

MONTE CARLO SIMULATION OF THE HEALTH RISK FROM EXPOSURE TO Rn-222 IN GROUNDWATER SOURCES IN THE NASARAWA LOCAL GOVERNMENT AREA OF NASARAWA STATE, NORTH-CENTRAL NIGERIA

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ABSTRACT

Aim : This study assesses ²²²Rn concentrations in groundwater sources within Nasarawa Local Government Area and evaluates the Excessive Lifetime Cancer Risk (ELCR) associated with their consumption.

Methods: Groundwater samples were collected from multiple locations and analyzed using a RAD-7 electronic radon detector with RAD-H₂O accessories. ²²²Rn concentrations were estimated using both a conventional formula and a Monte Carlo simulation performed over 10,000 iterations. These simulations were conducted using the Oracle Crystal Ball Software. ELCR values were validated against the 5th, 50th, and 95th percentiles of the resulting probability distribution.

Results: The mean ²²²Rn concentration was 2,201 Bq/m³, which significantly exceeded the World Health Organization (WHO) recommended limit of 300 Bq/m³. The annual effective dose due to ingestion (AED_{ing}) also surpassed the 0.1 mSv/yr threshold set by the European Union and the WHO, while the total annual effective dose from ingestion and inhalation exceeded the 1 mSv/yr maximum contamination limit. The highest ELCR value (2.97 ± 0.35) was recorded in Usha, likely due to the alaskite- and clay-rich geology of the region. All the ELCR values exceeded the recommended limit of 0.003875 set by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

Conclusions: These findings highlight a significant potential public health risk from ²²²Rn-contaminated groundwater, especially if consumed without pre-treatment. The implementation of intervention and remediation strategies is strongly recommended to reduce exposure, even though no radiological health effects have been reported in the region to date.

Key words: Groundwater, Radon, Monte Carlo, Simulation, Cancer, Exposure, Health risk

INTRODUCTION

Groundwater is essential for human development, and its quality has a direct impact on human health^{1,2}. Groundwater serves as the primary source of drinking water in many parts of the world^{2,3}, including Nasarawa State, North-Central Nigeria. Even sachet water, commonly referred to as “pure water”, is often derived from underground water sources, which are susceptible to radon contamination from the surrounding rocks and soils³⁻⁵.

Radon is the most common intermediate radionuclide in the uranium-238 (²³⁸U) decay chain^{6,7}. Its relatively short half-life of 3.8 days allows it to migrate efficiently through environmental media such as water, soil, rock, and air^{6,7}. Exposure to radon and its progeny accounts for over 50% of the total radiation dose humans receive from natural sources⁸⁻¹⁰. As a naturally occurring pollutant, radon is a significant health concern due to its ability to cause DNA mutations and increase cancer risk, particularly through the deposition of radioactive decay products in the lung¹¹.

Radon originates from the radium decay in soil and rocks and escapes through crevices and fissures via dissolution in groundwater^{12,13}. Its underground movement occurs through soil voids, where it dissolves in groundwater, is stored in pores, and can be re-adsorbed onto soil particles^{14,15}. Domestic human exposure to

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radon occurs mainly through two pathways: 1) ingestion of contaminated water, which delivers radiation directly to the gastrointestinal tract; and 2) inhalation of radon released into indoor air during household activities such as cooking, cleaning, or bathing^{16,17}. When radon-contaminated water is used domestically, radon gas can be released into the air and inhaled, further compounding the health risks associated with this radionuclide^{18,19}. Prolonged ingestion of such water exposes the gastric mucosa to radiation, increasing cancer risk¹⁹.

Epidemiological studies have shown that the alpha particles emitted by radon can pose serious health risks through both inhalation and ingestion, especially in areas dependent on groundwater^{20,21}. Residents of the Nasarawa Local Government Area (LGA) rely on groundwater for both domestic and commercial use; however, studies aimed at assessing the risk of radon exposure in groundwater within the Nasarawa LGA are scarce. Existing research has primarily focused on background radiation measurements, indoor air quality, building materials, mining soils, levels of uranium (U), thorium (Th), potassium (K), radium (Ra), heavy metals, and gross alpha/beta activity. In particular, little to no attention has been given to the potential radon exposure risk from groundwater consumption in the region.

A major challenge in radiation risk assessment is the uncertainty associated with the Excess Lifetime Cancer Risk (ELCR) estimation formula, which can either underestimate or overestimate the health risks associated with radiation exposure^{22,23}. Overestimation may lead to the misallocation of scarce resources towards unnecessary remediation efforts, while underestimation leaves residents exposed to unavoidable public health hazards. Although Monte Carlo methods have been employed globally for radon risk assessment, their use in assessing the health risks of radon (²²²Rn) from groundwater—particularly from both ingestion and inhalation pathways—remains limited in the study area. To date, no simulation-based studies have been conducted in the Nasarawa LGA of Nasarawa State, North-Central Nigeria.

This study aims to apply a Monte Carlo simulation approach as a robust alternative for predicting and assessing health risk associated with ²²²Rn groundwater in the Nasarawa LGA. This approach improves risk quantification and supports evidence-based decision-making for public health protection.

STUDY AREA

The Nasarawa LGA is located in Nasarawa State, within the North-Central zone of Nigeria. The administrative headquarters of this region is located in the town of Nasarawa. The LGA shares boundaries with the Toto LGA, parts of Benue State, and the Federal Capital Territory (Abuja).

The area comprises several towns and villages, including Usha, Loko, Guto, Mararaba-udege, Tammah, Angwan-wada, and the Millionaires' quarters. The Nasarawa LGA has an estimated population of over 188,903 inhabitants and is predominantly occupied by the Afo/Ajiri ethnic group; additional minority groups include the Gbagi, Agatu, Gade, Bassa, and Hausa. The major economic activities in the area involve agriculture and artisanal mining.

Due to the region's underlying geology, which includes radon-emitting rock formations and the widespread reliance on groundwater for domestic and commercial use, there are concerns about the concentration of radon (²²²Rn) in groundwater sources. This is particularly important given the ongoing mining activities in the region, which could increase the mobilization of radionuclides into groundwater systems. Despite these risks, there has been little to no prior assessment of radon exposure through groundwater in this area, highlighting the urgent need for scientific evaluations to safeguard public health.

METHODS

Sample Collection and Preparation

Groundwater samples were collected from 10 different sampling locations within the Nasarawa LGA using random sampling methods. The sampling sites were selected based on population density and frequency of groundwater usage, especially in areas where groundwater was the sole or dominant source of water for public consumption, livestock, and crop production.

Each sample was collected in a 300 mL plastic container, leaving minimal headspace to allow for thermal expansion but minimize radon escape. The containers were sealed immediately after collection to prevent the degassing of radon. Specifically, each container was wrapped with masking tape and labeled with a unique sample identification code (ID) using a permanent marker. The geographic coordinates of each sampling point were recorded with a global positioning system (GPS) device.

All labeled samples were securely packaged and transported to the Centre for Energy Research and Training (CERT) at Ahmadu Bello University, Zaria, in Kaduna State, Nigeria, for laboratory-based radon concentration measurements.

Radon Concentration Measurements

Experimental measurements of ^{222}Rn concentration in the collected groundwater samples were conducted using a RAD7 electronic radon detector (DurrIDGE Co., USA). The measurements were performed using the RAD-H₂O accessory following the Wat250 protocol, which is specifically designed for water samples. The RAD7 automatically recorded the highest and lowest radon concentrations in each sample.

RAD7 Operating Conditions

The operating conditions of the RAD7 during measurements were as follows:

- Cycle and Recycle settings: 005 and 004, respectively.
- Operating Mode: Medium sensitivity mode.
- Detection Range: 0–750,000 Bqm⁻³ ^{24,25}
- Relative Humidity: Before measurements, the RAD7 was purged with dry air until the internal relative humidity dropped to 6% (~30 minutes), ensuring optimal detection performance.
- Sample volume: 250 mL (drawn from the 300 mL sample containers for analysis).
- Measurement Duration: 30 minutes.
- Replicates: Each measurement was performed in triplicate to ensure accuracy and reproducibility. The mean values were used for further analysis.

The RAD7 device uses alpha spectrometry to detect radon as well as its short-lived decay products (specifically, the alpha particles from the decay of ^{218}Po and ^{214}Po). The RAD-H₂O setup involves aerating the water sample, trapping radon in a closed-loop air circuit, and subsequently analyzing its decay products within a scintillation chamber.

Figure 1 illustrates the setup for experimental ^{222}Rn concentration measurements.

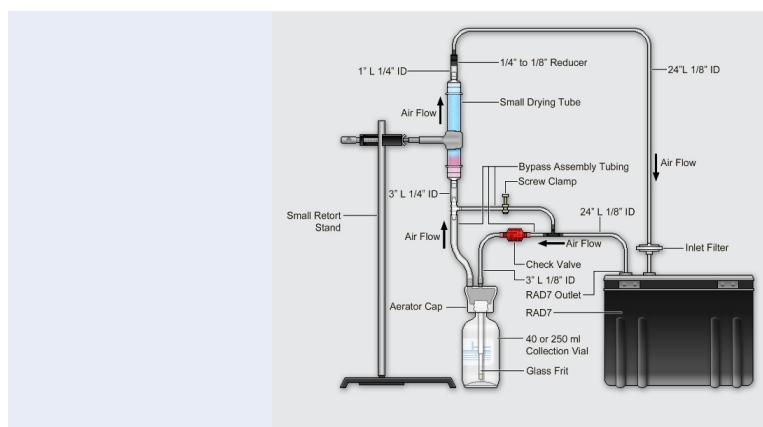


Figure 1: RAD-H₂O configuration of the RAD7 device ^{26,27}.

EXPERIMENTAL ANALYSIS

Annual Effective Dose for Ingestion

The annual effective dose for the ingestion of radon in groundwater was obtained from the documentation provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) ²⁷. Specifically, the annual effective dose for ingestion (ADE_{ing}) was calculated using Equation (1):

$$ADE_{ing} = C_{Rn} \times A_{wi} \times IDC_{ing} \quad (1)$$

where C_{Rn} is the radon activity concentration (Bq/m³), A_{wi} is the annual water intake (730 L/yr) for adults, and IDC_{ing} is the ingesting dose conversion factor for radon (3.5×10^{-6} Sv/Bq for adults) ^{28,29}.

Annual Effective Dose for Inhalation

The annual effective dose for the inhalation of radon (ADE_{inh}) due to radon in water released to the air was calculated using Equation (2):

$$AED_{inh} = C_{Rn} \times AWC_R \times IDC_{F_{inh}} \times EF \times IOT \quad (2)$$

where C_{Rn} is the radon activity concentration in water (Bq/m^3), AWC_R is the ratio of radon in air to radon in water ($10^{-4} Bq/m^3/Bq/L$), $IDC_{F_{inh}}$ is the ingesting dose conversion factor for radon ($9 \times 10^{-6} Sv/hr/Bq/m^3$), EF is the equilibrium factor between radon and its products (0.4), and IOT is the average indoor occupancy time per person (7,000 hr/y)²⁹.

Monte Carlo Method Simulation of Excessive Lifetime Cancer Risk

The probability of cancer induction from exposure to ^{222}Rn by the inhabitants of the Nasarawa LGA was estimated using the ELCR equation. ELCR represents the probability of an individual developing cancer over an average adult lifetime of 75 years due to ^{222}Rn exposure in groundwater. The ELCR was calculated using Equations 3 and 4:

$$D_{Total} (mSv/yr) = AED_{ing} + AED_{inh} \quad (3)$$

Where D_{Total} is the sum of the annual radon doses through ingestion and inhalation. From here, ELCR can be obtained from:

$$ELCR = D_{Total} \times DL \times RF \quad (4)$$

where DL is the assumed life expectancy of an average inhabitant (75 years), and RF is the stochastic risk factor ($0.055 Sv^{-1}$)^{28,29}.

The Oracle Crystal Ball version 11.1.2.4.850 software was used to perform the Monte Carlo simulations³⁰.

RESULTS AND DISCUSSION

In this study, the activity concentration (Bq/m^3), annual effective dose due to ingestion (AED_{ing}), inhalation (AED_{inh}), the combined ingestion and inhalation ($AED_{ing+inh}$), and ELCR of ^{222}Rn in groundwater used for drinking and domestic purposes in the Nasarawa LGA of Nasarawa state, North-Central Nigeria, were determined using a conventional approach as well as Monte Carlo simulation implemented with the Oracle Crystal Ball software.

Experimental Radon Concentration

Table 1 presents the experimentally measured ^{222}Rn concentrations obtained from RAD7 analysis from groundwater samples collected from various locations within the Nasarawa LGA. The location, ID, and sample code of each sample are listed.

* = Lowest radon concentration; ** = Highest radon concentration

Table 1 shows that the highest mean ^{222}Rn concentration was observed in the groundwater sample collected from Usha (N_1), which had a mean concentration of $2,810 Bq/m^3$ and a standard deviation, maximum, and minimum values of 335, 3,240, and $2,470 Bq/m^3$, respectively.

The mean radon concentration across all samples was $2,201 Bq/m^3$.

Annual Effective Doses

Table 2 presents the AED_{ing} , AED_{inh} , and $AED_{ing+inh}$ values as calculated using Equations (1) and (2).

The highest mean AED_{ing} was recorded in Usha (N_1 ; $7.18 \pm 0.86 mSv/yr$), with a maximum and minimum value of 8.28 ± 0.86 and $6.31 \pm 0.86 mSv/yr$, respectively, while the Police Station (N_5 ; $4.78 \pm 1.20 mSv/yr$) exhibited the lowest mean AED in the study area, with a maximum and minimum value of 5.65 ± 1.20 and $2.99 \pm 1.20 mSv/yr$, respectively. The mean AED_{ing} across all the samples was $5.62 \pm 1.19 mSv/yr$, with a peak of 6.86 ± 1.19 and a low of $4.25 \pm 1.19 mSv/yr$.

Notably, the AED_{ing} values from the groundwater samples collected from the Nasarawa LGA far exceed the maximum annual dose limit of $0.1 mSv/yr$ recommended by both the European Union (EU) and the World Health Organization (WHO).

Similarly, the highest AED_{inh} was recorded in Usha (N_1 ; $0.007 \pm 0.001 mSv/yr$), while the lowest was observed at the Police Station (N_5 ; $0.005 \pm 0.001 mSv/yr$).

Table 1: Results of experimentally measured radon concentrations

Concentration (Bq/m ³)					
S/N	Sample I.D	Sample Code	Mean	Highest	Lowest
1	N ₁	5604	2810±335**	3240±335	2470±335
2	N ₂	5704	2310±353	2790±353	2040±353
3	N ₃	5804	2110±246	2340±246	1900±246
4	N ₄	5904	2600±576	3090±576	1900±576
5	N ₅	6004	1870±470*	2210±470	1170±470
6	N ₆	6104	2020±449	2500±449	1450±449
7	N ₇	6204	2090±535	2650±535	1300±535
8	N ₈	6304	2050±705	2890±705	1020±705
9	N ₉	6404	1950±359	2350±359	1610±359
10	N ₁₀	6504	2200±642	2790±642	1760±642
Sum average			2201±467	2685±467	1662±467

Table 2: Annual effective dose (mSv/yr) from ingestion (AED_{ing}), inhalation (AED_{inh}), and the combination of both (AED_{ing+inh}).

S/N	Sample Location	Sample I.D	AED _{ing}			AED _{inh}			AED _{ing+inh} D _{Total} = AED _{ing} + AED _{inh}
			AED _{ing}	Highest _{ing}	Lowest _{ing}	AED _{inh}	Highest _{inh}	Lowest _{inh}	
1	Usha**	N ₁	7.18±0.86	8.28±0.86	6.31±0.86	0.007±0.001	0.008±0.001	0.006±0.001	7.19
2	Endo 1	N ₂	5.90±0.90	7.13±0.90	5.21±0.90	0.006±0.001	0.007±0.001	0.005±0.001	5.91
3	Endo 2	N ₃	5.39±0.63	5.98±0.63	4.86±0.63	0.005±0.001	0.006±0.001	0.005±0.001	5.40
4	Mararaba Udege	N ₄	6.64±1.47	7.90±1.47	4.86±1.47	0.007±0.002	0.008±0.002	0.005±0.002	6.65
5	Police Station*	N ₅	4.78±1.20	5.65±1.20	2.99±1.20	0.005±0.001	0.006±0.001	0.003±0.001	4.78
6	Mangwor Goma	N ₆	5.16±1.15	6.39±1.15	3.71±1.15	0.005±0.001	0.006±0.001	0.004±0.001	5.17
7	Angwan Birri	N ₇	5.34±1.37	6.77±1.37	3.32±1.37	0.005±0.001	0.007±0.001	0.003±0.001	5.35
8	Angwan Wada	N ₈	5.24±1.80	7.38±1.80	2.61±1.80	0.005±0.002	0.007±0.002	0.003±0.002	5.24
9	Millionaires Quarters	N ₉	4.98±0.92	6.00±0.92	4.11±0.92	0.005±0.001	0.006±0.001	0.004±0.001	4.99
10	Tammah	N ₁₀	5.62±1.64	7.13±1.64	4.50±1.64	0.006±0.002	0.007±0.002	0.004±0.002	5.63
Average sum			5.62±1.19	6.86±1.19	4.25±1.19	0.056±0.012	0.068±0.012	0.042±0.012	5.63

In contrast to the AED_{ing} , the AED_{inh} values across the study area were well within the limit of 1.0 mSv/yr recommended by international organizations, including the WHO.

The $AED_{ing+inh}$ represents the total absorbed dose from groundwater consumption in the Nasarawa LGA. The measured $AED_{ing+inh}$ ranged from 7.19 mSv/yr in Usha (N_1) to 4.78 mSv/yr in the Police Station sample (N_5).

Excessive Lifetime Cancer Risk Calculated Using Conventional Methods

The ELCR values due to the consumption of groundwater in the study areas, as estimated from conventional methods, are presented in Table 3.

Table 3: The Excessive Lifetime Cancer Risk due to ingestion ($ELCR_{ing}$), inhalation ($ELCR_{inh}$) and ingestion/ inhalation ($ELCR_{ing+inh}$; $ELCR_{tot}$). $ELCR_{max}$, and $ELCR_{min}$ are also presented.

S/N	Sample Location	Sample I.D	$ELCR_{ing}$	$ELCR_{inh}$	$ELCR_{ing+inh}$	$ELCR_{max}$	$ELCR_{min}$
1	Usha**	N_1	2.96	0.003	2.96 ± 0.35	3.42	2.61
2	Endo 1	N_2	2.43	0.002	2.44 ± 0.37	2.94	2.15
3	Endo 2	N_3	2.22	0.002	2.23 ± 0.26	2.47	2.00
4	Mararaba Udege	N_4	2.74	0.002	2.74 ± 0.61	3.26	2.00
5	Police Station*	N_5	1.97	0.002	1.97 ± 0.50	2.33	1.23
6	Mangworo Goma	N_6	2.13	0.002	2.13 ± 0.15	2.64	1.53
7	Angwan Birri	N_7	2.20	0.002	2.20 ± 0.56	2.80	1.37
8	Angwan Wada	N_8	2.16	0.002	2.16 ± 0.74	3.05	1.08
9	Millionaires Quarters	N_9	2.06	0.002	2.06 ± 0.38	2.48	1.70
10	Tammah	N_{10}	2.32	0.002	2.32 ± 0.68	2.94	1.86
Average sum			2.32	0.023	2.32 ± 0.49	2.83	1.75

Table 3 presents the ELCR due to ingestion ($ELCR_{ing}$), inhalation ($ELCR_{inh}$), and combined ingestion and inhalation ($ELCR_{ing+inh}$) as well as the maximum ($ELCR_{max}$) and minimum ($ELCR_{min}$) values based on ^{222}Rn measurements obtained from groundwater samples collected from the Nasarawa LGA. The samples exhibited an average $ELCR_{ing+inh}$ of 2.32 ± 0.49 , while the mean $ELCR_{ing}$, $ELCR_{inh}$, and $ELCR_{ing+inh}$ values were 2.32, 0.023, and 2.32 ± 0.49 , respectively. The highest $ELCR_{ing+inh}$ was recorded in the sample collected from Usha (N_1 ; 2.96 ± 0.35), while the lowest was found in the sample from the Police Station area (1.97 ± 0.50).

The $ELCR_{tot}$, $ELCR_{max}$, and $ELCR_{min}$ resulting from the ingestion and inhalation of ^{222}Rn in groundwater samples from the Nasarawa LGA exhibited mean values of 2.32, 2.83, and 1.75, respectively; these values represent the cumulative ELCR obtained from the analyzed samples.

Monte Carlo Simulation of the Excessive Lifetime Cancer Risk (ELCR)

ELCR due to the consumption of groundwater within the study areas, calculated using the Monte Carlo method, are presented in Table 4 and Table 5. These values were compared to the values obtained using the conventional method.

A total of 10,000 simulations were performed to determine the ELCR associated with ^{222}Rn exposure from groundwater samples obtained from the Nasarawa LGA. The 5th, 50th, and 95th percentiles of the ELCR probability were computed using Oracle Crystal Ball software, with the results summarized in Table 4 for each sampling location. These percentiles represent the minimum probable risk (5th percentile; best-case scenario), median risk (50th percentile; most probable scenario), and the maximum probable risk (95th percentile; worst-case scenario) attributable to ^{222}Rn inhalation and ingestion due to groundwater consumption.

Comparison Between the Radon Exposure Risk Calculated Using Conventional and Monte Carlo Methods

Table 4 compares the ELCR calculated from the conventional and Monte Carlo methods. Specifically, it presents the 5th and 95th percentiles obtained after 10,000 Monte Carlo simulations.

The calculated $ELCR_{ing/inh}$, simulated $ELCR_{ing/inh}$, (50th percentile), ELCR (5th percentile), and ELCR (95th percentile) values were 2.32 ± 0.49 , 2.32, 1.94 ± 0.00 , and 2.70 ± 0.06 , respectively.

Table 5 presents the ELCR values obtained from conventional methods as well as the 0th and 100th percentiles of the Monte Carlo simulation.

Table 4: ELCR values obtained from conventional and Monte Carlo methods.

Results using the formula			Monte Carlo at 5% and 95% percentiles for mitigation		
S/N	Sample Location/I.D	$ELCR_{ing+inh}$	$ELCR_{ing/inh}$	ELCR;5%	ELCR;95%
1	N_1	2.96	0.003	2.96 ± 0.35	3.42
2	N_2	2.43	0.002	2.44 ± 0.37	2.94
3	N_3	2.22	0.002	2.23 ± 0.26	2.47
4	N_4	2.74	0.002	2.74 ± 0.61	3.26
5	N_5	1.97	0.002	1.97 ± 0.50	2.33
6	N_6	2.13	0.002	2.13 ± 0.15	2.64
7	N_7	2.20	0.002	2.20 ± 0.56	2.80
8	N_8	2.16	0.002	2.16 ± 0.74	3.05
9	N_9	2.06	0.002	2.06 ± 0.38	2.48
10	N_{10}	2.32	0.002	2.32 ± 0.68	2.94
Sum average		2.32 ± 0.49	2.32	1.94 ± 0.00	2.70 ± 0.06

Table 5: A comparison between the calculated and simulated ELCR values in terms of the minimum and maximum radon risk obtained from both methods.

Calculated results						Simulated results; 10,000 Iterations:			
S/N	I.D	$ELCR_{tot}$	$ELCR_{max}$	$ELCR_{min}$	SD_{tot}	$ELCR_{tot/sim}$	$ELCR_{max/sim}$	$ELCR_{min/sim}$	$SD_{tot/sim}$
1	N_1	2.97	3.42	2.61	0.35	2.97	4.17	1.81	0.29
2	N_2	2.44	2.94	2.15	0.37	2.43	3.43	1.45	0.24
3	N_3	2.23	2.47	2.01	0.26	2.23	3.01	1.26	0.23
4	N_4	2.74	3.26	2.01	0.61	2.74	3.91	1.60	0.28
5	N_5	1.97	2.33	1.23	0.49	1.97	2.68	1.26	0.20
6	N_6	2.13	2.64	1.53	0.14	2.13	2.86	1.27	0.21
7	N_7	2.21	2.80	1.37	0.56	2.20	3.09	1.34	0.22
8	N_8	2.16	3.05	1.08	0.74	2.17	2.95	1.42	0.22
9	N_9	2.06	2.48	1.69	0.38	2.06	2.85	1.31	0.21
10	N_{10}	2.32	2.94	1.86	0.68	2.32	3.20	1.43	0.23
Sum average		2.32	2.83	1.75	0.49	2.32	3.22	1.42	0.23

Table 5 presents the ELCR values obtained from conventional methods as well as the 0th and 100th percentiles of the Monte Carlo simulation. Table 5 shows that in Usha (N₁), the mean calculated ELCR was 2.97 mSv/yr, while the simulated 5th, 50th, and 95th percentile ELCR values due to the ingestion and inhalation of ²²²Rn were 2.44 ± 0.00, 2.97 ± 0.29, and 3.45 ± 0.01, respectively. In contrast, in the sample from the Police station (N₅), the calculated ELCR was 1.97 mSv/yr, while the simulated 5th, 50th, and 95th percentile ELCR values were 1.65 ± 0.00, 1.97 ± 0.20, and 2.29 ± 0.01. Across all samples, the calculated mean ELCR was 2.32, while the simulated mean 5th, 50th, and 95th percentiles were 1.94 ± 0.00, 2.32 ± 0.23, and 2.70 ± 0.06, respectively. Figure 2 presents the calculated and simulated values of ELCR_{tot}, ELCR_{max}, ELCR_{min}, and SD_{tot}. This location demonstrated higher ELCR values in the simulation than the calculated value, with differences in the ELCR_{max}, ELCR_{min}, and SD of 0.35 (higher in the simulated value), 0.03 (higher in the simulated value), and 0.29 (lower in the simulated value), respectively.

Across all sampled locations in the Narasawa LGA, the mean simulated ELCR_{max/sim}, ELCR_{min/sim} and SD_{tot/sim} values were 3.22, 1.42, and 0.23, respectively, while the ELCR_{tot} and ELCR_{tot/sim} were 2.32 and 2.32, respectively (Figure 2). In contrast, the calculated ELCR_{max} and ELCR_{min} were 2.83 and 1.75 mSv/yr, respectively.

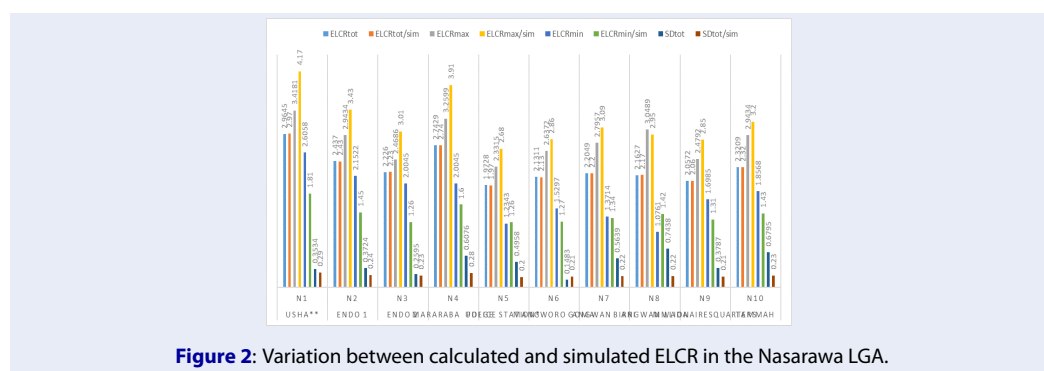


Figure 2: Variation between calculated and simulated ELCR in the Nasarawa LGA.

The observed variations in ELCR, with Usha exhibiting the highest risk, may be related to the presence of alaskites and clay in the region. These minerals are known to contain uranium, similar to granites. Groundwater samples collected from various locations across the Nasarawa LGA in Nasarawa state were analyzed by recording the ²²²Rn concentrations in these samples using a RAD-7 electronic radon detector equipped with a RAD-H₂O accessory. The data were evaluated using both conventional calculation methods and Monte Carlo simulations, with comparisons made between the two approaches. Risk assessments were further benchmarked against maximum radon exposure limits. The Oracle Crystal Ball software was used for advanced simulation and probabilistic analysis.

Among the samples, the groundwater from Usha (N₁) exhibited the greatest ELCR values with ELCR_{tot/cal} and ELCR_{tot/sim} of 2.97 and 2.97, respectively. In contrast, the sample from the Police Station in Nasarawa Central exhibited the lowest ELCR values with ELCR_{tot/cal} and ELCR_{tot/sim} of 1.97 and 1.97, respectively. The elevated ELCR in Usha is likely influenced by its sandy-loam soils and rocky/sandstone terrain, suggesting that local geology and environmental factors play a significant role in radon mobility and accumulation, even in the absence of mining activities.

The ²²²Rn concentrations reported in Table 1 are higher than the WHO reference level of 300 Bq/m³ for indoor air³¹. However, since the present study deals with groundwater, the more relevant comparison is with the USEPA guideline for drinking water, which recommends a maximum contaminant level of 11.1 Bq/L³². The measured values falls within this limit, indicating that while airborne radon exposure could pose risks if the water used domestically, the direct ingestion pathway remains within international safety standards.

CONCLUSIONS

The health risk assessment for ²²²Rn based on the ingestion and inhalation exposure pathways revealed that the AED_{ing} exceeds the WHO and also in comparison with that of ICRP recommended reference dose of 0.1 mSv/year. In contrast, the inhalation doses remain within the permissible annual dose of 1.0 mSv/year. This indicates that the ingestion of radon-contaminated water poses a significant radiological health threat in locations with elevated radon levels in their groundwater sources.

The Monte Carlo simulations proved to be a more robust and informative method of risk assessment compared to conventional methods, allowing for the determination of base case, mean, standard deviation, and 5th, 50th, and 95th percentile risk probabilities. These simulations further confirm elevated cancer risks across the study area. All simulated ELCR values exceeded the maximum permissible limit of 0.003875 recommended by the ICRP and the UNSCEAR. These findings highlight the urgent need for radiological protection measures as well as underscore the necessity of implementing appropriate remediation strategies to mitigate the risk of radon exposure due to groundwater consumption in the affected communities. It should be noted that the results in exceed the 300 Bq/m³ threshold recommended by the WHO³¹, while the results in Table 2 fall within the 11.1 Bq/L³² threshold recommended by the USEPA.

ABBREVIATIONS

GPS: Global Positioning System.
AED: Annual Effective Dose.
mSv/yr: mili Sievert Per Year.
Bq/m³: Becquerel per square metre.
ing: Ingestion.
inh: Inhalation.
ELCR: Excess Lifetime Cancer Risk.
CERT: Centre for Energy Research and Training.
ICRP: International Commission on Radiological Protection.
UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation.
USEPA: United States Environmental Protection Agency.
WHO: World Health Organization.
LGA: Local Government Area
SD: Standard Deviation.

COMPETING INTERESTS

The authors declared no competing interests.

AUTHORS' CONTRIBUTIONS

- Abubakar Bala Madaki: Writing-original draft, Conceptualization, Data Curation, Methodology, Resources, Investigation, Software, Formal Analysis, Visualization, and Validation.
- Abdulkarim Muhammad Hamza: Methodology, Supervision, Software, Validation, Conceptualization.
- Adamu Usman Mohammed: Software, Validation.
- Abubakar Sadiq Aliyu, and Muhammad Sanusi Liman: Supervision, Validation.
- Suleiman Jibrin Yaro: Methodology, Data Curation.
- Labaran Jamilu Ari & Ali Musa Kazzayo: Data Curation, Visualization.
- Haliru Dauda Aliyu, Abel Maruku, Kanita Mallam Shehu, Halima Nuhu Iliyasu, Amina Haruna Olesheye: Data Curation, Location Guide, Transportation.

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