

Health Risk Assessment of Heavy Metal Contamination in Water Sources at Michael Okpara University of Agriculture

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Abstract: This study evaluates the concentrations of heavy metals in water sources at Michael Okpara University of Agriculture and their associated health risks using Average Daily Intake (ADI), Hazard Index (HI), and Incremental Life Cancer Risk (ILCR) models. A total of 15 water samples were collected from five different locations within the university using acid-washed polyethylene bottles. The samples were analyzed using Atomic Absorption Spectroscopy (AAS) to determine the concentrations of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni), and lead (Pb). The measured concentrations ranged from 0.015–0.052 mg/L for As, 0.006–0.0173 mg/L for Cd, 0.075–0.127 mg/L for Co, 0.0077–0.015 mg/L for Cr, 0.0142–0.031 mg/L for Ni, and 0.0035–0.006 mg/L for Pb. Compared to regulatory standards, As and Cd concentrations exceeded the WHO limit of 0.01 mg/L and 0.003 mg/L, respectively, in multiple locations, posing significant health concerns. The ADI results showed that As had the highest dermal exposure value ($5.43E-08$ mg/kg/day), while Cr exhibited the highest ingestion exposure ($4.28E-09$ mg/kg/day). HI values for Cr ($5.22E-03$) and As ($4.90E-04$) suggest potential non-carcinogenic health risks, particularly through dermal absorption. ILCR analysis identified As as the most carcinogenic contaminant ($1.04E-07$), significantly surpassing the acceptable risk threshold of $1.0E-06$. Site 2 exhibited the highest heavy metal contamination levels, aligning with elevated health risk assessments. These

findings emphasize the need for water treatment interventions, enhanced regulatory oversight, and community awareness to mitigate contamination risks and safeguard public health.

Keywords: Heavy metals, water contamination, health risk assessment, hazard index, cancer risk

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1.0 Introduction

Water is essential for sustaining life, supporting industries, and facilitating agricultural and domestic activities. Approximately 70% of the Earth's surface is covered by water, but only 2.5% is freshwater, and of that, nearly 75% is locked in glaciers and ice caps, leaving a mere 1% accessible in lakes, rivers, and soils (Silva, 2017). The growing global population and increased industrialization have exacerbated freshwater demand, further straining limited resources. Access to safe drinking water is crucial for public health, as contaminated water is a leading cause of disease outbreaks (Rehman & Fatima, 2018). The link between waterborne diseases and contaminated water sources was recognized even before the scientific advancements of the 19th century.

Nigeria, like many developing nations, faces significant challenges related to water quality and accessibility. Rapid population growth, urban expansion, and industrial activities have contributed to environmental degradation, thereby increasing the risk of water contamination (Adelekan & Ogunde, 2012). Borehole water serves as a primary drinking water source for many Nigerian communities due to its natural filtration properties. In fact,

boreholes contribute over 50% of the global drinking water supply (Adelekan & Ogunde, 2012). However, contamination from industrial waste, agricultural runoff, and leachate from landfills threatens the safety of borehole water. Several studies have reported the presence of heavy metals in borehole water, which can pose significant health risks when ingested over time (Idris *et al.*, 2013; Kelepertzis, 2014; Izah *et al.*, 2016).

Heavy metals, such as arsenic (As), cobalt (Co), cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb), occur naturally in the Earth's crust and may enter groundwater through geogenic and anthropogenic processes (Khlifi & Hamza-Chaffai, 2011). Their presence in water is of concern due to their bioaccumulation potential and toxicity. Chronic exposure to heavy metals has been linked to various health complications, including neurological disorders, kidney damage, and carcinogenic effects (Alberts *et al.*, 2002). The contamination levels of borehole water depend on several environmental factors, including rainfall patterns, water table depth, percolation rates, and soil composition (Adelekan & Ogunde, 2012).

Despite various studies on water contamination, limited research has focused specifically on the heavy metal composition of borehole water in Michael Okpara University of Agriculture, Umudike, and its potential health risks. Existing studies on groundwater quality in Nigeria have largely concentrated on urban areas, leaving a knowledge gap in understanding the risk exposure of university communities that depend on borehole water. Additionally, previous studies have not adequately addressed the cumulative health risks posed by multiple heavy metals through comprehensive risk assessment methodologies such as the Target Hazard Quotient (THQ) and Hazard Index (HI).

This study aims to assess the levels of heavy metals in borehole water within Michael



Okpara University of Agriculture, Umudike, using Flame Atomic Absorption Spectrophotometry (FAAS). Additionally, it evaluates the potential health risks associated with metal exposure through ingestion and inhalation using risk assessment models. The findings of this study will provide essential data for regulatory authorities and contribute to the ongoing efforts to ensure water safety in Nigerian universities and beyond.

2.0 Materials and Methods

2.1 Study Area

This research was conducted at Michael Okpara University of Agriculture, Umudike (MOUUAU), and the surrounding Umudike area, located in Umuahia, southeastern Nigeria. Umuahia, the capital of Abia State, is positioned between latitudes 5.5250°N and 7.4922°N and longitudes 2.70°E and 4.35°E, covering an approximate area of 3,577 km². This includes 2,798 km² of land and 779 km² of water. The city lies between Owerri to the west and Enugu State to the east and is recognized as one of the fastest-growing and most populous cities in southeastern Nigeria. It serves as an economic hub with industrial activities generating significant waste. The region exhibits a humid climate, a short dry season, and diverse ecosystems, including tropical vegetation, rivers, creeks, and lagoons. Umudike, a prominent locality within Ikwuano Local Government Area (LGA), hosts MOUUAU and various small-scale enterprises. The extensive human activities in this region pose potential environmental risks, particularly to drinking and household water sources, necessitating continuous monitoring and assessment.

2.2 Water Sample Collection and Preparation

A total of fifteen borehole water samples were systematically collected from the study area, with three replicates taken from each borehole. The specific coordinates for each collection point are presented in Table 4. The samples were stored in pre-sterilized plastic containers to prevent contamination. Each sample was

securely sealed and transported to the laboratory under controlled conditions. Upon arrival, the samples were transferred to desiccators for stabilization before undergoing screening for microbial contamination. Additionally, the samples were analyzed for heavy metal content to assess their suitability for consumption.

2.3 Heavy Metal Analysis

The collected water samples were digested and analyzed for heavy metals using the procedure established by Yahaya et al. (2016). Each sample was placed in a pre-cleaned 100-mL beaker, to which 25 mL of analytical-grade aqua regia (HNO₃/HCl, 3:1) and 5 mL of 30% hydrogen peroxide (H₂O₂) were added. The mixture was subjected to digestion at 80°C until complete homogenization was achieved. The digested solution was then allowed to cool and subsequently filtered using Whatman No. 42 filter paper into a 50-mL volumetric flask, which was then diluted with deionized water. The filtrate was analyzed for the presence of copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and zinc (Zn) using a UNICAM 969 atomic absorption spectrophotometer.

2.4 Microbial Analysis

Microbial analysis of the water samples was conducted using Brock's membrane filtration technique to determine the total bacterial count. A sterile cellulose membrane filter was used to filter 100 mL of each water sample, and the filter was then placed on a nutrient agar plate. The plates were incubated at 35°C for 24 hours, after which bacterial colonies were counted using a colony counter. The same technique was applied to determine coliform counts. Additionally, a two-step enrichment technique was used to enhance microbial growth detection. The filters containing bacteria were first placed on an absorbent pad saturated with lauryl tryptose broth and incubated at 35°C for two hours. Subsequently, the filters were transferred to an M-Endo-saturated pad and incubated for an additional 22 hours. The



presence of sheen colonies was carefully observed and recorded.

2.4 Human Health Risk Assessment

2.4.1 Risk Assessment Methodology

The relationship between toxic metal concentrations and their potential health risks was evaluated using human health risk assessment models developed by the United States Environmental Protection Agency (USEPA, 2004, 2007). The Risk Assessment Information System (RAIS) (USEPA, 2004) was utilized alongside toxicological profiles from the USEPA's Integrated Risk Information System (IRIS) (Orosun et al., 2020; Orosun, 2021; USEPA, 2007) and the Agency for Toxic Substances and Disease Registry (ATSDR, 2007).

The assessment commenced with the calculation of the average daily intake (ADI) of each metal. Both ingestion and dermal exposure pathways were considered in determining potential toxic element exposure. The acceptable daily intake (mg/kg/day) for non-carcinogenic risk was computed using the following equations, as defined by USEPA (2001).

For the ingestion pathway, the ADI was calculated using Equation 1:

$$ADI_{ing-water} = \frac{C_w \times IngR_w \times EF \times ED}{BW \times AT} \quad (1)$$

where $ADI_{ingestion}$ is the average daily intake of heavy metals through water consumption (mg/kg/day), C_w is the concentration of heavy metals in water, BW represents body weight (kg), ED is the duration of exposure in years, $IngR_w$ is the ingestion rate of water (L/day), EF is the exposure frequency (days/year), and AT is the averaging time (days). For dermal exposure, the ADI was calculated using equation 2

$$ADI_{ing-water} = \frac{C \times SA \times KP \times AF \times ABS \times ET \times EF \times ED}{BW \times AT} \quad (2)$$

where SA is the skin surface area exposed (cm^2), KP is the skin permeability constant, AF represents the adherence factor, ABS is the

absorption fraction, and ET is the exposure time.

3.2 Carcinogenic and Non-Carcinogenic Risk Assessment

To assess non-carcinogenic risk, the Target Hazard Quotient (HQ) was calculated using Equation 3:

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

where ADI represents the chronic daily intake of the contaminant, and RfD is the oral reference dose of the metal (USEPA, 2001). A hazard quotient greater than 1 indicates a significant risk of adverse health effects, while an HQ below 1 suggests minimal risk (Rinklebe et al., 2019). The Hazard Index (HI) was then obtained by summing the individual HQ values for all metals using Equation 4:

$$HI = \sum HQ \quad (4)$$

Based on the classification system of the International Agency for Research on Cancer (IARC) and the World Health Organization (WHO), heavy metals such as Pb, Cd, Co, Ni, As, and Cr are recognized as potential human carcinogens. Carcinogenic risk assessment was performed using the Incremental Lifetime Cancer Risk (ILCR) model, as expressed in equation 5:

$$ILCR = ADI \times SF \quad (5)$$

where $ILCR$ denotes the lifetime probability of developing cancer due to prolonged exposure to contaminated water, ADI is the average daily intake (mg/kg/day), and SF is the carcinogenic slope factor ($mg/kg/day$)⁻¹. Elevated $ILCR$ values indicate heightened cancer risk, while values within regulatory thresholds suggest an insignificant risk.

2.5 Exposure Parameters and Toxicological Data

Tables 1, 2, and 3 present the standard values used in the health risk calculations, including exposure factors, reference doses (RfD), and carcinogenic slope factors (SF) for various heavy metals, based on established literature (USEPA, 2001; Orosun et al., 2020; Isinkaye, 2018). These parameters were used to quantify



potential health risks associated with metal contamination in the study area.

3.0 Results and Discussion

Heavy metals are significant pollutants in water bodies due to their potential toxicity, persistence, and bioaccumulation in aquatic ecosystems. The present study assessed the concentrations of selected heavy metals, namely Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Nickel (Ni), and Lead (Pb), across five sampling locations. The results are presented and discussed in relation to regulatory limits set by the World Health Organization (WHO), United States Environmental Protection Agency (USEPA),

and the European Commission for the Environment (ECE).

3.1 Heavy Metal Concentrations in Water Samples

Table 1 presents the concentrations of six heavy metals—Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Nickel (Ni), and Lead (Pb)—in water samples collected from five different sites. The table also includes the geographical coordinates (latitude and longitude) and elevation of each sampling location. The observed variations in heavy metal concentrations across the five sites suggest differences in pollution sources, geological factors, and hydrological conditions affecting water quality.

Table 1: Concentrations of Heavy Metals in Water Samples (ppm)

Site	Latitude	Longitude	Elevation (m)	As	Cd	Co	Cr	Ni	Pb
Site 1	5.476605	7.541130	376	0.054	0.0027	0.1133	0.0103	0.0617	0.0014
Site 2	5.477228	7.533025	365	0.059	0.028	0.130	0.0123	0.0063	0.0055
Site 3	5.477308	7.531888	360	0.0527	0.0237	0.1287	0.016	0.0243	0.0183
Site 4	5.481600	7.541680	397	0.0457	0.0273	0.1073	0.0167	0.0407	0.0019
Site 5	5.480685	7.542013	380	0.04667	0.0047	0.1563	0.0183	0.02267	0.0016

Arsenic concentrations range from 0.0457 ppm (Site 4) to 0.059 ppm (Site 2), with an average of approximately 0.0512 ppm across all sites. These values significantly exceed the WHO permissible limit of 0.01 ppm, indicating arsenic contamination in the water sources. Site 2 recorded the highest concentration of arsenic, which may be attributed to anthropogenic sources such as industrial discharge, pesticide use, or natural arsenic-bearing minerals in the region. The relatively lower concentration at Site 4 could suggest either dilution effects due to elevation (397 m) or lower arsenic leaching in that specific location. The trend for the concentration of arsenic explained above is illustrated by a 3-D model shown in Fig. 1 below.

Cadmium levels varied from 0.0027 ppm (Site 1) to 0.028 ppm (Site 2). While most sites exhibited cadmium concentrations below the WHO limit of 0.03 ppm, Site 2 and Site 4 recorded levels close to this threshold, suggesting potential risks. Cadmium is a toxic metal known to originate from industrial effluents, battery waste, and agricultural runoff. The significantly low value at Site 1 suggests minimal industrial or agricultural impact in that area. However, the high concentrations at Sites 2 and 4 may be due to localized contamination, possibly from mining activities or atmospheric deposition. Similar information is shown in Fig. 2.

As shown in the Table and also demonstrated by Fig. 3, cobalt concentrations ranged from 0.1073 ppm (Site 4) to 0.1563 ppm (Site 5), with an overall mean of 0.127 ppm. There are no specific regulatory limits for cobalt in drinking water, but its presence at elevated levels can have adverse effects on human health. The highest cobalt concentration at Site 5 suggests possible leaching from



geological formations rich in cobalt-bearing minerals or contamination from metal industries.

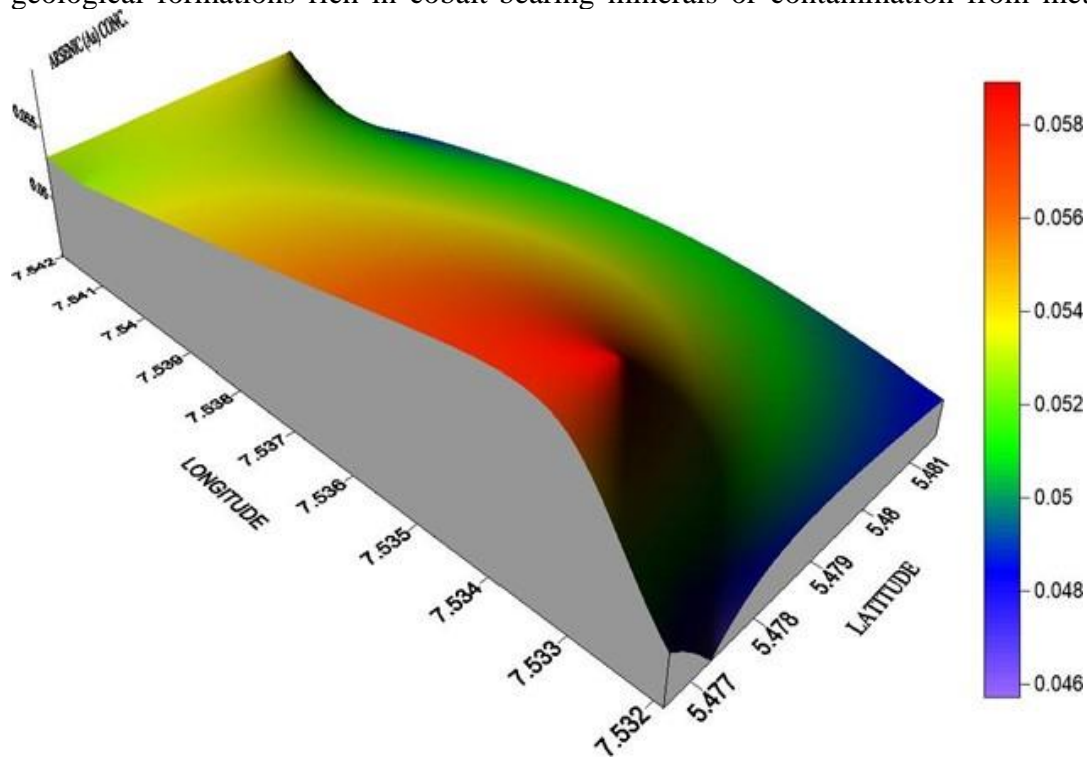


Fig. 1: 3D model of Arsenic (As) Concentration representation with respect to study area

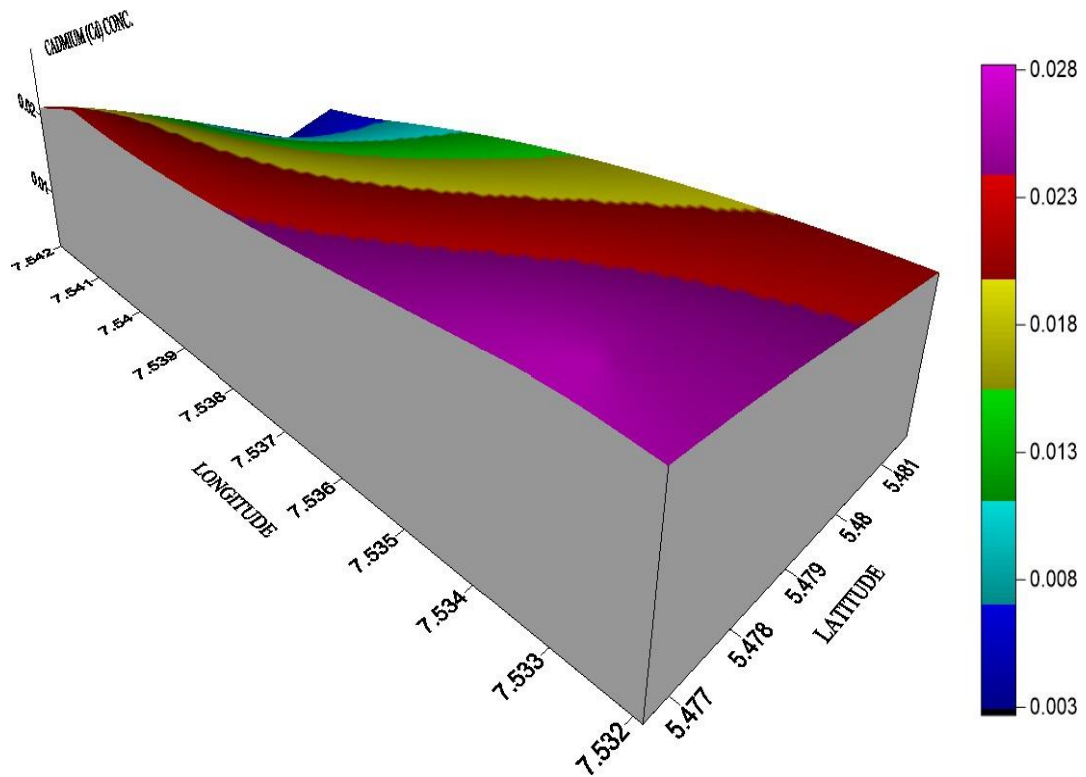


Fig. 2: 3D model of Cadmium (Cd) Concentration representation with respect to study area



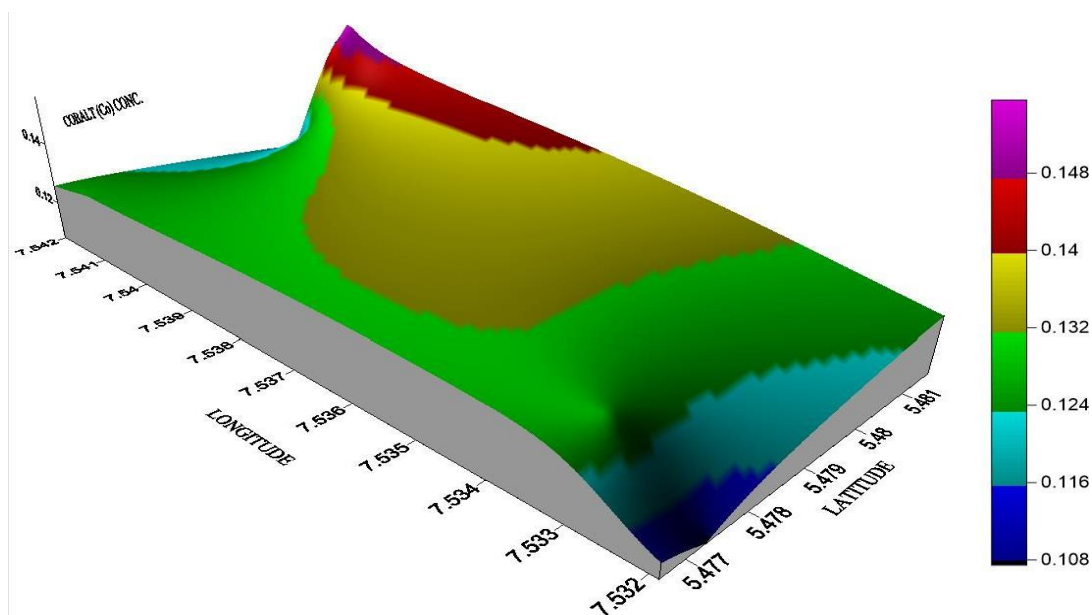


Fig. 3: 3D model of Cobalt (Co) Concentration representation with respect to study area

The relatively lower cobalt levels at Site 4 indicate site-specific variations in cobalt Chromium levels (Fig. 4) were lowest at Site 1 (0.0103 ppm) and highest at Site 5 (0.0183 ppm), with an average concentration of 0.0147 ppm. These values remain well within the WHO guideline of 0.05 ppm, indicating no immediate concern for chromium

distribution, which could be influenced by groundwater flow patterns.

contamination. However, the gradual increase in chromium concentrations from Site 1 to Site 5 suggests an increasing influence of potential pollution sources, possibly industrial effluents or naturally occurring chromium deposits.

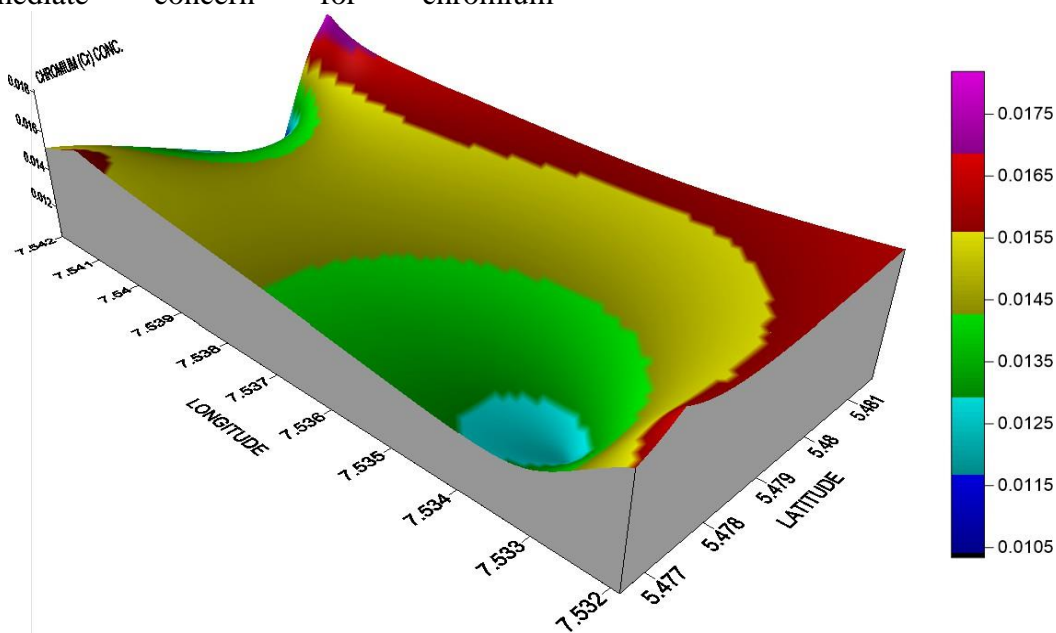


Fig. 4: 3D model of Chromium (Cr) Concentration representation with respect to study area



Nickel concentrations ranged from 0.0063 ppm (Site 2) to 0.0617 ppm (Site 1) as shown in Fig. 5. The WHO permissible limit for nickel in drinking water is 0.07 ppm, meaning none of the sites exceed this threshold. However, Site 1 recorded the highest nickel concentration,

suggesting localized contamination, possibly from industrial activities or geological weathering. The lowest value at Site 2 could be due to dilution effects or lower nickel-bearing minerals in that region.

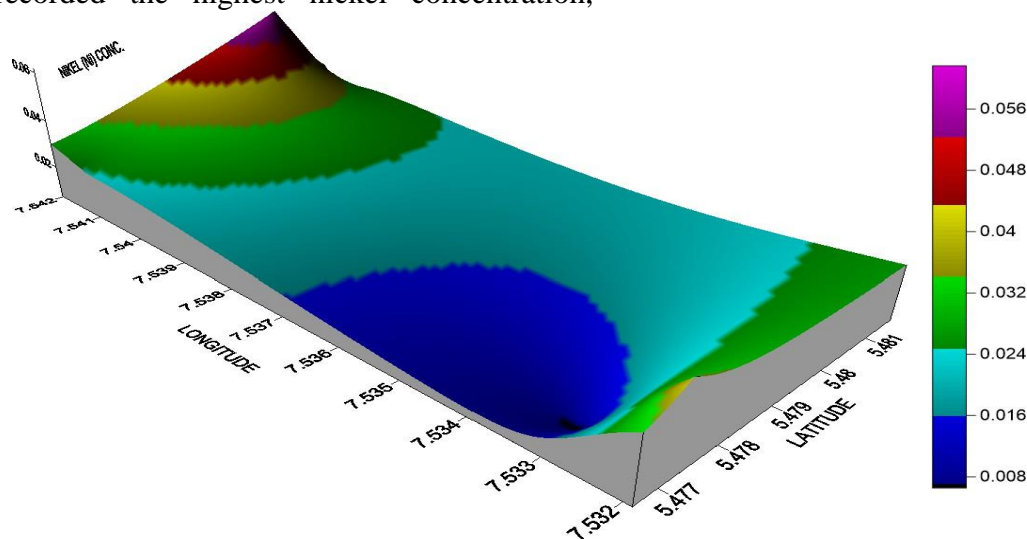


Fig. 5: 3D model of Nickel (Ni) Concentration representation with respect to study area

Lead levels (which is also indicated by Fig. 6) varied from 0.0014 ppm (Site 1) to 0.0183 ppm (Site 3). While most sites recorded lead concentrations below the WHO limit of 0.01 ppm, Site 3 exceeded this threshold, indicating potential lead contamination. This could be due

to industrial discharges, lead-containing pipes, or vehicular emissions depositing lead into nearby water sources. The lower lead concentrations at other sites suggest minimal contamination, possibly due to lower anthropogenic influence or effective dilution processes.

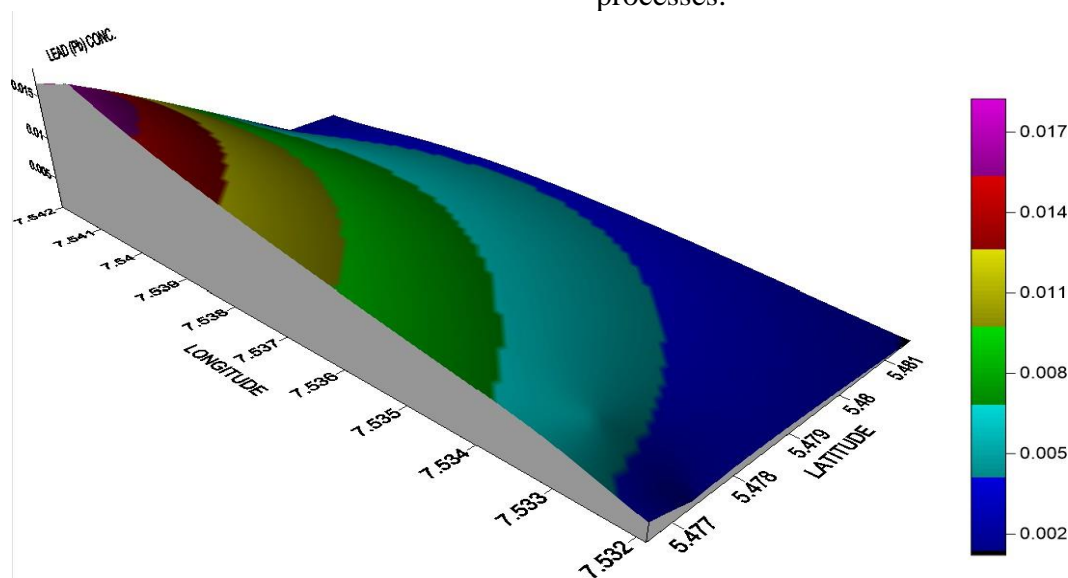


Fig. 6: 3D model of Lead (Pb) Concentration representation with respect to study area



The observed differences in heavy metal concentrations among the five sampling sites can be attributed to several factors. Geographical influence played a significant role, as sites located at higher elevations, such as Site 4 at 397 meters, generally exhibited lower concentrations of certain metals like arsenic and cobalt. This trend is likely due to reduced runoff accumulation in elevated areas. Anthropogenic activities also contributed to the variations, with Site 2 displaying the highest levels of arsenic and cadmium. This suggests a strong influence of human-related factors, including industrial emissions, agricultural runoff, and waste disposal. Additionally, natural geochemical processes appeared to

impact the distribution of metals, as the relatively high levels of cobalt and nickel at Site 5 suggest possible leaching from metal-rich geological formations. Hydrological factors further influenced the metal concentrations, with variations in water flow, dilution, and sediment interactions affecting the distribution of heavy metals across different sites.

3.2 Statistical Summary of Heavy Metal Concentrations

A statistical summary of the heavy metal concentrations, including minimum, maximum, mean, median, standard deviation, variance, kurtosis, and skewness, is presented in Table 2.

Table 2: Statistical Summary of Heavy Metal Concentrations (ppm)

Statistical Parameter	As	Cd	Co	Cr	Ni	Pb
Minimum	0.029	0.002	0.097	0.008	0.004	0.0011
Maximum	0.068	0.077	0.174	0.020	0.070	0.045
Mean	0.052	0.0173	0.127	0.015	0.031	0.006
Median	0.053	0.006	0.117	0.015	0.027	0.0018
Standard Deviation	0.0113	0.0199	0.0238	0.0038	0.0207	0.011
Variance	0.00013	0.0004	0.00056	0.0000142	0.0004	0.00012
Kurtosis	0.154	5.335	0.1495	-0.849	-0.494	13.974
Skewness	-0.683	2.055	1.018	-0.389	0.661	3.688

Table 3 shows regulatory standards for the various heavy metals that is relevant in assessing the the environmental and health risks posed by these metals, the obtained concentrations when compared with international regulatory limits set by WHO, USEPA, and ECE (Table 3).

Table 3: Regulatory Standards for Heavy Metals in Water (ppm)

Regulatory Body	As	Cd	Co	Cr	Ni	Pb
WHO	0.01	0.03	N/A	0.05	0.07	0.01
USEPA	0.01	0.05	N/A	0.10	0.70	0.02
ECE	0.01	0.05	N/A	0.05	0.05	0.01

The statistical summary of heavy metal concentrations in the water samples provides insights into their distribution and potential

environmental and health risks. The values were compared with regulatory standards set by the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA), and the European Commission for the Environment (ECE). Arsenic concentrations in the water samples ranged from 0.029 to 0.068 ppm, with a mean value of 0.052 ppm. These values exceed the permissible limit of 0.01 ppm set by WHO, USEPA, and ECE. The negative skewness of -0.683 suggests that most of the recorded values are above the mean, which indicates a consistent elevation of arsenic levels in the samples. Prolonged exposure to such high levels of arsenic poses serious health risks, including carcinogenic effects, skin lesions, and cardiovascular diseases.



Cadmium concentrations varied between 0.002 and 0.077 ppm, with an average of 0.0173 ppm. While most of the recorded values are within the limits set by WHO (0.03 ppm), USEPA (0.05 ppm), and ECE (0.05 ppm), an outlier at 0.077 ppm exceeds all regulatory limits. The high kurtosis value of 5.335 and a strong right-skew of 2.055 indicate that while cadmium levels are generally low, there are occasional spikes that significantly increase the mean. Chronic exposure to cadmium can lead to kidney damage and bone demineralization, making it necessary to investigate possible sources of contamination.

Cobalt concentrations ranged from 0.097 to 0.174 ppm, with a mean value of 0.127 ppm. Regulatory bodies do not specify limits for cobalt in drinking water, but excessive exposure has been associated with neurological and cardiovascular effects. The moderate right-skewness of 1.018 suggests that higher values occur more frequently, implying localized sources of pollution that may require further investigation.

Chromium levels in the water samples were found to be between 0.008 and 0.02 ppm, with an average concentration of 0.015 ppm. These values are well within the permissible limits set by WHO (0.05 ppm), ECE (0.05 ppm), and USEPA (0.1 ppm). The slight negative skewness of -0.389 suggests that most values are concentrated at the higher end, but there is no immediate risk associated with chromium contamination. However, continuous monitoring is recommended, as hexavalent chromium (Cr(VI)) can be highly toxic even at low concentrations.

Nickel concentrations varied between 0.004 and 0.07 ppm, with a mean value of 0.031 ppm. While all recorded values remain below the USEPA standard of 0.7 ppm, some samples approached the WHO and ECE limit of 0.07 ppm. The presence of nickel in water is concerning because exposure is linked to allergic reactions, respiratory problems, and potential carcinogenic effects. The moderate

right-skewness of 0.661 indicates that higher concentrations occur more frequently in some locations.

Lead concentrations in the samples ranged from 0.0011 to 0.045 ppm, with an average value of 0.006 ppm. Although most values fall within acceptable limits set by WHO (0.01 ppm), USEPA (0.02 ppm), and ECE (0.01 ppm), the highest recorded value of 0.045 ppm exceeds all regulatory standards. The extremely high kurtosis of 13.974 and skewness of 3.688 suggest that a few locations have significantly high lead concentrations. Lead contamination is particularly concerning due to its neurotoxic effects, especially in children. Even low levels of lead exposure can cause developmental and cognitive impairments, making it imperative to identify and mitigate its sources.

The standard deviation values indicate substantial variability in cadmium (0.0199 ppm), cobalt (0.0238 ppm), and lead (0.011 ppm), which suggests that heavy metal concentrations fluctuate significantly across different locations. Similarly, the high variance for cobalt (0.00056) and cadmium (0.0004) further confirms that their levels are inconsistent. The statistical parameters also reveal that cadmium and lead exhibit extreme kurtosis, highlighting the presence of occasional high-value outliers.

The environmental and health implications of these findings are significant. Arsenic concentrations consistently exceed regulatory limits, posing a long-term carcinogenic risk to the affected populations. The occasional spikes in cadmium and lead levels suggest potential localized pollution sources that require immediate attention. While chromium and nickel concentrations remain within permissible limits, continuous monitoring is necessary to prevent long-term accumulation. The possible sources of heavy metal contamination in the water samples vary. Arsenic and lead are often associated with industrial effluents, mining activities, and



improper disposal of electronic waste. Cadmium and chromium contamination may originate from electroplating, battery manufacturing, and paint industries. Nickel and cobalt, on the other hand, are commonly linked to natural weathering of rocks, industrial discharge, and metal processing plants.

In conclusion, the high levels of arsenic in the water samples call for urgent intervention, including identifying pollution sources and implementing appropriate remediation strategies. Continuous monitoring of cadmium and lead levels is essential to ensure that occasional spikes do not pose health risks. Pollution control measures should be enforced, particularly in industrial areas, to prevent further contamination. Additionally, community awareness programs should be introduced to educate the public on the dangers of heavy metal pollution and promote safe waste disposal practices. A comprehensive health risk assessment, including bioaccumulation studies, is recommended to evaluate the long-term effects of heavy metal exposure on local populations.

3.3 Environmental and Health Implications

The results indicate significant arsenic contamination, which is a major health concern due to its toxicity. Cadmium and lead contamination in some locations could also

pose risks to human health, including kidney damage and neurological effects. The variability in concentrations across locations suggests that pollution sources are not uniform, likely influenced by industrial discharge, agricultural runoff, and natural geological formations.

The differences in heavy metal concentrations among the sampling sites can be further understood by analyzing their potential health impacts through the Average Daily Intake (ADI), Hazard Index (HI), and Incremental Life Cancer Risk (ILCR) presented in Tables 4, 5, and 6.

Table 4 provides the ADI values for ingestion and dermal pathways of heavy metals in the water samples. Arsenic (As) had an ADI_{ing} value of 1.48E-08 mg/kg/day and an ADI_{derm} of 5.43E-08 mg/kg/day, which indicates a higher exposure through dermal contact. Similarly, chromium (Cr) showed a significantly high ADI_{derm} value of 3.13E-07 mg/kg/day compared to its ingestion pathway (4.28E-09 mg/kg/day). These results suggest that dermal absorption plays a critical role in heavy metal exposure for specific contaminants. Lead (Pb) and cadmium (Cd) had relatively lower ADI values compared to other metals, though their presence remains a concern.

Table 4: ADI for ingestion and dermal pathways for the Heavy metals in the samples

Heavy Metals	Conc (mg/L)	ADI _{ing}	ADI _{derm}
As	0.052	1.48E-08	5.43E-08
Cd	0.0173	4.93E-09	
Co	0.127	3.62E-08	
Cr	0.015	4.28E-09	3.13E-07
Ni	0.031	8.84E-09	
Pb	0.006	1.71E-09	6.26E-09

Table 5 presents the Hazard Index (HI), which is a cumulative risk assessment metric based on non-carcinogenic effects. The highest HI value was observed for chromium (HI = 5.22E-03), followed by arsenic (HI = 4.90E-04). These values indicate potential health risks,

particularly for Cr exposure. The total hazard index for cadmium (HI = 4.93E-06) and lead (HI = 1.24E-05) were significantly lower but still contribute to overall risk assessment. The results suggest that chromium contamination poses the highest non-carcinogenic threat



among the studied heavy metals, primarily through dermal exposure pathways.

Table 5: Hazard Index for the water samples within the study site

Heavy Metals	Mean Conc (mg/L)
As	0.0453
Cd	0.012
Co	0.075
Cr	0.0077
Ni	0.0142
Pb	0.0035

Table 6 evaluates the Incremental Life Cancer Risk (ILCR) for the heavy metals in the water samples. Arsenic exhibited the highest ILCR value (1.04E-07), indicating a higher potential cancer risk, primarily driven by dermal exposure (ILCR_{derm} = 8.14E-08). Chromium and cadmium had ILCR values of 2.14E-09 and 1.87E-09, respectively, while lead showed the lowest ILCR value (1.45E-11). The findings confirm that arsenic poses the most significant carcinogenic risk among the studied metals, with its dermal absorption pathway being the most critical exposure route.

Table 6: Incremental Life Cancer Risk for the water samples within the study site

Heavy Metals	Mean Conc (mg/L)
As	0.0453
Cd	0.012
Co	0.075
Cr	0.0077
Ni	0.0142
Pb	0.0035

When comparing these results to the observed differences in heavy metal concentrations across sampling sites, it is evident that geographical location, anthropogenic activities, natural geochemical processes, and hydrological factors play a major role in determining metal distribution. Site 2, which exhibited the highest levels of arsenic and cadmium, aligns with the findings in Tables 4, 5, and 6, confirming elevated health risks

associated with these contaminants. Additionally, the high cobalt and nickel concentrations at Site 5 suggest possible leaching from geological formations, though their health risks appear to be lower based on

the findings from this study reveal that arsenic and chromium pose the highest health risks, with arsenic showing a greater potential for both non-carcinogenic and carcinogenic effects, particularly through dermal exposure.

Chromium exhibits the highest hazard index among the analyzed metals, indicating a significant non-carcinogenic threat. Cadmium and lead, although present at lower concentrations, contribute to overall health risks, while cobalt and nickel show minimal risk based on hazard and cancer risk assessments. The observed variations in metal concentrations across sampling sites suggest that anthropogenic activities, natural geochemical processes, and local hydrological conditions influence contamination levels. The presence of high arsenic and cadmium concentrations at specific sites aligns with the risk assessment, confirming the need for intervention. The study concludes that heavy metal contamination in water sources poses a measurable health risk, with arsenic and chromium being of particular concern due to their elevated hazard and cancer risk indices. The findings emphasize the importance of regular monitoring, stringent regulatory enforcement, and effective remediation measures to mitigate contamination. It is recommended that water treatment processes be improved to reduce heavy metal concentrations to safe levels. Further research should explore advanced remediation techniques, particularly for arsenic and chromium, to minimize health risks. Public awareness campaigns should also be implemented to educate communities on potential health hazards associated with heavy metal exposure from water sources.

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Compliance with Ethical Standards

Declaration

Ethical Approval

Not Applicable

Competing interests

The authors declare no known competing financial interests

Data Availability

Data shall be made available on request

Conflict of Interest

The authors declare no conflict of interest

Ethical Considerations



This research adhered to ethical guidelines, ensuring that all data collection and analysis procedures complied with environmental and scientific research standards.

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Authors' Contributions

KKO, CNO designed the work. CFJ, COI, UAE, MMO and CLK were involved in field work, data analysis and drafting of the manuscript

