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RADON IN GROUNDWATER OF IPERINDO, OSUN STATE, NIGERIA: SPATIAL DISTRIBUTION, MINING INFLUENCE AND PUBLIC HEALTH IMPLICATIONS.

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Abstract: This study assessed dissolved ^{222}Rn in groundwater and surface-water sources in Iperindo, Atakumosa East Local Government Area, Osun State—an artisanal gold-mining area—to evaluate spatial patterns and potential health implications. A spatially distributed set of hand-dug wells, boreholes, and streams was sampled using airtight 750 mL bottles; radon was measured with a RAD7 detector coupled to the RAD H_2O aeration accessory and corrected for decay to the sampling time. Results show source-dependent variability: wells (n=17) ranged 4.22–24.98 $Bq \cdot L^{-1}$ (mean 13.48 $Bq \cdot L^{-1}$, SD 6.19), boreholes (n=7) 9.20–18.85 $Bq \cdot L^{-1}$ (mean 14.60 $Bq \cdot L^{-1}$, SD 3.43), and streams (n=7) lower and less variable (mean ≈9.36 $Bq \cdot L^{-1}$). The overall mean was 12.79 $Bq \cdot L^{-1}$. Although all values are well below the WHO screening reference of 100 $Bq \cdot L^{-1}$, several wells and boreholes exceed the U.S. EPA guideline of ~11 $Bq \cdot L^{-1}$. One-way ANOVA and nonparametric considerations indicate source-related patterns consistent with hydrogeological controls, though limited sample sizes reduce statistical power. The study recommends targeted surveillance—prioritizing shallow wells—periodic indoor-air monitoring where water is used indoors, and simple point-of-entry aeration for higher-activity wells to minimize inhalation and ingestion risks.

Keywords: Radon, water sources, Iperindo, Rad 7, artisanal mining

Introduction

Groundwater is sourced from geologic formations, called aquifers. Drinking water supplies from aquifers may contain radon due to radium content in the basement rocks and minerals/phosphate-rich soils surrounding it (Hassan et al., 2024). Radon-222 is a naturally occurring radioactive noble gas which is ubiquitous in soils and rocks. As part of the uranium-238 decay chain, radon is the only element to exist as a gas and can therefore be liberated from its parent material and transported by groundwater to a receiving surface waterbody. Radon is chemically inert, so it will not be absorbed to aquifer material, or react with dissolved ions during its transport. Given that the bulk of surface water is not in contact with radon emanating rock, there exist a sharp radon concentration gradient between groundwater and surface, typically of 2 to 4 orders of magnitude. The combination of these characteristics makes ^{222}Rn ideal as a natural tracer of groundwater discharge to lakes (Appleton, 2007; Wilson et al., 2024)

Radon is highly soluble in water under pressure, consequently resulting in groundwater that has passed through soils that are rich in uranium, exhibiting high levels of radon. The concentrations of radon in groundwater sources are 2 to 3 times greater than that of other radioisotopes substances, which may pose a significant health risk to human health at high concentrations (Kurnaz et al., 2018). Inhalation or ingestion of drinking water containing radon and its progeny are considered the most prevalent causes of cancer of the lung as the alpha particles produced through the decay process can potentially damage DNA and protein products, ultimately leading to cancerous growth in damaged epithelia cells (Hassan et al., 2024). Radon and radionuclides in water samples have been measured in a number of nations. These studies indicate that the danger increases considerably when groundwater is utilized as the primary water supply for enclosed facilities that pump water directly to users (Hassan et al., 2024). The unique properties of naturally occurring radioactive radon gas have led to its use as a geophysical tracer for identifying the geological structure and hidden faults, measuring and monitoring groundwater movement into the lake and sea water along the shore, in earthquake prediction and uranium deposit exploration, and as a tracer in the study of atmospheric transfer processes (Siraz et al., 2023; Yakubu et al., 2019)

The geological environment is the most critical factor influencing the spatial distribution of ^{222}Rn, which, along with its decay products, is commonly found in groundwater-derived domestic and drinking water, including hot springs. This presence can constitute a considerable health risk (Baptista et al., 2024). Nevertheless, the wide-ranging concentration of ^{222}Rn makes it difficult to accurately estimate the radiation dose received by the population.

In many West African nations, including Nigeria, groundwater obtained from locally dug wells, rather than public distribution systems, serves as the main source of domestic drinking water (Baptista et al., 2024). The concentration of ^{222}Rn in this water is determined by its emanation coefficient, a function of recoil and diffusion. This coefficient is highly sensitive to the concentration and distribution of ^{226}Ra in the bedrock, alongside factors like porosity, moisture, grain size, clay content, weathering, and organic matter richness (Baptista et al., 2024; Dong et al., 2024; Nurohman et al., 2024; Zhang et al., 2024).

Real-world scenarios demonstrate that radon gas migrates over long distances from the subsurface to the surface. This movement is complicated by varied rock properties and pore structures, which cause significant differences in the rocks ability to adsorb the gas. Yet, comprehensive data connecting long-distance radon transport rates to specific rock characteristics are limited. Crucially, during its travel, radon breaks down into its long-lived, solid decay products (^{210}Pb, ^{210}Bi and ^{210}Po). These daughters are readily adsorbed by soil and rock due to their stable chemical and physical traits. Consequently, their concentration in the environment is relatively constant, serving as an indicator of the parent radon's sustained accumulation (Ayo-Bali & Ajayi, 2024).

Assessment of radiological, physicochemical and hydrological quality of groundwater and drinking water have been done by several researchers in Nigeria (Adagunodo et al., 2018; Alabere & Alabere, 2019; Bello et al., 2013; Ibe & Egereonu, 2013; Onugba & Alabi, 2016; Orosun et al., 2020; Sappa et al., 2014; Yakubu et al., 2019). The purpose of this research and choice of the study area is because of the gold mining activities that dominate the research area which pose questions on the quality of the water sources available for the people for domestic and agricultural purposes.

Materials and Method

Description of the Study Area

Located in Southwestern Nigeria in Osun State, Atakumosa East Local Government Area, Iperindo is situated between 7.49°N - 7.51°N and 4.81°E - 4.84°E. The area's climate is tropical, characterized by an average yearly temperature of 27ºC and temperatures peaking in March (33–35°C) and dipping in July (22°C). It features a lengthy wet season (April – October) with high rainfall (1200-1500 mm) and humidity (above 70%), which supports the lush tropical rain forest vegetation and extensive farms (cocoa, oil palm, cassava). Conversely, the dry season (November-March) is marked by low rainfall (under 50 mm), lower humidity (below 40%), and the presence of dry, dusty Harmattan winds (Amodu et al., 2024).

The Iperindo area, with its undulating landscape (300 – 450 meters above sea levels), depends on seasonal streams (tributaries of the Osun River), shallow wells, and boreholes for its main water supply (Amodu et al., 2024) . Underlying this area is the Precambrian Basement Complex comprising of Migmatite-gneiss, Quartzite, schist and granite intrusions, which dictates groundwater movement. This geology is significant because it can release naturally occurring radionuclides (like uranium and radium) that decays into radon gas (Ajayi and Balogun, 2018). Adding to this risk, artisanal gold mining around Iperindo physically disrupts the geology, potentially increasing the mobility of these radionuclides into the water sources (Garba, 2003). The danger is magnified because residents in surrounding rural communities use nearby wells, boreholes and even water from mining pits for domestic purposes.

This research specifically investigates water sources affected by gold mining because previous assessments in similar Nigerian mining areas have revealed high radionuclides levels. Iperindo was selected for the study due to reports of radiological contamination linked to mining, an activity that likely enhances radon dissolution in local water supplies. The Iperindo community primarily relies on subsistence farming of growing cocoa, yam, maize and cassava, trading and artisanal gold mining for their livelihood. Since access to treated, pipe-borne water is limited, residents depend mainly on natural groundwater sources – hand-dug wells, boreholes, and streams – for domestic and agricultural needs (Bayowa et al., 2014)

Figure 1: Satellite image of Iperindo town showing the Gold Mine and major landmarks.

Materials Used

750 ml air-tight plastic bottles were used to collect water samples. Their air-tight design is essential to prevent the degassing (loss) of highly volatile (UNSCEAR 2000*)*

Global Positioning. A handheld GPS receiver was used to record the precise latitude and longitude of each sampling point. This data allows for the spatial mapping of radon concentrations in the water sources (USGS, 2019). Ice

Chest and Cooler were used to store and preserve the samples at low temperatures, minimizing any potential radon loss before laboratory analysis (WHO, 2009). RAD7 Electronic Radon Detector with RAD H2O Accessory, a solid-state alpha spectrometer, was utilized for radon gas detection. When coupled with the RAD H2O accessory, it measures water-based radon by aerating the sample and transferring the released radon into a closed air loop (Electronic Radon Detector User Manual, n.d.). Syringes and Tubing were required to transfer the water samples directly into the RAD H2O system without introducing air contamination

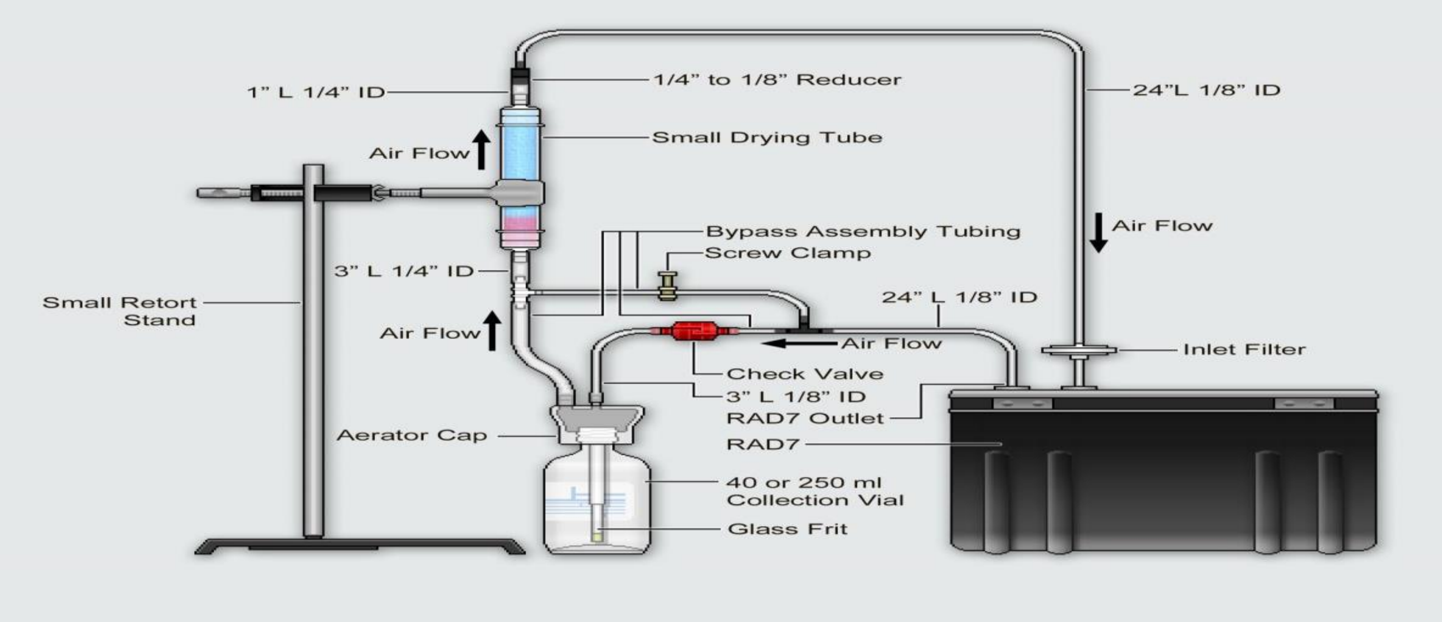

Figure 2: (*RAD7 Radon Detector - DURRIDGE Scientific Research Radon Detectors*, n.d.)

Sample Collection

Water Samples were collected spatially throughout the Iperindo community to cover the major sources: hand-dug well, borehole, and streams, used by residents, ensuring statistical validity (IAEA, 2014). At each site, the collection process followed strict guidelines to prevent radon loss. Water samples were collected using methods that replicate public fetching techniques to ensure representative results. For hand-dug wells accessed via bailers, the water was carefully transferred into a 750 ml air-tight bottle following the EPA drinking water sample collection guide (WHO, 2011). For hand-dug wells equipped with manual pumps, the water was pumped directly into the 750 ml air-tight bottle. Filling them completely and slowly to minimize aeration and the formation of air bubbles. Each bottle was immediately sealed and labelled with a unique code, source type, location and the collection date. To ensure preservation, which is vital given radon's half-life of 3.82 days, all samples were immediately placed in ice-cooled containers and swiftly transported to the laboratory for analysis. Proper sealing and refrigeration prevent the volatile radon from escaping (WHO, 2011).

Radon Measurement Technique

The ^{222}Rn concentration in groundwater samples was determined using a RAD7 electronic radon detector coupled with the Rad H_2O accessories. This versatile RAD7 system (comprising the RAD7 unit, aerator, and desiccant) provides measurements within minutes, covering a concentration range of 0.004 to 750 Bq/L with an absolute accuracy of ±5%.

Before each measurement, the RAD7 sample cell was thoroughly dried using a desiccant. This is crucial because high humidity can reduce the efficiency of ^{218}Po collection. The air inlet includes a 1 mm filter to block fine dust and all existing radon daughters from entering the cell. The system uses a closed-loop aeration scheme (the Wat-250 protocol) where the water and air volumes remain constant. Air is recirculated through the water sample until the dissolved radon is extracted and equilibrium is achieved. This protocol typically results in an extraction efficiency of 94%. The extracted radon is collected in the RAD7 unit's 0.7 L hemispheric sample cell, which is coated with an electrical conductor. A solid-state, ion-implanted planar silicon alpha detector is located at the center of the cell. The RAD7 applies a high potential difference (≈2,000 to 2,500 V) between the detector and the cell surface. This electric field propels the positive ^{218}Po ions, which result from the decay of the ^{222}Rn nucleus, towards the detector. The ^{218}Po ions decay on the active surface of the detector, emitting an alpha particle. This particle has a 50% chance of entering the detector and producing an electrical signal. The RAD7 then amplifies this signal and uses the resulting ^{218}Po count to determine the original ^{222}Rn concentration.

Since laboratory measurements of radon concentration in groundwater samples occur later than the actual collection time, the resulting value does not accurately reflect the original concentration in situ. Therefore, it is essential to correct the measured concentration back to the value at the time of sampling using the Decay Correction Factor (DCF).

The relationship between a radionuclide's activity A at any time t and its original activity A_O is expressed as:

$$A = A_O(e^{-\lambda t})$$

Where the factor $e^{-\lambda t}$ is the decay correction factor and λ is the decay constant. The measure radon concentration is multiplied by DCF to obtain the corrected radon concentration (Ajiboye et al., 2022).

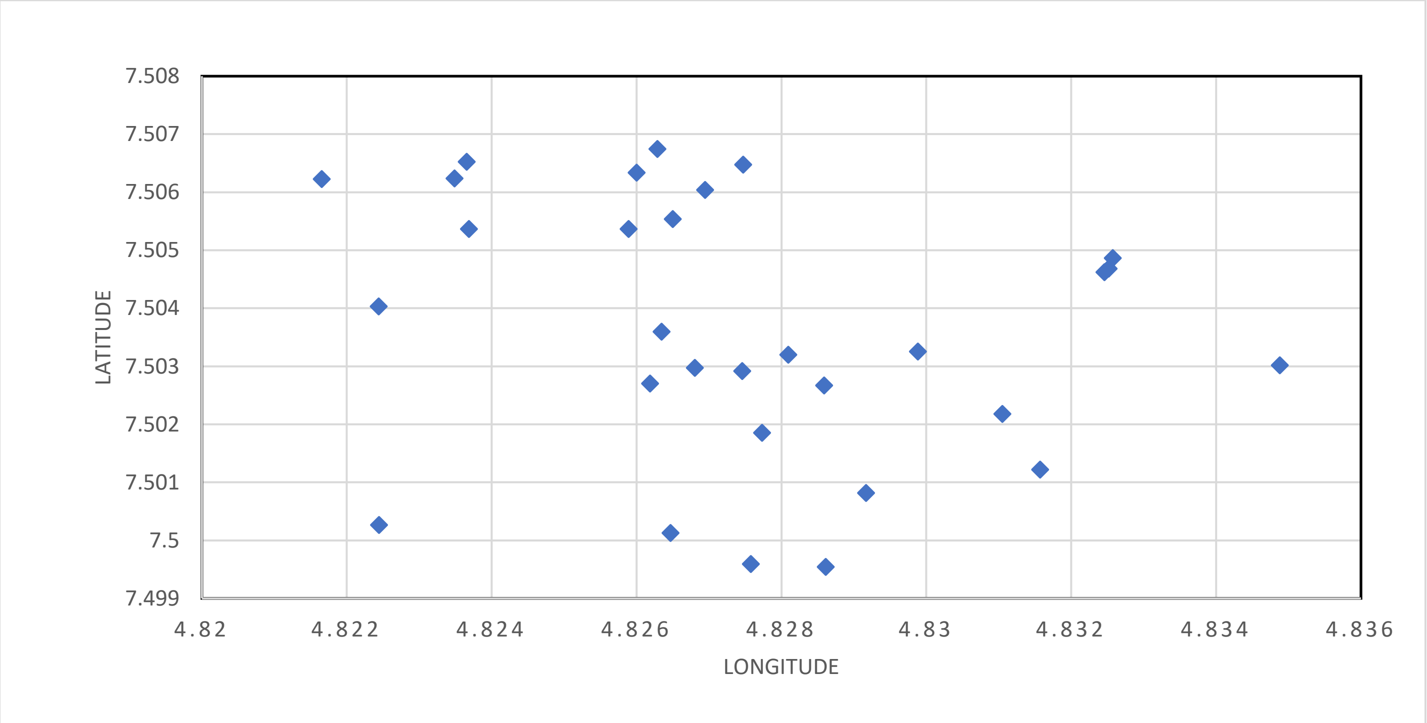

Figure 3: Locations of Water Sources in Iperindo.

Results and Discussion

Radon Concentration in Water Samples

The borehole dataset consists of seven representative samples spread across the community. Concentrations span from 9.203 to 18.847 Bq/L. The computed mean radon concentration is 14.596 Bq/L, while the median is 15.834 Bq/L. A standard deviation of 3.434 Bq/L reflects moderate variability. Seventeen hand-dug wells were assessed, with concentrations ranging from 4.216 to 24.980 Bq/L, the broadest spread among all sources. The mean radon level is 13.476 Bq/L, the median 12.343 Bq/L, and the standard deviation 6.193 Bq/L, reflecting strong variability. Seven streams sources were sampled, with concentrations ranging from 4.95 to 12.16 Bq/l. the mean radon level is 9.36Bq/l, the median is 9.20 Bq/l and standard deviation of 2.51 Bq/l.

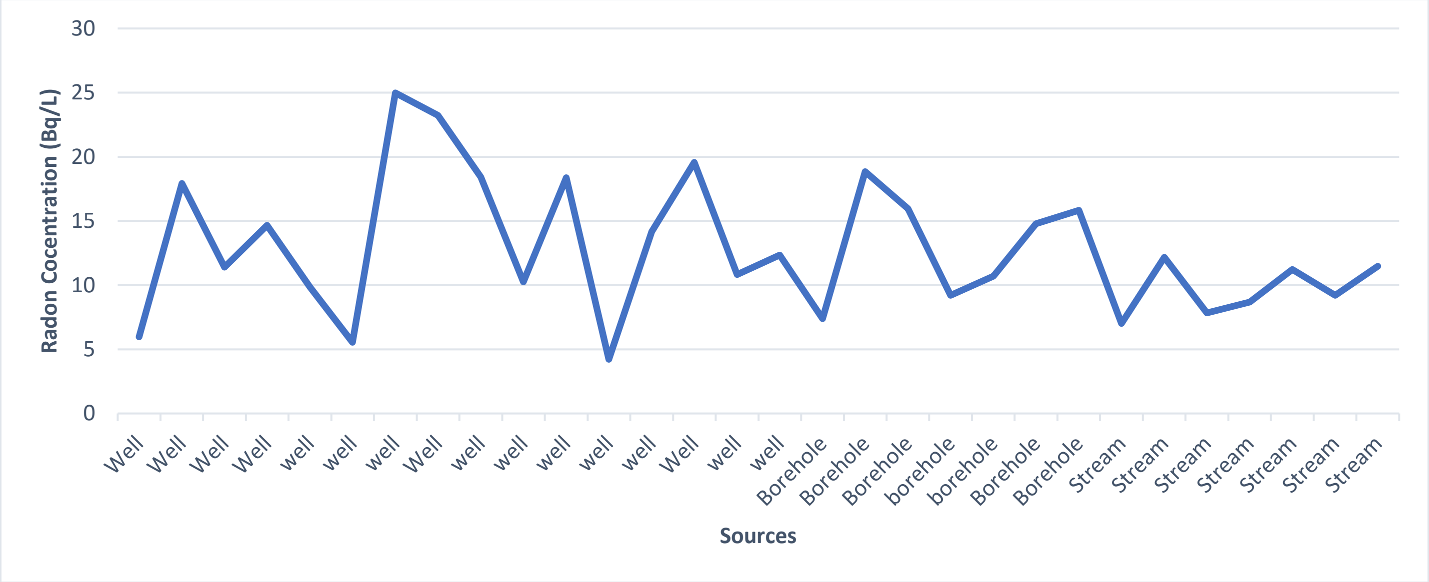

Figure 4: Line Graph Showing Variation of Radon Concentration Across Samples

Table 1: Comparative Analysis of Water Sources

Samples	**N**	**Mean (Bq/L)**	**Median (Bq/L)**	**Std**	**Min (Bq/L)**	**Max (Bq/L)**
Borehole	**7**	**12.43**	**14.79**	**4.18**	**9.203**	**18.847**
Hand-dug well	**17**	**13.85**	**13.25**	**6.18**	**4.216**	**24.98**
Streams	**7**	**9.65**	**9.203**	**1.98**	**7.0**	**12.168**

Across the three sources, boreholes display the highest mean and median radon concentrations, closely followed by wells, while streams consistently show the lowest central tendency and variability. Wells exhibit the widest distribution, a reflection of the heterogeneity inherent in shallow weathered profiles, differences in construction methods, and greater susceptibility to degassing processes. Boreholes, by contrast, which penetrate deeper fractured horizons, record moderately elevated but more tightly clustered values. Streams, in turn, demonstrate the smallest variability, which aligns with their dynamic hydrological character, where rapid atmospheric exchange and short residence times limit the accumulation of dissolved radon. This result suggests that groundwater sources (wells and boreholes) are more influenced by geological formations than streams, which lose radon more easily to the atmosphere.

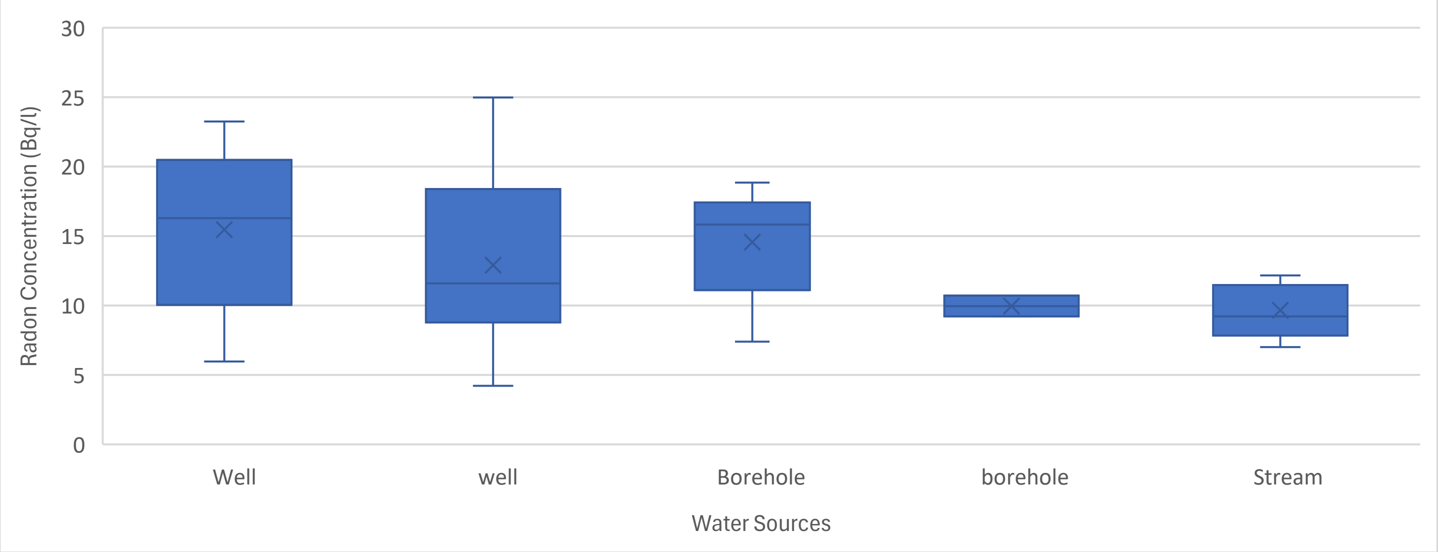

Figure 6: Boxplot showing variations of water sources with radon concentrations

ANOVA Test

To evaluate whether the differences between borehole, well, and stream water radon concentrations are statistically significant, a one-way ANOVA test was conducted. The results yielded:

Table 2: Anova Test

Source of variation	**Sum of Squares (SS)**	**df**	**Mean Square (MS)**	**F-value**	**p-value**
Between groups	74.24	2	37.12	1.43	0.257
Within groups	700.88	27	25.96		
Total	**775.12**	**29**			

Since the p-value is 0.257, the differences between water sources are statistically significant at the 95% confidence level**.** A one-way ANOVA (F ≈ 1.43, p ≈ 0.257) found no significant mean differences at α = 0.05. This likely reflects limited sample sizes (n=7 for boreholes and streams). This indicates that the variations in radon levels are not due to random chance but are likely influenced by geological and hydrological factors specific to each source. The distribution shows mild right skew, driven mainly by high well values near 25 Bq/L. Boreholes cluster in the mid-teens with moderate spread, while streams are compact around ~9 Bq/L. Boxplots confirm the order Stream < Well ≈ Borehole, with wells showing the widest interquartile range and most outliers. Histograms indicate unimodal patterns: wells exhibit broader dispersion, boreholes peak near 15–16 Bq/L, and streams center around 8–10 Bq/L.

Discussion of Findings

The World Health Organization's WHO, 2017, WHO 2011recommend that radon screening levels in water be anchored to national indoor-air reference levels, with ~100 Bq/L widely applied as a practical ceiling. All values measured in Iperindo fall comfortably below this reference point. The (United States Environmental Protection Agency, 2012) has considered two regulatory thresholds: a Maximum Contaminant Level (MCL) of ~11 Bq/L (300 pCi/L) and an Alternative Maximum Contaminant Level (AMCL) of 150 Bq/L (4,000 pCi/L), the latter tied to indoor-air mitigation programs. Several borehole and well samples from Iperindo exceed the 11 Bq/L threshold but remain far below the AMCL. WHO further notes that 1000 Bq/L in water could increase indoor air concentrations by ~100 Bq/m³ during household use. With all Iperindo values <25 Bq/L, the contribution to indoor air is expected to be negligible. Nevertheless, several borehole and well samples exceed the U.S. EPA's proposed MCL of 11 Bq/L, meaning that if such a standard were adopted in Nigeria, mitigation or integrated air–water management might be recommended.

In Nigeria, the agency with a mandate similar to the U.S. EPA is the National Environmental Standards and Regulations Enforcement Agency (NESREA**),** established under the Federal Ministry of Environment. Unlike the U.S. EPA, NESREA has not yet developed explicit standards for radon in water or indoor air. In practice, Nigeria relies on WHO frameworks and international guidance to address radiological water safety. This makes the WHO's air-anchored approach the most relevant comparator in the Nigerian policy context.

The observed differences among sources reflect fundamental hydrogeological processes. Streams consistently show the lowest values due to turbulent mixing, atmospheric degassing, and minimal contact with mineralized substrates. Wells display the widest variability, reflecting shallow aquifer heterogeneity, differences in regolith thickness, ventilation, and construction practices. Boreholes, tapping deeper fractured horizons, yield moderately elevated but stable values due to longer water–rock contact times and steady geochemical conditions. These distinctions align with global radon hydrogeology.

Table 3: Comparison of the result of this study with other results

Region	Radon concentration in water (Bq/l)	Mean radon concentrations (Bq/l)	References
Kuwait	3.51- 19.35	9.01	(Hassan et al., 2024)
Indonesia	0.2-13.4	3.4	(Nurohman et al., 2024)
Bangladesh	0.077 – 0.494	0.250	(Siraz et al., 2023)
Nigeria	1.6 – 271	35.9 +-38.4	(Ajiboye et al., 2022)
Nigeria	12.10 -22.40	14.9	(Jibril et al., 2021)
Iran	5.2 – 14.4	9.7	Fard et al., 2020
Iraq	1.1 -10.3	6.8	Ezzuldin and Mansour, 2020
Punjab, India	1.4 – 5.3	3.5	Jakhu et al., 2020
Kenya	4.6-22.5	12.4	Rotich et al., 2020
Nigeria	4.21 – 24.98	12.73	This Study, 2026

Conclusions

This study demonstrates that dissolved ^{222}Rn is present across groundwater and surface-water sources in Iperindo, with source-dependent variability: boreholes and hand-dug wells show higher and more variable activities while streams record lower, less variable values. All measured concentrations are well below the WHO screening reference (100 Bq·L⁻¹) and far below the AMCL (150

Bq·L⁻¹), but several wells and boreholes exceed the U.S. EPA guideline of ~11 Bq·L⁻¹, indicating localized enrichment likely driven by geology and mining-related disturbance.

From a public-health perspective, the measured levels pose low immediate risk for ingestion, yet they warrant attention because waterborne radon can contribute to indoor-air concentrations during household use and thus to cumulative inhalation dose. Practical, low-cost interventions—prioritizing point-of-entry aeration for higher-activity wells and periodic indoor-air monitoring in homes using such water—would reduce potential inhalation exposure while remaining proportionate to the measured levels.

Key limitations include the single-season snapshot, modest sample sizes for some source types, and limited temporal replication. Future work should combine repeated seasonal sampling, mapping of U-series mineralization and fracture density, and household surveys of water use and well construction to refine exposure estimates and predictive models. Such integrated efforts will better identify hotspots, guide cost-effective mitigation, and ensure safe water use in mining-affected communities.

Ethical and Safety Considerations

Permission was obtained from household owners and community leaders before sampling. Water sources were not contaminated during sampling. All procedures followed safety protocols recommended by the International Commission on Radiological Protection (ICRP, 2011).

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