<0.001	0.033	0.015	0.010	0.01	4×10^{-3}
Cd	<0.001	<0.001	<0.001	<0.001	0.005	0.005	0.003	1×10^{-3}
Mn	<0.001	<0.001	<0.001	0.047	0.050	-	0.2	1×10^{-3}

Human health risk assessment

Non-carcinogenic health risk

The assessment of heavy metal concentrations in water samples from four distinct sources for potential health risks associated with exposure to these substances showed that the ingestion exposure levels via ingestion (ADDing) in adults ranged from 0.0016 to 1.22, with a consistent value of 0.0016, 0.0016 to 0.069, 0.0016 to 31, 0.0016 to 0.05, 0.0016 to 0.0036, and 0.0036 to 0.073 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively. Similarly, the level of exposure through ingestion (ADDing) in children ranged from 0.013 to 10, 0.013 (same value for all samples), 0.013 to 0.58, 0.013 to 0.1, 0.013 to 0.42, 0.013 (same value for all samples), and 0.013 to 0.6 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively (Table 4). The observed dermal exposure (ADDderm) levels in adults ranged from 3.6E-05 to 4.6E-03, 3.6E-05 to 6.2E-05, 6.2E-05 to 2.8E-04, 1.2E-05 to 6.2E-05, 9.9E-05 to 1.6E-03, 6.2E-05 (same value for all samples), and 2.9E-04 to 1.6E-03 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively, while in children, they ranged from 3.57E-05 to 2.6E-02, 3.57E-05 to 3.6E-05, 3.57E-05 to 0.0016, 3.6E-05 to 2.9E-04, 5.7E-04 to 1.3E-02, 3.57E-05 to 3.6E-05, and 1.7E-03 to 1.3E-02 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively (Table 4). The exposure levels (ADDing) in adults varied from 0.0016 to 1.22, with a consistent value of 0.0016 across all samples, ranging from 0.0016 to 0.069 for Zn, from 0.0016 to 31 for Cr, from 0.0016 to 0.05 for Pb, from 0.0016 to 0.0036 for Cd, and from 0.0036 to 0.073 for Mn, respectively.

Table 4 also presents the hazard quotient ingestion (HQing) for adults which ranged from 0.0023 to 1.7, 0.0054 (same value for all samples), 0.041 to 1.74, 0.33 to 2.5, 0.046 to 1.44, 0.16 (same value for all samples), and 0.12 to 0.52, for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively. The HQ ingestion for children ranged from 0.018 to 14.3, 0.043 (same value for all samples), 0.32 to 14.4, 2.6 to 20.5, 0.37 to 12.1, 1.3 (same value for all samples), and 0.091 to 4.3, for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively. The HQ dermal (HQderm) values for adults vary from 0.000088 to 0.0065, 0.001 (same value for all samples), 0.0052 to 0.017, 0.21 to 1.03, 0.19 to 3.1, 3.19 to 6.2, and 0.16 to 0.89, for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively. Additionally, the HQderm values for a child were in the range of 0.000051 to 0.038, 0.00059 to 0.0006, 0.0029 to 0.13, 0.0006 to 4.8, 1.1 to 24.4, 3.6 (same value for all samples), and 0.91 to 7.1, for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively (Table 4).

Hazard Index (HI) oral values ranged from 0.89 in Agbayai Lake water to 5.15 in River water and 7.25 in Agbayai Lake water to 42.35 in River water for adults and children, respectively (Table 4). Moreover, the HI dermal values ranged from 7.80 in dug-well water to 10.39 in Agbayai Lake water, and 6.88 in Well water to 36.20 in River water for adults and children, respectively (Table 4).

Carcinogenic health risk (CR)

In the case of adults, the sum of average exposure dose through ingestion (LADDing) which represents the CR oral values fell in a range between 1.61E-06 and 1.18E-03, 1.61E-06 (same value for all samples), 1.61E-05 and 7.24E-05, 3.22E-05 and 2.58E-04, 2.41E-06 and 7.99E-05, 1.61E-06 (same value for all samples) and, 1.61E-06 and 7.57E-05 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively (Table 5). Additionally, the percentage LADDing indicated that Cu was the highest in Underground water, Fe was highest in the River, Cd was highest in Agbayai Lake, and Mn was highest in dug-well water (Figure 2). On the other hand, the sum of average exposure dose for dermal contact (LADDderm) values ranged from 1.61E-06 to 1.18E-03, 1.61E-06 (same value for all samples), 1.61E-05 to 2.58E-04, 2.41E-06 to 7.99E-05, 1.61E-06, and 1.61E-06 to 7.57E-05 for Fe, Zn, Cu, Cr, Pb, Cd, and Mn, respectively (Table 5). The percentage LADDderm indicated that Pb was highest in Underground water, Fe was highest in the River, Cr was highest in Agbayai Lake, and Pb was highest in dug-well water (Figure 3). The oral accumulative carcinogenic risk (Rtotal) values were 0.22, 0.7, 0.31, and 0.23 for Underground, River, Agbayai Lake, and dug-well water respectively, while the dermal accumulative Rtotal values were 8.77E-05, 2.97E-04, 6.68E-05, and 1.12E-04 for Underground, River, Agbayai Lake, and dug-well water, respectively.

Table 4: Evaluation of Non-carcinogenic Hazards to Human Health Linked to Heavy Metal Contamination in the Water Bodies of Odi and Kaiama

	Heavy Metals							
	Fe	**Zn**	**Cu**	**Cr**	**Pb**	**Cd**	**Mn**	**HI**
RfDing (mg/L/day)	0.7	0.3	0.04	0.005	0.035	0.01	0.14	
RfDderm (mg/kg/day)	$7.0X10^{-1}$	$6.0X10^{-2}$	$1.2X10^{-2}$	$6.0X10^{-5}$	$5.25X10^{-4}$	$1.0X10^{-5}$	$1.84X10^{-3}$	
Underground	**Adult**							
ADDing	$1.6X10^{-3}$	$1.6X10^{-3}$	$5.0X10^{-2}$	$1.6X10^{-3}$	$3.6X10^{-2}$	$1.6X10^{-3}$	$1.6X10^{-3}$	
ADDderm	$6.2X10^{-5}$	$6.2X10^{-5}$	$2.04X10^{-4}$	$6.2X10^{-5}$	$1.4X10^{-4}$	$6.2X10^{-5}$	$1.6X10^{-3}$	
HQing	$2.3X10^{-3}$	$5.4X10^{-3}$	1.26	$3.3X10^{-1}$	1.02	$1.6X10^{-1}$	$1.6X10^{-2}$	2.79
HQderm	$8.8X10^{-5}$	$1.0X10^{-3}$	$1.7X10^{-2}$	1.03	$2.7X10^{-1}$	6.19	$8.9X10^{-1}$	8.40
Underground	**Children**							
ADDing	$1.3X10^{-2}$	$1.3X10^{-2}$	$4.2X10^{-1}$	$1.3X10^{-2}$	$2.9X10^{-1}$	$1.3X10^{-2}$	$1.3X10^{-2}$	
ADDderm	$3.6X10^{-5}$	$3.6X10^{-5}$	$1.2X10^{-3}$	$3.6X10^{-5}$	$8.2X10^{-4}$	$3.6X10^{-5}$	$1.3X10^{-2}$	
HQing	$1.8X10^{-2}$	$4.3X10^{-2}$	10.6	2.6	8.4	1.3	$9.1X10^{-2}$	23.05
HQderm	$5.1X10^{-5}$	$5.9X10^{-4}$	$9.8X10^{-2}$	$5.9X10^{-1}$	1.6	3.6	6.9	12.79
River	**Adult**							
ADDing	1.22	$1.6X10^{-3}$	$1.6X10^{-3}$	$1.2X10^{-2}$	$2.5X10^{-2}$	$1.6X10^{-3}$	$1.6X10^{-3}$	
ADDderm	$4.6X10^{-3}$	$6.2X10^{-5}$	$6.2X10^{-5}$	$5.0X10^{-5}$	$9.9X10^{-5}$	$6.2X10^{-5}$	$1.6X10^{-3}$	
HQing	1.7	$5.4X10^{-3}$	$4.1X10^{-2}$	2.5	$7.1X10^{-1}$	$1.6X10^{-1}$	$1.2X10^{-2}$	5.15
HQderm	$6.5X10^{-3}$	$1.0X10^{-3}$	$5.2X10^{-3}$	$8.3X10^{-1}$	$1.9X10^{-1}$	6.2	$8.8X10^{-1}$	8.10
River	**Children**							
ADDing	10.0	$1.3X10^{-2}$	$1.3X10^{-2}$	$1.0X10^{-1}$	$2.0X10^{-1}$	$1.3X10^{-2}$	$1.3X10^{-2}$	
ADDderm	$2.6X10^{-2}$	$3.6X10^{-5}$	$3.6X10^{-5}$	$2.9X10^{-4}$	$5.7X10^{-4}$	$3.6X10^{-5}$	$1.3X10^{-2}$	
HQing	14.3	$4.3X10^{-2}$	$3.2X10^{-1}$	20.5	5.8	1.3	$9.1X10^{-2}$	42.35
HQderm	$3.8X10^{-2}$	$5.9X10^{-4}$	$3.0X10^{-3}$	4.80	1.10	3.60	7.10	16.64
Agbayai Lake	**Adult**							
ADDing	$1.6X10^{-3}$	$1.6X10^{-3}$	$1.6X10^{-3}$	3.1X10	$1.6X10^{-3}$	$1.6X10^{-3}$	$1.6X10^{-3}$	
ADDderm	$6.2X10^{-5}$	$6.2X10^{-5}$	$6.2X10^{-5}$	$1.2X10^{-5}$	$1.6X10^{-3}$	$6.2X10^{-5}$	$1.6X10^{-3}$	
HQing	$2.3X10^{-3}$	$5.4X10^{-3}$	$4.1X10^{-2}$	$6.2X10^{-1}$	$4.6X10^{-2}$	$1.6X10^{-1}$	$1.2X10^{-2}$	$8.9x10^{-1}$
HQderm	$8.8X10^{-5}$	$1.0X10^{-3}$	$5.2X10^{-3}$	$2.1X10^{-1}$	3.1	6.2	$8.8X10^{-1}$	10.39
Agbayai Lake	**Children**							
ADDing	$1.3x10^{-2}$	$1.3x10^{-2}$	$1.3x10^{-2}$	$2.6x10^{-2}$	$1.3x10^{-2}$	$1.3x10^{-2}$	$1.3x10^{-2}$	
ADDderm	$3.57x10^{-5}$	$3.57x10^{-5}$	$3.57x10^{-5}$	$7.2x10^{-5}$	$1.3x10^{-2}$	$3.57x10^{-5}$	$1.3x10^{-2}$	
HQing	$1.8x10^{-2}$	$4.3x10^{-2}$	$3.2x10^{-1}$	5.11	$3.7x10^{-1}$	1.3	$9.1x10^{-2}$	7.25

HQderm	5.1x10^{-5}	5.9x10^{-4}	2.9x10^{-3}	1.2	24.4	3.6	7.0	36.20
Dug-well	**Adult**							
ADDing	1.6x10^{-3}	1.6x10^{-3}	6.9x10^{-2}	1.6x10^{-3}	5.0x10^{-2}	1.6x10^{-3}	7.3x10^{-2}	
ADDderm	6.2x10^{-5}	6.2x10^{-5}	2.8x10^{-4}	6.2x10^{-5}	2.0x10^{-4}	6.2x10^{-5}	2.9x10^{-4}	
HQing	2.3x10^{-3}	5.4x10^{-3}	1.74	3.3x10^{-1}	1.44	1.6x10^{-1}	5.2x10^{-1}	4.20
HQderm	8.8x10^{-5}	1.0x10^{-3}	2.3x10^{-2}	1.03	3.9x10^{-1}	6.20	1.6x10^{-1}	7.80
Dug-well	**Children**							
ADDing	1.3x10^{-2}	1.3x10^{-2}	5.8x10^{-1}	1.3x10^{-2}	4.2x10^{-1}	1.3x10^{-2}	6.0x10^{-1}	
ADDderm	3.6x10^{-5}	3.6x10^{-5}	1.6x10^{-3}	3.6x10^{-5}	1.2x10^{-3}	3.6x10^{-5}	1.7x10^{-3}	
HQing	1.8x10^{-2}	4.3x10-2	14.4	2.6	12.1	1.3	4.3	34.76
HQderm	5.1x10^{-5}	6.0x10^{-4}	1.3x10^{-1}	6.0x10^{-4}	2.25	3.6	9.1x10^{-1}	6.88

Table 5: Assessment of Carcinogenic Risk to Human Health Associated with Heavy Metal Pollution in Odi and Kaiama Water Bodies

	Heavy Metals							
	Fe	Zn	Cu	Cr	Pb	Cd	Mn	**Rtotal**
LADDing								
Underground	1.2x10^{-1}	1.24x10^{-2}	4.10	6.21x10^{-3}	2.43x10^{-2}	1.86x10^{-1}	1.24x10^{-2}	2.2x10^{-1}
River	91.608	1.24x10^{-2}	1.24x10^{-2}	4.97x10^{-1}	1.69x10^{-2}	1.86x10^{-1}	1.24x10^{-2}	7.0x10^{-1}
Agbayai Lake	1.24x10^{-1}	1.24x10^{-2}	1.24x10^{-2}	1.24x10^{-1}	1.05x10^{-3}	1.86x10^{-1}	1.24x10^{-2}	3.1x10^{-1}
Dug-well	1.24x10^{-1}	1.24x10^{-2}	5.59	6.21x10^{-3}	3.48x10^{-2}	1.86x10^{-1}	5.83	2.3x10^{-1}
SF	NA	NA	NA	0.5	8.5x10^{-3}	15	NA	
LADDderm								
Underground	1.61x10^{-6}	1.61x10^{-6}	5.31x10-5	3.22x10^{-5}	5.55x10^{-5}	1.61x10^{-6}	1.61x10^{-6}	8.77x10^{-5}
River	1.18x10^{-3}	1.61x10^{-6}	1.61x10^{-6}	2.58x10^{-4}	3.86x10^{-5}	1.61x10^{-6}	1.61x10^{-6}	2.97x10^{-4}
Agbayai Lake	1.61x10^{-6}	1.61x10^{-6}	1.61x10^{-6}	6.44x10^{-5}	2.41x10^{-6}	1.61x10^{-6}	1.61x10^{-6}	6.68x10^{-5}
Dug-well	1.61x10^{-6}	1.61x10^{-6}	7.24x10^{-5}	3.22x10^{-5}	7.97x10^{-5}	1.61x10^{-6}	7.57x10^{-5}	1.12x10^{-4}
SF	NA	NA	NA	20	1.5	NA	NA	

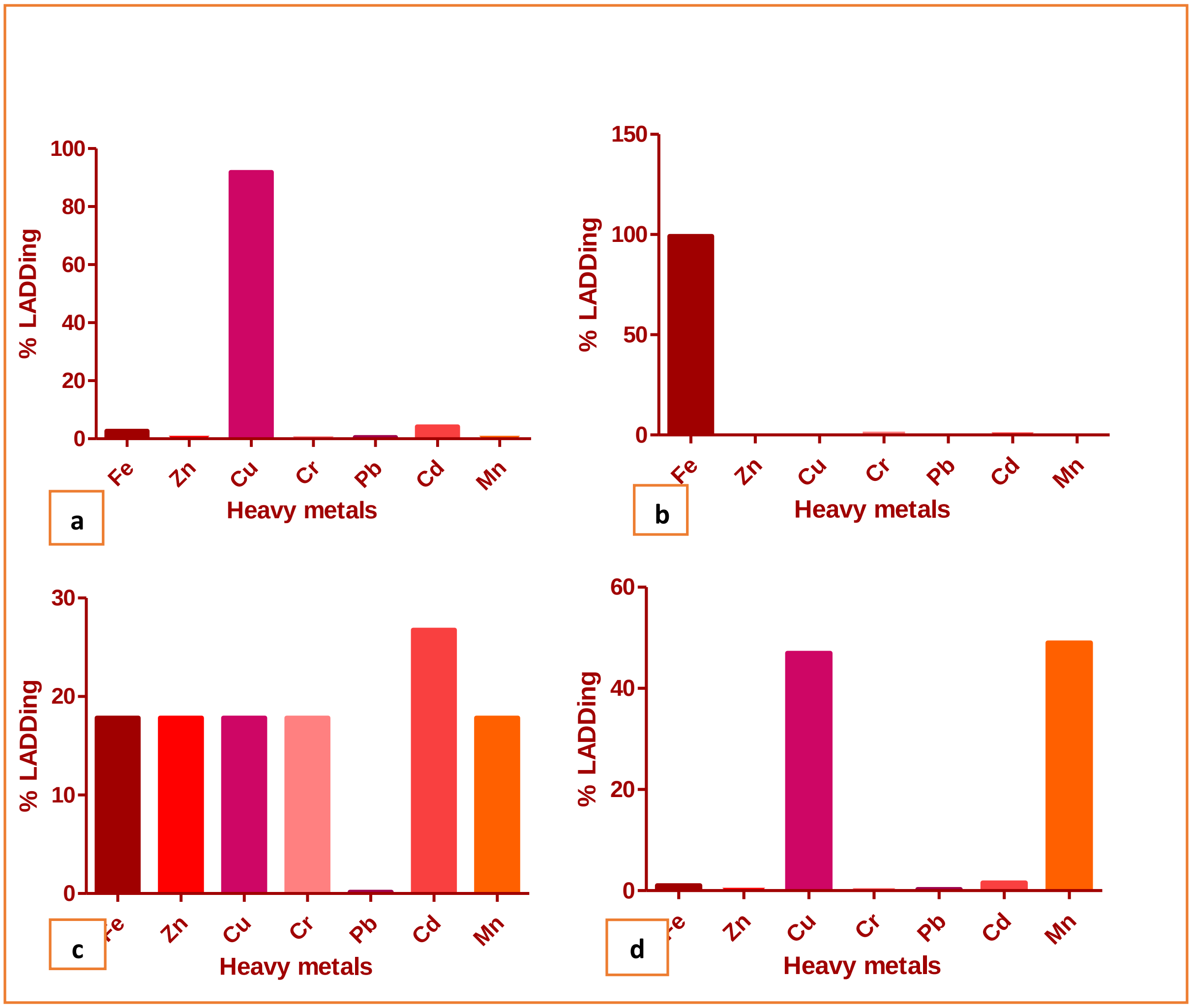

Figure 2: Percentage exposure dose through ingestion (LADDing) associated with heavy metal pollution in (a) Underground water (b) River water (c) Agbayai Lake water (d) Dug-well water

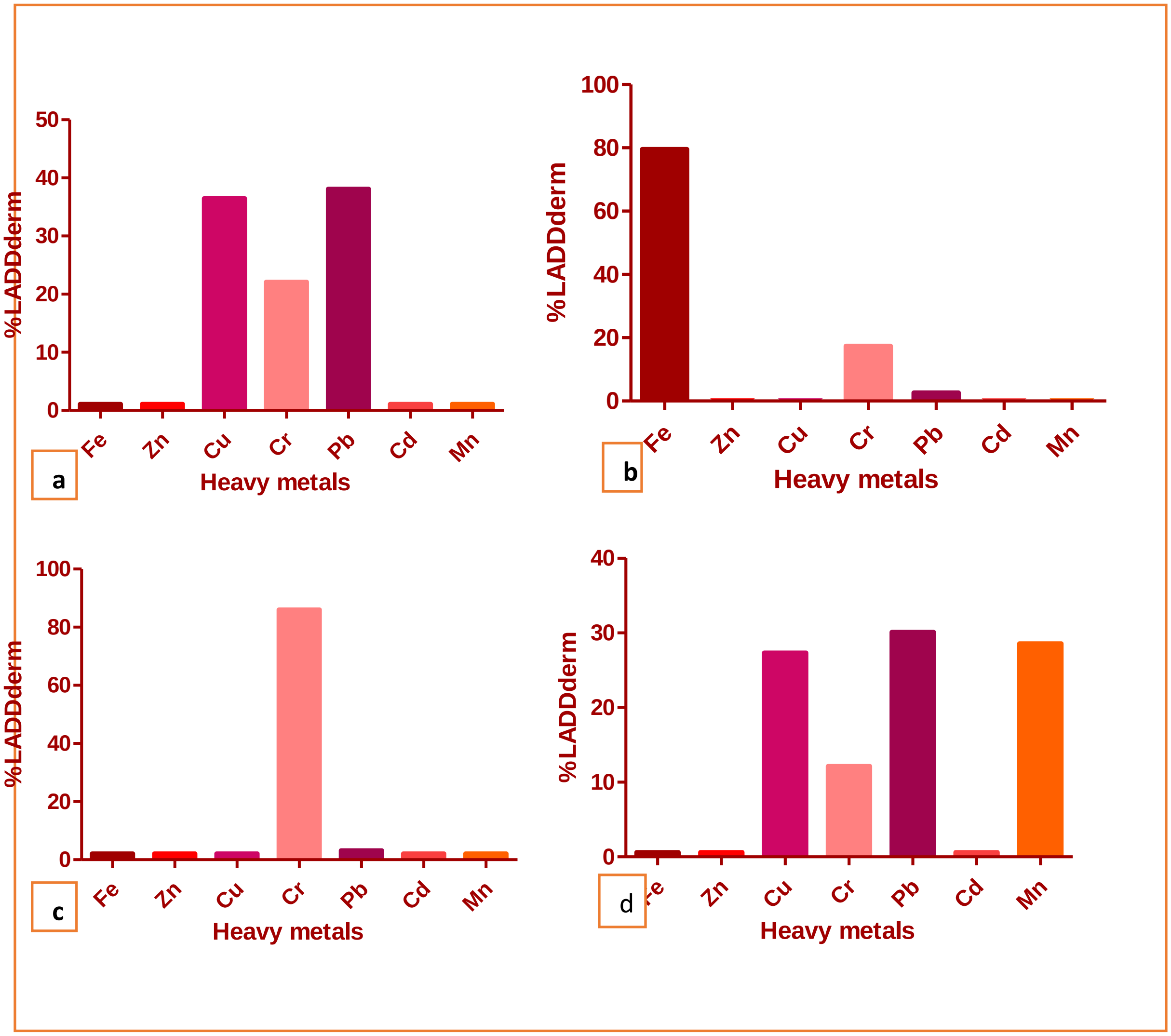

Figure 3: Percentage exposure dose through dermal contact (LADDderm) associated with heavy metal pollution in (a) Underground water (b) River water (c) Agbayai Lake water (d) Dug-well water

Discussion

The Niger Delta environment is characterized by various sources of toxic substances related to crude oil, exposing the average resident to these pollutants. Numerous legal and illegal operations involving metal chelates from various industries, along with the careless application of heavy metal-laden fertilizers and pesticides in farming areas (Adesiyan *et al*., 2018), as well as crude oil extraction, transportation, mining, theft, bunkering, and pipeline sabotage, lead to spills and flaring. This results in pollution of the soil and water, making these natural resources and the air considerably unsafe for living (Oyeyemi *et al*., 2024). Consequently, this research aimed to evaluate the primary water sources used by the inhabitants of the Odi and Kaiama communities within the Niger Delta environment, which include underground (borehole), river, lake, and dug-well water, focusing on their physicochemical properties, concentrations of heavy metals, and the health risks posed by the detected heavy metals.

Physicochemical variations in the water samples

The pH measurements indicate that the water samples taken from the chosen sites range from neutral to alkaline, aligning with the acceptable standards (USEPA, 2009; WHO, 2017). Conversely, Koinyan *et al*. (2013) performed a study in the Niger Delta region and found a pH range of 6.8-7.8, which is akin to the findings of the current study. In contrast, Tariwari and Bright (2015) discovered pH values of 5.24 and 4.72 in underground (borehole) water within the Niger Delta region. Nkansah *et al*. (2010) stated that pH values below 6.5 are regarded as excessively acidic for human consumption and can lead to health issues like acidosis, which may adversely affect the digestive and lymphatic systems of individuals. The toxicity levels of metals in aquatic environments are influenced by the pH level of the water body. When the pH decreases, the solubility of most metals increases, making them more accessible to aquatic life. The greater the acidity, the more soluble and mobile the metals are, increasing the likelihood of absorption and accumulation in organisms (Hadzi *et al*., 2015). Given the pH ranges found in this research, the water samples can be classified as neutral to alkaline, adhering to the NIS, WHO and USEPA drinking water quality standards of 6.5 to 8.5. The recorded temperature values in this study were below the WHO's limit of 29 °C for potable water. Temperature plays a critical role in aquatic ecosystems, influencing both water organisms and the physicochemical properties of water (Syed *et al*., 2022). Total dissolved solids refer to the number of substances that could not dissolve in the water. The levels of total dissolved solids depend on various factors, particularly nutrients such as nitrate, phosphate, and chloride (Tariwari & Bright, 2015), which are highlighted in the study outcomes. This study found that the concentration of dissolved solids tends to be lower in underground water while higher in dug-well water. This variance can be attributed to the underground water treatment before use, which reduces particulate matter through filtration. The conductivity measurements from underground, river, and Agbayai Lake water samples showed a relatively low salt or ion content, below the NIS and WHO's permissible limit for drinking water of 500 µs/cm. However, the conductivity of well water exceeded the WHO permissible limit, as reflected in the concentrations of chloride, sulphate, nitrate, and phosphate ions measured in this study. The WHO guideline for turbidity in drinking water is 5 NTU. The relatively elevated turbidity levels may be due to larger particles, such as organic matter and dissolved solids (Hadzi et al., 2015). Additionally, Akoto and Adiyiah (2007) found that high turbidity could indicate the presence of pathogens like bacteria, viruses, and parasites that can result in symptoms such as nausea, cramps, diarrhoea, and related headaches. In 2020, Ogbole and Oyelana reported a turbidity level of 10.3 NTU in the Sagbama River, which is located in the Niger Delta environment, along with the detection of high concentrations of faecal pathogens like *E. coli*, *Salmonella spp*., and *Vibrio cholera*. Therefore, the significantly higher turbidity levels of the river water sample in this study may suggest possible faecal contamination in the drinking water sourced from the river. The primary cause of this faecal contamination in the river stems from the practice of open defecation occurring in Odi and Kaiama by residents. Previous research has also reported the presence of faecal pathogens in surface water used for drinking (Eluma & Onaji, 2015; Akrong &Amu-Mensah, 2019). It is essential to control faecal contamination in drinking water systems and sources wherever it arises (WHO, 2017).

Heavy metals

The presence of heavy metals above allowable levels in drinking water can pose significant risks to communities where agricultural practices and metal-related human activities have occurred (Wu *et al*., 2019; Kumar *et al*., 2022). The concentrations of heavy metals found in the water samples varied greatly. The relatively low amounts of Cd and Zn indicate that their source may not be linked directly to mining efforts, as Cd can naturally occur alongside zinc and sulphide ores (Olatunji & Osibanjo, 2012). Nevertheless, long-term exposure to Cd can lead to serious health issues, including lung cancer, prostatic proliferative lesions, bone fractures, kidney dysfunction, and hypertension (Haidar *et al*., 2023). The elevated levels of Fe in river water could originate from natural geological processes or corroded iron materials carried by seasonal runoff due to illegal mining activities. Additionally, there are significantly high levels of Pb in underground, river, and dug-well water compared to the allowable limits established by US EPA and WHO. A related study noted that concentrations of Fe and Pb in the Sagbama River exceeded the allowable limits set by USEPA and WHO (Ogbole & Oyelana, 2020). Prolonged exposure to Pb is still prevalent and can lead to various health issues affecting the nervous system, as well as contributing to diabetes mellitus, impairing cognitive development, and causing heart disorders (Pizzol *et al*., 2010; Samuel *et al*., 2022).

Health risk assessment

The occurrence and spread of heavy metals in water samples and the pathway system might heighten human health risks through different exposure routes (oral and dermal). Evaluating human health hazards and risks includes estimating the kinds and degrees of adverse health effects that may arise in individuals when they come into contact with toxic substances (USEPA, 2004).

Non-carcinogenic health risk

The health risks related to non-carcinogenic heavy metal pollution for both children and adults in the analyzed water samples were assessed based on ingestion and dermal exposure routes. These exposure routes are the primary ways people come into contact with heavy metals in water bodies, particularly those using the water for drinking and domestic activities. The analysis of heavy metals in the water samples for potential adverse health impacts from exposure to these substances indicated that the ingestion exposure level (ADDing) of all the metals in the underground water for adults was below their respective RfDings. However, the exposure level of Cu was above the Rfding value. The ADDderm values (adult and child) of Cr, Pb, and Cd in underground water were above their respective RfDderms. The ADD values (ingestion and dermal) of Fe, Cd, Cr, Pb, and Mn in river water for both adults and children were above their respective RfDs. Additionally, the ADD values (ingestion and dermal) of Cr, Cd, and Pb in Agbayi Lake were above their respective RfDs for both adults and children. Similarly, the ADD values (ingestion and dermal) of Cu, Pb, Cd, Cr, and Mn in dug-well water were above their respective RfDs for both adults and children.

In the current study, the hazard quotient during ingestion (HQing) for Cu, Pb, and HQderm for Cr and Cd from underground water were higher than 1.0 in adults, whereas in children, HQing for Cr, Cu, Pb, Cd and HQderm for Pb, Cd, Mn surpassed 1.0. The HQing for Fe, Cr, and HQderm for Cd from River water were likewise above 1.0 in adults, while children showed HQing levels exceeding 1.0 for Fe, Cr, Pb, Cd and HQderm levels above 1.0 for Cr, Pb, Cd, Mn. Conversely, all HQing values for heavy metals in Agbayai Lake water were below 1.0; however, HQderm for Pb and Cd in adults were above 1.0. In children, HQing for Cr, Cd, and HQderm for Cr, Pb, Cd, and Mn from Agbayai Lake water exceeded 1.0. Additionally, HQing for Pb, Cu, and HQderm for Cr and Cd from dug-well water were above 1.0 in adults, whereas children had HQing levels above 1.0 for Cu, Cr, Pb, Cd, Mn and HQderm levels surpassing 1.0 for Pb and Cd. According to the risk assessment guidelines provided by USEPA, a hazard quotient (HQ) value greater than 1.0 indicates a significant likelihood of adverse health effects from exposure (Nkoom et al., 2013). The findings of this study suggest a heightened risk of health issues for residents relying on these water sources, particularly among children, due to generally higher HQing and HQderm levels observed in them compared to adults, with the potential for continuous accumulation if no action is taken. Communities that rely on these water sources for drinking or bathing may be at considerable risk for health problems related to high exposure to contaminants.

The hazard index (HI) serves as an important measure for evaluating the potential health risks associated with heavy metals found in the water bodies of Odi and Kaiama within the Niger Delta environment. It takes into account two exposure pathways, including ingestion and skin contact. The hazard quotients (HQs) for each heavy metal and exposure route are aggregated to determine the HI (Kumar *et al*., 2019). This thorough method offers a more comprehensive understanding of the collective health dangers related to heavy metal pollution in the water resources of the Niger Delta environment. The HI value is a critical measure for evaluating the overall health effects and safety of water sources in the region. It can be observed that the HI values for oral and dermal exposure for both adults and children exceeded safe limits (HI > 1) in the water samples, although the HI was below 1 in the water from Agbayai Lake for adults. The HI results indicate that children are more susceptible to heavy metal exposure through oral and dermal contact compared to adults.

Carcinogenic risks

Carcinogenic risks evaluate the likelihood of developing cancer due to prolonged exposure to a pollutant or a mix of contaminants. The acceptable range for carcinogenic risk set by the USEPA is between 1×10^{-6} and 1×10^{-4}. The LADDderm for all metals in the water samples fell within the permissible limits established by the USEPA. However, the LADDing for all metals in the water samples exceeded the allowable limit, which raises concerns about carcinogenic risks for the residents of Odi and Kaiama and their surrounding areas. This risk is particularly linked to exposure to heavy metals through ingestion. Heavy metals such as cadmium (Cd), chromium (Cr), and lead (Pb) are known to pose a greater potential for inducing cancer risk in humans. Consequently, a range of cancers may develop due to prolonged exposure to low levels of these toxic metals (Bawa-Allah, 2023). Extended exposure to Cd can adversely affect the kidneys and bones, while exposure to Cr may lead to skin issues. Even minimal exposure to Pb can have negative cognitive effects on children. The accumulated oral and dermal carcinogenic risk (Rtotal) values for Cd, Cr, and Pb underscore the long-term risks involved. Carcinogenic risk assessments further underline the urgency for water treatment measures to reduce long-term health impacts. Comparisons of the average concentrations of heavy metals in water bodies with drinking water standards previously discussed indicate that the levels of these heavy metals (Cd, Cr, and Pb) exceed permissible limits, potentially contributing to the associated human health risks observed (WHO, 2017). Similar findings were noted when assessing the heavy metal content in global water bodies, highlighting significant health risks to both children and adults linked to Cd, Cr, cobalt (Co), and nickel (Ni) in surface water bodies (Kumar *et al*., 2019).

Conclusion

The Niger Delta is situated along the Atlantic Ocean. The region is rich in inland water resources, which many local communities rely on for drinking and other household needs. A significant number of individuals in this population engage in commercial fish farming, making their livelihoods from fishing activities. The importance of reducing and managing pollution in water bodies, particularly surface waters, cannot be overstated. This current study represents a groundbreaking addition to the field as it is the first to provide an assessment of human health risks associated with heavy metals found in the water bodies of the examined locations. It is expected that the findings from this study will emphasize the necessity for both state and federal governments, along with relevant regulatory bodies, to collaborate effectively on controlling and managing heavy metal pollution in the Niger Delta's aquatic ecosystems. Implementing surveillance and monitoring systems is crucial for tracking and addressing pollution levels to avert public health and environmental catastrophes. It is essential to recognize that these assessments include assumptions and uncertainties that arise from data sources. Therefore, it is vital to continually monitor exposure levels and update risk assessments to protect the region's water resources and the health of its inhabitants.

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Declaration of Competing Interest
There are no known competing interests

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