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Health Risk Assessment of Heavy Metals in Water Sources from Selected Regions in Yola North, Adamawa State, Nigeria

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Abstract

Access to clean drinking water is essential for sustainable development and human health, but heavy metal contamination poses a significant threat. This study assessed health risks linked to heavy metals in drinking and household water sources in Yola North. Water samples from surface water (Benue River), groundwater (wells and boreholes), and tap water were analysed for physicochemical properties and heavy metal content. The average daily dosage (ADD), hazard quotient (HQ), and hazard index were estimated to assess the non-carcinogenic risk (HI) and carcinogenic risk (LCR) of heavy metals from the study water sources. The physicochemical properties of water samples showed pH values within WHO limits, with temperature ranging from 23°C to 32°C, turbidity within acceptable levels, electrical conductivity varying significantly, and total dissolved solids generally meeting WHO standards. The levels of cadmium (Cd) and lead (Pb) exceeded WHO guidelines in all water samples, with the highest concentrations found in tap water (90 µg/L Cd) and surface water (210 µg/L Pb). There were considerable non-carcinogenic hazards indicated by the HQ and HI values for Pb and Cd via ingestion exceeding the threshold of 1. The LCR estimates revealed carcinogenic risks from Cd exposure in all water sources and elevated cancer risk from arsenic in surface water and tap water. Across all sources, lead presented a tolerable

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cancer risk. The study emphasises how critical it is to implement mitigation plans and other measures to address heavy metal contamination in the area's water sources.

Keywords: Carcinogenic, Heavy metals, Risk, Toxicity, Water contamination

INTRODUCTION

Access to safe drinking water is a fundamental human right and a prerequisite for sustainable development (United Nations (UN), 2010). However, this crucial resource is increasingly threatened by various contaminants, including heavy metals. Heavy metals are naturally occurring elements with high atomic weights and densities greater than 5 g/cm^3. While some are essential for human health in trace amounts, others are highly toxic even at low concentrations (Briffa, Sinagra, & Blundell, 2020). Their persistence in the environment and ability to bioaccumulate pose significant risks to human health and ecosystem integrity (Wahiduzzaman, Islam, Sikder, & Parveen, 2022).

Anthropogenic activities such as industrial processes, mining, agricultural practices and improper waste disposal are the primary sources of heavy metal contamination in water sources (Akhtar, Syakir Ishak, Bhawani, & Umar, 2021). These activities release heavy metals into the environment, where they can leach into soil and eventually pollute surface and groundwater resources. Additionally, natural weathering of rocks and minerals can also contribute to heavy metal levels in water (Kapoor & Singh, 2021). The extent of heavy metal contamination varies considerably across geographical regions, depending on local geology, industrial activities and water management practices (Mukherjee, Singh, & Singh, 2021). However, the issue is particularly concerning in developing countries, where inadequate infrastructure and lax environmental regulations often exacerbate the problem (Jehan et al., 2020).

Exposure to heavy metals can occur through various pathways, including ingestion of contaminated water and food, inhalation of dust particles and dermal contact (Briffa et al., 2020). The severity of health effects depends on several factors, including the specific metal, its concentration, duration of exposure and individual susceptibility. However, even low-level exposure to certain heavy metals can have detrimental consequences for human health (Wong, Roberts, & Saab, 2022). Some of the most common health effects associated

with heavy metal exposure include neurological disorders leading to cognitive impairment, memory loss and behavioural problems (Vázquez Cervantes et al., 2023); cardiovascular diseases linked to an increased risk of heart disease, stroke and other cardiovascular ailments (Sevim, Doğan, & Comakli, 2020); kidney dysfunction (Jalili et al., 2021); cancer (Parida & Patel, 2023); and developmental and reproductive issues (Dutta, Gorain, Choudhury, Roychoudhury, & Sengupta, 2022).

Nigeria, like many developing countries, faces significant challenges in ensuring access to safe drinking water. According to the FMWR, NBS, and UNICEF (2020) nearly 42 million Nigerians lack access to safe drinking water. This situation is further compounded by the growing threat of heavy metal contamination in water sources. Previous studies have reported elevated levels of various heavy metals, including lead, cadmium, arsenic and chromium, in water sources across different regions of Nigeria (Adefemi & Awokunmi, 2010; Eyankware & Obasi, 2021; Izah, Chakrabarty, & Srivastav, 2016; Raji, Ibrahim, & Ehinmidu, 2010). These findings raise concerns about the potential health risks faced by millions of Nigerians who rely on these contaminated water sources for their daily needs.

Yola North, located in Adamawa State, Nigeria, is an area of particular concern due to its unique geological setting and potential sources of heavy metal contamination. The presence of mining activities, industrial facilities and agricultural practices in the surrounding areas raises concerns about the potential for heavy metal leaching into water sources (Vincent et al., 2022). Additionally, the limited access to safe drinking water alternatives for the population further increases their vulnerability to exposure. Given the potential health risks associated with heavy metal contamination in water sources and the limited data available for Yola North, this study aims to conduct a comprehensive health risk assessment of heavy metals in various water sources used for drinking and domestic purposes in the area.

METHODS

Sampling Area

The study area for the assessment of health risk associated with heavy metals in water sources was Yola North, located in Adamawa State, northeastern Nigeria. Yola North (9°16'N, 12°25'E) is a semi-arid region with a tropical continental climate marked by discernible dry and brief wet seasons (Abdul, Tashikalma, Maurice, & Shittu, 2017). The dry season spans from November to April, while the wet season occurs from May to

October, with an average annual rainfall of approximately 900 mm (Chukwuneke et al., 2022). The region's topography is predominantly flat, with an elevation about 215 meters above sea level (Aliyu et al., 2023). The region is drained by the Benue River, a significant tributary of the Niger River, along with its associated tributaries, which play essential roles as water sources for domestic and agricultural.

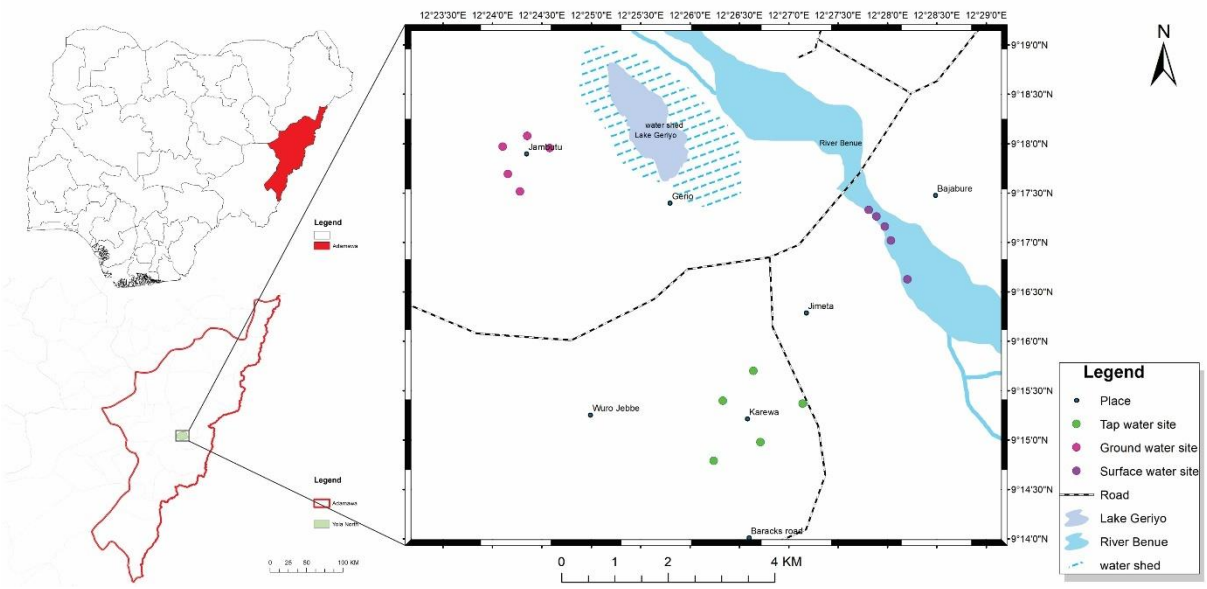

Figure 1: Map of Yola North showing water bodies and the sampling location

Water Sample Collection

Water samples were procured from three regions within the Yola region s delineated in Figure 1, representing the major water sources utilized by local communities. Surface water samples were collected from the Benue River (9°17'13.956"N, 12°27'57.312"E) in five replicates. Samples were collected approximately 1 meter from the riverbank, at 30 cm depth below the surface. Ground water samples were collected from boreholes and wells situated in the Jambutu community (9°18'4.644"N, 12°24'22.716"E). Five replicate samples were collected directly from five different wells. Tap water samples were obtained from the Karewa residential area (9°15'21.492"N, 12°26'43.008" E), where the municipal water supply is primarily sourced from the state waterboard.

Physiochemical Parameters

The physiochemical parameters analysed in this study included pH, temperature, total dissolved solids (TDS), electrical conductivity and turbidity. The pH of the water samples was determined using a calibrated digital pH meter (Wagtech pH meter, model CP 1000,

Singapore) following method described by Walter (1961). The temperature of the water samples was measured *in situ* using a digital thermometer (Bio Abron student mercury thermometer, model AP-942MSA110). Turbidity was determined using a nephelometric turbidity meter (Wagtech model: WE140JMP Kit 1) according to method described by Walter (1961). Electrical conductivity and TDS were determined using a calibrated conductivity meter (Wagtech, H198311) following method described by Walter (1961). For TDS determination, the conductivity meter was set to TDS mode, which calculated the TDS value based on the measured electrical conductivity and a predetermined conversion factor.

Determination Of Heavy Metals

Water Digestion

Water sample digestion was carried out using standard methods (1998). Five water sample digestions were conducted. Each sample, measured at 100 mL, was placed into separate 250 mL conical flasks. Concentrated nitric acid (HNO_3) was then added to each flask. Additionally, 15 mL of a ternary acid mixture containing 20 mL of concentrated $HClO_4$, 50 mL of concentrated HNO_3, and 50 mL of concentrated H_2SO_4 was introduced to each water sample. The samples underwent digestion in a block digester within a fume hood for a duration of 24 minutes. Following digestion, the solutions were allowed to cool before the addition of distilled water. Subsequently, the solutions were filtered into 100 mL Pyrex volumetric flasks using Whatman No. 42 filters with a pore size of 9 μm. Finally, distilled water was added to fill the volumetric flasks. These prepared solutions were stored for subsequent analysis of heavy metals using an atomic absorption spectrophotometer.

Atomic Absorption Spectrophotometric Analysis (AAS)

The concentrations of heavy metals in the digested water samples were determined using an atomic absorption spectrophotometer (210 VGP model) according to standard methods (1998). The digested water samples were taken into the air-acetylene flame of the AAS instrument. The absorption of light by the atomized metal atoms was measured at specific wavelengths corresponding to each metal. The absorbance values were then compared with the calibration curves prepared from the standard solutions.

Assessment of Human Health Risks Associated with Heavy Metal Exposure

In this study, we evaluate the non-carcinogenic human health risks posed by heavy metals through ingestion (HQ_{ing}) and dermal contact (HQ_{derm}). The hazard quotient (HQ), as per the methodology outlined by Yang et al. (2018) was used to ascertain potential health hazards. A HQ exceeding 1 indicates a significant hazard, whereas a HQ below 1 suggests minimal risk. The heavy metals considered in this assessment were subjected to risk evaluations.

The determination of HQ_{ing} and HQ_{derm} risks involved a stepwise process detailed in accordance with the guidelines provided by the United States Environmental Protection Agency (1986). The average daily dose (ADD) for both ingestion (ADD_{ing}) and dermal exposure (ADD_{derm}) was estimated using the following formulas:

$$ADD_{ing} = \frac{C \times IR \times FE \times ED}{Bw \times AT} \quad (1)$$

$$ADD_{derm} = \frac{C \times SA \times Kp \times FE \times ET \times ED \times CF}{Bw \times AT} \quad (2)$$

Where, C = average concentration of heavy metals; IR = ingestion rate, set at 2 litres per day (L/day) for adults; FE = frequency of exposure, established 350 days per year (2004); ED = exposure duration, considered to be 70 years for adults; BW stands for the Body Weight, established at 70 kilograms (kg) for adults; AT denotes the Average Exposure Time, calculated as 365 days per year multiplied by 70 years for adults; SA represents the Skin Surface Area, for adults set at 18,000 cm^2; Kp signifies the Dermal Coefficient of Permeability for each heavy metal, as provided by Saleem, Iqbal, and Shah (2019); ET indicates the Exposure Time during Bathing, set at 0.25 hours/day; and CF denotes the Unit Conversion Factor, established at 0.001 L/cm^3.

The non-carcinogenic risk was evaluated by calculating the HQ for both ingestion and dermal exposure using the formula:

$$\mathrm{HQ} = \frac{ADD}{RfD} \quad (3)$$

Where ADD represents the average daily dosage obtained from the aforementioned equations and RfD (mg/kg/d) denotes the oral reference doses for each heavy metal as provided Miletić, Lučić, and Onjia (2023) which is shown in Table 1.

Table 1: The values utilized for Reference Dose (RfD) and Carcinogenic Slope Factor (CSF) in this study.

Metal	**RfD**$_{ing}$ (mg/kg/d)	**RfD**$_{derm}$ (mg/kg/d)	**CSF**$_{ing}$	**CSF**$_{derm}$
Cd	1×10^{-4}	1×10^{-5}	0.38	6.3
As	3×10^{-4}	1.23×10^{-4}	1.5	1.5
Cr	3×10^{-3}	6×10^{-5}	0.5	41.0
Pb	3.5×10^{-3}	5.25×10^{-4}	0.0085	0.042
Cu	4×10^{-2}	1.2×10^{-2}	–	–
Mg	–	–	–	–
Mn	140×10^{-3}	1.8×10^{-3}	–	–
Fe	7.0×10^{-1}	7.0×10^{-1}	–	–

Source: Miletić et al. (2023)

Non-carcinogenic health risks

The non-carcinogenic health risks from ingestion and dermal exposure to heavy metals were calculated using the hazard index (HI) formula:

$$HI = \sum HQ = HQ_{ing} + HQ_{derm} \quad (4)$$

HI > 1 indicates potential non-carcinogenic risk, while HI ≤ 1 indicates no significant health risks (Saleem et al., 2019).

Carcinogenic Risk Assessment

The lifetime cancer risk (LCR) was estimated to determine the health risk posed by carcinogenic heavy metals. This estimation was carried out by calculating the cumulative life cancer risk rating as described by the United States Environmental Protection Agency (2004) using the formula:

$$\text{LCR} = \left(ADD_{ing} + ADD_{derm}\right) \times \text{CSF} = \sum \text{cancer risk} = cancer\ risk_{ing} + cancer\ risk_{derm} \quad (5)$$

In this formula, the Carcinogenic Slope Factor (CSF) (refer to Table 1) is a specific value assigned to each metal for the two exposure pathways, as described by Miletić et al. (2023).

Where, LCR < 10^{-6}: No carcinogenic risk; LCR > 10^{-4}: High cancer risk; LCR between 10^{-6} and 10^{-4}: Acceptable risk

Statistical Analysis

The data was presented as mean ± S.E.M. RStudio (R Core Team, 2017) and SPSS V27 were used to analyse all of the data.

RESULTS

Physicochemical Properties

The physicochemical quality of the water samples is presented in Table 2. The pH values ranged from 6.78 to 7.00, falling within the WHO recommended range for drinking water (2022). The Ground water sample had the lowest pH of 6.78, indicating mildly acidic conditions, while the Surface water was neutral. Water temperature varied from 23°C to 32°C. Turbidity met the WHO guideline value in all samples. Electrical conductivity ranged widely from 43.3 µS/cm in tap water to 554 µS/cm in Ground water. Total dissolved solids were between 0.02-0.3 g/L.

Table 2: Physicochemical Constituents in surface, ground and tap water.

Parameters	Surface water	Ground water	Tap	WHO limit
pH	7.00 ± 0.23	6.78 ± 0.31	6.88 ± 0.27	6.5 - 8.5
Temperature (℃)	32.00 ± 0.32	23.00 ± 0.40	27 ± 0.13	-
Turbidity (NTU)	0.97 ± 0.03	0.62 ± 0.02	0.59 ± 0.01	<0.5
Conductivity (µS/cm)	106 ± 1.43	554 ± 1.23	43.30 ± 0.85	-
Total dissolved solids (g/L)	0.05 ± 0.00	0.30 ± 0.01	0.02 ± 0.00	<0.3

Values are expressed as mean ± standard error of mean, n=5.

Heavy Metal Constituents

Heavy metal analysis of the water samples is shown in Table 3. Cadmium (Cd) concentrations were highest in the tap water (90 ± 1.44 µg/L) and Surface water (80 ± 0.96 µg/L), exceeding the World Health Organization (WHO) (2022) limit of 3 µg/L and NESREA (2014) limit of 10 µg/L. Ground water Cd was 50 ± 1.05 µg/L. Arsenic (As) ranged from 3 ± 0.05 µg/L to 10 ± 0.15 µg/L, with the tap water meeting the WHO

standard of 10 µg/L. Chromium was detected only in Surface water at 0.7 ± 0.01 µg/L, below the WHO threshold of 5 µg/L. Lead was several times higher than the WHO limit of 10 µg/L in all samples, from 160 ± 2.08 µg/L to 240 ± 3.60 µg/L. Copper and magnesium levels met guidelines in the samples. Manganese also met the WHO limit of 100 µg/L, ranging from 10 ± 0.25 µg/L to 80 ± 1.52 µg/L across sources. Iron was only detected in Surface water at 10 ± 0.12 µg/L, well below the threshold of 300 µg/L.

Table 3: Heavy Metal constituent of some water samples.

Heavy Metals	Surface Water	Ground Water	Tap Water	WHO	NESREA limit
Cd (µg/L)	80 ± 0.96	50 ± 1.05	90 ± 1.44	3	10
As (µg/L)	10.21 ± 0.15	4.02 ± 0.08	3.00 ± 0.05	10	50
Cr (µg/L)	0.70 ± 0.01	0.30 ± 0.01	0.00 ± 0.00	5	1
Pb (µg/L)	210 ± 4.62	240 ± 3.60	160 ± 2.08	10	10
Cu (µg/L)	125 ± 2.38	109 ± 1.42	124 ± 2.11	50	1
Mg (µg/L)	0 ± 0.00	0 ± 0.00	0 ± 0.00	-	4×10^4
Mn (µg/L)	80 ± 1.52	10 ± 0.25	50 ± 1.25	100	50
Fe (µg/L)	10 ± 0.12	0 ± 0.00	0 ± 0.00	300	50

Values are expressed as mean ± standard error of mean, n=5; WHO: World Health Organization; NESREA is The National Environmental Standards and Regulations Enforcement Agency

Health Risk Assessment

The health risks were evaluated by calculating ADD and HQ (Table 4). For Surface water, the HQ exceeded 1 for Cd (HQ=21.92) and Pb (HQ=1.64) via ingestion, indicating risks. Other metals had HQ values less than 1, suggesting minimal risks. In Ground water, high hazard HQs were found for Cd (HQ=13.70) and Pb (HQ=1.88) from ingestion. Tap water posed the highest risk from Cd (HQ=24.66) ingestion. The HI exceeded 1 for Cd and Pb in all samples (Table 5), confirming risks. HI was highest for Cd in Tap water (24.66) and Surface water (21.92). Other metals had HI less than 1 indicating minimal potential for non-cancer effects. The LCR provide cancer risk estimation over 70 years. LCR exceeded 1 x 10^-4 for Cd in all samples, suggesting high cancer risk. Arsenic posed risk in Surface (LCR = 4.11 x 10^-4) and tap water (LCR = 1.23 x 10^-5). Lead showed acceptable risk between 1 x 10^-6 and 10^-4. Other metals had negligible cancer risks.

Table 4: Results showing the ADD and the HQ values from the domestic water for adults.

Metals	**ADD_{ing} (mg/kg/-d)**	**ADD_{derm} (mg/kg/-d)**	**HQ_{ing}**	**HQ_{derm}**
Surface water				
Cd	2.19×10^{-3}	1.63×10^{-7}	21.92	0.00327
As	2.74×10^{-4}	4.09×10^{-8}	0.91	0.00033
Cr	1.92×10^{-5}	2.86×10^{-9}	0.01	0.00005
Pb	5.75×10^{-3}	1.72×10^{-6}	1.64	0.00327
Cu	3.42×10^{-3}	2.55×10^{-7}	0.09	0.00002
Mg	0.00	0.00	0.00	0.00
Mn	2.19×10^{-3}	1.63×10^{-7}	0.02	0.00009
Fe	2.74×10^{-4}	2.04×10^{-8}	0.00	0.00
Ground water				
Cd	1.37×10^{-3}	1.02×10^{-7}	13.7	0.00204
As	1.10×10^{-4}	1.63×10^{-8}	0.37	0.00013
Cr	8.22×10^{-6}	1.23×10^{-9}	0.00	0.00002
Pb	6.58×10^{-3}	1.96×10^{-6}	1.88	0.00374
Cu	2.99×10^{-3}	2.23×10^{-7}	0.07	0.00002
Mg	0.00	0.00	0.00	0.00
Mn	2.74×10^{-4}	2.04×10^{-8}	0.00	0.00001
Fe	0.00	0.00	0.00	0.00
Tap (Treated) water				
Cd	2.47×10^{-3}	1.84×10^{-7}	24.66	0.00368
As	8.22×10^{-5}	1.23×10^{-8}	0.27	0.0001
Cr	0.00	0.00	0.00	0.00
Pb	4.38×10^{-3}	1.31×10^{-6}	1.25	0.00249
Cu	3.40×10^{-3}	2.53×10^{-7}	0.08	0.00002
Mg	0.00	0.00	0.00	0.00
Mn	1.37×10^{-3}	1.02×10^{-7}	0.01	0.00006
Fe	0.00	0.00	0.00	0.00

HQ > 1: High risk; HQ < 1: Minimal risk.

Table 5: Results showing the HI and LCR values from domestic water sources for adults.

Metal	HI	Interpretation	LCR	Interpretation
Surface water				
Cd	21.92	Significant risk	8.34×10^{-4}	Carcinogenic risk
As	0.91	No significant risk	4.11×10^{-4}	Carcinogenic risk
Cr	0.01	No significant risk	9.71×10^{-6}	No carcinogenic risk
Pb	1.64	Significant risk	4.90×10^{-5}	Acceptable risk
Cu	0.09	No significant risk	–	–
Mg	0.00	–	–	–
Mn	0.02	No significant risk	–	–
Fe	0.00	No significant risk	–	–
Ground water				
Cd	13.70	Significant risk	5.21×10^{-4}	Carcinogenic risk
As	0.37	No significant risk	1.64×10^{-5}	Acceptable risk
Cr	0.00	No significant risk	4.16×10^{-6}	No carcinogenic risk
Pb	1.88	Significant risk	5.60×10^{-5}	Acceptable risk
Cu	0.07	No significant risk	–	–
Mg	0.00	–	–	–
Mn	0.00	No significant risk	–	–
Fe	0.00	No significant risk	–	–
Tap (Treated) water				
Cd	24.66	Significant risk	9.38×10^{-4}	Carcinogenic risk
As	0.27	No significant risk	1.23×10^{-5}	Acceptable risk
Cr	0.00	No significant risk	0.00	No carcinogenic risk
Pb	1.25	Significant risk	3.73×10^{-5}	Acceptable risk
Cu	0.08	No significant risk	–	–
Mg	0.00	–	–	–
Mn	0.01	No significant risk	–	–
Fe	0.00	No significant risk	–	–

HI > 1: Potential non-carcinogenic risk, HI ≤ 1: No health risks, LCR < 1×10^{-6}: No carcinogenic risk LCR > 1×10^{-4}: Carcinogenic risk LCR 1×10^{-6} to 1×10^{-4}: Acceptable risk

DISCUSSION

The analysed water samples from Surface water, Ground water and tap sources in the Yola region showed pH, temperature, turbidity, conductivity and total dissolved solids levels compliant with World Health Organization drinking water guidelines, indicating acceptable baseline quality (2022). However, some variations existed between sampling locations. A previous study in India found similar minor differences in physicochemical levels between ground and surface sources attributed to local environmental conditions (Sarkar, Pal, & Islam, 2022). Although no immediate health concerns emerged, alterations could signify changing land use patterns or early contamination issues in the region (Du et al., 2020). Ongoing monitoring is advisable to track any emerging water quality issues that could necessitate interventions.

While the water supplies had reasonable physicochemical qualities, the detection of heavy metals above regulatory limits poses contamination and health issues for local communities depending on these sources. In particular, cadmium (Cd) and lead (Pb) occurred at concentrations substantially exceeding the WHO thresholds of 3 µg/L and 10 µg/L, respectively (2022). Cadmium is highly toxic upon accumulation in bodily tissues, with excessive intake linked to kidney dysfunction, osteoporosis and cancer (Onakpa, Njan, & Kalu, 2018). Lead has pronounced neurocognitive impacts, especially during developmental stages and also affects the renal, cardiovascular, immune and reproductive systems (Debnath, Singh, & Manna, 2019). Though some background presence naturally arises from mineral weathering and leaching, the levels found suggest additional anthropogenic inputs to the water systems. Rapid urbanization and industrial development in the region may have elevated discharge from metal product manufacturing, fossil fuel processing, battery disposal and various chemical applications (Khan et al., 2022). Sewage contamination or agricultural runoff are other possible delivery routes that call for source investigations and management efforts (Onakpa et al., 2018).

The average daily doses (ADD) of metal intake through drinking and skin contact were converted into HQ to quantify non-cancer risks for local populations utilizing the water sources. Cadmium and lead showed hazard levels greatly surpassing the threshold of 1 for toxic effects via oral ingestion exposure (2004). Cadmium posed the most severe risk, with HQs up to 25 times higher than the limit in one sample. Research documents that daily exposure to cadmium above safety margins elicits accumulation in bodily tissues over years,

resulting in kidney dysfunction, bone fragility and potentially irreversible impairments (Satarug, 2018). Lead also indicated pronounced hazards from drinking contaminated water, congruent with studies confirming neurocognitive declines in children and cardiovascular impacts across age groups above trace exposure levels (Dignam, Kaufmann, LeStourgeon, & Brown, 2019).

Combining the aggregate ingestion and dermal threats, the hazard indices (HI) substantially exceeded action levels for cadmium and lead (HI>>1), but not other detected metals. This again highlights the priority risks attributing to these two metals entering area water supplies. The cancer risk analysis echoed similar patterns, with cadmium showing likelihoods of developing disease from lifelong contaminated water use vastly surpassing the 1 in 100,000 risk threshold used in regulatory guidelines (2004). Lead posed lesser but still potentially unacceptable cancer risks between 1 in 10,000 to 1 in 100,000.

CONCLUSION

The analysis of water quality and heavy metal contamination in Yola North metropolis revealed some risk issues for local communities dependent on these resources. The physical and chemical screening indicates acceptable baseline conditions, meeting criteria for domestic use and human consumption. However, high levels of cadmium and lead exceeding health standards by up to 30-fold or more emerged as priority hazards, especially relating to ingestion as the main exposure route. The calculated health risks underscore elevated threats of non-cancer and cancer outcomes above regulatory thresholds in individuals utilizing the affected water supplies over long durations.

Author's Contribution

HS: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft. HS, RS, RMA: Writing - Review & Editing, Supervision, Project administration. WNB: Investigation, Formal analysis, Writing - Review & Editing, Data curation, Visualization.

Conflict-Of-Interest Disclosure

The authors assert that they have no conflicts of interest to declare.

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