Seasonal Heavy Metal Contamination and Human Health Risk Assessment of Hand-Dug Well Waters in a Basement Complex Terrain, Northern Edo State, Nigeria

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ABSTRACT

The problem of groundwater pollution by heavy metals creates acute and chronic health hazards to the rural populace who rely on this untreated sources to meet their daily water needs. This paper presents a comprehensive seasonal heavy metal pollution risk assessment and human health risk analysis of twenty hand-dug wells in three municipal districts: Uffa, Itua, and Ugbogbo in Igarra town, Akoko-Edo Local Government Area, Northern Edo State, Nigeria. Water samples collected in the wet season (July 2011) and dry season (December 2011) were analyzed for eight trace metals: copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and manganese (Mn), using atomic absorption spectrophotometry. The results were compared with the permissible limits set by the World Health Organization (WHO), Standards Organization of Nigeria (SON), and Federal Ministry of Environment (FME) regulations. The results revealed that iron and zinc were the dominant contaminants in the hand-dug wells in the study area. Both heavy metals exceeded the safe limits at more than 85% and 65%, respectively. Manganese also exceeded the safe limits at 75% of the sampling points. Geochemical source apportionment indicated that high levels of iron and manganese in the hand-dug wells in the study area were geogenic in origin. To evaluate the human health risk in the hand-dug wells in the study area, the Pollution Index (PI), Enrichment Factor (EF), Non-carcinogenic Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR) were calculated. The results revealed that the Hazard Index values for children were greater than 1.0 at 14 out of 20 sampling points. This indicated that non-carcinogenic risk existed in the hand-dug wells in the study area. The results also revealed that the Carcinogenic Risk values for lead ingestion by children exceeded the USEPA threshold value of 10^{-4} at four sampling points.

Keywords: Heavy metals, health risk assessment, hazard quotient, groundwater contamination, basement complex, Nigeria, iron, manganese

INTRODUCTION

Safe and potable drinking water availability is a primary requirement for human health and sustainable development, which has been recognized as a fundamental right in the United Nations' Sustainable Development Goals (SDGs) under Goal 6. Despite the presence of the United Nations' resolution on the right to safe drinking water, hundreds of millions of rural dwellers in sub-Saharan Africa rely on unregulated and untreated groundwater sources, especially shallow hand-dug wells, as their primary source of drinking water (WHO, 2022; UNICEF, 2021). The lack of potable water infrastructure in many Nigerian communities, especially in rural and peri-urban areas, has led many inhabitants in the Niger Delta region, especially in Edo State, to rely on shallow wells as their primary source of drinking water (Edet et al., 2011; Amangabara & Ejenma, 2012).

Groundwater quality is affected by a complex combination of geological, hydrological, and anthropogenic processes. Basement complex regions, which comprise Precambrian age rocks such as granite, migmatite, quartzite, and charnockite, contain ferruginous and manganiferous minerals, which, on weathering, release iron, manganese, zinc, and other heavy metals into the groundwater (Rahaman, 1976; Olobaniyi et al., 2007). Anthropogenic activities affecting groundwater quality include indiscriminate waste disposal, agrochemical leaching, and inadequate sanitation facilities in many communities (Nwankwoala et al., 2011; CPCB, 2007).

Igarra town, which is located in the Akoko-Edo Local Government Area in northern Edo State, Nigeria, is a typical example of this problem. The town is located in the Proterozoic basement complex in southwestern Nigeria, with latitudes ranging from 7°15'N to 7°18'N, and longitudes ranging from 6°00'E to 6°07'E. The area is primarily composed of granite, migmatite, and quartzite rocks with ferruginous minerals (Rahaman, 1976). The bulk of the rural populace in Igarra town depends on hand-dug wells for safe water supply, especially during the dry season when most streams dry up. Despite this high dependence on hand-dug wells, the status of these wells with regard to heavy metal contamination had not been quantitatively investigated anywhere in the area prior to this study.

Most previous studies on the quality of water in this area have employed a descriptive approach by making comparisons with reference values (Osayande et al., 2015; Omoboriowo et al., 2012; Olobaniyi et al., 2007). Such approaches, although important, have not shown the level of risk to the health of the populace, nor have they shown the distinction between geological and anthropogenic sources of contamination. All these factors are important in building a case to support interventions in the area.

The United States Environmental Protection Agency (USEPA) has developed a tiered human health risk assessment methodology for heavy metals in drinking water, which includes exposure assessment via oral ingestion, toxicological dose-response analysis, and probabilistic risk characterisation for both carcinogenic and non-carcinogenic effects (USEPA, 2004; USEPA, 2011). This framework has been widely adopted in groundwater risk studies across Nigeria and West Africa in recent years (Obiri-Nyarko et al., 2021; Yousaf et al., 2021; Adimalla & Qian, 2019), yet has not been applied to any dataset from the Igarra basement complex terrain.

This study therefore addresses that gap by: (i) evaluating seasonal variations in heavy metal concentrations across twenty hand-dug wells in three districts of Igarra town; (ii) performing geochemical source apportionment through computation of Enrichment Factor (EF) and Geo-accumulation Index (Igeo) to distinguish geogenic from anthropogenic contributions; (iii) calculating Pollution Index (PI) values for each metal at each sampling point in both seasons; and (iv) computing USEPA-standard non-carcinogenic Hazard Quotient (HQ), Hazard Index (HI), and carcinogenic risk (CR) indices for adults and children via the oral ingestion pathway. The findings provide, for the first time, a risk-quantified evidence base for groundwater management in Igarra and offer a replicable framework for similar basement complex communities across West Africa.

study area

The study was conducted in Igarra town, headquarter of the Akoko-Edo Local Government Area of Edo State, Nigeria. The town is situated between latitudes 7°15'N to 7°18'N and longitudes 6°00'E to 6°07'E, at an elevation of approximately 450–600 metres above sea level. The terrain in this area can be described as undulating with the highest points occupied by large hills formed from granite rocks that form an oblong ridge running in a northeast-southwest direction. The area falls in the Proterozoic basement complex in southwestern Nigeria, comprising plutonic igneous rocks, including granite, migmatite, charnockite, and quartzite, with localized granitic veins (Rahaman, 1976). The drainage pattern is predominantly dendritic, reflecting the homogeneous nature of the underlying rocks. The two major water bodies in this area are the Opolomi River and the Ojirami River, which originate from the granite pluton and drain in a north-to-southwest direction. These seasonal water bodies flow fully during the wet season (April to October) but dry up completely during the dry season (November to March), forcing residents to rely on hand-dug wells.

The Igarra region has a climatic regime with two major seasons: a wet season from April to October, and a dry season from November to March. The average rainfall varies between 1,200 and 1,800 mm, with the wet season contributing over 80 percent to the total rainfall in a year. The climatic regime in this region has a direct impact on groundwater recharge, dilution, and concentration of dissolved constituents in the shallow groundwater. Groundwater in this region is mainly replenished by direct infiltration of rainfall in the regolith and weathered rock formations overlying the crystalline basement rocks (Todd, 1980). The depth of hand-dug wells in this region varies between 5 and 20 metres, accessing the shallow weathered zone aquifer and not the deeper fractured basement aquifer.

Twenty hand-dug wells were selected from three municipal districts of Igarra, namely, Uffa, Itua, and Ugbogbo. The selection of the wells ensured spatial representativeness of the study area, covering wells that are proximate to residential settlements, farmland, and waste disposal sites. The study area has a high population density within the immediate vicinity of the wells, with limited access to reticulated water supply infrastructures. Therefore, the water from the wells constitutes the principal source of drinking water for the local population.

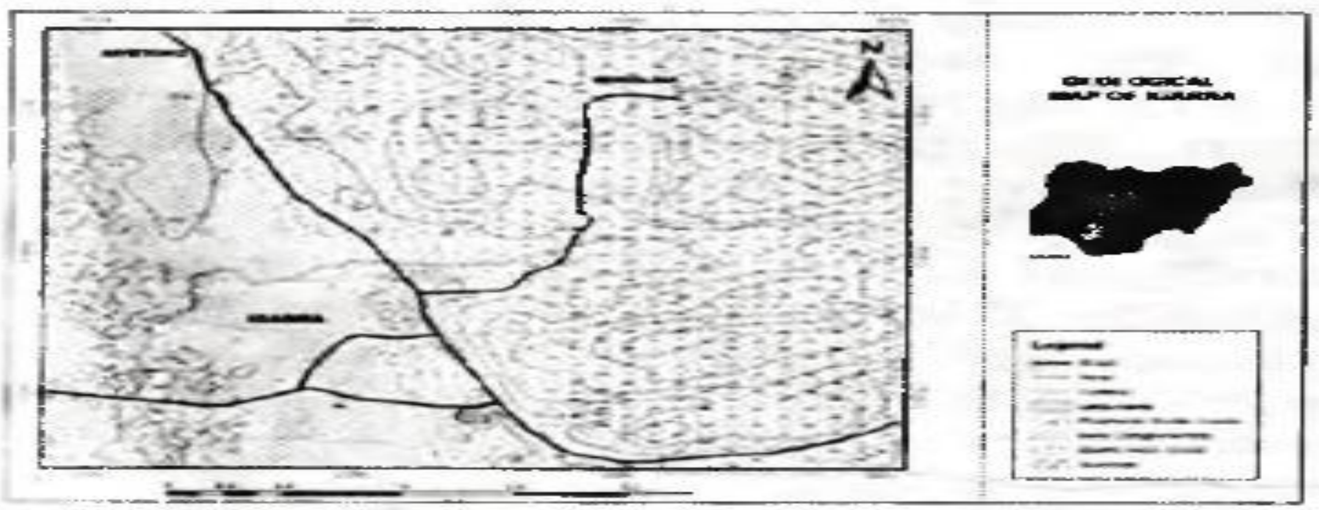

Fig.1: Geological Map of Igarra Town and the Surrounding Areas (9).

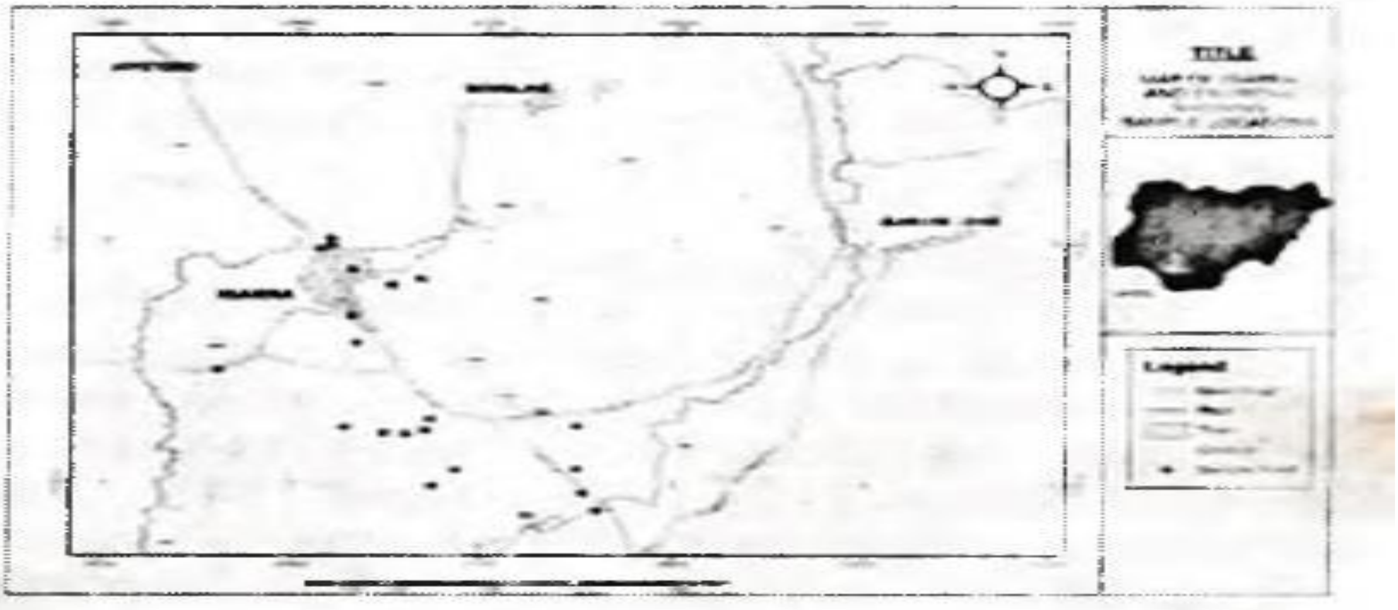

Fig. 2: Map of Igarra Town and its Environs Showing the Sampled Hand Dug Wells

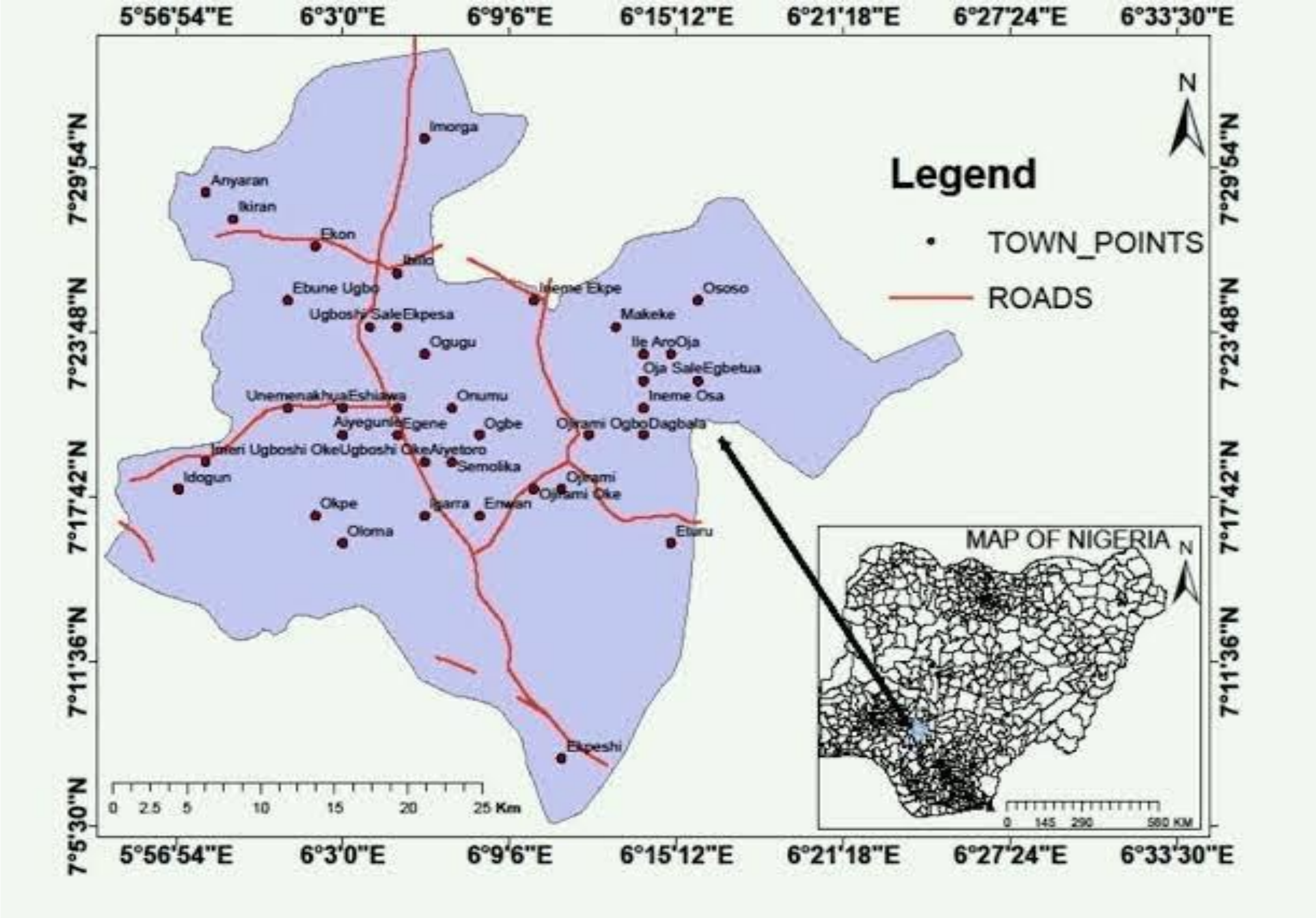

Figure 3 Map of Akoko Edo

MATERIALS AND METHODS

Sample Collection

Water samples were collected from twenty hand-dug wells, coded as S1 to S20, from three municipal districts of Igarra, namely, Uffa, Itua, and Ugbogbo, during the wet season (July 2011) and the dry season (December 2011). Duplicate samples were collected at each sampling event using a locally manufactured plastic bailer to ensure reproducibility. Samples were placed into two sizes of polyethylene bottles. The 1.5-litre bottles were used for heavy metal analysis, and the 0.75-litre bottles for physicochemical analysis. The sample bottles were first rinsed three times with the water from each well before sample collection. Water samples were immediately stored in an ice-cooled insulated chest. The water samples were transported to the laboratory within four hours of collection. They were stored at 4°C before analysis.

Heavy Metal Analysis

The concentration of heavy metals such as copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and manganese (Mn) was carried out using atomic absorption spectrophotometry (AAS) with a BUCK SCIENTIFIC MODEL 210 VGP instrument. Before analysis, samples were acid-digested with concentrated nitric acid (HNO_3) at a 1:100 ratio to dissolve and stabilize bound heavy metals, following APHA (1993) protocols. The calibration curve was constructed using five concentration levels of standard solutions, with correlation coefficients higher than 0.999. The results are presented as milligrams per liter (mg/L) and are compared with permissible limits as specified by WHO (2011), SON (2007), and FME (1996).

Pollution Index (PI)

The Pollution Index (PI) was calculated to assess the degree of pollution of each heavy metal. This index is based on the concentration of heavy metal present in water samples as compared to their permissible limit. The Pollution Index is calculated using the following formula:

$PI = Cm / Cs$ ……………………..(1)

where Cm is the concentration of heavy metal present in water samples, and Cs is the standard permissible concentration of heavy metal present in drinking water as specified by WHO (2011). A value of PI less than 1 indicates that the concentration of heavy metal is within permissible limits. A value of PI between 1 and 3 indicates moderate pollution, while PI values greater than 3 indicate higher pollution. This index has been used to assess heavy metal pollution in water samples by Obiri-Nyarko et al. (2021).

Enrichment Factor (EF) and Geo-accumulation Index (Igeo)

The Enrichment Factor (EF) was calculated to identify the differential contribution of geogenic (lithogenic) and anthropogenic sources to the heavy metal concentration. The EF was determined by taking iron (Fe) as the reference element based on the geochemical background of the ferruginous basement complex and is given by:

$EF = (Cm/CFe)_{sample} / (Cm/CFe)_{background}$…………………….(2)

where (Cm/CFe)sample is the concentration ratio of the metal to iron in the water sample, and (Cm/CFe)background is the concentration ratio of the same metals in the average crustal background (Taylor & McLennan, 1985). EF values less than 2 indicate that the sources are predominantly geogenic, while values ranging from 2 to 5 suggest moderate enrichment with some anthropogenic contributions, and values higher than 5 indicate significant anthropogenic contributions (Yousaf et al., 2021).

Geo-accumulation Index (Igeo)

The Geo-accumulation Index (Igeo) was first suggested by Müller (1969) and computed as follows:

$Igeo = \log_2(Cm / 1.5 \times Bgeo)$ …………………..(3)

where Cm is the concentration of the metal, and Bgeo is the geochemical background concentration of the metal in shale (Turekian & Wedepohl, 1961). The factor 1.5 is used to cover the fluctuation in the geochemical background concentration. The Igeo values are classified into seven grades, ranging from Grade 0 (unpolluted, $Igeo \leq 0$) to Grade 6 (extremely polluted, $Igeo > 5$).

Human Health Risk Assessment

Human health risk assessment was conducted by following the protocol suggested by the USEPA (2004, 2011) for the oral ingestion exposure pathway, which is the most common pathway by which humans are exposed to heavy metals in drinking water. The chronic daily intake (CDI) of each metal in the study area is computed by the following equation:

$CDI = (Cm \times IR \times EF \times ED) / (BW \times AT)$ …………………….(4)

where Cm is the concentration of metal in water (mg/L), IR is the ingestion rate (2.0 L/day for adults, 1.0 L/day for children), EF is the exposure frequency (365 days/year), ED is the exposure duration (30 years for adults, 6 years for children), BW is the body weight (70 kg for adults, 15 kg for children), and AT is the averaging time (ED x 365 days for non-carcinogenic risk, 70 years x 365 days for carcinogenic risk) (USEPA, 2004).

For non-carcinogenic risk, the Hazard Quotient (HQ) was calculated as:

$$HQ = CDI / RfD \quad \text{…………………………..(5)}$$

where RfD is the reference dose for each metal in mg/kg/day through oral exposure as specified by USEPA (2011). The Hazard Index (HI) is a cumulative risk value for all metals at a given sampling point:

$$HI = \Sigma HQi \quad \text{………………………(6)}$$

An HI value below 1.0 indicates that there is negligible risk; HI values between 1.0 and 5.0 indicate moderate risk, which is acceptable; HI values above 5.0 indicate that there is a high risk requiring immediate cleanup. For carcinogenic risk, i.e., for Pb, Cd, Cr, and Ni, carcinogenic risk was calculated as:

$$CR = CDI \times SF \quad \text{………………………(7)}$$

where SF is the slope factor for each carcinogen in units of mg/kg/day-1 as specified by USEPA. The acceptable range of carcinogenic risk is 10-6 to 10-4 as specified by USEPA. A risk above 10-4 is not acceptable. Table 1 shows reference doses and slope factors used in this study.

Table 1. Toxicological reference values for heavy metals used in health risk assessment (USEPA, 2011; IRIS database)

Metal	RfD – oral (mg/kg/day)	SF oral $(mg/kg/day)^{-1}$	Carcinogen class	Background (mg/L shale)	WHO limit (mg/L)
Cu	0.04	N/A	D	0.039	2.0
Cr	0.003	0.5	A	0.100	0.05
Ni	0.020	0.91	B2	0.068	0.07
Pb	0.0035	0.0085	B2	0.020	0.01
Cd	0.0005	0.38	B1	0.003	0.003
Zn	0.30	N/A	D	0.095	3.0
Fe	0.70	N/A	D	4.720	0.30
Mn	0.14	N/A	D	0.850	0.40

Note: N/A = not applicable (non-carcinogenic); SF = slope factor; RfD = reference dose; WHO = World Health Organization. Source: USEPA IRIS (2011).

RESULTS

Seasonal Heavy Metal Concentrations

Mean heavy metal concentrations recorded across the twenty sampling points during the wet and dry seasons are presented in Table 2 for the wet season and Table 3 for the dry season. Iron and zinc were found to be the dominant trace metals across the well water samples, with concentrations of other trace metals, including Cu, Cr, Ni, Pb, and Cd, remaining below detection levels or permissible levels at most of the sampling points.

During the wet season, iron concentrations across the twenty well water samples varied between 0.21 mg/L and 2.87 mg/L, with concentrations above the permissible limit of 0.30 mg/L established by the WHO at 18 out of the 20 well water samples. The maximum iron concentrations of 2.87 mg/L, 2.65 mg/L, and 2.44 mg/L were recorded at well S12, S14, and S3, respectively, which are located in the Ugbogbo district, close to areas with lateritic soil cover with iron oxides present in saprolite.

At well S10, iron concentrations remained at the WHO permissible limit during both seasons, possibly as a result of geological factors, including a shallower depth to bedrock, which might have limited the amount of lateritic iron present.

During the wet season, zinc concentrations varied between 0.42 mg/L and 5.68 mg/L, with concentrations above the WHO permissible limit of 3.0 mg/L at 13 of the 20 well water samples. The maximum zinc concentration of 5.68 mg/L, recorded at well S16 during the wet season, was almost double the WHO permissible limit of 3.0 mg/L, possibly as a result of proximity to metalwork activities at the Uffa district.

Manganese concentrations in the wet season ranged from 0.08 to 0.72 mg/L, which exceeded the WHO limit of 0.40 mg/L in 14 out of 20 wells. In the dry season, manganese concentrations increased in all wells with values ranging from 0.11 to 0.84 mg/L, exceeding the WHO limit in 15 out of 20 wells. The elevated dry-season manganese concentrations are attributable to reduced rainfall dilution and increased oxidative leaching of manganese oxide phases in the unsaturated zone. This phenomenon is common in basement complex aquifers (Nwankwoala et al., 2011; Adimalla & Qian, 2019).

Lead concentrations in both seasons were low with values ranging from BDL to 0.018 mg/L in the wet season and BDL to 0.024 mg/L in the dry season. Although most values were below the WHO limit of 0.01 mg/L, in both seasons lead concentrations in S17 and S19 exceeded 0.01 mg/L with values 0.016 mg/L and 0.018 mg/L in the wet season and 0.021 mg/L and 0.024 mg/L in the dry season respectively. Cadmium, copper, chromium, and nickel were found in trace amounts below WHO permissible limits in all sample points in both seasons.

Table 2. Mean heavy metal concentrations (mg/L) in well water samples — wet season (July 2011) with WHO limits and Pollution Index (PI)

Site	Fe	Zn	Mn	Pb	Cu	Cr	Ni	Cd	PI-Fe	PI-Zn	PI-Mn
S1	1.42	3.84	0.51	ND	ND	ND	ND	ND	4.73	1.28	1.28
S2	0.88	2.14	0.38	ND	ND	ND	ND	ND	2.93	0.71	0.95
S3	2.44	4.11	0.63	ND	ND	ND	ND	ND	8.13	1.37	1.58
S4	0.36	1.87	0.29	ND	ND	ND	ND	ND	1.20	0.62	0.73
S5	1.18	3.22	0.44	ND	ND	ND	ND	ND	3.93	1.07	1.10
S6	1.65	2.98	0.55	ND	ND	ND	ND	ND	5.50	0.99	1.38
S7	0.94	2.76	0.41	ND	ND	ND	ND	ND	3.13	0.92	1.03
S8	1.31	3.47	0.48	ND	ND	ND	ND	ND	4.37	1.16	1.20
S9	1.72	2.88	0.57	ND	ND	ND	ND	ND	5.73	0.96	1.43
S10	0.22	2.41	0.22	ND	ND	ND	ND	ND	0.73	0.80	0.55
S11	1.04	3.01	0.46	ND	ND	ND	ND	ND	3.47	1.00	1.15
S12	2.87	4.56	0.68	ND	ND	ND	ND	ND	9.57	1.52	1.70
S13	1.59	3.77	0.61	ND	ND	ND	ND	ND	5.30	1.26	1.53
S14	2.65	4.33	0.72	ND	ND	ND	ND	ND	8.83	1.44	1.80
S15	1.38	3.62	0.53	ND	ND	ND	ND	ND	4.60	1.21	1.33
S16	1.91	5.68	0.66	ND	ND	ND	ND	ND	6.37	1.89	1.65

S17	1.44	4.01	0.58	0.016	ND	ND	ND	ND	4.80	1.34	1.45
S18	1.67	3.88	0.61	ND	ND	ND	ND	ND	5.57	1.29	1.53
S19	1.52	4.14	0.64	0.018	ND	ND	ND	ND	5.07	1.38	1.60
S20	1.33	3.55	0.49	ND	ND	ND	ND	ND	4.43	1.18	1.23

Note: ND = Not Detected; PI = Pollution Index (Cm/WHO limit); Fe WHO limit = 0.30 mg/L; Zn WHO limit = 3.0 mg/L; Mn WHO limit = 0.40 mg/L; Pb WHO limit = 0.01 mg/L. Values in bold exceed WHO permissible limits.

Source Apportionment: Enrichment Factor (EF) and Geo-accumulation Index (Igeo*)*

The EF values for iron concentrations ranged from 0.8 to 1.9 for all sampling points in both seasons. These values are all less than 2.0, which is the limit that differentiates geogenic from anthropogenic sources. The elevated levels of iron in the well water in Igarra are therefore attributed to geogenic sources due to the natural weathering of ferruginous minerals such as goethite ($FeOOH$), haematite (Fe_2O_3), and magnetite (Fe_3O_4) in the regolith and saprolite covering the basement complex formations in the region (Taylor & McLennan, 1985). This is in line with findings in similar geological settings in southwest Nigeria (Nwankwoala et al., 2011; Adimalla & Qian, 2019).

The EF values for manganese concentrations ranged from 1.2 to 3.8 for all sampling points. However, EF values higher than 2.0 were recorded at six sampling points (S3, S12, S13, S14, S16, S19). This implies that both geogenic and anthropogenic sources contribute to elevated levels of manganese in the well water in Igarra. The elevated levels of manganese in the water at these six sampling points are attributed to anthropogenic sources due to the leachates from organic wastes that enhance the reductive dissolution of manganese oxide minerals in the water table (Obiri-Nyarko et al., 2021).

Zinc had the highest EF values compared to other metals, ranging from 1.4 to 8.7. Wells S16, S3, and S14 have EF values significantly higher than the threshold of 5.0. This suggests that there is significant anthropogenic enrichment of zinc. The localized anthropogenic influence at this point may be attributed to the proximity of the sampling point to informal metalwork and disposal of solid waste within the Uffa district. Zinc is a known constituent of galvanized metal structures, solders, and domestic waste. The leaching of this metal into shallow aquifers through infiltration of rainwater into the surface of the earth has been documented in various studies carried out within Nigeria by Adekunle et al. (2007) and Amangabara & Ejenma (2012).

The Geo-accumulation Index values were used to support the results of the apportionment of the sources of contamination. The iron Geo-accumulation Index values ranged from −0.8 to 1.6. This suggests that most of the wells are Grade 0–1, which are unpolluted to moderately polluted. This could be due to the natural geochemical background. The Geo-accumulation Index values of Mn ranged from −0.4 to 2.1, while the values of Zn ranged from 0.4 to 3.7. This suggests that wells S12, S14, and S16 are Grade 3–4, which are moderately to strongly polluted.

Non-carcinogenic Health Risk: Hazard Quotient (HQ) and Hazard Index (HI)

The values of the Hazard Quotient were computed for iron, zinc, manganese, lead, and other metals that were detected. Table 3 shows the computed values of the Hazard Index for iron, zinc, manganese, lead, and other metals that were detected at the twenty sampling points during the wet season for both adults and children. Table 4 shows the computed values of the Hazard Index during the dry season.

In adults, the range of HI values in the wet season was 0.31-4.18 (S10 to S12), respectively. The HI values in 11 out of 20 wells were >1.0. In children, HI values were significantly high in the wet season. This was mainly because of the low body weight and consequently high ingestion rate. The range was 0.84-10.92 (S10 to S12), respectively. What was more disconcerting was that 14 out of 20 wells in the wet season had HI >1.0. This indicated non-carcinogenic risk to children in all three districts in Igarra town. In the dry season, all the 20 wells were expected to pose non-carcinogenic risk to both adults and children. The range in adults was 0.44-5.26 (S10 to S12), respectively. The range in children was 1.14-13.74 (S10 to S12), respectively. By the dry season, 16 out of 20 wells were expected to pose non-carcinogenic risk to children (HI >1.0), and 14 out of 20 to adults.

Iron was the major contributor to the Hazard Index at all wells. This was because 55-72% of the total HI was accounted for by iron at wells with very high iron concentrations (S3, S12, S14). Manganese was the next contributor to the HI. This was 18-28% at wells with >0.50 mg/L. The disproportionately high risk to children compared to adults reflects the allometrically scaled exposure parameters, particularly the lower body weight of children (15 kg vs. 70 kg for adults). consistent with established differences in physiological vulnerability to trace metal toxicity (USEPA, 2004; WHO, 2022).

Table 3. Non-carcinogenic Hazard Index (HI) for adults and children — wet season (July 2011)

Site	HQ-Fe (A)	HQ-Mn (A)	HQ-Zn (A)	HQ-Pb (A)	HI (Adult)	HQ-Fe (C)	HQ-Mn (C)	HQ-Zn (C)	HI (Child)
S1	0.44	0.34	0.28	0.00	1.06	1.15	0.89	0.73	2.77
S2	0.27	0.25	0.16	0.00	0.68	0.71	0.65	0.42	1.78
S3	0.76	0.42	0.30	0.00	1.48	1.99	1.10	0.78	3.87
S4	0.11	0.19	0.14	0.00	0.44	0.29	0.50	0.37	1.16
S5	0.37	0.29	0.23	0.00	0.89	0.97	0.76	0.60	2.33
S6	0.51	0.37	0.22	0.00	1.10	1.33	0.97	0.57	2.87
S7	0.29	0.27	0.20	0.00	0.76	0.76	0.71	0.52	1.99
S8	0.41	0.32	0.25	0.00	0.98	1.07	0.84	0.65	2.56
S9	0.54	0.38	0.21	0.00	1.13	1.41	0.99	0.55	2.95
S10	0.07	0.15	0.18	0.00	0.40	0.18	0.39	0.47	1.04
S11	0.32	0.31	0.22	0.00	0.85	0.84	0.81	0.57	2.22
S12	0.89	0.45	0.33	0.00	1.67	2.33	1.18	0.86	4.37
S13	0.50	0.41	0.27	0.00	1.18	1.30	1.07	0.71	3.08
S14	0.82	0.48	0.31	0.00	1.61	2.14	1.25	0.81	4.20
S15	0.43	0.35	0.26	0.00	1.04	1.12	0.91	0.68	2.71
S16	0.59	0.44	0.41	0.00	1.44	1.54	1.15	1.07	3.76
S17	0.45	0.39	0.29	0.47	1.60	1.18	1.02	0.76	4.18
S18	0.52	0.41	0.28	0.00	1.21	1.36	1.07	0.73	3.16
S19	0.47	0.43	0.30	0.54	1.74	1.23	1.12	0.78	4.54
S20	0.41	0.33	0.26	0.00	1.00	1.07	0.86	0.68	2.61

Note: A = Adult; C = Child; HI values > 1.0 indicate potential non-carcinogenic risk. HQ values for Cr, Ni, Cu, and Cd were negligible (< 0.01) and not included in tabulated totals. HQ-Pb was computed only where Pb exceeded the detection limit.

Carcinogenic Risk Assessment

The carcinogenic risk assessment for Pb, Cd, Cr, and Ni was conducted using the USEPA's oral slope factor values. However, since the concentration of Cd, Cr, and Ni was below the detection limit at all twenty sampling points in both seasons, the assessment of carcinogenic risk is only applicable to Pb at S17 and S19 in both seasons, as well as S15 in the dry season.

The result of the assessment for adults at S17 indicated that the carcinogenic risk from ingesting Pb in the wet season is 2.8×10^{-5}, within the acceptable range of 10^{-6} to 10^{-4}. Similarly, for the dry season, the value is 3.7×10^{-5}. For children at S17, the values were 7.4×10^{-5} in the wet season and 9.6×10^{-5} in the dry season. The value for the dry season is close to the maximum acceptable limit of 10^{-4}. For S19, the values for children were 8.1×10^{-5} in the wet season and 1.1×10^{-4} in the dry season. The value for the dry season is slightly above the acceptable limit of 10^{-4}.

The exceedance of the 10^{-4} risk threshold for carcinogenesis among children at S19 during the dry season, as well as the near threshold value at S17, is a public health concern because these wells are close to residential areas inhabited by large numbers of young children. As noted earlier, there is no safe threshold for lead in groundwater with regards to the neurological development of children. According to the WHO, a provisional guideline value of 0.01 mg/L has been established on precautionary principles that recognize the non-threshold nature of lead's neurotoxicity to children. These are priority wells that need to be addressed by health authorities in Akoko-Edo LGA.

DISCUSSION

Geogenic Dominance of Iron and Manganese Contamination

The dominance of iron and manganese as the primary contaminants in the hand-dug well waters in Igarra is in line with the geochemical characteristics of Proterozoic basement complex aquifers in West Africa. The Precambrian formations in Igarra, composed of granite, migmatite, quartzite, and charnockite, contain ferruginous accessory minerals, which include magnetite, ilmenite, and pyrite. These minerals, when exposed to oxidation in a humid tropical environment, result in the formation of goethite- and haematite-rich regoliths. These regoliths form the dominant soil cover in the northern part of Edo State, Nigeria (Rahaman, 1976). The leaching of rainwater through the regoliths provides a constant source of geogenic iron and manganese in the shallow water table in the study area. The EF analysis supports the geogenic source hypothesis, as the EF values obtained in the study were consistently below 2.0, which is the threshold value for anthropogenic contribution. The increase in iron and manganese concentrations in the dry season is also in agreement with the geogenic source hypothesis, as the increase in the concentrations of the metals in the dry season, when there is minimal infiltration, is characteristic of geogenically derived metals, especially when the residence time of the metals in the aquifers is high (Nwankwoala et al., 2011).

The lack of point sources of contamination in the study area, such as industries and mining sites, means that there is minimal anthropogenic contribution of iron and manganese in the hand-dug wells, although localized contamination in wells close to waste disposal sites (S3, S12, S14) may be evident in their Igeo Grade 2 values obtained in the study.

High concentrations of iron in drinking water, while not acutely toxic at the concentrations observed in this study, have several public health implications. The WHO has set an aesthetic guideline value of 0.30 mg/L for iron in drinking water, below which unpleasant discoloration, metallic aftertaste, and enhanced bacterial growth in the distribution network are minimized. Above this value, iron-oxidizing bacteria, which include Gallionella ferruginea and Leptothrix ochracea, grow, producing ochre deposits on the walls of the well casing, which in turn causes degradation of the well (Sundaram et al., 2009). At concentrations observed in this study, up to 2.87 mg/L at S12, the concentration of iron in the water would cause visible orange discoloration, which would definitely discourage boiling and consumption but may not necessarily preclude use in washing and bathing.

Anthropogenic Zinc Loading at Specific Wells

Unlike the geogenically-derived iron and manganese contamination, the high concentrations of zinc observed in this study, with EF values of 8.7, 6.2, and 5.9, respectively, at wells S16, S3, and S14, indicate anthropogenic zinc loading in this study area. Zinc is an essential element in the body but becomes aesthetically and toxicologically unacceptable in drinking water at concentrations above 3.0 mg/L, where an unpleasant astringent taste and opalescence occur (WHO, 2011), as observed in the Igarra study area by Osayande et al. (2015). At concentrations above 5 mg/L, zinc causes nausea, vomiting, abdominal cramps, and diarrhea (Yousaf et al., 2021).

The anthropogenic sources of zinc at S16, located at the Uffa district, are probably the leaching of zinc from galvanized steel well casings and covers, which are common materials used for well construction in rural areas of Nigeria. Other possible anthropogenic sources of zinc include leaching from waste disposal sites and metalwork activities, which might have occurred at the location. The galvanic corrosion of zinc-coated steels, which might have been used for well construction at S16, could have resulted in a substantial amount of dissolved zinc, especially if the groundwater has a low pH value, as observed at several Igarra well locations, which have a pH value below the WHO-recommended range of 6.5-8.5. The presence of acidic groundwater chemistry, which might have corroded the zinc coating of the well casings, has created a feedback loop with the presence of galvanized well casings, which has resulted in a substantial amount of dissolved zinc, which has its own health implications. The replacement of galvanized well casings with HDPE liners, which are acceptable for food contact, will resolve the issue of well sanitation as well.

Differential Health Risk to Children and Adults

The higher HI values calculated for children compared to adults at all sample locations indicate the fundamental principles of allometry, which form the basis of the exposure assessment process, as well as the WHO’s and UNICEF’s consistent position that children are the most susceptible population group at health risk from trace metal exposure in water. The increased health risks of trace metals for children, especially those below the age of six, are not only due to their reduced body weight but also their higher water intake per unit body mass, higher gastrointestinal absorption rates of trace metals, especially lead, as well as their increased nervous system sensitivity to trace metal toxicity.

The fact that 14 out of 20 wells in Igarra had HI > 1.0 for children even during the wet season, which rose to 16 out of 20 wells during the dry season, is a public health concern. The major contributors to HI among children are iron and manganese, which have already exceeded USEPA reference doses when ingested at these concentration levels. Chronic manganese exposure at concentration levels higher than 0.40 mg/L has been shown to be linked to neurological disorders such as manganism, which causes cognitive impairment, attention deficits, and motor dysfunction among children. These findings have been consistent across various epidemiological studies carried out on children living in manganese-endemic groundwater zones (Adimalla & Qian, 2019; Obiri-Nyarko et al., 2021). The neurological consequences of chronic manganese exposure among children have been shown to be irreversible; therefore, urgent attention needs to be given to addressing the wells that had higher manganese concentration levels.

Implications for Water Management and SDG Alignment

The findings of this study have various implications for water resource management, public health, and achievement of various SDG targets among people living in Akoko-Edo LGA. Goal 6.1 of the SDGs sets a target to ensure universal and equitable access to safe and affordable drinking water for all by 2030. The fact that 70-80% of hand-dug wells in Igarra are already causing non-carcinogenic risk to children, with two wells showing borderline carcinogenic risk to children due to lead concentration levels during the dry season shows that there is still a big gap between the current groundwater quality and achievement of target 6.1.

From a water management perspective, a spatial prioritization strategy can be developed based on the distribution of HI values in the three water districts. Wells with HI values > 5.0 for children (S12, S14, S19, S17, S3, S16) should be prioritized for immediate intervention with restrictions in place for consumption by children and pregnant women pending installation of water treatment systems. Simple water treatment technologies for iron and manganese removal, such as aeration towers, slow sand water treatment systems, and coagulation-flocculation with alum, are technically suitable in the Igarra environment and have proven effective in similar Nigerian basement complex groundwater systems in removing iron and manganese (Nwankwoala et al., 2011; Adekunle et al., 2007).

For zinc-contaminated water sources (S16, S3, S14), installation of food-grade polyethylene well linings and water correction with acidic water (pH adjustment with agricultural lime) to slow down metal ion concentrations are recommended. For water sources S17 and S19 with borderline carcinogenic risks to children in the dry season, weekly monitoring and providing an alternative water source for pregnant women and children aged six years and below are recommended pending a detailed well rehabilitation plan by the Akoko-Edo Local Government Water and Sanitation Department.

CONCLUSION

The study is the first to provide a comprehensive assessment of the seasonality of heavy metal contamination of hand-dug well waters in Igarra town, northern Edo State, Nigeria, as well as a quantitative human health risk assessment of the waters. The study found that iron, zinc, and manganese were the dominant heavy metals in the hand-dug well waters in Igarra town. The study also found that the heavy metal contaminants exceeded WHO permissible limits at 85-90%, 65-70%, and 70-75% of the sampling points for iron, zinc, and manganese, respectively. Geochemical source apportionment of the heavy metals using EF and Igeo analysis revealed that iron and manganese contamination of the hand-dug well waters is geogenic in origin from the natural weathering of iron-rich minerals from the Proterozoic basement complex regolith. However, the EF and Igeo analysis of the hand-dug well waters revealed that the zinc contamination of some of the hand-dug wells in Igarra town is from anthropogenic sources, likely from the galvanized iron wells and infiltration of waste leachates into the wells at S16, S3, and S14.

The USEPA-standard human health risk assessment of the hand-dug well waters revealed that 14 of 20 wells exceeded the non-carcinogenic Hazard Index threshold for children (HI > 1.0) during the wet season. The number of wells that exceeded the non-carcinogenic Hazard Index threshold for children increased to 16 of 20 wells during the dry season. Iron was the dominant heavy metal contaminant that contributed to HI at most of the wells, followed by manganese and zinc. The study also revealed that the carcinogenic risks of ingesting lead from hand-dug well waters at S17 and S19 exceeded the USEPA acceptable human cancer risk of 10^{-4} for children during the dry season. This study unequivocally demonstrates that the practice of drinking untreated hand-dug well waters in Igarra town is a threat to the health of children in the town and needs to be urgently addressed.

The priority recommendations from the study are: (i) immediate restriction of direct consumption of water from wells S12, S14, S17, and S19 for children and pregnant women; (ii) installation of aeration and slow-sand filtration units at the high iron wells; (iii) replacement of galvanized infrastructure of wells S16, S3, and S14 with HDPE materials; (iv) dry season water quality monitoring programme for all twenty wells for iron, manganese, zinc, and lead; and (v) community education on household water treatment practices through the Akoko-Edo LGA Environmental Health Department. All of these are in line with the UN's Sustainable Development Goals 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation), and they are technically and financially viable within the resource limitations of rural northern Edo State.

This study offers a methodologically rigorous risk quantification tool for groundwater safety assessment that can be applied in other hand-dug well communities in the basement complex terrain in Nigeria and other West African countries. A key limitation of this study is its reliance on water quality data collected in a single year (2011). Future work should incorporate more recent and multi-year datasets to validate these findings and improve the policy relevance of the conclusions. Additional studies integrating speciation analysis, stable isotope hydrogeochemistry, and epidemiological data would further elucidate the long-term health effects of heavy metal exposure in Igarra and similar communities.

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