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Pollution Status and Health Risk Assessment of Heavy Metal in Groundwater Within the Vicinity of Dei-Del in Abuja

Emeka Chima Ogoko*, Bilkisu Jalo Abdullahi, and Donard Emeziem
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Abstract: *Access to safe drinking water is essential for protecting human health; however, groundwater contamination by toxic heavy metals poses significant public health concerns. This study assessed the concentrations of selected heavy metals and their associated human health risks in borehole and dug-well water from Dei-Dei District, Federal Capital Territory (FCT), Nigeria. Twenty groundwater samples comprising ten borehole and ten dug-well water samples were collected from four communities and analyzed for Fe, Zn, Cd, As, Cr, Mn, Pb, and Ni using Atomic Absorption Spectrophotometry (AAS). Mean concentrations (mg/L) in borehole water were Fe (0.225), Zn (0.325), Cd (0.002), As (0.002), Cr (0.023), Mn (0.247), Pb (0.004), and Ni (0.035), whereas dug-well water contained Fe (0.492), Zn (0.225), Cd (0.003), As (0.004), Cr (0.025), Mn (0.273), Pb (0.021), and Ni (0.046). Iron and arsenic in dug-well water exceeded the World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guideline values, while manganese and nickel exceeded the NSDWQ limits in borehole water. Estimated Daily Intake (EDI) values were consistently higher for consumers of dug-well water than borehole water, indicating greater exposure to heavy metals. The Hazard Quotient (HQ) values for all individual metals were below unity (HQ < 1), suggesting no significant non-carcinogenic risk from individual metals. However, the mean Hazard Index (HI) was 0.695 for borehole water and 1.110 for dug-well water, with approximately 45% of the dug-well samples exhibiting HI values greater than 1, indicating potential cumulative non-carcinogenic health risks. The mean Incremental Lifetime Cancer Risk (ILCR) values for chromium and nickel in both groundwater sources exceeded the acceptable limit (1×10^{-4}), while arsenic exceeded the permissible carcinogenic risk threshold only in dug-well water. The mean Total Lifetime Cancer Risk (TLCR) was 2.34×10^{-3} for borehole water and 3.08×10^{-3} for dug-well water, both substantially higher than the acceptable safety threshold. These findings demonstrate that although the groundwater sources pose minimal non-carcinogenic risks from individual heavy metals, prolonged consumption, particularly of dug-well water, presents significant cumulative non-carcinogenic and carcinogenic health risks. Regular groundwater monitoring, effective water treatment, and pollution control measures are therefore recommended to safeguard public health..*

Keywords: *Drinking water quality, heavy metal contamination, health risk, hazard quotient, lifetime cancer risk.*

Emeka Chima Ogoko
Department of Chemistry, National Open University of Nigeria, Abuja, Nigeria
Email: eogoko@noun.edu.ng
https://orcid.org/0000-0002-0409-4708

Bilkisu Jalo Abdullahi
Department of Chemistry, National Open University of Nigeria, Jabi, Abuja, Nigeria.
Email: jalodazal@gmail.com

Also available@ https://doi.org/10.5281/zenodo.21318609

Donard Emeziem
Department of Science Laboratory Technology, Temple-Gate Polytechnic, Aba, Abia State, Nigeria.
Email: donaldoni4real2006@yahoo.com

1.0 Introduction

Access to safe drinking water is indispensable for human health, socioeconomic development, and environmental sustainability. However, rapid urbanization, population growth, industrialization, agricultural activities, and inadequate waste management have increasingly compromised the quality of both surface water and groundwater resources worldwide. Groundwater remains the primary source of drinking water for many communities because of its relatively good quality and year-round availability, yet it is increasingly threatened by chemical contamination, particularly heavy metals. (Ahamefuna et al., 2014; Elumalai et., 2020; Eneje & Ogoko, 2025). Water resources are natural sources of water that is thought to be valuable for man. Surface water and groundwater are the commonest natural sources of fresh water. Water resources have constantly been threatened because of water scarcity, water pollution and climate change (Gleeson et al, 2012; Ogoko et., 2015). Groundwater is water that exists beneath the Earth's surface within soil pores and fractures in geological formations. It serves as a major source of potable water in both urban and rural communities owing to its natural filtration and relatively stable supply (Ibrahim et al., 2015; Mihret & Wuletaw, 2025; Güntner, A., et al.2026).

Boreholes and hand dug wells are groundwater sources while surface water sources are exemplified by rivers, streams and lakes. Groundwater contamination may result from both natural geological processes and anthropogenic activities including industrial discharges, mining operations, agricultural runoff, landfill leachates, sewage disposal, and the excessive use of agrochemicals. Among the various groundwater contaminants, heavy metals have attracted considerable attention because they are persistent, non-biodegradable, bioaccumulative, and capable of causing serious toxic effects even at low concentrations. Metals such as arsenic, cadmium, chromium, lead and nickel have been associated with neurological disorders, kidney damage, developmental abnormalities, cardiovascular diseases and various forms of cancer following prolonged exposure. Mercury, lead, arsenic, cadmium, copper and nickel are some of the toxic heavy metals (Ogoko & Ajani, 2020). These metals are not biodegradable, but their relative stability relates to their persistency in the environment and toxicity. Standard organisations worldwide have implemented regulations in terms of maximum permissible limits for the release of these metals in the environment as pollution control measures. Despite the various pollution control measures, heavy metals are obnoxiously being discharged at concentration levels higher than the recommended maximum permissible limits particularly through anthropogenic point source, and consequently leading to water pollution and health hazard

Evaluating the human health risks associated with heavy metal contamination is an important component of groundwater quality assessment. Continuous exposure through drinking water may result in both non-carcinogenic and carcinogenic health effects. Human health risk assessment commonly employs the Hazard Quotient (HQ), Hazard Index (HI), and Lifetime Cancer Risk (LCR) to estimate the probability of adverse health outcomes resulting from chronic exposure to contaminated drinking water.
(Mihret & Wuletaw, 2025).

Numerous studies conducted across Africa and other developing regions have consistently reported elevated concentrations of heavy metals in groundwater located near urban

settlements, industrial facilities and waste disposal sites. These studies demonstrate that groundwater quality is strongly influenced by local hydrogeological conditions, land-use practices and anthropogenic activities, thereby necessitating location-specific investigations.

Ogoko (2019) assessed the water quality of dug wells in Lagos Island and observed that hardness, conductivity, lead, zinc, calcium, manganese and potassium contents exceeded their permissible limits. He concluded that dug well water was not safe for drinking. Omada et al (2024), carried out a study on water quality and health risk assessment of surface and ground water around Gosa dumpsite, Abuja. In their findings, the hazard quotient for Pb, Cd and As surpassed one (1.0), whereas hazard index (HI) exceeded the threshold value (1.0) in the metals under study, signifying attendant potential chronic non-carcinogenic health risks. They concluded that incremental lifetime cancer risks for Cd, As, Cr and Ni exceeded the acceptable safe limits ($< 1\times 10^{-4}$), showing a potential cancer risk associated with ingestion of carcinogenic metals through drinking water. In the study conducted by Kana (2022) on heavy metal contents of groundwater in part of Karu, central Abuja, the groundwater was considerably polluted with heavy metals at concentrations higher than the World Health Organisation safe limit for drinking water. It was therefore concluded that the elements such as Pb, Zn, Cu, Fe and Ni contribute significantly to the overall groundwater pollution. Other proceeding studies in the federal capital territory, Abuja, have reported higher concentrations of Pb, Cd, Cr, Mn and Fe in groundwater, predominantly in zones predisposed to urbanization and dumpsite activities. These studies recognized anthropogenetic contributions, in addition to municipal waste disposal and leachate migration, as main sources of pollution which elicited potential non-carcinogenic and carcinogenic health risks linked to long-term ingestion of contaminated groundwater (Jibrin et al., 2015; Opasola et al., 2024; Uzonu et al., 2026). Collectively, these studies demonstrate that heavy metal contamination of groundwater is an emerging environmental and public health concern within the Federal Capital Territory. However, variations in contamination levels among different locations indicate that groundwater quality is spatially heterogeneous and should not be generalized across Abuja.

Therefore, this study aimed to determine the concentrations of selected heavy metals in groundwater obtained from boreholes and hand-dug wells within Dei-Dei district, Abuja, evaluate the degree of contamination relative to international drinking water standards, assess the associated non-carcinogenic and carcinogenic health risks to adults through drinking water ingestion, and provide baseline information for groundwater quality management and public health protection.

The findings of this study will provide valuable information for environmental regulators, public health authorities and water resource managers regarding the current status of groundwater quality in Dei-Dei. The study also contributes baseline data for future groundwater monitoring programmes and supports evidence-based decision-making aimed at reducing heavy metal exposure and protecting public health in rapidly urbanizing communities.

2.0 Materials and Methods

2.1 Study Area Description

The study was performed in Dei-Dei District, Federal Capital Territory (FCT), Nigeria. Boreholes and dug wells were the core sources of domestic water evaluated, and samples were obtained in June, 2025 from Saburi, Timber Shed, and Dakwa communities. Dei-Dei District is one of the rapidly developing suburban areas within the Federal Capital Territory characterized by increasing residential settlements, commercial activities, automobile workshops, timber markets, small-scale industries, and agricultural practices. Groundwater obtained from boreholes and

hand-dug wells constitutes the principal source of domestic water for the majority of residents. The study area lies between latitudes 8.25°N and 9.20°N and longitudes 6.45°E and 7.39°E. The climate is tropical, characterized by distinct wet (April–October) and dry (November–March) seasons with an average annual rainfall of approximately 1,200–1,600 mm. A total of thirty groundwater samples were collected during June 2025, comprising fifteen borehole water samples and fifteen hand-dug well water samples from Saburi, Timber Shed and Dakwa communities.

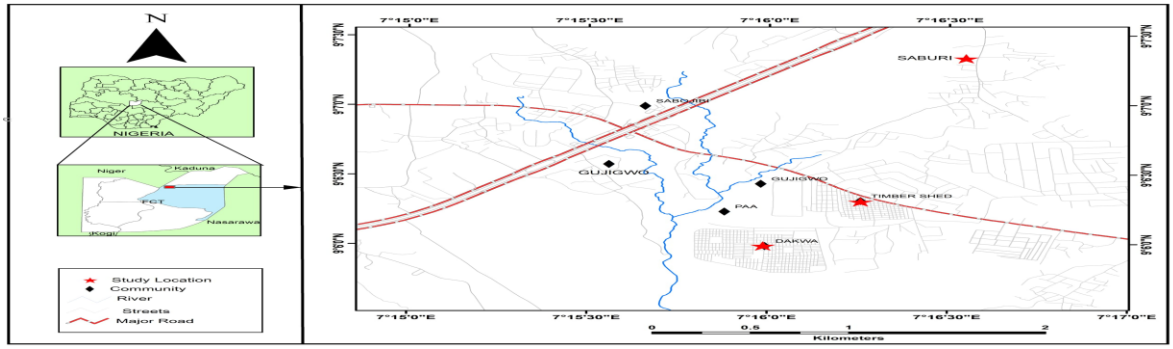

Figure 1: Map of Federal Capital Territory (FCT) showing the Dei-Dei District

2.2 Materials and sampling

A total of thirty groundwater samples were collected during June 2025, comprising fifteen borehole water samples and fifteen hand-dug well water samples from Saburi, Timber Shed and Dakwa communities. The samples were properly labelled as in Table 1, transported to the laboratory and stored in a refrigerator at 4ºC prior to analysis. Prior to sample collection, the polyethylene bottles were soaked in 10% nitric acid for 24 h, rinsed thoroughly with deionized water, and finally rinsed three times with the respective water samples before collection. Samples intended for heavy metal analysis were acidified immediately after collection to pH < 2 using ultrapure nitric acid to minimize adsorption of metals onto the walls of the sample containers. All samples were transported to the laboratory in ice-packed coolers and stored at 4°C until analysis, which was completed within 48 h of collection.

2.3 Heavy metals determination

Water samples were digested following the USEPA acid digestion procedure for dissolved metals. Ten millilitres of freshly prepared aqua regia (HCl_3, 3:1 v/v) was added to each sample and heated on a hot plate until near dryness. After cooling, 20 mL of deionized water was added, the digest was filtered through Whatman No. 42 filter paper, and the filtrate was transferred into acid-washed volumetric flasks for analysis. Instrument calibration was performed using multi-element standard solutions prepared from certified stock standards before sample analysis.Twenty (20) milliliters (mL) of deionized water was then added, stirred vigorously for 3 minutes and filtered using Whatman filter paper. Analysis of the filtrates of the samples gotten after digestion for Fe, Zn, Cd, As, Cr, Mn, Pb and Ni were conducted at their corresponding wavelength (248.3, 212, 227, 193.7, 358, 278, 217, 231 nm) using flame furnace atomic absorption spectrophotometer (Schdmazu AA-6800, Tokyo, Japan). The limit of detection for most of the elements analysed ranged from 0.001 – 0.002 ppm, while the blank (deionized water) reading for all the metals was 0.000 ppm.

2.4 Method validation

The analyte samples were spiked with 0.5 mg/L of standard solutions of the respective metals prior to digestion, in order to assess the accuracy of metals analysis. Interestingly, the spiked samples were subjected to similar

experimental conditions as the analyte sample and % recovery was evaluated (equation 1) :

$$\% \text{ Recovery} = \frac{Conc.\ spiked\ sample - Conc.\ unspiked\ sample}{Actual\ spike\ conc.} \quad (1)$$

Table 1: Sample Description and Location Coordinates

S/N	Sample Identity	Sample Location and Source	Area Council	Latitude	Longitude
1	A1 (B)	Saburi, Borehole water	AMAC	9.12272	7.27652
2	A2 (B)	Saburi, Borehole water	AMAC	9.12767	7.27566
3	A3 (B)	Saburi, Borehole water	AMAC	9.11828	7.27567
4	A4 (B)	Saburi, Borehole water	AMAC	9.11942	7.27628
5	A5 (B)	Saburi, Borehole water	AMAC	9.12286	7.27662
6	A1 (W)	Saburi, Dug-well water	AMAC	9.12157	7.27542
7	A2 (W)	Saburi, Dug-well water	AMAC	9.12098	7.27557
8	A3 (W)	Saburi, Dug-well water	AMAC	9.11741	7.27496
9	A4 (W)	Saburi, Dug-well water	AMAC	9.11572	7.27536
10	A5 (W)	Saburi, Dug-well water	AMAC	9.12572	7.27546
11	B1 (W)	Timber Shade Dug-well water	AMAC	9.10736	7.25854
12	B2 (W)	Timber Shade Dug-well water	AMAC	9.10754	7.25784
13	B3 (W)	Timber Shade Dug-well water	AMAC	9.10749	7.25725
14	B4 (W)	Timber Shade Dug-well water	AMAC	9.10756	7.25758
15	B5 (W)	Timber Shade Dug-well water	AMAC	9.10768	7.25768
16	B1 (B)	Timber Shade Borehole water	AMAC	9.10844	7.25925
17	B2 (B)	Timber Shade Borehole water	AMAC	9.1075	7.2597
18	B3 (B)	Timber Shade Borehole water	AMAC	9.10881	7.25812
19	B4 (B)	Timber Shade Borehole water	AMAC	9.10953	7.25863
20	B5 (B)	Timber Shade Borehole water	AMAC	9.10983	7.25883
21	C1 (W)	Dakwa, Dug-well water	Bwari	9.0985	7.21596
22	C2 (W)	Dakwa, Dug-well water	Bwari	9.09904	7.21602
23	C3 (W)	Dakwa, Dug-well water	Bwari	9.10002	7.21451
24	C4 (W)	Dakwa, Dug-well water	Bwari	9.09912	7.21462
25	C5 (W)	Dakwa, Dug-well water	Bwari	9.09922	7.21472
26	C1 (B)	Dakwa, Borehole water	Bwari	9.09793	7.21623
27	C2 (B)	Dakwa, Borehole water	Bwari	9.09985	7.21454
28	C3 (B)	Dakwa, Borehole water	Bwari	9.10047	7.21577
29	C4 (B)	Dakwa, Borehole water	Bwari	9.09573	7.21599
30	C5 (W)	Dakwa, Borehole water	Bwari	9.09593	7.21619

The percentage recovery of Fe, Zn, Cd, As, Cr, Mn, Pb and Ni ranged from 93 – 100 %, which indicates the performance of the method.

2.5 Health risks assessment

Health risks assessment was carried out to determine the potential risks associated with oral ingestion of toxic metals via water. The assessment will include the determination of estimated daily intake (EDI), hazard index (HI), and incremental lifetime cancer risk (ILCR).

2.5.1 Estimated daily intake (EDI)

The estimated daily intake of heavy metals via consumption of portable water is expressed in mg/kg body weight /day and calculated with the equation (2).

$$EDI = \frac{CR}{BW} \times IR \quad (1)$$

where CR = metal concentration of heavy metals in water (mg/L), IR = daily ingestion rate of water (L/day), and BW = average body weight (kg)

The exposure parameters considered for health risks assessment in this present study were based on USEPA guidelines and previous Nigeria studies with the assumption that the average body weight of 70kg and daily water ingestion rate of 2L/day for adult, whereas children were assumed to have a body weight of 15kg and daily water ingestion of 1L/day

2.5.2 Non-Carcinogenic Risk

Non carcinogenic health risks of heavy metals were assessed using the hazard quotient (HQ) for individual metals and the cumulative risks from all metals were evaluated using hazard index (HI). The hazard quotient (HQ) was calculated using Equation (3) (Omada et al., 2024)

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

where RfD is the oral reference dose (mg/kg/day), indicating the maximum allowable daily exposure to a contaminant with significant health risk. The oral reference dose values used in this study were: Cd (0.001), Cr (0.003), As (0.0003), Ni (0.02), Hg (0.0001), Pb (0.004), Cu (0.04), Zn (0.3), Mn (0.14), Fe (0.70) and Co (0.02) mg/kg/day [21,24]. An HQ value less than 1(HQ <1), indicates no significant non-carcinogenic risk, while HQ >1 suggests possibility of chronic non-carcinogenic health effect.

The Hazard Index (HI) represents the cumulative non-carcinogenic risk resulting from simultaneous exposure to multiple heavy metals and was calculated as the sum of the individual hazard quotients (equation 4)

$$\mathrm{HI} = \sum \mathrm{HQ} \quad (4)$$

An HI values less than 1(HI <1), indicates no significant health risk, whereas HI >1 indicates potential chronic health risk.

2.5.3 Carcinogenic risk

Carcinogenic risk was evaluated using the incremental lifetime cancer risk ($ILCR$), which predicts the possibility of developing cancer over a lifetime because of exposure to toxic and carcinogenic metals. Incremental lifetime cancer risk was calculated using Equation (5) (Ogoko et al., 2023).

$$ILCR = CDI\ x\ CSF \quad (5)$$

Where CDI = chronic daily intake (mg/kg body weight/day) and CSF = cancer slope factor.

Cancer slope factors used for Pb, Ni, Cd, As and Cr were 0.009, 1.7, 0.6, 1.5 and 0.501 respectively.

$$\mathrm{CDI} = \frac{\boldsymbol{EDI\ x\ EF\ x\ ED}}{\boldsymbol{AT}} \quad (6)$$

where EF = expose frequency (365 days/year), ED = exposure duration or life expectancy (60 years for adult Nigerian) and AT = average exposure time, defined as AT = 365 x 60 = 21,900 days

3.0 Results and Discussion

The concentrations of heavy metals detected in borehole and hand-dug well water collected from Dei-Dei District, Abuja are presented in Tables 1 and 2, while the corresponding World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) permissible limits are provided in Table 3.

Table 1: Heavy metals content in borehole water in the study area along with their mean values

Samples ID	Fe (mg/L)	Zn (mg/L)	Cd (mg/L)	As (mg/L)	Cr (mg/L)	Mn (mg/L)	Pb (mg/L)	Ni (mg/L)
A_1B	0.282	0.024	0.001	0.001	0.021	0.241	0.005	0.030
A_2B	0.474	0.489	0.001	0.002	0.025	0.365	0.001	0.033
A_3B	0.676	0.025	0.001	0.003	0.021	0.287	0.010	0.029
A_4B	0.113	0.030	0.002	0.002	0.030	0.324	0.003	0.037
A_5B	0.123	0.040	0.003	0.003	0.041	0.336	0.002	0.047
B_1B	0.474	0.489	0.001	0.001	0.023	0.187	0.004	0.035
B_2B	0.101	0.474	0.002	0.002	0.025	0.285	0.003	0.047
B_3B	0.212	0.468	0.001	0.002	0.022	0.046	0.006	0.042
B_4B	0.192	0.478	0.002	0.003	0.013	0.268	0.007	0.038
B_5B	0.182	0.468	0.001	0.004	0.023	0.274	0.005	0.048
C_1B	0.209	0.484	0.001	0.003	0.015	0.176	0.003	0.031
C_2B	0.266	0.483	0.001	0.001	0.025	0.182	0.007	0.022
C_3B	0.191	0.487	0.002	0.002	0.028	0.231	0.002	0.033
C_4B	0.041	0.452	0.001	0.001	0.025	0.314	0.003	0.034
C_5B	0.045	0.462	0.003	0.002	0.029	0.324	0.002	0.043
D_1B	0.101	0.201	0.010	0.002	0.022	0.287	0.003	0.025
D_2B	0.153	0.251	0.001	0.002	0.027	0.206	0.004	0.027
D_3B	0.244	0.263	0.002	0.001	0.018	0.189	0.004	0.034
D_4B	0.211	0.211	0.001	0.002	0.012	0.209	0.004	0.031
D_5B	0.221	0.223	0.003	0.001	0.015	0.212	0.005	0.037
mean	0.225	0.325	0.002	0.002	0.023	0.247	0.004	0.035
WHO	0.3	3.0	0.003	0.01	0.05	0.5	0.01	0.07
NSDWQ	0.3	3.0	0.003	0.01	0.05	0.2	0.01	0.02

The concentrations varied considerably among sampling locations, reflecting differences in local hydrogeological characteristics and anthropogenic influences.

3.1 Heavy metals in borehole water

The concentrations of heavy metals in borehole water are presented in Table 1. Iron (Fe) concentrations ranged from 0.041 to 0.676 mg/L with a mean value of 0.225 mg/L. Although the mean concentration was below the WHO (0.30 mg/L) and NSDWQ (0.30 mg/L) permissible limits, some individual borehole samples (e.g., A2B, A3B, and B1B) exceeded these limits, indicating localized iron enrichment. Elevated iron concentrations in groundwater are commonly associated with natural weathering of iron-bearing minerals as well as corrosion of metallic pipes and borehole casings. Although iron is not generally considered highly toxic, excessive concentrations may impart undesirable colour, taste, staining of household fixtures, and promote microbial growth in water distribution systems.

Zinc concentrations varied from 0.024 to 0.489 mg/L with a mean value of 0.325 mg/L, which is substantially below the WHO and NSDWQ guideline value of 3.0 mg/L (Table 1). This suggests that zinc contamination is minimal within the study area. Zinc is an essential trace element and only becomes toxic at much higher concentrations than those observed in this study.

Cadmium concentrations ranged from 0.001 to 0.010 mg/L with an average value of 0.002 mg/L. The mean concentration was below the maximum permissible limit of 0.003 mg/L, although sample D1B recorded a concentration (0.010 mg/L) that exceeded both WHO and NSDWQ standards.

Table 2: Heavy metals content in Dug-well water in the study area along with their mean values

	Fe (mg/L)	Zn (mg/L)	Cd (mg/L)	As (mg/L)	Cr (mg/L)	Mn (mg/L)	Pb (mg/L)	Ni (mg/L)
A_1W	1.008	0.046	0.002	0.003	0.027	0.335	0.005	0.056
A_2W	0.911	0.046	0.004	0.010	0.031	0.433	0.017	0.061
A_3W	0.324	0.041	0.002	0.006	0.025	0.341	0.015	0.045
A_4W	0.315	0.042	0.001	0.005	0.032	0.384	0.029	0.062
A_5W	0.325	0.052	0.002	0.006	0.042	0.395	0.039	0.072
B_1W	0.587	0.475	0.002	0.001	0.036	0.026	0.023	0.054
B_2W	0.470	0.048	0.003	0.004	0.024	0.340	0.019	0.045
B_3W	0.404	0.489	0.004	0.001	0.018	0.020	0.011	0.036
B_4W	0.370	0.053	0.002	0.003	0.021	0.313	0.008	0.039
B_5W	0.391	0.066	0.001	0.002	0.031	0.323	0.009	0.039
C_1W	0.487	0.472	0.003	0.004	0.025	0.103	0.009	0.038
C_2W	0.413	0.473	0.002	0.005	0.024	0.262	0.060	0.036
C_3W	0.504	0.477	0.002	0.007	0.031	0.251	0.005	0.045
C_4W	0.568	0.481	0.002	0.001	0.011	0.267	0.020	0.042
C_5W	0.578	0.491	0.003	0.002	0.021	0.275	0.030	0.052
D_1W	0.513	0.556	0.003	0.005	0.023	0.249	0.051	0.035
D_2W	0.405	0.044	0.003	0.002	0.019	0.284	0.010	0.037
D_3W	0.473	0.040	0.002	0.001	0.015	0.263	0.015	0.044
D_4W	0.392	0.051	0.004	0.003	0.018	0.290	0.014	0.039
D_5W	0.399	0.061	0.003	0.002	0.028	0.296	0.024	0.049
Mean	0.492	0.225	0.003	0.004	0.025	0.273	0.021	0.046

Table 3: World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) permissible limits for heavy metals in drinking water

Heavy Metal	WHO Standard (mg/L)	NSDWQ Standard (mg/L)
Iron (Fe)	0.30	0.30
Zinc (Zn)	3.00	3.00
Cadmium (Cd)	0.003	0.003
Arsenic (As)	0.010	0.010
Chromium (Cr)	0.050	0.050
Manganese (Mn)	0.50	0.20
Lead (Pb)	0.010	0.010
Nickel (Ni)	0.070	0.020

Sources: World Health Organization (WHO). *Guidelines for Drinking-water Quality*, 4th Edition incorporating the 1st and 2nd Addenda (2022); Nigerian Standard for Drinking Water Quality (NSDWQ), Standards Organisation of Nigeria (2015).

Cadmium is a highly toxic metal capable of causing renal dysfunction, skeletal damage, and carcinogenic effects following prolonged exposure. Its occurrence in isolated locations may be associated with improper waste disposal, battery waste, metal scraps, or industrial activities.

Arsenic concentrations ranged between 0.001 and 0.004 mg/L with a mean concentration of 0.002

mg/L, considerably below the permissible limit of 0.010 mg/L. Chromium concentrations ranged from 0.012 to 0.041 mg/L with an average concentration of 0.023 mg/L, remaining within the recommended guideline value of 0.05 mg/L. Likewise, lead concentrations (0.001–0.010 mg/L) had a mean value of 0.004 mg/L, which complied with the permissible limit of 0.01 mg/L despite a few samples approaching the regulatory threshold.

Manganese concentrations varied from 0.046 to 0.365 mg/L with a mean value of 0.247 mg/L. Although the average concentration remained below the WHO guideline value (0.50 mg/L), it exceeded the more stringent NSDWQ limit of 0.20 mg/L, suggesting moderate manganese contamination in several borehole samples. Excessive manganese exposure has been associated with neurological disorders following long-term consumption.

Nickel concentrations ranged from 0.022 to 0.048 mg/L with a mean value of 0.035 mg/L. While this concentration was below the WHO guideline value of 0.07 mg/L, it exceeded the NSDWQ permissible limit of 0.02 mg/L, indicating potential nickel contamination of borehole water. Elevated nickel concentrations may originate from corrosion of plumbing materials, industrial emissions, or weathering of nickel-bearing geological formations. Chronic exposure to nickel has been associated with allergic reactions and increased carcinogenic risk.

Overall, the borehole water exhibited acceptable concentrations of most heavy metals based on WHO standards. However, exceedances of iron, manganese and nickel relative to national standards at some sampling locations indicate localized contamination requiring periodic monitoring.

3.2 Heavy metals in hand-dug well water

The concentrations of heavy metals detected in hand-dug well water are summarized in **Table 2**. Compared with borehole water, hand-dug wells generally exhibited higher concentrations of most heavy metals, suggesting greater susceptibility to contamination because of their shallow depth and direct interaction with surface activities.

Iron concentrations ranged from 0.315 to 1.008 mg/L with a mean concentration of 0.492 mg/L, exceeding both WHO and NSDWQ permissible limits of 0.30 mg/L. Approximately three-quarters of the samples recorded iron concentrations above the guideline value, indicating widespread iron contamination. Elevated iron concentrations in shallow wells may result from weathering of iron-rich geological materials, surface runoff, corrosion of well linings, and infiltration of domestic wastes.

Zinc concentrations ranged from 0.040 to 0.556 mg/L with a mean value of 0.225 mg/L, remaining well below the WHO and NSDWQ guideline values. Cadmium concentrations varied between 0.001 and 0.004 mg/L with an average concentration of 0.003 mg/L, which was approximately equal to the maximum permissible limit. Although most samples complied with drinking water standards, samples A2W and D4W slightly exceeded the guideline value, indicating localized cadmium pollution.

Arsenic concentrations ranged from 0.001 to 0.010 mg/L with a mean concentration of 0.004 mg/L. Although the average concentration remained below the WHO guideline value, sample A2W reached the maximum permissible limit of 0.010 mg/L, suggesting possible anthropogenic inputs. Arsenic contamination may result from geogenic weathering processes as well as leaching from agricultural chemicals and municipal wastes.

Chromium concentrations ranged from 0.011 to 0.042 mg/L with a mean value of 0.025 mg/L, remaining below the WHO and NSDWQ guideline value of 0.05 mg/L. Manganese concentrations ranged from 0.020 to 0.433 mg/L with an average concentration of 0.273 mg/L, exceeding the NSDWQ limit (0.20 mg/L) but remaining below the WHO guideline value. This indicates that manganese contamination may constitute an emerging concern in the study area.

Lead concentrations ranged from 0.005 to 0.060 mg/L with a mean concentration of 0.021 mg/L, which exceeded both WHO (0.01 mg/L) and NSDWQ (0.01 mg/L) permissible limits. The elevated lead concentrations observed in many hand-dug wells are of significant public health concern because lead is a cumulative toxic metal associated with neurological impairment, developmental disorders in children, kidney damage and cardiovascular diseases.

Nickel concentrations varied from 0.035 to 0.072 mg/L with a mean concentration of 0.046 mg/L. Although these concentrations remained below the WHO guideline value (0.07 mg/L), they substantially exceeded the NSDWQ permissible

limit (0.02 mg/L), indicating widespread nickel contamination in shallow groundwater.

The generally higher heavy metal concentrations observed in hand-dug wells compared with boreholes can be attributed to the shallow nature of these water sources, which makes them more vulnerable to infiltration of contaminated surface runoff, refuse dumps, septic systems, commercial activities and other anthropogenic pollutants. Similar observations have been reported in previous groundwater quality studies conducted in Abuja and other rapidly urbanizing regions of Nigeria, where shallow groundwater consistently exhibited greater contamination than deeper aquifers.

Overall, the results demonstrate that borehole water was of better chemical quality than hand-dug well water. While most borehole samples complied with international drinking water standards for the majority of heavy metals, hand-dug wells showed elevated concentrations of iron, manganese, lead and nickel in several locations. These findings suggest that untreated hand-dug well water within the study area may pose greater long-term health risks than borehole water, emphasizing the need for routine groundwater monitoring, pollution control measures and appropriate water treatment before domestic consumption.

Table 4: Estimated daily intake of heavy metals in borehole water (mg/kg body weight /day)

Sample ID	Fe	Zn	Cd	As	Cr	Mn	Pb	Ni
A_1B	8.81E-03	7.51E-04	3.13E-05	3.13E-05	6.56E-04	7.53E-03	1.56E-04	9.38E-04
A_2B	1.48E-02	1.53E-02	3.13E-05	6.25E-05	7.81E-04	1.14E-02	3.13E-05	1.03E-03
A_3B	2.11E-02	7.81E-04	3.13E-05	9.38E-05	6.56E-04	8.96E-03	3.13E-03	9.06E-04
A_4B	3.53E-03	9.38E-04	6.25E-05	6.25E-05	9.38E-04	1.01E-02	9.38E-05	1.16E-03
A_5B	3.84E-03	1.25E-03	9.38E-05	9.38E-05	1.28E-03	1.05E-02	6.25E-05	1.47E-03
B_1B	1.48E-02	1.53E-02	3.13E-05	3.13E-05	7.19E-04	5.84E-03	1.25E-03	1.09E-03
B_2B	3.16E-03	1.48E-02	6.25E-05	6.25E-05	7.81E-04	8.91E-03	9.38E-05	1.47E-03
B_3B	6.62E-03	1.46E-02	3.13E-05	6.25E-05	6.88E-04	1.44E-03	1.88E-04	1.31E-03
B_4B	6.0E-03	1.49E-02	6.25E-05	9.38E-05	4.06E-04	8.37E-03	2.19E-04	1.18E-03
B_5B	5.69E-03	1.46E-02	3.13E-05	0.000125	7.19E-04	8.56E-03	1.56E-04	1.5E-03
C_1B	6.53E-03	1.51E-02	3.13E-05	9.38E-05	4.69E-04	5.5E-03	9.38E-05	9.69E-04
C_2B	8.31E-03	1.51E-02	3.13E-05	3.13E-05	7.81E-04	5.69E-03	2.19E-04	6.88E-04
C_3B	5.97E-03	1.52E-02	6.25E-05	6.25E-05	8.75E-04	7.22E-03	6.25E-05	1.03E-03
C_4B	1.28E-03	1.41E-02	3.13E-05	3.13E-05	7.81E-04	9.81E-03	9.38E-05	1.06E-03
C_5B	1.41E-03	1.44E-02	9.38E-05	6.25E-05	9.06E-04	1.01E-02	6.25E-05	1.34E-03
D_1B	3.16E-03	6.28E-03	0.000313	6.25E-05	6.88E-04	8.97E-03	9.38E-05	7.81E-04
D_2B	4.78E-03	7.84E-03	3.13E-05	6.25E-05	8.44E-04	6.44E-03	1.25E-04	8.44E-04
D_3B	7.62E-03	8.22E-03	6.25E-05	3.13E-05	5.63E-04	5.91E-03	1.25E-04	1.06E-03
D_4B	6.59E-03	6.59E-03	3.13E-05	6.25E-05	3.75E-04	6.53E-03	1.25E-04	9.69E-04
D_5B	6.91E-03	6.97E-03	9.38E-05	3.13E-05	4.69E-04	6.62E-03	1.56E-04	1.16E-03
Mean	7.03E-03	1.01E-02	6.25E-05	6.25E-05	7.19E-04	7.72E-03	1.25E-04	1.09E-03

3.3 Estimated Daily Intake (EDI) of Heavy Metals

The estimated daily intake (EDI) of heavy metals through ingestion of borehole water by adults is presented in Table 4, while the

corresponding EDI values for dug-well water are shown in Table 5. The EDI provides an estimate of the quantity of each metal ingested daily relative to body weight and serves as the first step in evaluating potential health risks associated with drinking contaminated water.

As shown in Table 4, the mean EDI values for borehole water followed the decreasing order: Zn (1.01×10^{-2}) > Mn (7.72×10^{-3}) > Fe (7.03×10^{-3}) > Ni (1.09×10^{-3}) > Cr (7.19×10^{-4}) > Pb (1.25×10^{-4}) > Cd = As (6.25×10^{-5} mg kg^{-1} day^{-1}).

Among all the metals, zinc exhibited the highest daily intake due to its relatively higher concentration in borehole water, followed by manganese and iron, whereas cadmium and arsenic recorded the lowest daily exposure. Sample A3B exhibited the highest iron intake (2.11×10^{-2} mg kg^{-1} day^{-1}), while D1B recorded the highest cadmium intake (3.13×10^{-4} mg kg^{-1} day^{-1}) owing to the elevated cadmium concentration measured in that sample.

Similarly, the estimated daily intake through dug-well water (Table 5) showed mean values ranging from 9.38×10^{-5} mg kg^{-1} day^{-1} for Cd to 1.54×10^{-2} mg kg^{-1} day^{-1} for Fe, following the order:

Fe (1.54×10^{-2}) > Mn (8.53×10^{-3}) > Zn (7.03×10^{-3}) > Ni (1.44×10^{-3}) > Cr (7.81×10^{-4}) > Pb (6.56×10^{-4}) > As (1.25×10^{-4}) > Cd (9.38×10^{-5} mg kg^{-1} day^{-1}).

Table 5: Estimated daily intake of heavy metals in dug well water (mg/kg body weight /day)

	Fe	Zn	Cd	As	Cr	Mn	Pb	Ni
A_1W	3.15E-02	1.43E-03	6.25E-05	9.38E-05	8.44E-04	1.05E-02	1.56E-04	1.75E-03
A_2W	2.85E-02	1.43E-03	0.000125	0.000313	9.69E-04	1.35E-02	5.31E-04	1.91E-03
A_3W	1.01E-02	1.2E-03	6.25E-05	0.000188	7.81E-04	1.06E-02	4.69E-04	1.41E-03
A_4W	9.84E-03	1.31E-03	3.13E-05	0.000156	1.00E-03	1.2E-02	9.06E-04	1.93E-03
A_5W	1.01E-02	1.62E-03	6.25E-05	0.000188	1.31E-03	1.23E-02	1.22E-03	2.25E-03
B_1W	1.83E-02	1.48E-03	6.25E-05	3.13E-05	1.13E-03	8.13E-04	7.19E-04	1.68E-03
B_2W	1.46E-02	1.5E-03	9.38E-05	0.000125	7.50E-04	1.06E-02	5.94E-04	1.40E-03
B_3W	1.26E-02	1.53E-03	0.000125	3.13E-05	5.63E-04	6.25E-04	3.44E-04	1.12E-03
B_4W	1.15E-02	1.66E-03	6.25E-05	9.38E-05	6.56E-04	9.78E-03	2.5E-04	1.22E-03
B_5W	1.22E-02	2.06E-03	3.13E-05	6.25E-05	9.69E-04	1.01E-02	2.81E-04	1.22E-03
C_1W	1.52E-02	1.47E-02	9.38E-05	1.25E-04	7.81E-04	3.21E-03	2.81E-04	1.19E-03
C_2W	1.29E-02	0.014781	6.25E-05	1.56E-04	7.50E-04	8.18E-03	1.88E-03	1.13E-03
C_3W	1.57E-02	0.014906	6.25E-05	2.19E-04	9.69E-04	7.84E-03	1.56E-04	1.41E-03
C_4W	1.77E-02	0.015031	6.25E-05	3.13E-05	3.44E-04	8.34E-03	6.25E-04	1.33E-03
C_5W	1.81E-02	0.015344	9.38E-05	6.25E-05	6.56E-04	8.59E-03	9.38E-04	1.63E-03
D_1W	1.60E-02	0.017375	9.38E-05	1.56E-04	7.19E-04	7.78E-03	1.59E-03	1.09E-03
D_2W	1.26E-02	1.38E-03	9.38E-05	6.25E-05	5.94E-04	8.87E-03	3.13E-04	1.16E-03
D_3W	1.48E-02	1.25E-03	6.25E-05	3.13E-05	4.69E-04	8.21E-03	4.69E-04	1.37E-03
D_4W	1.22E-02	1.59E-03	0.000125	9.38E-05	5.63E-04	9.06E-03	4.38E-04	1.21E-03
D_5W	1.24E-02	1.91E-03	9.38E-05	6.25E-05	8.75E-04	9.25E-03	7.5E-04	1.53E-03
Mean	1.54E-02	7.03E-03	9.38E-05	1.25E-04	7.81E-04	8.53E-03	6.56E-04	1.44E-03

The highest individual EDI values were observed in samples A1W and A2W for iron, sample A2W for arsenic (3.13×10^{-4} mg kg^{-1} day^{-1}), sample A5W for chromium (1.31×10^{-3} mg kg^{-1} day^{-1}), and sample A5W for nickel (2.25×10^{-3} mg kg^{-1} day^{-1}), indicating greater contaminant loading in several dug wells than in boreholes.

Comparison of the two groundwater sources revealed that dug-well water generally

exhibited higher mean EDI values for Fe, Cd, As, Cr, Mn, Pb and Ni than borehole water, whereas borehole water recorded a higher zinc intake. Specifically, the mean EDI of iron in dug-well water was approximately 2.2 times that of borehole water, while arsenic, cadmium, lead and nickel intakes were approximately 2.0, 1.5, 5.2 and 1.3 times higher, respectively. These findings indicate that dug wells are more susceptible to contamination from surface-derived pollutants because of their shallow depth and greater interaction with anthropogenic activities, including waste disposal, runoff infiltration and weathering of contaminated soils.

Although the calculated EDI values for individual metals remained below levels expected to cause immediate toxic effects, continuous consumption of groundwater containing toxic metals such as cadmium, arsenic, chromium, lead and nickel may result in gradual bioaccumulation within body tissues. Chronic exposure to these metals has been associated with kidney dysfunction, neurological disorders, developmental abnormalities and increased cancer incidence. Therefore, the observed daily intake values warrant further evaluation through non-carcinogenic and carcinogenic risk assessment.

3.4 Non-carcinogenic Health Risk Assessment

The non-carcinogenic health risk associated with the ingestion of borehole and dug-well water was evaluated using the Hazard Quotient (HQ) for individual metals and the Hazard Index (HI), which represents the cumulative non-carcinogenic risk arising from simultaneous exposure to multiple metals. The calculated HQ and HI values for borehole and dug-well water are presented in Tables 6 and 7, respectively.

The results in Table 6 show that the mean HQ values for Fe, Zn, Cd, As, Cr, Mn, Pb and Ni in borehole water were 1.00×10^{-2}, 3.39×10^{-2}, 6.25×10^{-2}, 2.08×10^{-1}, 2.39×10^{-1}, 5.51×10^{-2}, 3.13×10^{-2} and 5.47×10^{-2}, respectively. All individual HQ values were less than the critical threshold of 1.0, indicating that exposure to each metal through borehole water alone is unlikely to produce adverse non-carcinogenic health effects. Among the investigated metals, chromium **(Cr)** exhibited the highest mean HQ (0.239), followed by arsenic (As) (0.208), suggesting that these two toxic metals contributed most significantly to the overall non-carcinogenic health burden. Although iron, zinc and manganese occurred at relatively higher concentrations in some samples, their comparatively large oral reference doses resulted in much lower HQ values, indicating minimal toxicological concern. Cadmium and nickel also contributed moderately to the cumulative risk, whereas lead recorded one of the lowest HQ values because of its relatively low concentration in the borehole samples.

The cumulative Hazard Index (HI) values for borehole water ranged from 0.509 to 1.010, with a mean value of 0.695 (Table 6). The majority of the samples recorded HI values below the permissible limit of **1.0**, indicating that long-term consumption of borehole water from most sampling locations is unlikely to cause appreciable non-carcinogenic health effects. However, sample A5B recorded an HI value of 1.010, which marginally exceeded the safety threshold, suggesting that continuous exposure at this location may pose a slight health concern. The elevated HI observed for this sample is primarily attributable to the combined contributions of chromium, arsenic and cadmium rather than any single contaminant. This finding demonstrates the importance of evaluating cumulative exposure because individual metals may satisfy drinking water standards while their combined effects approach or exceed acceptable health limits. A comparison with the dug-well water presented in Table 7 reveals a noticeably higher non-carcinogenic health burden. The mean HQ values for Fe, Zn, Cd, As, Cr, Mn, Pb and Ni in dug-well water were 2.20×10^{-2}, 2.34×10^{-2},

9.38×10^{-2}, 4.17×10^{-1}, 2.60×10^{-1}, 6.09×10^{-2}, 1.64×10^{-1} and 7.19×10^{-2}, respectively. Similar to borehole water, the HQ values for individual metals remain below unity, indicating that none of the metals alone is expected to induce non-carcinogenic toxicity. Nevertheless, arsenic exhibited the highest mean HQ (0.417), approximately twice that observed in borehole water, while chromium (0.260) remained the second highest contributor.

Table 6: Hazard quotient of heavy metals in borehole water

Sample ID	Fe ($\times10^{-2}$)	Zn ($\times10^{-2}$)	Cd ($\times10^{-2}$)	As ($\times10^{-2}$)	Cr ($\times10^{-2}$)	Mn ($\times10^{-2}$)	Pb ($\times10^{-2}$)	Ni ($\times10^{-2}$)	HI = ∑HQ
A1B	1.26	0.25	3.13	10.40	21.90	5.38	3.90	4.69	0.509
A2B	2.12	5.09	3.13	20.80	26.00	8.15	0.78	5.16	0.713
A3B	3.02	0.26	3.13	31.30	21.90	6.41	7.82	4.53	0.783
A4B	0.50	0.31	6.25	20.80	31.30	7.23	2.35	5.78	0.745
A5B	0.55	0.42	9.38	31.30	42.70	7.50	1.56	7.35	1.010
B1B	2.12	5.09	3.13	10.40	24.00	4.17	3.13	5.47	0.575
B2B	0.45	4.94	6.25	20.80	26.00	6.36	2.35	7.35	0.745
B3B	0.95	4.88	3.13	20.80	22.90	1.03	4.70	6.57	0.650
B4B	0.86	4.98	6.25	31.30	13.50	5.98	5.48	5.94	0.743
B5B	0.81	4.88	3.13	41.70	24.00	6.12	3.90	7.50	0.920
C1B	0.93	5.04	3.13	31.30	15.60	3.93	2.35	4.85	0.672
C2B	1.19	5.03	3.13	10.40	26.00	4.06	5.48	3.44	0.588
C3B	0.85	5.07	6.25	20.80	29.20	5.16	1.56	5.16	0.740
C4B	0.18	4.71	3.13	10.40	26.00	7.01	2.35	5.32	0.591
C5B	0.20	4.81	9.38	20.80	30.20	7.23	1.56	6.72	0.809
D1B	0.45	2.09	31.30	20.80	22.90	6.41	2.35	3.91	0.902
D2B	0.68	2.61	3.13	20.80	28.10	4.60	3.13	4.22	0.673
D3B	1.09	2.74	6.25	10.40	18.80	4.22	3.13	5.32	0.519
D4B	0.94	2.20	3.13	20.80	12.50	4.67	3.13	4.85	0.522
D5B	0.99	2.32	9.38	10.40	15.60	4.73	3.90	5.78	0.531
Mean	1.00	3.39	6.25	20.80	23.90	5.51	3.13	5.47	0.695

Lead also showed a substantial increase in dug-well water, with a mean HQ of 0.164, compared with only 0.031 in borehole water. These elevated HQ values reflect the generally higher concentrations of arsenic, lead and cadmium measured in dug-well water, most likely resulting from shallow groundwater vulnerability to anthropogenic contamination, surface runoff, waste disposal activities and weathering of surrounding geological formations.

The cumulative HI values for dug-well water ranged from 0.593 to 1.860, with a mean value of 1.110 (Table 7). Unlike borehole water, where nearly all samples remained within acceptable limits, several dug-well samples including A2W (1.860), A5W (1.650), C2W (1.480), D1W (1.440), C3W (1.350), A4W (1.310), and A3W (1.230) exceeded the recommended threshold of HI = 1.0. Overall, approximately 45% of the dug-well samples exhibited unacceptable cumulative non-carcinogenic risk, indicating that prolonged consumption of untreated dug-well water could result in adverse health effects, particularly among sensitive populations such as children, pregnant women and immunocompromised individuals.

The elevated HI values are largely driven by the combined effects of arsenic, chromium and lead, which are recognized for their chronic toxicity and tendency to accumulate in biological tissues following long-term exposure.

Table7: Hazard quotient of heavy metals in dug well water

Sample ID	Fe ($\times10^{-2}$)	Zn ($\times10^{-2}$)	Cd ($\times10^{-2}$)	As ($\times10^{-2}$)	Cr ($\times10^{-2}$)	Mn ($\times10^{-2}$)	Pb ($\times10^{-2}$)	Ni ($\times10^{-2}$)	HI = ∑HQ
A1W	4.50	0.48	6.25	31.30	28.10	7.48	3.90	8.75	0.908
A2W	4.07	0.48	12.50	104.00	32.30	9.67	13.30	9.53	1.860
A3W	1.45	0.43	6.25	62.70	26.00	7.61	11.70	7.03	1.230
A4W	1.41	0.44	3.13	52.00	33.30	8.57	22.70	9.69	1.310
A5W	1.45	0.54	6.25	62.70	43.80	8.82	30.50	11.30	1.650
B1W	2.62	4.95	6.25	10.40	37.50	0.58	18.00	8.44	0.887
B2W	2.10	0.50	9.38	41.70	25.00	7.59	14.90	7.03	1.080
B3W	1.80	5.09	12.50	10.40	18.80	0.45	8.60	5.63	0.633
B4W	1.65	0.55	6.25	31.30	21.90	6.99	6.25	6.10	0.810
B5W	1.75	0.69	3.13	20.80	32.30	7.21	7.03	6.10	0.790
C1W	2.17	4.92	9.38	41.70	26.00	2.30	7.03	5.94	0.995
C2W	1.84	4.93	6.25	52.00	25.00	5.85	46.90	5.63	1.480
C3W	2.25	4.97	6.25	73.00	32.30	5.60	3.90	7.03	1.350
C4W	2.54	5.01	6.25	10.40	11.50	5.96	15.60	6.57	0.638
C5W	2.58	5.11	9.38	20.80	21.90	6.14	23.50	8.13	0.975
D1W	2.29	5.79	9.38	52.00	24.00	5.56	39.90	5.47	1.440
D2W	1.81	0.46	9.38	20.80	19.80	6.34	7.83	5.78	0.722
D3W	2.11	0.42	6.25	10.40	15.60	5.87	11.70	6.88	0.593
D4W	1.75	0.53	12.50	31.30	18.80	6.47	11.00	6.10	0.884
D5W	1.78	0.64	9.38	20.80	29.20	6.61	18.80	7.66	0.948
Mean	2.20	2.34	9.38	41.70	26.00	6.09	16.40	7.19	1.110

Comparison of Tables 6 and 7 clearly demonstrates that dug-well water poses a greater non-carcinogenic health risk than borehole water. The mean HI increased from 0.695 in borehole water to 1.110 in dug-well water, representing an increase of approximately 60%. Similarly, the HQ values of arsenic, lead and cadmium were considerably higher in dug-well water, highlighting the greater susceptibility of shallow groundwater sources to contamination. These findings agree with previous studies reporting that shallow wells generally exhibit poorer water quality than deeper boreholes because they are more directly influenced by agricultural activities, indiscriminate waste disposal, septic systems and other surface-derived pollutants. Although most individual HQ values were consistently below the critical limit, the cumulative HI emphasizes that simultaneous exposure to multiple metals substantially increases overall health risk. Consequently, routine monitoring, appropriate water treatment and effective groundwater protection strategies are essential to minimize chronic exposure to toxic metals, particularly for communities relying on untreated dug-well water as their primary source of drinking water.

3.5 Carcinogenic Health Risk Assessment

The carcinogenic risk associated with the long-term consumption of borehole and dug-well water was evaluated using the Incremental Lifetime Cancer Risk (ILCR) model for cadmium (Cd), arsenic (As), chromium (Cr), lead (Pb) and nickel (Ni). The computed ILCR values and Total Cancer Risk (TCR) for borehole and dug-well water are presented in Tables 8 and 9, respectively.

Table 8: Incremental life cancer risk (ILCR) for adult population in borehole water

Sample ID	Cd ($\times10^{-5}$)	As ($\times10^{-5}$)	Cr ($\times10^{-4}$)	Pb ($\times10^{-6}$)	Ni ($\times10^{-3}$)	TCR ($\times10^{-3}$)
A1B	1.88	4.70	3.29	1.40	1.80	1.99
A2B	1.88	9.38	3.91	0.28	1.75	2.26
A3B	1.88	14.10	3.29	2.82	1.54	2.03
A4B	3.75	9.38	4.70	0.84	1.97	2.57
A5B	5.63	14.10	6.42	0.56	2.50	3.34
B1B	1.88	4.70	3.60	1.13	1.86	2.29
B2B	3.75	9.38	3.91	0.84	2.50	3.02
B3B	1.88	9.38	3.45	1.69	2.23	2.69
B4B	3.75	14.10	2.03	1.97	2.02	2.40
B5B	1.88	18.80	3.60	1.40	2.55	3.12
C1B	1.88	14.10	2.35	0.84	1.65	2.04
C2B	1.88	4.70	3.91	1.97	1.17	1.63
C3B	3.75	9.38	4.38	0.56	1.75	2.32
C4B	1.88	4.70	3.91	0.84	1.81	2.26
C5B	5.63	9.38	4.54	0.56	2.29	0.61
D1B	18.80	9.38	3.45	0.84	1.33	1.96
D2B	1.88	9.38	4.23	1.13	1.44	1.97
D3B	3.75	4.70	2.82	1.13	1.81	2.17
D4B	1.88	9.38	1.88	1.13	1.65	1.95
D5B	5.63	4.70	2.35	1.40	1.97	2.30
Mean	3.75	9.38	3.60	1.13	1.86	2.34

The ILCR results for borehole water (Table 8) indicate that the mean lifetime cancer risks for Cd, As, Cr, Pb and Ni were 3.75×10^{-5}, 9.38×10^{-5}, 3.60×10^{-4}, 1.13×10^{-6} and 1.86×10^{-3}, respectively. Comparison of these values with the United States Environmental Protection Agency (USEPA) acceptable cancer risk range (10^{-6}–10^{-4}) shows that the mean ILCR values for cadmium, arsenic and lead remain within or close to the acceptable risk range. In contrast, chromium and nickel exceeded the maximum acceptable limit of 1×10^{-4}, indicating potential carcinogenic health risks associated with prolonged ingestion of borehole water. Nickel recorded the highest mean ILCR (1.86×10^{-3}), nearly five times greater than chromium and almost twenty times higher than arsenic, demonstrating that nickel represents the dominant carcinogenic contaminant in borehole water. Chromium also contributed substantially to cancer risk because of the well-established carcinogenic properties of hexavalent chromium compounds, particularly following long-term oral exposure.

The cumulative Total Cancer Risk (TCR) values for borehole water ranged from 0.61×10^{-3} to 3.34×10^{-3}, with a mean value of 2.34×10^{-3} (Table 8). Since all TCR values substantially exceeded the recommended acceptable limit of 1×10^{-4}, continuous

consumption of borehole water may increase lifetime cancer risk among exposed populations. Although most individual metals satisfied regulatory guidelines for concentration, their cumulative carcinogenic effects indicate that prolonged exposure cannot be considered entirely safe.

The carcinogenic risk assessment for dug-well water (Table 9) showed consistently higher ILCR values than those observed for borehole water. The mean ILCR values for Cd, As, Cr, Pb and Ni were 4.69×10^{-5}, 1.71×10^{-4}, 3.93×10^{-4}, 5.17×10^{-6} and 2.46×10^{-3}, respectively. Compared with borehole water, cadmium increased by approximately 25%, arsenic by 82%, chromium by about 9%, lead by more than 350%, and nickel by approximately 32%. The markedly higher arsenic concentration in dug-well water caused its mean ILCR to exceed the USEPA acceptable limit, thereby classifying arsenic, together with chromium and nickel, as major carcinogenic contaminants in the shallow groundwater sources.

Table 9: Incremental life cancer risk (ILCR) for adult population in dug well water

Sample ID	Cd ($\times10^{-5}$)	As ($\times10^{-4}$)	Cr ($\times10^{-4}$)	Pb ($\times10^{-6}$)	Ni ($\times10^{-3}$)	TCR ($\times10^{-3}$)
A1W	3.75	1.41	4.23	1.40	2.97	3.58
A2W	7.50	4.70	4.86	4.78	3.24	4.28
A3W	3.75	2.82	3.91	4.22	2.39	3.11
A4W	1.88	2.34	5.01	8.15	3.25	4.06
A5W	3.75	2.82	6.58	11.00	3.82	4.81
B1W	3.75	0.47	5.64	6.47	2.87	3.52
B2W	5.63	1.88	3.76	5.34	2.39	3.02
B3W	7.50	0.47	2.82	3.10	1.91	2.32
B4W	3.75	1.41	3.29	2.25	2.07	2.58
B5W	1.88	0.94	4.85	2.52	2.07	2.67
C1W	5.63	1.88	3.91	2.53	2.02	2.66
C2W	3.75	2.34	3.76	16.80	1.91	2.58
C3W	3.75	3.29	4.86	1.40	2.39	0.85
C4W	3.75	0.47	1.72	5.63	2.23	2.49
C5W	5.63	0.94	3.29	8.44	2.76	3.25
D1W	5.63	2.34	3.60	1.43	1.86	2.51
D2W	5.63	0.94	2.98	2.82	1.96	2.42
D3W	3.75	0.47	2.35	4.22	2.33	2.66
D4W	7.50	1.41	2.82	3.94	2.07	2.57
D5W	5.63	0.94	4.38	6.75	2.60	3.20
Mean	4.69	1.71	3.93	5.17	2.46	3.08

Nickel remained the largest contributor to cancer risk, followed by chromium and arsenic, whereas cadmium and lead contributed comparatively smaller proportions.

The Total Cancer Risk (TCR) values for dug-well water ranged from 0.85×10^{-3} to 4.81×10^{-3}, with a mean value of 3.08×10^{-3} (Table 9). This mean TCR is approximately 32% higher than that obtained for borehole water (2.34×10^{-3}), confirming that dug-well water presents a substantially greater carcinogenic health risk. The highest TCR values occurred in samples A5W (4.81×10^{-3}), A2W (4.28×10^{-3}) and A4W (4.06×10^{-3}), reflecting the elevated concentrations of arsenic, chromium and nickel measured in these locations.

Comparison of Tables 8 and 9 demonstrates that dug-well water consistently exhibits higher carcinogenic risks than borehole water. The elevated cancer risks are attributable to the greater concentrations of arsenic, chromium and nickel in shallow groundwater, likely arising from anthropogenic activities, geological weathering, domestic waste infiltration and other surface contamination pathways. Overall, both water sources produced TCR values well above the internationally acceptable threshold of 1×10^{-4}, indicating that long-term consumption without treatment may increase the probability of cancer development over a lifetime. These findings underscore the urgent need for continuous groundwater quality monitoring, implementation of appropriate treatment technologies, pollution source control and public health interventions to reduce chronic exposure to carcinogenic heavy metals in the study area.

4.0 Conclusion

This study assessed the concentrations of selected heavy metals (Fe, Zn, Cd, As, Cr, Mn, Pb, and Ni) in borehole and dug-well water from Dei-Dei District, Federal Capital Territory, Nigeria, and evaluated the associated non-carcinogenic and carcinogenic health risks resulting from their consumption. The results revealed that borehole water generally exhibited better quality than dug-well water. Although most heavy metals in borehole water complied with the maximum permissible limits prescribed by the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ), elevated concentrations of iron and manganese were observed in some samples. Dug-well water showed relatively higher concentrations of iron, arsenic, lead and nickel, reflecting the greater susceptibility of shallow groundwater to anthropogenic contamination and surface infiltration.

The estimated daily intake (EDI) values indicated continuous human exposure to both essential and toxic heavy metals through drinking water. While individual Hazard Quotient (HQ) values for all metals remained below the critical threshold of unity, suggesting no immediate non-carcinogenic risk from single-metal exposure, the cumulative Hazard Index (HI) demonstrated that several dug-well water samples exceeded the acceptable limit ($HI > 1$). This finding indicates that prolonged exposure to multiple heavy metals through untreated dug-well water may result in adverse non-carcinogenic health effects. Arsenic and chromium were identified as the principal contributors to the overall non-carcinogenic risk.

The carcinogenic risk assessment further revealed that chromium and nickel in both borehole and dug-well water, together with arsenic in dug-well water, produced incremental lifetime cancer risk (ILCR) values above the internationally accepted threshold (1×10^{-4}). Furthermore, the total lifetime cancer risk (TCR) for both water sources exceeded the recommended acceptable limit, indicating that continuous consumption of untreated groundwater from the study area may increase the probability of cancer development over a lifetime. Dug-well water consistently exhibited higher carcinogenic and non-carcinogenic risks than borehole water, confirming its poorer overall quality.

Overall, the study demonstrates that although borehole water represents a relatively safer source of domestic water than dug-well water, neither source can be considered completely risk-free with respect to long-term exposure to toxic heavy metals. The findings underscore the need for routine groundwater quality monitoring, implementation of appropriate water treatment technologies before consumption, protection of groundwater recharge zones from anthropogenic pollution, and enforcement of environmental regulations aimed at safeguarding public health. Continuous surveillance and public awareness programmes are also recommended to

minimize chronic exposure to heavy metals and ensure sustainable access to safe drinking water in the study area.

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Compliance with Ethical Standards

Declaration Ethical Approval

Not Applicable

Competing interests

The authors declare that they have no known competing financial interests

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Availability of data and materials

Data would be made available on request.

Author Contributions

Emeka Chima Ogoko conceived and designed the study, supervised the research, performed data analysis and interpretation, and drafted the manuscript. Bilkisu Jalo Abdullahi participated in sample collection, laboratory analyses, data validation, and manuscript revision. Donard Emeziem contributed to methodology development, statistical analysis, interpretation of results, critical manuscript review, and approved the final version for publication.