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Risk Assessment and Uncertainty Analysis of Radon-222 Concentrations in Groundwater Within Abuja, Nigeria, Using Liquid Scintillation Counting

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Abstract

Radon-222 (^{222}Rn) in groundwater is a potential source of internal radiation exposure through ingestion, particularly in regions where groundwater constitutes a major source of drinking water. This study presents an assessment of ^{222}Rn concentrations, radiological risks, and measurement uncertainties in groundwater within Kubwa, Abuja, Nigeria, using liquid scintillation counting. Thirty groundwater samples collected during the peak dry season were analysed using a calibrated Tri-Carb 1000 TR liquid scintillation analyser, with corrections for radioactive decay and partitioning effects. The ^{222}Rn concentrations ranged from below the detection limit to 2.30 Bq L^{-1}, with a mean of 0.29 ± 0.43 Bq L^{-1}. Estimated annual effective doses were of the order of 10^{-3} mSv y^{-1}, well below the recommended reference level of 0.1 mSv y^{-1}. Expanded relative uncertainties (k = 2) ranged from approximately 6% for higher-activity samples to over 20% for samples near the detection limit. The results indicate a very low radiological risk from ^{222}Rn ingestion through groundwater and provide baseline data for the study area. The findings also demonstrate the importance of considering detection limits and measurement uncertainty in environmental radioactivity assessments.

Keywords: Groundwater; Radon-222; Liquid Scintillation Counting; Risk Assessment; Uncertainty Analysis; Detection Limit; Abuja, Nigeria.

I. Introduction

Access to safe drinking water remains a significant challenge in many developing countries, where boreholes are the primary source of water for rapidly growing urban populations. Rapid urbanization and population growth in Abuja have placed considerable pressure on existing municipal water supply systems, resulting in increasing dependence on borehole sources for domestic water consumption. In many parts of Abuja, particularly Kubwa and Igu, boreholes remain the primary source of water. Despite the dependence on groundwater, the radiological quality, especially with respect to naturally occurring radionuclides, has received very little attention [1-4].

Radon-222 is a radioactive noble gas produced through the decay of radium-226 in the uranium-238 series [5-6]. It is of significant concern to public health due to its established carcinogenicity. While its inhalation in indoor environments is the dominant exposure pathway, ingestion of radon dissolved in drinking water and its subsequent transfer to indoor air can contribute to the total radiation dose [6-8].

The occurrence of radon in groundwater is strongly influenced by geological conditions, with elevated concentrations typically associated with uranium-rich formations such as granites, gneisses, and schists [9-10]. Abuja is underlain by basement complex rocks, which host uranium-bearing minerals, suggesting a potential for radon occurrence in groundwater systems [1-2]. However, unlike other regions in Nigeria, such as Zaria and Zamfara, where elevated radon levels have been reported [11], no comprehensive baseline data exist for Abuja. This represents a critical gap, particularly given the city's rapid urbanization and heavy reliance on groundwater.

This study addresses this gap by providing the first systematic risk assessment of radon-222 concentrations in borehole water in selected districts of Abuja through sample collection during the peak dry season, incorporating uncertainty analysis to ensure measurement reliability [12]. In addition to quantifying radon levels, the study assesses spatial variability in relation to geological formations and evaluates potential radiological risks through ingestion dose modelling for both adults and children. By establishing a baseline dataset for an urban center underlain by uranium-bearing geology yet exhibiting low radon concentrations, this work contributes to a more nuanced understanding of groundwater radioactivity in Nigeria and informs future monitoring and regulatory efforts.

II. Guidelines For Manuscript Preparation

A. Study Area

The study was conducted in Abuja, the Federal Capital Territory of Nigeria, located between latitudes 8.25°N and 9.20°N and longitudes 6.45°E and 7.39°E. The area covers approximately 7,315 km^2 and is characterized by a tropical climate with distinct wet (April–October) and dry (November–March) seasons. Mean annual temperatures range from 24 to 30°C, with annual rainfall between 1,200 and 1,500 mm. Geologically, Abuja lies within the Nigerian Basement Complex, consisting predominantly of migmatites, gneisses, granites, schists, and quartzites. These lithologies are known to host uranium-bearing minerals, which may contribute to radon generation in groundwater systems [1-2].

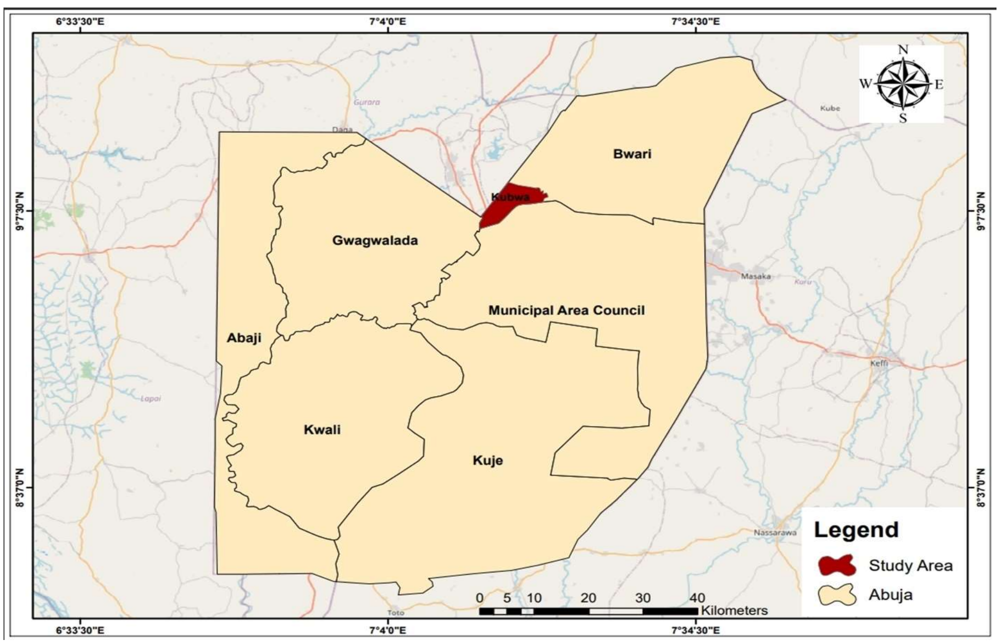

Fig. 1. Map of Abuja, showing the study area.

B. Sample Collection

A total of 30 borehole water samples were collected from Kubwa and Igu. Before sampling, each borehole was purged for at least three minutes to remove stagnant water and ensure the collection of fresh groundwater. Samples were collected in 20 mL glass scintillation vials pre-filled with 10 mL of a toluene-based scintillation cocktail. Using a hypodermic syringe, 10 mL of water was carefully injected beneath the cocktail layer to minimize radon loss. Vials were immediately sealed with airtight caps and stored in dark, cool conditions before analysis. The time interval between sampling and counting was recorded and accounted for in decay correction calculations.

C. Sample Preparation and Equilibration

Collected samples were shaken vigorously for three minutes to facilitate the transfer of radon-222 from the aqueous phase into the organic scintillation phase. The samples were then allowed to equilibrate for a minimum of three hours to establish secular equilibrium between radon-222 and its short-lived progeny [1-2].

D. Radon Measurement and Concentration Calculation

Radon concentrations were determined using a liquid scintillation counter (Tri-Carb LSA 1000, Packard

Instruments) [13-14]. The system detects scintillation photons generated by alpha emissions from radon decay, which are converted into electrical pulses and recorded as counts per minute (CPM). Instrument calibration was performed using standard radon solutions, and background counts were subtracted from sample measurements to obtain net count rates [13], [15]. Counting efficiency and calibration factors were applied to convert count rates into activity concentrations.

The radon-222 concentration in groundwater samples was determined using a decay-corrected liquid scintillation counting method according to (1).

$$\frac{100(SC-BC)e^{\lambda t}}{60\times CF\times F} \tag{1}$$

where C_R is the radon-222 concentration in water (Bq L^{-1}), SC is the sample count rate (counts min^{-1}), BC is the background count rate (counts min^{-1}), t is the elapsed time between sampling and counting (min), λ is the decay constant of radon-222 (1.26×10^{-4} min^{-1}), CF is the experimentally determined calibration factor of the counting system (13.57), and F is the partition coefficient of radon between water and the scintillation cocktail (0.96).

The factor 100 converts the activity measured in a 10 mL water sample to activity per litre, while the factor 60 converts the count rate from count per minute to count per second. The parameter F = 0.96 accounts for the precise partitioning behavior in an equal 1:1 volume ratio of water to cocktail vial configuration, ensuring alignment between experimental and uncertainty configurations. Background measurements were performed under identical experimental conditions, and the measured background count rate was subtracted from all sample count rates to obtain the net count rate. Samples with net count rates statistically indistinguishable from background were treated as below detection limits.

E. Annual Effective Dose Calculation

For the estimation of the annual effective dose due to ingestion of radon-222 in drinking water, the following international models were used [7], [8]:

$$\text{AED} = C_R \times \text{I} \times DCF \tag{2}$$

where AED is the annual effective dose (mSv y^{-1}), C_R is the radon-222 concentration in water (Bq L^{-1}), I is the annual water intake (L y^{-1}), and DCF is the ingestion dose conversion factor for radon-222 (mSv Bq^{-1}).

The annual water intake values were set at 730 L y^{-1} for adults (2 L day^{-1}), and 365 L y^{-1} for children (1 L day^{-1}), while the ingestion dose conversion factors for adults and children were defined as in (3) and (4) [7].

$$DCF_{adult} = 3.5 \times 10^{-9}\ Sv\ Bq^{-1} \tag{3}$$

$$DCF_{child} = 7.0 \times 10^{-9}\ Sv\ Bq^{-1} \tag{4}$$

The specific annual effective dose equations for both adults and children are evaluated as follows:

$$AED_{adult} = C_R \times 730 \times 3.5 \times 10^{-9} \tag{5}$$

$$AED_{child} = C_R \times 365 \times 7.0 \times 10^{-9} \tag{6}$$

F. Uncertainty Analysis and Minimum Detectable Activity

1) Propagation of Uncertainty

An uncertainty analysis was performed to evaluate the reliability and precision of the measured radon-222 concentrations. The analysis considered both statistical uncertainties arising from radioactive counting and systematic uncertainties associated with calibration, partitioning, and timing. The net count rate was determined using (7).

$$R_n = R_s - R_b \tag{7}$$

Where R_s is the sample count rate, and R_b is the background count rate. Radioactive decay counting follows Poisson statistics, where the variance in counts equals the mean number of counts. For measurements involving both sample and background counts, the combined uncertainty in the net count rate was calculated using (8).

$$\sigma_{R_n} = \sqrt{\sigma_{R_s}^2 + \sigma_{R_b}^2} \tag{8}$$

The combined standard uncertainty in radon concentration, as recommended by the Guide to the Expression of Uncertainty in Measurement, was used to evaluate standard error propagation [8].

$$\sigma_C = C\sqrt{\left(\frac{\sigma_{R_n}}{R_n}\right)^2 + \left(\frac{\sigma_k}{k}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2 + (\lambda\sigma_t)^2} \tag{9}$$

Using relative uncertainties of approximately 5% for calibration $\left({}^{\sigma_k}/_{k} = 0.05\right)$ and 3% for the partition coefficient (σ_F/F = 0.03), (9) simplifies to (10).

$$\sigma_C = C\sqrt{\left(\frac{\sigma_{R_n}}{R_n}\right)^2 + (0.05)^2 + (0.03)^2} \tag{10}$$

The expanded uncertainty (U) was calculated using a coverage factor of 2, corresponding to a 95% confidence level.

$$U = 2\sigma_C \tag{11}$$

2) Minimum Detectable Activity (MDA) Evaluation

The minimum detectable activity was estimated using (12).

$$\text{MDA} = \frac{2.71 + 4.65\sqrt{B}}{t_c \times k \times F} \times \frac{100}{60} \tag{12}$$

where B represents background counts, and t_c is the counting time.

Based on the experimental background count rates and a nominal counting time of 50 minutes, the numerical value of the calculated MDA for this system was determined to be 0.015 Bq L^{-1}, while samples with net count rates statistically indistinguishable from background fluctuations were appropriately classified as below this detection limit (<0.015 Bq L^{-1}).

III. Results and Discussion

A. Distribution of Radon-222 Concentration in Groundwater

The measured radon-222 concentrations with their associated expanded uncertainties are presented in Table I, and the statistical summary by location is provided in Table II. Measured concentrations ranged from below the detection limit (<0.015 Bq L^{-1}) to 2.30 Bq L^{-1}, with an overall mean concentration of 0.289 ± 0.437 Bq L^{-1}.

Table I. Distribution of Radon-222 Concentration in Groundwater Samples with Expanded Uncertainty.

Sample ID	Location	Radon Concentration (Bq L^{-1})	Expanded Uncertainty (Bq L^{-1})	Result (Bq L^{-1})
Tap 1	Igu	0.083	0.021	0.083 ± 0.021
Tap 2	Igu	0.175	0.034	0.175 ± 0.034
Tap 3	Igu	0.207	0.038	0.207 ± 0.038
Tap 4	Igu	0.252	0.044	0.252 ± 0.044
Tap 5	Igu	0.369	0.062	0.369 ± 0.062
Tap 6	Igu	0.188	0.036	0.188 ± 0.036
Tap 7	Igu	0.064	0.018	0.064 ± 0.018
Tap 8	Igu	0.172	0.034	0.172 ± 0.034
Tap 9	Igu	0.040	0.013	0.040 ± 0.013
Tap 10	Igu	0.257	0.044	0.257 ± 0.044
Tap 11	Igu	0.597	0.090	0.597 ± 0.090
Tap 12	Igu	0.756	0.106	0.756 ± 0.106
Tap 13	Igu	0.174	0.034	0.174 ± 0.034
Tap 14	Igu	—	—	Below Detection (< 0.015)
Tap 15	Igu	0.058	0.016	0.058 ± 0.016
Tap 16	Igu	0.066	0.018	0.066 ± 0.018
Tap 17	Igu	0.018	0.008	0.018 ± 0.008
Tap 18	Igu	0.225	0.041	0.225 ± 0.041
Tap 19	Igu	0.062	0.017	0.062 ± 0.017
Tap 20	Igu	0.219	0.040	0.219 ± 0.040
Tap 21	Igu	0.101	0.023	0.101 ± 0.023
Kubwa 1	Kubwa	0.064	0.018	0.064 ± 0.018
Kubwa 2	Kubwa	0.126	0.027	0.126 ± 0.027
Kubwa 3	Kubwa	0.113	0.025	0.113 ± 0.025
Kubwa 4	Kubwa	—	—	Below Detection (< 0.015)
Kubwa 5	Kubwa	0.137	0.028	0.137 ± 0.028
Kubwa 6	Kubwa	0.173	0.034	0.173 ± 0.034
Kubwa 7	Kubwa	0.152	0.031	0.152 ± 0.031
Kubwa 8	Kubwa	2.300	0.290	2.300 ± 0.290

Table II. Statistical Summary of Radon-222 Concentrations by Location.

Location	Number of Samples	Mean (Bq L^{-1})	Standard Deviation (Bq L^{-1})	Minimum (Bq L^{-1})	Maximum (Bq L^{-1})
Igu	21	0.204	0.184	< 0.015	0.756
Kubwa	8	0.438	0.759	< 0.015	2.300
Overall	29	0.289	0.437	< 0.015	2.300

Because environmental radioactivity datasets with low absolute counts are typically heavily skewed, the 95% confidence interval for the overall true mean concentration spans from 0.123 to 0.455 Bq L^{-1}. The observed concentrations are generally low and comparable to baseline values previously reported under similar hydrogeological conditions [9], [11].

Spatial variability is evident between the two primary sampling sectors. The Igu area displays a highly uniform profile with a lower mean concentration (0.204 ± 0.184 Bq L^{-1}), suggesting dominant hydrogeological dilution effects or weaker local source terms. Conversely, the Kubwa dataset exhibits substantially higher internal variability and a higher mean value (0.438 ± 0.759 Bq L^{-1}), reflecting regional lithological heterogeneity.

B. Geological Interpretation and the Kubwa 8 Outlier

The elevated concentration observed in sample Kubwa 8 (2.30 Bq L^{-1}) is significantly higher than all other samples within the study area. While the regional geology of the Abuja Basement Complex includes migmatites, gneisses, and granites, which host trace uranium-bearing minerals, the sharp difference between Kubwa 8 and neighboring wells indicates that this represents a localized structural anomaly rather than a widespread regional hazard [1-2].

Radon emanation and migration are strongly accelerated by localized subsurface structural features such as fault splays, highly fractured granite terrains, or weathered contact zones within the host rock crystalline matrix. Because site-specific borehole lithology logs and local high-resolution radiometric maps were unavailable for these exact coordinates, this interpretation remains a plausible inference based on regional trends. To definitively rule out a temporal spike or establish if this location marks a permanent geological hotspot, systematic multi-seasonal repeat sampling at the Kubwa 8 site is highly warranted.

C. *Uncertainty Analysis and Curve-Fitting Interpretation*

The uncertainty analysis demonstrated a clear inverse relationship between radon concentration and relative uncertainty, as illustrated in Fig. 2. This behavior is mathematically dictated by Poisson statistics [12], where relative statistical fluctuations scale as $N^{-0.5}$ and become dominant at low net count rates. Because this relationship is fundamentally non-linear and governed directly by the physics of radioactive decay rather than an empirical linear correlation, the inclusion of a standard linear regression (R^2) equation would be physically inappropriate. Higher activity samples produced larger net count rates, successfully reducing the relative contribution of counting uncertainty. Expanded uncertainties (k=2) ranged from approximately 6% for the high-activity Kubwa 8 sample to more than 20% for low-level samples near the detection limit.

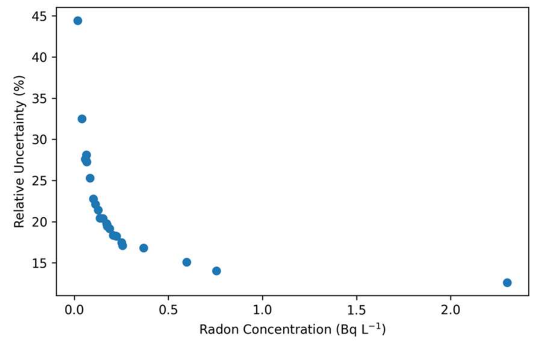

Fig. 2. Relative Uncertainty as a Function of Radon Concentration.

D. *Annual Effective Dose Assessment*

The estimated annual effective doses due to the ingestion of radon-222 are presented in Table III. To present a conservative, upper-bound safety scenario, the water intake relationships modeled in Fig. 3 were generated using the maximum observed concentration (2.30 Bq L^{-1} from Kubwa 8). This represents the worst-case radiological dose scenario possible under peak dry-season conditions.

Table III. Estimated Annual Effective Dose Due to Ingestion of Radon-222 in Groundwater for Adults and Children.

Sample ID	Location	Radon Concentration (Bq L^{-1})	Adult Dose (mSv y^{-1})	Children Dose (mSv y^{-1})
Tap 1	Igu	0.083	2.12×10^{-4}	4.24×10^{-4}
Tap 2	Igu	0.175	4.47×10^{-4}	8.94×10^{-4}
Tap 3	Igu	0.207	5.29×10^{-4}	1.06×10^{-3}
Tap 4	Igu	0.252	6.44×10^{-4}	1.29×10^{-3}
Tap 5	Igu	0.369	9.43×10^{-4}	1.89×10^{-3}
Tap 6	Igu	0.188	4.80×10^{-4}	9.61×10^{-4}
Tap 7	Igu	0.064	1.63×10^{-4}	3.27×10^{-4}
Tap 8	Igu	0.172	4.39×10^{-4}	8.79×10^{-4}
Tap 9	Igu	0.040	1.02×10^{-4}	2.04×10^{-4}
Tap 10	Igu	0.257	6.57×10^{-4}	1.31×10^{-3}
Tap 11	Igu	0.597	1.53×10^{-3}	3.05×10^{-3}
Tap 12	Igu	0.756	1.93×10^{-3}	3.87×10^{-3}
Tap 13	Igu	0.174	4.44×10^{-4}	8.89×10^{-4}
Tap 14	Igu	< 0.015	—	—
Tap 15	Igu	0.058	1.48×10^{-4}	2.96×10^{-4}
Tap 16	Igu	0.066	1.68×10^{-4}	3.37×10^{-4}
Tap 17	Igu	0.018	4.59×10^{-5}	9.18×10^{-5}
Tap 18	Igu	0.225	5.75×10^{-4}	1.15×10^{-3}
Tap 19	Igu	0.062	1.58×10^{-4}	3.16×10^{-4}
Tap 20	Igu	0.219	5.59×10^{-4}	1.12×10^{-3}
Tap 21	Igu	0.101	2.58×10^{-4}	5.15×10^{-4}
Kubwa 1	Kubwa	0.064	1.63×10^{-4}	3.27×10^{-4}
Kubwa 2	Kubwa	0.126	3.22×10^{-4}	6.43×10^{-4}
Kubwa 3	Kubwa	0.113	2.88×10^{-4}	5.77×10^{-4}
Kubwa 4	Kubwa	< 0.015	—	—
Kubwa 5	Kubwa	0.137	3.50×10^{-4}	7.00×10^{-4}
Kubwa 6	Kubwa	0.173	4.42×10^{-4}	8.84×10^{-4}
Kubwa 7	Kubwa	0.152	3.88×10^{-4}	7.76×10^{-4}
Kubwa 8	Kubwa	2.300	5.88×10^{-3}	1.18×10^{-2}

Adult annual effective doses ranged from 4.59×10^{-5} to 5.88×10^{-3} mSv y^{-1}, while child doses ranged from 9.18×10^{-5} to 1.18×10^{-2} mSv y^{-1}. All estimated doses remain substantially below the internationally recommended reference level of 0.1 mSv y^{-1}, indicating negligible radiological risk from ingestion [6]. Children consistently exhibited higher annual effective doses than adults due to their lower body mass and higher ingestion dose conversion factors. Under hot-season conditions in Abuja, where ambient temperatures frequently reach 35 to 40°C, physical hydration demands may double water intake [3-4], [16]. Even under an extreme consumption scenario, the calculated upper-bound doses remain significantly below international safety thresholds.

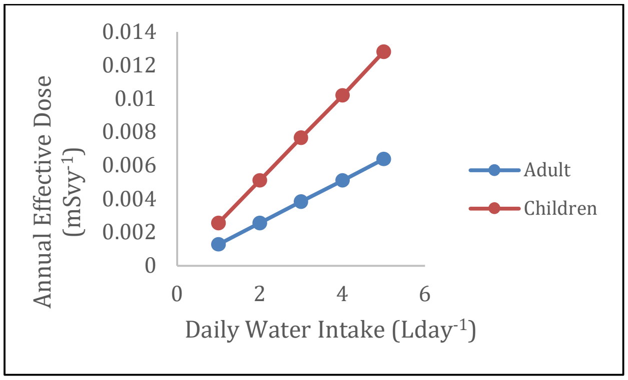

Fig. 3. Variation of annual effective dose with water intake for adults and children.

IV. Conclusion

This study presents the first conservative dry-season assessment of radon-222 concentration in groundwater sources within Abuja, Nigeria, combining liquid scintillation counting with an expanded uncertainty analysis. Measured radon concentrations were generally low and substantially below internationally recommended guideline values for drinking water. Although a localized elevated concentration was observed in sample Kubwa 8 (2.30 Bq L^{-1}), likely associated with localized fracturing within the basement complex terrain, the corresponding annual effective doses for all demographics remained safely below international action limits. The integration of a calculated system MDA (0.015 Bq L^{-1}), Poisson error propagation models, and conservative upper-bound sampling strategies establishes a rigorous baseline dataset for future groundwater environmental management frameworks in similar geological environments.

Conflict of Interest

The authors declare no conflicts of interest.

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