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Groundwater sustainability in hard rock terrains and related health risks assessment in semi-urban Nigeria

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ABSTRACT

Ten representative groundwater samples were randomly collected from public hand dug wells in the Igarra Town and analyzed to assess their quality for drinking purpose and associated health risks following established methodological standards. The results revealed that pH values ranged from 5.25 to 6.63, indicating slightly to moderately acidic conditions and deviation from World Health Organization (WHO) and Nigeria drinking water standards (NSDWQ). Electrical conductivity (135–535 μS/cm), total dissolved solids (65–112 mg/L), and hardness were within permissible limits, indicating low mineralization. Major ions were relatively uniform, with Ca^{2+} and HCO_3^- dominant. Piper trilinear diagram revealed mixed hydrochemical facies including Ca-Cl, Mg-HCO_3, Na-Cl, and Na-HCO_3 types, indicating evolving groundwater influenced by rock-water interaction, ion exchange, and minor evaporation, supported by Gibbs plots. Heavy metals showed widespread contamination, with Iron (Fe), Arsenic (As), Cadmium (Cd), Nickel (Ni), and Chromium (Cr) exceeding guideline limits in most wells. Arsenic, Cd, and Cr were particularly elevated, indicating potential toxic and carcinogenic risks. Zinc was generally lower but exceeded aesthetic limits in some locations. Spatial patterns suggest geogenic control with localized enrichment processes. Health risk assessment showed Hazard Index values above unity in all wells, indicating non carcinogenic risks, with children more vulnerable than adults. Incremental lifetime cancer risk values for As, Cd, Ni, and Cr exceeded USEPA acceptable limits (10^{-6}-10^{-4}) by several orders of magnitude, indicating severe carcinogenic risk. Wells 1, 7, 8 and 9 in particular had relatively high health risk levels and are therefore a priority The results indicate that, despite satisfactory bulk physicochemical quality, Igarra's public hand dug wells are contaminated with heavy metals, particularly As, Cd, Ni, and Cr, exceeding WHO, NSDWQ, and USEPA limits, with elevated health risks requiring urgent treatment, protection measures and public awareness campaign.

Introduction

Access to clean, safe freshwater remains a global challenge, especially in regions where groundwater is the primary source. This challenge is particularly acute in basement terrains, where fresh groundwater is frequently compromised by mineral dissolution within aquifer systems (Elumalai et al., 2025; Omozeje et al., 2025; Elbarghmi, 2024; Oseji et al., 2024; UNDP, 2023; Kumar et al., 2022; Everett et al., 2010). In such settings, the use of shallow, vulnerable aquifers increases the risk of contamination from both natural geological processes and anthropogenic activities (Omorogieva et al., 2024a; Michael, 2023; Adebimpe and Adekunle, 2021; Maju-Oyovwikowhe and Shuab, 2019). These contaminants, especially toxic heavy metals, pose serious health risks, including cancer, developmental issues, and reproductive disorders (Olumodeji et al., 2025; Badmus et al., 2024; Adimalla et al., 2020; Gintamo et al., 2022; WHO, 2017; Omorogieva et al., 2025; Battogtokh et al., 2014; Dirisu and Olomukoro, 2015; Selinus et al., 2013; Ji et al., 2008). Sustainable groundwater management therefore requires not only the protection of aquifer systems from contamination but also the maintenance of water quality at levels that ensure long term safety for human consumption and domestic use.

In Nigeria, groundwater remains the primary source of domestic and industrial water supply. Yet, access to safe potable water is hindered by factors such as high drilling costs, inadequate infrastructure, and widespread pollution (Ogoke et al., 2024; Akanni et al., 2023; Omorogieva et al., 2023). In rural and peri-urban areas, hand dug wells are

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often the preferred alternative due to their lower cost and ease of access. However, these wells are often shallow, poorly cased, and susceptible to surface contamination, especially in geologically complex terrains such as the Igarra region of Edo State (Gabresilasie et al., 2021; Kehinde et al., 2015). Igarra sits on fractured Precambrian basement rocks, predominantly schists intruded by Pan-African granites (Salami and Akperi, 2023; Hassan et al., 2021). Groundwater in this region is commonly sourced from hand dug wells that interact directly with mineral rich host rocks and surface pollutants. Previous studies have assessed the hydrogeological, geochemical characteristics of the Igarra aquifer and heavy metal assessments (Salami and Akperi, 2023; Ayodele and Ofuyah, 2017; Ikhifa et al., 2008; Adegoke et al., 2021; Ozegin et al., 2024) and have identified elevated concentrations of metals. However, most of these studies focus on water quality parameters in relation to regulatory standards (Umoru et al., 2021; Maju-Oyovwikowhe and Emorfurienta, 2021), without adequate evaluation of the long term health impacts of chronic exposure through oral ingestion.

Beyond conventional water quality evaluation, groundwater sustainability is increasingly been assessed using indicators that reflect the long term suitability of water resources for human consumption and public health protection. These indicators include groundwater quality status, contaminant occurrence, exposure related health risks, and the capacity of aquifer systems to provide safe water without compromising future use. In regions where groundwater serves as the primary source of drinking water, sustainability is closely linked to minimizing cumulative health effects associated with prolonged exposure to toxic contaminants. Consequently, the assessment of carcinogenic and non-carcinogenic health risks associated with heavy metal contamination provides a practical sustainability indicator for evaluating whether groundwater resources remain suitable for continued drinking purpose. Integrating hydrogeochemical characterization of specific heavy metal of public concern with health risk assessment therefore offers a more comprehensive framework for evaluating groundwater sustainability than reliance on physicochemical quality parameters alone.

This gap in knowledge at Igarra necessitates the study to comprehensively assess the health risks associated with groundwater consumption in the Igarra area, particularly from hand dug wells that serve as the main freshwater source. Furthermore, while previous investigations have provided valuable information on groundwater chemistry, limited attention has been given to the implications of groundwater quality for long term sustainability and human health protection. This study therefore aimed at quantifying heavy metal iron (Fe), arsenic (As), copper (Cu), nickel (Ni), chromium (Cr), cadmium (Cd), zinc (Zn), and major ions including sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-) concentrations in selected public wells and to evaluate the associated carcinogenic and non-carcinogenic health risks based on established models. The specific objectives of the study include collecting and analyzing groundwater samples from public hand dug wells in Igarra's semi-urban environment; determine the concentrations of selected heavy metals by using validated analytical methods and established standard of USEPA to assessing both carcinogenic and non-carcinogenic health risks posed by the assessed heavy metal through oral exposure pathway.

By linking geochemical processes with public health implications, this study offers critical insights into groundwater safety and sustainability. The combined evaluation of heavy metal occurrence and associated carcinogenic and non-carcinogenic health risks serves as a practical sustainability indicator for assessing the long term suitability of groundwater resources for domestic use. The findings will contribute to baseline data for the region, support public health interventions, and inform policies on groundwater protection. Ultimately, this research supports the achievement of several UN Sustainable Development Goals (UN, 2026), including Goal 3 (Good Health and Well-being), Goal 6 (Clean Water and Sanitation), and Goal 11 (Sustainable Cities and Communities).

Materials and methods

Study area description

Igarra, located between longitudes 6°03′30″ E and 6°08′00″ E and latitudes 7°14′50″ N and 7°22′05″ N, covers approximately 85.68 km^2 and is characterized by undulating topography with elevations of up to 350 m above sea level (Salami and Akperi, 2023; Omosuyi and Akinola, 2021). The area lies within the Precambrian Basement Complex and is predominantly underlain by metasedimentary rocks (Ozoko and Afolabi, 2023). It experiences a tropical rainforest climate with distinct wet and dry seasons, which influence groundwater recharge and availability (Omorogieva and Tonjoh, 2020). The local population is mainly engaged in farming, artisanal and commercial mining, and trading activities, while land use is dominated by residential, agricultural, commercial, educational, and quarrying activities (Ozoko and Afolabi, 2023). The geological framework and groundwater flow characteristics of the study area are presented in Figs. 1a and 1b, respectively. Groundwater

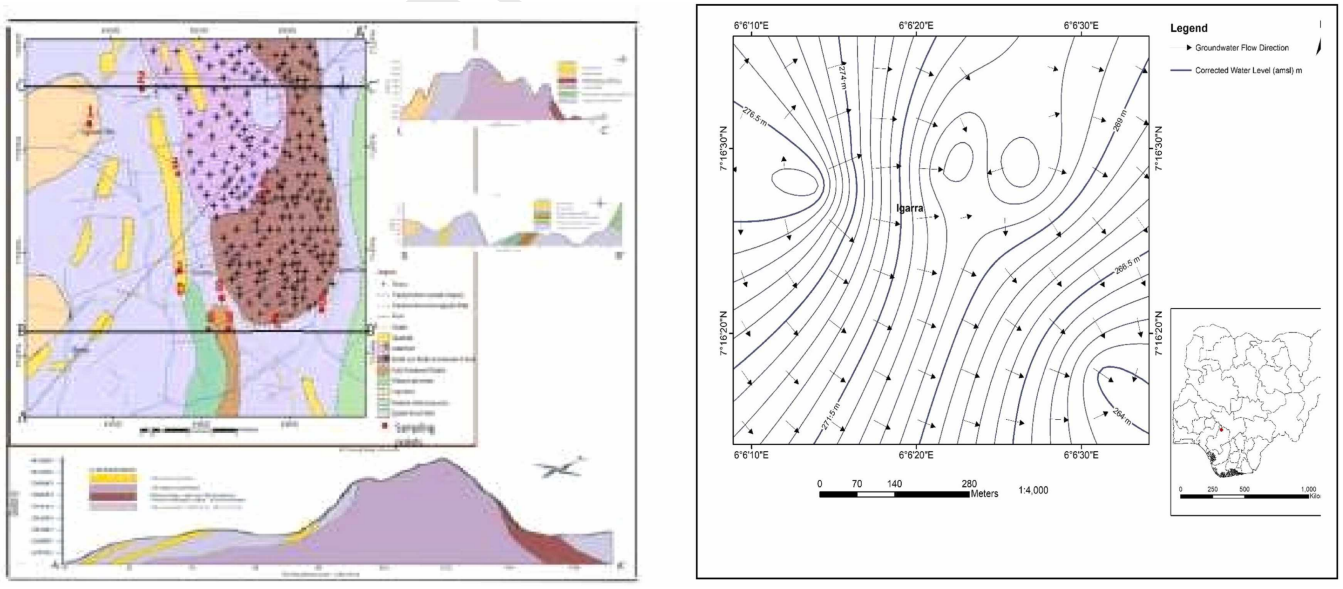


Fig. 1. a: Geological cross section of Igarra region after Salami and Akperi, (2023). Fig. 1b Groundwater flow map.

occurs beneath an overburden thickness of approximately 5.5–23.5 m, with sampled wells ranging from 2.4 to 9.26 m in depth. The average well depth is 5.38 m; these wells serves as the source of freshwater for drinking, domestic, agricultural, industrial, commercial, and livestock purposes. However, the groundwater quality in the study area are vulnerable to contamination due to shallow depth from septic systems, waste disposal practices, agricultural chemicals, and mining-related activities, which may introduce microbial and chemical pollutants into the aquifer system and threaten the long term sustainability of groundwater resources.

Fig. 1b show that groundwater generally flowing eastward and southward (east-southeastward) from areas of higher hydraulic head in the western and northwestern parts of the study area to areas of lower hydraulic head in the eastern and southeastern parts of the study area. Flow direction is more or less at right angles to the corrected water-level contours, indicated by the flow-direction arrows. The contoured areas of the western and central parts of the region show a relatively large hydraulic gradient and consequently a relatively high groundwater flow velocity while the contoured areas toward the eastern and southeastern parts of the region show a relatively small gradient and consequently a relatively low groundwater flow velocity. The groundwater flow regime is mainly northwest - southeast to east-southeast, with localized hydraulic controls in the area of the closed contours where local variations in flow direction are evident.

Sample collection and preparation

Groundwater samples were collected randomly from ten (10) representative public hand dug wells spread across the study area in the month of January, 2025 (Dry season). The depth of well 1–10 are 7.03 m, 6.15, 9.26 m, 6.25 m, 4.36 m, 3.34 m, 5.51 m, 2.40 m, 3.71 m and 5.47 m respectively. The regional aquifer system is typically encountered within the fracture basement rocks beneath an overlying overburden of thickness ranging from about 5.5–23.5 m, while groundwater levels vary seasonally depending on rainfall and recharge conditions. Water from the dug wells are used for domestic activities, irrigation, industrial and commercial purposes, and animal husbandry. The dominant land use in the area is primarily for quarry, mineral exploitation, farming and urban development. Samples collected were stored in a pre-cleaned plastic bottles, each sample was collected following standard procedures. Prior to collection, the bottles were thoroughly rinsed with groundwater to be sampled to avoid contamination. In situ parameters such as pH, temperature, and electrical conductivity were measured directly on site.

Collected samples were immediately filtered through a 0.45 μm membrane to remove suspended particles and subsequently acidified with nitric acid to preserve it for heavy metal analysis. Samples were transported promptly to the laboratory for analysis, following the guidelines recommended by the American Public Health Association (APHA, 2017); Ren et al. (2024) and ISO (2006). At the laboratory, samples were kept in a refrigerator at 4°C to maintain its original condition when it is later analyzed. The geographic coordinates of all sampling locations were recorded using a Garmin GPS 64S device to ensure precise spatial documentation.

Quality assurance and quality control (QA/QC)

Groundwater data were processed by applying wide rang quality assurance/quality control (QA/QC) procedures to assure accuracy, precision, and reliability. The sample collection, filtering on 0.45 μm membrane filters, immediate preservation in nitric acid, transportation and storage at 4 °C were all performed according to standard operating procedures (Ren et al., 2024; APHA, 2017; Csuros, 1994), ensuring uniformity and integrity of the samples. To further ensure data reliability, three randomly sampled hand dug wells were duplicated and samples were analyzed independently. Duplicate analyses confirmed an inclusive relative method precision of about ±5% and results that showed variations more than 5% were discarded and reanalyzed to validate good analytical strength. A multi-element standard solution was used regularly for instrument calibration, which resulted in very linear calibration curves ($R^2 > 0.995$). Further evidence of instrument accuracy was obtained by performing and field blanks with levels of contamination that were negligible. The accuracy of the method and analytical performance were confirmed by certified reference materials (CRMs) and spike recovery tests with results of 95–105 %. Duplicate blank measurements and calibration data were used to establish limits of detection (LOD) and limits of quantification (LOQ) to ensure the sufficient sensitivity for trace metal analysis. Furthermore, uncertainty in the measurements was assessed using duplicate analysis and instrument precision and is reported at a 95% confidence level (k = 2), which gives an overall confidence in the analytical data. The sampling method used was for groundwater in public hand dug wells, which was prepared according to the acid digestion method recommended by the American Public Health Association (APHA, 2017). The concentrations of the various heavy metals were estimated by flame atomic absorption spectrometry (FAAS) using the air acetylene flame. The study was conducted on elements of iron (Fe), arsenic (As), copper (Cu), nickel (Ni), chromium (Cr), cadmium (Cd) and zinc (Zn). The elements selected (Fe, As, Cu, Ni, Cr, Cd and Zn) are chosen because they collectively provide a good indicator of geogenic and anthropogenic sources of groundwater contamination. In the basement complex terrains, Fe, Cr and Ni from silicate and metamorphic minerals can be released to the aquifers through natural water-rock interactions (Salami and Akperi, 2023). Mining, blasting and quarrying, however, can encourage the mobilization of metals, such as As and Cd associated with sulfides and mineralized Cu and Zn (Olowoyo, 2024). Other contamination pathways include agricultural activities, such as application of fungicides and micronutrients, which can lead to higher levels of Cu and Zn in shallow groundwater, and phosphate fertilizers which may contain Cd (Olujimi et al., 2023). Therefore, this metal suite is a good foundation for the separation of the natural geological weathering from the anthropogenic overlapping contamination sources coupled with the Gibbs plot. In addition, the study also included the major ions such as sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Carbonate (CO_3^{2-}), Bicarbonate (HCO_3^-), Sulfate (SO_4^{2-}) and Chloride (Cl^-).

FAAS method is scientifically suitable for metal analysis with a high detention limit, but limited to arsenic quantification. This knowledge allows an adequate QA/QC process with analytical performance that is satisfactory. In particular, the use of internal standards for matrix correction and mass range signal optimization have been reported to enhance the quantification of trace metals in environmental waters (Yüksel and Arıca, 2018; Ustaoğlu et al., 2025). The in situ physicochemical parameters were determined in situ directly at the sampling sites using calibrated hand held meters, such as pH, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity (TA), and turbidity. All the analyses were carried out in the controlled laboratory of the Central Laboratory, Faculty of Agriculture, University of Benin, Nigeria. Groundwater flow was analyzed in a spatial manner using ArcGIS software by incorporating hydrological field data and applying the kriging interpolation technique to create groundwater distribution maps. The analytical results are given in Tables 1 and 2.

Assessment of human health risk (AHHR)

The human health risk assessment (HHRA) that was used in this study was developed to assess the possible adverse health impacts from extended groundwater use via oral ingestion pathway. Both non-carcinogenic and carcinogenic health risks were assessed based on commonly used risk indicators, such as Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), and Incremental Lifetime Cancer Risk (ILCR) which were calculated according to USEPA (2004). Non-carcinogenic risks were determined by HQ and HI values, with HI value > 1 implying potential adverse health effects, and HI value ≤ 1 implying

Table 1
Physicochemical Parameters and Heavy Metal Concentrations of Groundwater Samples Compared with WHO and SON Standards.

Parameters	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	WHO (2017/2011)	SON (2015)
pH	5.94	6.14	5.84	6.08	6.63	6.53	5.25	5.58	5.96	6.13	6.50–8.50	6.50–8.50
EC (μS/cm)	315.00	458.00	363.00	535.00	462.00	424.00	135.00	142.00	370.00	420.00	1200.00	1000.00
TDS (mg/L)	70.30	85.60	73.00	75.20	112.00	90.40	65.00	68.00	70.60	88.40	250.00	250.00
TA (mg/L)	88.90	90.60	88.00	92.40	96.50	94.00	82.80	85.70	89.60	90.00	200.00	100.00
Turbidity (NTU)	12.30	14.50	11.60	10.40	9.36	9.30	10.80	10.00	12.00	16.30	< 4.00	N/A
Fe (mg/L)	1.58	0.87	1.50	1.33	0.56	0.58	2.11	1.88	1.60	1.54	0.30	0.30
As (mg/L)	0.10	0.07	0.10	0.07	0.06	0.06	0.13	0.10	0.07	0.07	0.01	0.003
Cu (mg/L)	2.38	2.24	2.50	2.35	1.66	2.20	2.60	2.53	2.44	2.30	2.00	1.00
Cd (mg/L)	0.06	0.08	0.04	0.04	0.01	0.01	0.01	0.01	0.10	0.10	0.003	0.003
Ni (mg/L)	0.24	0.20	0.20	0.18	0.12	0.13	0.30	0.28	0.25	0.20	0.07	0.02
Cr (mg/L)	0.09	0.08	0.06	0.10	0.06	0.07	0.09	0.10	0.10	0.08	0.05	0.05
Zn (mg/L)	4.24	4.30	4.00	4.32	4.45	4.40	5.35	5.31	3.86	4.30	3.00	5.00

Note: N/A indicates not available

Table 2
Major Ion Concentrations in Groundwater Samples (mg/L).

Sample Code	Na^+	Ca^{2+}	Mg^{2+}	K^+	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Cl^-
Well 1	3.03	9.00	3.32	0.78	3.77	1.20	3.42	6.60
Well 2	6.33	9.45	3.64	1.23	4.32	1.47	3.90	7.02
Well 3	4.45	8.25	3.26	0.75	2.00	1.04	3.30	6.80
Well 4	6.25	8.60	3.53	1.00	3.85	1.24	3.70	6.88
Well 5	6.40	10.60	5.80	2.45	4.64	2.44	5.60	12.70
Well 6	6.35	10.20	5.72	2.30	4.56	2.40	5.35	10.30
Well 7	3.00	8.00	2.40	0.60	1.14	0.65	2.65	5.22
Well 8	4.28	8.16	2.80	0.74	2.66	0.76	3.26	6.10
Well 9	3.30	9.33	3.14	0.89	3.80	1.23	3.50	6.85
Well 10	5.10	10.00	3.55	1.14	4.15	1.43	3.81	6.89

negligible risk (Ren et al., 2024; Zhang et al., 2018). The carcinogenic risks were evaluated by ILCR and risks below 1×10^{-4} were considered acceptable and any risk above this value was considered as high lifetime cancer risk (Adamu et al., 2015). These equations were used in this study:

Chronic daily intake (CDI)

The Chronic Daily Intake (CDI) was calculated in mg/kg/day for children (≤ 6 years; body weight = 15 kg) and adults (≤ 70 years; body weight = 70 kg) using Eq. (1) (USEPA, 2004, 2006):

$$CDI = \frac{C_W \times IR_W \times EF \times ED}{BW \times AT} \quad (1)$$

where:
C_W = heavy metal concentration in groundwater (mg/L)
IR_W = ingestion rate (2 L/day for adults; 1 L/day for children)
EF = exposure frequency (365 days/year)
ED = exposure duration (70 years for adults; 6 years for children)
BW = body weight (70 kg for adults; 15 kg for children)
AT = averaging time (25,550 days for adults; 2190 days for children (Duggal et al. 2017; Barzegar et al., 2018b)

Hazard Quotient (HQ)

The Hazard Quotient (HQ) for each heavy metal was calculated using Eq. (2) (Li et al., 2016; Zhang et al., 2018; Ren et al., 2024):

$$HQ = \frac{CDI}{RfD} \quad (2)$$

Hazard Index (HI)

The Hazard Index (HI), representing the cumulative non-carcinogenic risk from multiple contaminants, was calculated as:

$$HI = \sum_{i=1}^{n} HQ_i \quad (3)$$

where RfD is the reference dose, defined as the maximum acceptable daily oral exposure below which no adverse non-carcinogenic health effects are expected over a lifetime (USEPA, 2011; Barzegar et al., 2018b).

Lifetime average daily dose (LADD)

The Lifetime Average Daily Dose (LADD) was calculated for carcinogenic risk assessment using the USEPA (1989) model:

$$ADD = \frac{C \times EF}{AT} \times \left(\frac{CR_{child} \times ED_{child}}{BW_{child}} + \frac{CR_{adult} \times ED_{adult}}{BW_{adult}} \right) \quad (4)$$

Incremental lifetime cancer risk (ILCR)

The Incremental Lifetime Cancer Risk (ILCR) was calculated using Eq. (5):

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

Where cancer slope factor (CSF) is determined by the following equation

$$CSF = \frac{ILCR}{CDI}; \quad (6)$$

Subramaniam et al., (2006); USEPA, (1989) and USEPA (2005).

In this study, the established guideline (USEPA, 2011) was adopted. According USEPA (2011), CSF for As (1.5), Cd (6.3), Ni (0.84) and Cr (42). Iron, copper, and zinc are not classified as carcinogens; available evidence is insufficient to establish their carcinogenic potential (Subramaniam et al., 2006). Therefore, Cancer Slope Factor (CSF) values are not assigned to these metals; instead, their potential non-carcinogenic health effects are assessed using an Oral Reference Dose (RfD).

ILCR is probability of developing cancer over a lifetime as a result of exposure to a carcinogenic contaminant (Adamu et al., 2015). According to regulatory guidelines, ILCR values between 1×10^{-6} and 1×10^{-4} are generally considered acceptable, whereas values exceeding 1×10^{-4} indicate an increased lifetime cancer risk (Li et al., 2013; USEPA, 1989).

Results

Groundwater quality in the study area was evaluated based on the guidelines for drinking water quality recommended by the World Health Organization (WHO, 2011; 2017) and the Nigerian Standard for Drinking Water Quality issued by the Standards Organization of Nigeria (SON, 2015). These standards served as reference benchmarks for assessing the suitability of groundwater for domestic consumption.

The analytical results (Table 1) indicate that pH values ranged from 5.25 to 6.63, reflecting moderately acidic conditions and deviation from the acceptable range for potable water. Electrical conductivity (135.00–535.00 μS/cm) and total dissolved solids (65.00–112.00 mg/L) were within the permissible limits stipulated by both WHO and SON standards (1000–1200 μS/cm for EC; 250 mg/L for TDS). Total alkalinity values also complied with regulatory limits, suggesting no immediate concern from these parameters in relation to drinking water quality.

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In contrast, turbidity and several heavy metals, including iron (Fe), arsenic (As), copper (Cu), cadmium (Cd), nickel (Ni), and chromium (Cr), exceeded the recommended limits for safe drinking water in all sampled locations. Zinc (Zn) concentrations exceeded 3.00 mg/L threshold value recommended by World Health Organization (WHO) for assessing water quality but remained generally below the SON permissible limit of 5 mg/L. Overall, the exceedance pattern indicates significant contamination, particularly for turbidity and toxic trace metals.

Spatial distribution patterns indicated elevated turbidity levels in Wells 1, 2, 3, 9, and 10, while higher iron (Fe) concentrations were observed in Wells 1, 3, 4, 7, 8, 9, and 10. Zinc (Zn) showed comparatively higher values in Wells 7 and 8. In contrast, the remaining parameters exhibited relatively uniform spatial distribution across the sampled wells.

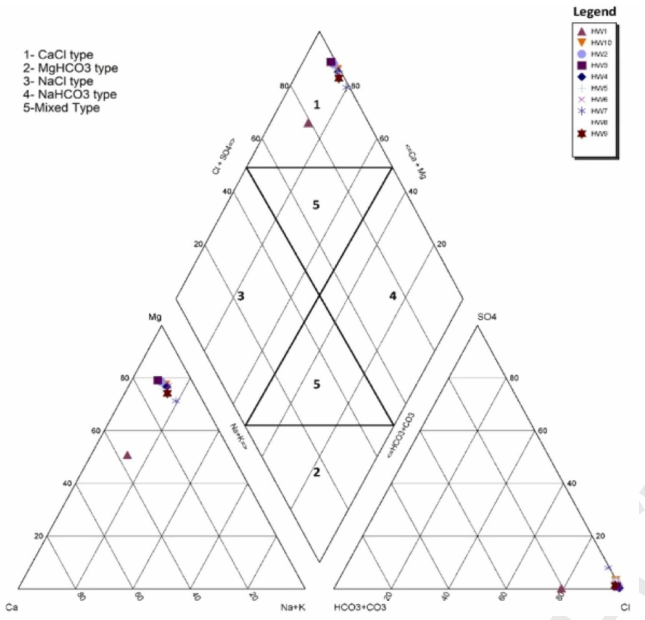


Fig. 2. Piper trilinear diagrams showing the hydrogeochemical facies distribution of groundwater samples.

These patterns suggest the presence of both localized and diffuse sources of contamination, reflecting the influence of anthropogenic activities in the study area and underscoring the need for continuous monitoring of groundwater quality.

Table 2 presents the concentrations of major cations and anions measured in the groundwater samples. The major cations analyzed were sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). These ions were generally well distributed across the sampled wells, exhibiting only slight spatial variation. Sodium concentrations ranged from 3.00 to 6.40 mg/L, with the highest value recorded in Well 5 and the lowest in Well 7. Calcium concentrations ranged from 8.00 to 10.60 mg/L, magnesium from 2.40 to 5.80 mg/L, and potassium from 0.60 to 2.45 mg/L. Comparatively higher concentrations of these cations were observed in Wells 5 and 6, indicating localized enrichment within these sampling locations.

Similarly, the major anions, including carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), and chloride (Cl^-), were detected in all groundwater samples. Their concentrations ranged from 1.14 to 4.64 mg/L for CO_3^{2-}, 0.65–2.44 mg/L for HCO_3^-, 2.65–5.60 mg/L for SO_4^{2-}, and 5.22–12.70 mg/L for Cl^-. Elevated concentrations of these anions were generally observed in Wells 5 and 6. Nevertheless, the relatively narrow variation in ion concentrations across the sampled wells suggests a fairly homogeneous geochemical environment and a common source of dissolved constituents within the aquifer system. The ionic composition of the groundwater samples was further evaluated using a Piper trilinear diagram (Fig. 2) to classify the groundwater types and identify the dominant hydrochemical facies within the study area.

The hydrogeochemical facies identified from the Piper trilinear diagram (Fig. 2) indicate that the groundwater is predominantly characterized by Ca-Cl, Mg-HCO_3, Na-Cl, Na-HCO_3, and mixed water types. Most of the samples exhibited mixed cationic compositions, with nearly equal proportions of Ca^{2+} and Mg^{2+}, whereas the remaining samples were dominated by Na^+. The anionic composition was largely represented by the HCO_3^- type, although a few samples displayed mixed anionic characteristics.

To further elucidate the sources and controlling mechanisms of dissolved ions in the groundwater system, Gibbs diagrams (Fig. 3) were employed by plotting total dissolved solids (TDS) against the ratios $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/(Cl^- + HCO_3^-)$. The distribution of the data points on the

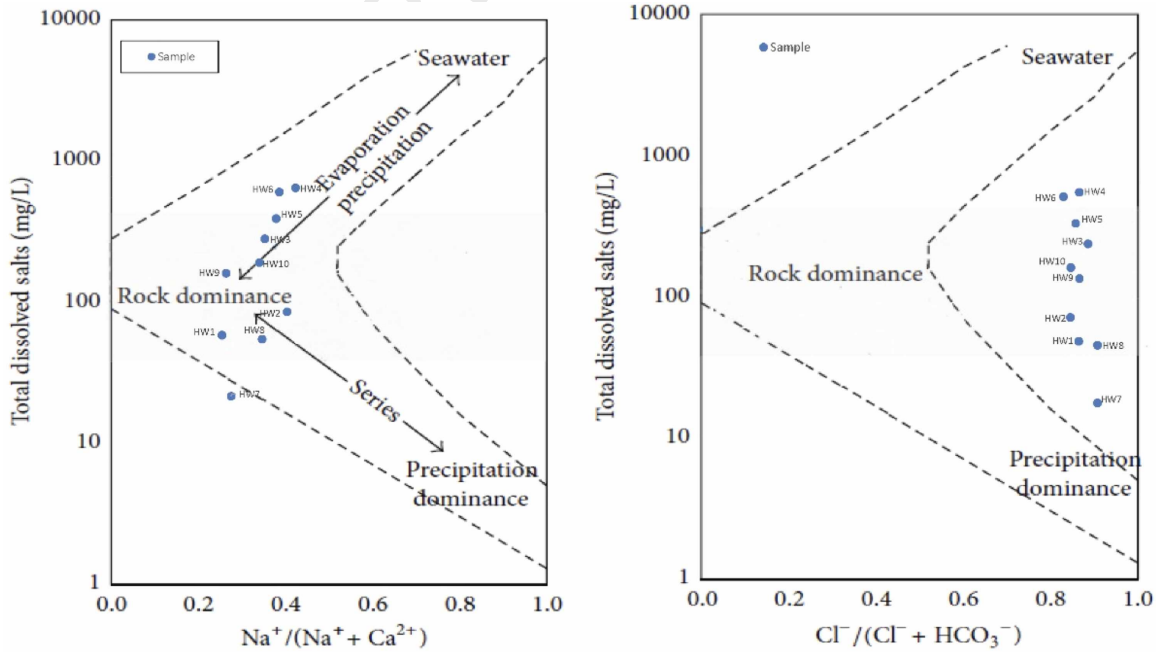


Fig. 3. Gibbs plots for the major ions measured.

Table 3
Hazard Quotient (HQ) and Hazard Index (HI) for the study.

Station	Population Group	Iron	Arsenic	Copper	Cadmium	Nickel	Chromium	Zinc	HI
Well 1	Children	15.00	22.20	4.00	8.00	0.80	20.00	0.90	71.00
	Adult	6.40	9.50	1.70	3.40	0.30	8.60	0.40	30.40
Well 2	Children	8.30	15.60	3.70	10.70	0.70	17.80	1.00	57.60
	Adult	3.60	6.70	1.60	4.60	0.30	7.60	0.40	24.70
Well 3	Children	14.30	22.20	4.20	5.30	0.70	0.00	0.90	47.60
	Adult	6.10	9.50	1.80	2.30	0.30	0.00	0.40	20.40
Well 4	Children	12.70	15.60	3.90	5.30	0.60	22.20	1.00	61.30
	Adult	5.40	6.70	1.70	2.30	0.30	9.50	0.40	26.30
Well 5	Children	5.30	13.30	2.80	1.20	0.40	13.30	1.00	37.40
	Adult	2.30	5.70	1.20	0.50	0.20	5.70	0.40	16.00
Well 6	Children	5.50	13.30	3.70	1.20	0.40	15.60	1.00	40.70
	Adult	2.40	5.70	1.60	0.50	0.20	6.70	0.40	17.40
Well 7	Children	20.10	28.90	4.30	1.30	1.00	20.00	1.20	76.80
	Adult	8.60	12.40	1.90	0.60	0.40	8.60	0.50	32.90
Well 8	Children	17.90	22.20	4.20	1.30	0.90	22.20	1.20	70.00
	Adult	7.70	9.50	1.80	0.60	0.40	9.50	0.50	30.00
Well 9	Children	15.20	15.60	4.10	13.30	0.80	22.20	0.90	72.10
	Adult	6.50	6.70	1.70	5.70	0.40	9.50	0.40	30.90
Well 10	Children	14.70	15.60	3.80	13.30	0.70	17.80	1.00	66.80
	Adult	6.30	6.70	1.60	5.70	0.30	7.60	0.40	28.60

Note: An HQ or HI value greater than 1.00 indicates potential non-carcinogenic health risk.

Gibbs plots suggests that groundwater chemistry in the study area is primarily controlled by rock-water interaction, with additional influences from evaporation and precipitation processes.

Non-carcinogenic risk assessment (NCRA)

Table 3 presents the calculated Hazard Index (HI) values for heavy metals in groundwater from public wells in the study area. The results show that the cumulative non-carcinogenic risk associated with heavy metals was higher for children than for adults across all wells, indicating greater vulnerability of children to contaminant exposure. On average, five out of the seven analyzed metals (approximately 71%) exhibited Hazard Quotient (HQ) values greater than 1, indicating potential non-carcinogenic health risks, whereas nickel (Ni) and zinc (Zn) generally showed HQ values less than 1, suggesting relatively low risk. Metals such as iron (Fe), arsenic (As), copper (Cu), cadmium (Cd), and chromium (Cr) consistently exceeded the safe threshold (HQ > 1) in most wells for both age groups, highlighting their dominant contribution to the overall health risk. In contrast, Ni and Zn generally remained within acceptable limits (HQ < 1), with only isolated instances approaching the threshold value.

Among the sampled locations, Well 7 recorded the highest cumulative HI values for both children (76.80) and adults (32.90), followed by Wells 9, 1, and 8, indicating that residents consuming water from these wells are more vulnerable to non-carcinogenic health effects. The consistently elevated HI values observed across all wells further suggest that long-term consumption of untreated groundwater may pose adverse health implications to the local population.

The relatively elevated concentrations of Fe, As, Cu, Cd, and Cr are likely influenced by both geogenic and anthropogenic factors, including the weathering of feldspathic and silicate minerals, dissolution of metal-bearing rocks, and possible contributions from human activities within the area. These findings underscore the need for regular groundwater monitoring and the implementation of appropriate mitigation measures to minimize health risks associated with heavy-metal exposure in the Igarra region.

Cancer risk assessment (CRA)

The cancer risk assessment for heavy metals in groundwater was conducted following the guidelines established by the United States Environmental Protection Agency (USEPA, 1989, 2004, 2005 and 2011), and methodologies adopted by Li et al. (2013) and Ren et al. (2024). This was used to evaluate the carcinogenic risks associated with exposure to heavy metals in groundwater from public hand dug wells spread across Igarra. Among the analyzed metals, arsenic (As), cadmium (Cd), nickel (Ni), and chromium (Cr) were identified as the primary carcinogenic elements of public health concern.

The Incremental Lifetime Cancer Risk (ILCR) values (Table 4), calculated using the method of Adamu et al. (2015) indicated elevated cancer risks for both children and adults. For children, ILCR values ranged from 7.0×10^{-3} to 1.0×10^{-2} for As and 4.2×10^{-3} to 2.5×10^{-2} for Cd. For adults, As ranged from 2.6×10^{-3} to 7.0×10^{-3}, Cd from 2.9×10^{-3} to 7.0×10^{-3}, Ni from 7.3×10^{-3} to 1.1×10^{-2}, and Cr from 0.0 to 2.8×10^{-1}. These values substantially exceed the acceptable carcinogenic risk range of 1×10^{-6} to 1×10^{-4} recommended by the USEPA, indicating a significant potential cancer risk for both children and adults exposed to these metals through oral ingestion of the groundwater.

The exceptionally high ILCR values observed for arsenic, cadmium,

Table 4
Incremental Lifetime Carcinogenic Risk (ILCR) of Heavy Metals in Groundwater.

Well	Age Group	Arsenic (As)	Cadmium (Cd)	Nickel (Ni)	Chromium (Cr)
Well 1	Children	1.00×10^{-2}	2.52×10^{-2}	1.34×10^{-1}	2.52×10^{-1}
	Adult	4.30×10^{-3}	1.08×10^{-2}	5.80×10^{-3}	1.08×10^{-1}
Well 2	Children	7.00×10^{-3}	3.40×10^{-2}	1.10×10^{-2}	2.24×10^{-1}
	Adult	3.00×10^{-3}	1.44×10^{-2}	4.80×10^{-3}	9.60×10^{-2}
Well 3	Children	1.00×10^{-2}	1.68×10^{-2}	1.12×10^{-2}	6.00×10^{-2}
	Adult	4.30×10^{-3}	7.20×10^{-3}	4.80×10^{-3}	6.00×10^{-2}
Well 4	Children	7.00×10^{-3}	1.68×10^{-2}	1.01×10^{-2}	2.80×10^{-1}
	Adult	3.00×10^{-3}	7.20×10^{-3}	4.30×10^{-3}	1.20×10^{-1}
Well 5	Children	6.00×10^{-3}	3.80×10^{-3}	6.70×10^{-3}	1.68×10^{-1}
	Adult	2.60×10^{-3}	1.60×10^{-3}	2.90×10^{-3}	7.20×10^{-2}
Well 6	Children	6.00×10^{-3}	3.80×10^{-3}	7.30×10^{-3}	1.96×10^{-1}
	Adult	2.60×10^{-3}	1.60×10^{-3}	3.10×10^{-3}	8.40×10^{-2}
Well 7	Children	1.30×10^{-2}	4.20×10^{-3}	1.68×10^{-2}	2.52×10^{-1}
	Adult	5.60×10^{-3}	1.80×10^{-3}	7.20×10^{-3}	1.08×10^{-1}
Well 8	Children	1.00×10^{-2}	4.20×10^{-3}	1.57×10^{-2}	2.80×10^{-1}
	Adult	4.30×10^{-3}	1.80×10^{-3}	6.70×10^{-3}	1.20×10^{-1}
Well 9	Children	7.00×10^{-3}	4.20×10^{-2}	1.40×10^{-2}	2.80×10^{-1}
	Adult	3.00×10^{-3}	1.80×10^{-2}	6.00×10^{-3}	1.20×10^{-1}
Well 10	Children	7.00×10^{-3}	4.20×10^{-2}	1.12×10^{-2}	2.24×10^{-1}
	Adult	3.00×10^{-3}	1.80×10^{-2}	4.80×10^{-3}	2.24×10^{-1}

Table 4: Incremental Lifetime Carcinogenic Risk (ILCR) values for arsenic (As), cadmium (Cd), nickel (Ni), and chromium (Cr) in groundwater from public wells. The acceptable cancer risk range recommended by the USEPA is 1×10^{-6} to 1×10^{-4}. Values exceeding this range indicate potential carcinogenic health risks associated with long-term exposure through groundwater consumption.

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nickel, and chromium suggest that prolonged ingestion of contaminated groundwater may increase the likelihood of developing cancer related health conditions among residents of the study area. The elevated cancer risks highlight the urgent need for groundwater quality management, routine monitoring, and the adoption of appropriate water treatment strategies to reduce human exposure to carcinogenic contaminants.

Discussion

Groundwater in the study area is characterized by slightly to moderately acidic conditions, falling below the recommended drinking water limits of Word Health Organization (WHO) and Nigeria Standard for Drinking Water (NSDWQ). Although electrical conductivity, total dissolved solids, and total hardness remain within acceptable limits, the acidic nature of the groundwater may enhance trace metal mobility through increased mineral dissolution and desorption processes, while also promoting corrosion of water distribution materials.

The hydrochemical characteristics of groundwater indicate relatively uniform major ion chemistry, suggesting a common geochemical origin. The dominance of Ca^{2+}-HCO_3^- facies reflects silicate weathering as the main control on groundwater composition, while Na-Cl and Na-HCO_3 types indicate secondary processes such as ion exchange and mineral dissolution. Piper and Gibbs diagram interpretations confirm that rock-water interaction is the dominant mechanism governing groundwater evolution, with minor contributions from evaporation and precipitation, typical of basement aquifer systems. Notwithstanding the generally acceptable major ion chemistry, trace metal contamination is widespread, with Fe, As, Cd, Ni, and Cr exceeding WHO and NDWS guideline values in most wells. Iron enrichment is largely geogenic, linked to natural mineral weathering, whereas elevated levels of toxic metals such as arsenic, cadmium, nickel, and chromium pose significant health risks due to their persistence and mobility. The overall contamination pattern is mainly attributed to geogenic processes driven by prolonged rock-water interaction, with limited anthropogenic influence. This interpretation is supported by Positive Matrix Factorization (PMF) studies in similar settings, which show that geogenic sources can contribute up to 48.1% of total metal loads for elements such as Al, As, and Cd (Ustaoğlu et al., 2025). This findings buttress the assertion that arsenic and chromium enrichment is predominantly natural in origin and highlights the value of combining geochemical and receptor modeling approaches for robust groundwater source attribution.

The health risk assessment indicates that both non-carcinogenic and carcinogenic risks from groundwater consumption are significant, with hazard index values exceeding safe limits in all sampled wells. Children are consistently more vulnerable than adults due to higher water intake relative to body weight and greater physiological sensitivity relating to the immune system development (Hazra et al., 2026). Key contributors to non-carcinogenic risk include arsenic, cadmium and chromium with Wells 1, 7, 8, and 9 showing the highest risk levels. Carcinogenic risk assessment shows that ILCR values for arsenic, cadmium, nickel, and chromium are far above the acceptable USEPA range, with chromium being the dominant contributor in several locations. The findings indicate severe long term health risks associated with continuous consumption of untreated groundwater.

Synthesis and implications

Taken together, the findings demonstrate a groundwater system that meets acceptable standards for bulk physicochemical parameters such as electrical conductivity, total dissolved solids, and hardness, yet is significantly compromised by toxic trace metal contamination. The hydrogeochemical evidence strongly indicates that rock-water interaction is the dominant control on groundwater chemistry; however, under acidic conditions, this natural process becomes a major pathway for mobilizing hazardous metals into groundwater. The concurrence of elevated non-carcinogenic and carcinogenic risk indices highlights a serious dual health burden, particularly for children who represent the most vulnerable population group. These findings underscore the need for routine monitoring of groundwater quality with emphasis on arsenic, cadmium, chromium, nickel, and iron, as well as the implementation of mitigation strategies such as pH stabilization, point of use treatment systems, and improved well construction and protection. Public health interventions and risk communication strategies are also essential to reduce exposure, especially in high risk wells identified in this study. It is strongly recommended that public awareness campaign and policy regulation for public borehole and hand dug well should be strictly adopted for sustainability measures.

Limitations and future research

The study highlights several methodological and analytical limitations in the current groundwater risk assessment framework. The reliance on deterministic models (HI and ILCR) limits the ability to capture uncertainty, supporting the need for probabilistic approaches such as Monte Carlo simulation (Ustaoğlu et al., 2025). Additionally, the lack of metal speciation, particularly for chromium and the use of less sensitive techniques for arsenic analysis suggest that future studies should adopt advanced methods such as ICP-MS to improve accuracy. Improvements are also needed in spatial and temporal sampling design, including higher resolution aquifer based sampling and seasonal or intra seasonal monitoring to capture variability and event driven contamination pulses. Beyond human health risk assessment, integrating ecological tools such as Ecological Risk Indices (ERI) and Nutrient Pollution Indices (NPI), as applied by Hazra et al. (2026), would provide a more holistic evaluation of watershed environmental quality. Overall, incorporating probabilistic modeling, improved analytical techniques, and expanded ecological indicators would significantly strengthen groundwater assessment frameworks. These approaches enhance confidence in risk estimates, improve source to risk interpretation, and support more effective policy formulation geared towards sustainable environmental management and effective communication strategies.

Conclusion

The groundwater quality in Igarra region was found to have an acceptable major physicochemical concentration. However, the high level of heavy metal contamination and high turbidity coupled with the acidity has severely limited the groundwater quality to be used for domestic drinking. In most cases, the sampled wells exceeded the recommended drinking water range for pH, and Fe, As, Cu, Cd, Ni and Cr concentrations were exceeded in most wells for international and national guideline values. The concentrations of Zn were also found to be higher than WHO guideline in several locations, but were within the SON limit. Based on the control of the hydrochemical characteristics, supported by Piper and Gibbs plots, it is concluded that the rock-water interaction is the dominant process affecting the chemistry of groundwater, with evaporation and precipitation being minor processes. Consequently, an increase in the dissolution of minerals could lead to the mobilization and continued existence of potentially toxic metals in the aquifer under the current acidity. The health risk assessment also suggests that the use of untreated groundwater could pose significant health risks. The hazard indices were above the acceptable range in all sampled wells; children had higher non-carcinogenic risk than adults probably due to their developmental stage of immune system. The main contributors to this risk were arsenic, cadmium, chromium, iron and copper. Likewise the estimated incremental lifetime cancer risk for As, Cd, Ni and Cr were well outside of the acceptable USEPA cancer risk range, suggesting that long term exposure to the contaminated groundwater can be of serious concern for cancer risks to exposed populations. Wells 1, 7, 8 and 9 in particular had relatively high health risk levels and are therefore a priority. In general, the results suggest that the groundwater system has a relatively low concentration of dissolved solutes and a fairly uni-

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form dominant mineral composition, but that trace metals are causing problems with the drinking water quality for the groundwater system, and the associated health risk. The findings highlight the importance of continued monitoring of groundwater quality, including for As, Cd, Cr, Ni and Fe, in addition to efforts to enhance well protection and construction, buffer against groundwater pH, and offer adequate point of use or centralized treatment prior to consumption. There should also be an enhanced focus on public health education, risk communication and policy framework that would ensure safety compliance of borehole and hand dug well siting. This is particularly suggested within the communities that heavily depend on untreated groundwater. Seasonal and higher resolution sampling, metal speciation, more sensitive analytical methods and probabilistic risk assessment should be included in future investigations to better capture metal variability, exposure uncertainty and potential long term effects on health. Igarra's sustainable groundwater management and Public health protection require all of these measures.

Author Contributions

Omorogieva, Osakpolor Marvellous (OOM) and Ataminyo, Ogheneyerovwo Success (AOS) conceptualized the study. OOM, Ogueh, Edeh Desiree (OED), SOA and Orobosa Praise Ekponwen (OPE) carried out the data acquisition. OED, AOS and OPE prepared the samples for instrumental analysis. OOM lead the data interpretation while OED, AOS and OPE made significant contributions to the data interpretation. The initial manuscript draft was prepared by OED and SOA while OOM and OPE did the final manuscript revision. All authors and approved the final draft for publication.

Ethics approval and concept to participate in the study

Ethical approval is not applicable in the study.

Consent for publication

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Declaration of Competing Interest

The authors affirm that they have no financial, professional, or personal relationships that could be perceived as influencing the results or interpretation of the data presented in this study.

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Data availability

Data will be made available on request.

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