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Radon in groundwater sources of Bosso Community in North Central Nigeria and concomitant doses to the public

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ABSTRACT

Realizing the probable health hazards from radon exposure, potable groundwater samples (hand-dug wells and boreholes) in the Bosso community of North Central Nigeria were collected and assayed for radon concentration. Durridge RAD-7 detector together with RAD-H_2O accessories was employed in this study. The committed effective dose to different ICRP age groups was computed using various parameters including the annual water consumption characteristics. The mean ^{222}Rn activity in water samples from hand-dug wells and boreholes were 9.81 ± 1.85 Bq/L and 24.78 ± 2.48 Bq/L respectively. The average whole-body committed effective dose due to ingestion and inhalation of waterborne radon from the two groundwater sources are 0.026 mSv/y and 0.067 mSv/y for hand-dug wells and boreholes respectively, which are below the safety threshold of 0.1 mSv/y recommended by the European Union. The results showed that there is no significant radiation threat to public health from inhalation and ingestion of waterborne radon within the community.

1. Introduction

The demand for potable water to meet the challenge of population growth, especially in urban areas has taken the centre stage in many parts of Nigeria and the world at large. Most inhabitants have turned to groundwater as the readily available source of potable water, with communities and individuals taking to drilling boreholes and deep wells to meet up with their water demands for daily domestic use. Radon (^{222}Rn) with a half-life of 3.8222 days, is a radioactive, noble gas which is produced from the disintegration of primordial radionuclides such as uranium and thorium found naturally in basement rocks and soils (Ajiboye et al., 2018; Opoku-Ntim et al., 2019; Pervin et al., 2022). Radon migrates through pores in the soil, fractures in rocks and along other weak zones into groundwater. Its concentration in water bodies, according to Choubey and Ramola (1997), is governed primarily by the physiognomies of the aquifer, the time interval within which the aquifer retains the water, rock-water interaction, and mineral composition of the bedrock among others. Ramola et al. (1990) reported that the distention of rock masses as a result of the increase in regional stress can cause the surface area of rocks to increase due to cracking and also increase the flow rate of pore fluids out of the interstitial space. Thus, the migration of radon from its original hutch into groundwater is enhanced through the mechanism of recoil, diffusion and transport through porosity in soil, fractures in rocks and movement along other weak zones (Choubey et al., 1994).

Internal exposure to dissolved radon in the groundwater, which has become a potential radiation risk to human life can occur through two principal pathways: direct ingestion of water containing radon and

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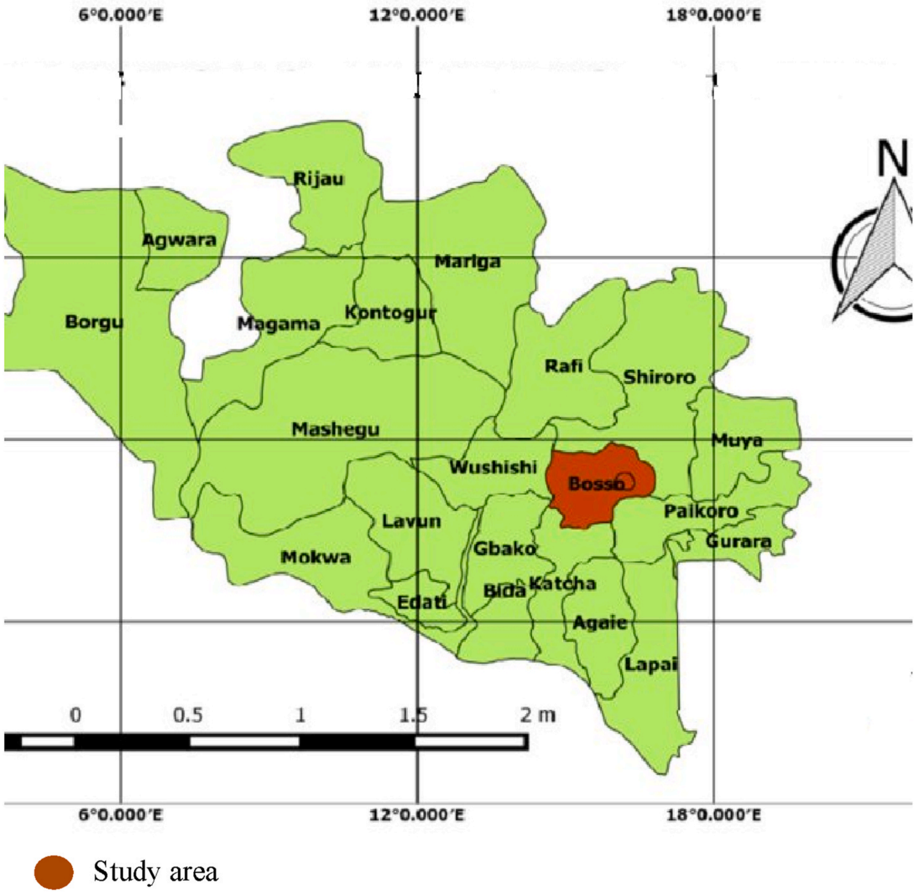

Fig. 1. Map of Niger State showing the study area.

inhalation of radon gas in indoor air (Ademola and Abdulkareem, 2019; Kendall and Smith, 2002; Balakrishnan et al., 2021). According to the World Health Organization WHO (2011), enhanced levels of waterborne radon are responsible for about 1–7% of deaths from lung cancer. Furthermore, a high level of radon in potable water can result in stomach cancer, gastrointestinal cancer, and cancer of various internal organs (Kendall and Smith, 2002; Ravikumar and Somashekar, 2014). It is therefore important that radon levels in groundwater sources be checked to ascertain the level of human exposure from constant domestic use of water.

Several studies have been conducted in different parts of Nigeria to determine the level of contamination of groundwater by radon gas and the consequent effective dose to man (Ademola and Abdulkareem, 2019; Ajiboye et al., 2018; Akinnagbe et al., 2018; Isinkaye et al., 2021; Kalip et al., 2018; Oni and Adagunodo, 2019; Shuaibu et al., 2021). But data on the radon content of groundwater sources in the Bosso community is very scarce. This study is therefore a pioneering attempt aimed at assessing the radon concentration in hand-dug wells and borehole water in the Bosso community and estimating the consequent annual effective dose. Findings from this study will serve as a baseline for further similar studies.

2. Materials and method

2.1. Location and geology of the study area

Bosso, a community in Niger State, North Central Nigeria (Fig. 1) lies between latitudes 09° 40′ N to 09° 42′ N and longitudes 06° 30′ E to 06° 36 ′ E. It is located within the Guinea Savanna ecological zone of Nigeria, characterized by grasses, trees and shrubs. It is marked by two distinct seasons, the rainy season which lasts from the month of April to October, and the dry season which lasts from November to March/April. Annual rainfall values range from 900 mm to 1000 mm. The temperature varies with season but generally hovers around 32 °C. Cooler temperatures lower than 28 °C are recorded during the short Harmattan season between December and January while maximum temperature peaks around 38 °C–40 °C in the months of March and April. Geologically, the Bosso area is underlain by basement complex rocks comprising undifferentiated granitic rocks which are believed to be part of the Older Granitic suites of Nigeria and various metamorphic rocks consisting of gneisses, schists, quartzites and some migmatites (Momoh et al.,2012; Ako et al., 2013, 2014; Ali et al., 2018). Structurally, most of the rocks are non-deformed to slightly deformed (Oke et al., 2009), with secondary structures such as faults, folds, foliations and lineations that are obvious on the in situ rocks.

2.2. Sample collection, preparation and analysis

Bosso community serves as the host for one of the campuses of the Federal University of Technology Minna, Nigeria. A larger percentage of the students of the University reside in rented apartments which are generally en-suite, within the community. Furthermore, the majority of local farmers displaced from their host communities as a result of banditry activities have been settled within the Bosso community by the State Government, resulting in a high population density of the community. Water supply systems by the government have not therefore been sufficient enough to meet the water demands of the growing population within the community. Hence, drilling of deep wells and boreholes becomes the readily available alternative water supply system for the growing population. Additionally, most of the locally built

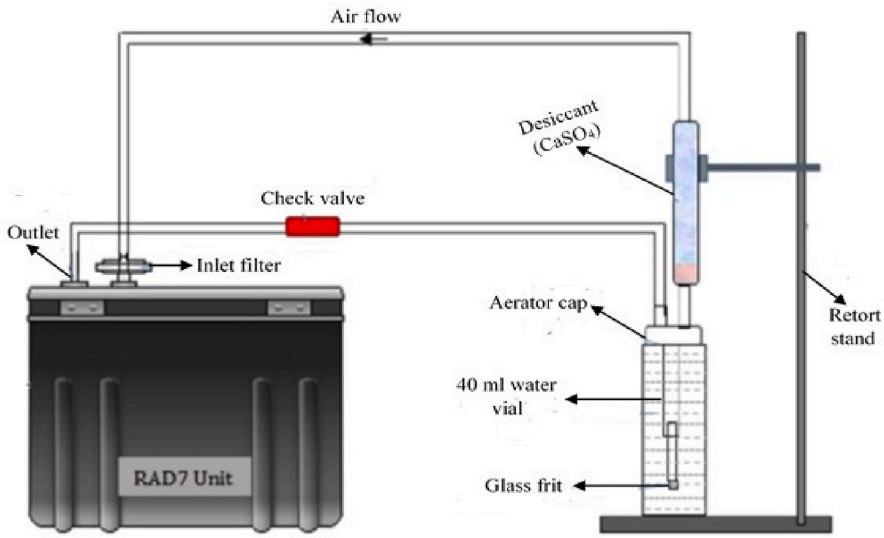

Fig. 2. Schematic diagram of RAD-H_20 set for measurement of waterborne radon.

houses and rented apartments within the community are poorly ventilated. Thus, the likelihood of constant population exposure to accumulated radon from groundwater used for laundry, bathing, dishwashing and other domestic activities within the community cannot be neglected simply.

20 water samples from two groundwater sources in the Bosso Community of Minna, Niger State were sampled and analyzed for their radon (^{222}Rn) concentration. The samples were collected from two prominent groundwater sources in the community which are hand-dug wells (HDW, 10 samples) and boreholes (BHW, 10 samples). The sampling was undertaken between the last week of July and the first week of August, during the rainy season, when the concentration of dissolved radon in groundwater is expected to be at its maximum. Samples from the hand-dug wells were drawn using a bucket attached to a long rope (bailer), while borehole water was collected from the borehole tap-head directly. To ensure that freshwater samples were collected into the sampling bottles, all the tap heads were left to run for about 5 min to dispose of the upper stagnant water. The freshwater samples were carefully collected by avoiding unnecessary agitations and bubbling that will lead to the escape of radon gas, into well-cleaned sample collection plastic bottles, adequately cocked, and transferred to Radioanalytical Research Laboratory, Ekiti State University, Ado Ekiti, Nigeria, for analysis. The analysis was carried out using a RAD-7 radon analyzer coupled to RAD-H_2O accessories (Fig. 2), manufactured by Durridge Co., USA. Details of the sample analysis procedure and detector setup are given in Ravikumar and Somashekar (2014) and Isinkaye et al. (2021). The detector setup is such that the bubbling kit is used to discharge radon gas from the water sample. The discharged radon, through the process of air circulation, is channeled into the hemisphere chamber where it decays into its daughter nuclei, polonium (Po) (Chew et al., 2021). The Po ions are deposited on a solid-state silicon detector maintained on a high electric field, from which they are counted using in-built software. Radon concentration in the water sample is finally estimated from the count rate of Po nuclei (Durridge, 2011). Polonium ions generated through the decay of radon are often neutralized by water particles, thus, high relative humidity decreases the detection efficiency of the RAD-7 detector. The Air stream entering the detector must therefore be kept dry at all times (using the desiccant) and the relative humidity of the radon chamber be kept below 10% to achieve better precision of the obtained result.

Each water sample was subjected to four analytical cycles of 5 min each such that the average value of the four readings represents the radon concentration of the analyzed water sample. This is to satisfy the quality control requirement and to ensure that the obtained results are reliable. Since the analysis was not carried out at the sample collection point immediately, the time interval between the sample collection and analysis will constitute an error in the analysis due to radioactive decay. The results of the analysis were therefore decay-corrected to the initial concentration values at the time of sampling. The decay correction for ^{222}Rn concentration was computed from the equation:

$$C_0 = C\left[e^{-\lambda t}\right]^{-1} \tag{1}$$

where C_0 is the concentration of radon at the time of sampling, C is the measured radon concentration, λ is the decay-time constant for radon ($0.1814\ d^{-1}$) and t is the time from sample collection to sample analysis, measured in days.

Table 1
ICRP age groups and their corresponding ACR (IAEA, 1996).

		Water consumption	
Age group	Age range (year)	(L/day)	(L/yr)
3 months	0–1	0.55	200
1 year	1–2	0.71	260
5 year	2–7	0.82	300
10 year	7–12	0.96	350
15 year	12–17	1.64	600
Adult	>17	2.00	730

2.3. Annual effective dose estimation

2.3.1. Committed effective dose to respective age groups

The measure of exposure to radon experienced by the human respiratory and gastrointestinal tract defines the annual committed effective dose (ACED), expressed in Sievert (Sv), micro-sievert (μ), or milli-sievert (mSv) per year. Human exposure to waterborne radon takes place on daily basis via ingestion of potable water. The product of equivalent doses delivered to individual organs and tissues of the human body together with their respective tissue-weighting factors, summed up over the given human organs gives the committed effective doses or the dose coefficients (DCs) measured in Sv/kg. In computing the ACED for ingestion of water in this study, a dose conversion coefficient of 5.0×10^{-9} Sv/Bq for ingestion of ^{222}Rn provided by UNSCEAR (1993) was adopted. ICRP age groups together with their respective average annual water consumption rates (ACR) considered in this study are given in Table 1.

Table 2
Radon concentration in groundwater (hand-dug wells and borehole) with corresponding ACED to ICRP age groups in the study area.

Sample ID	Location coordinates		^{222}Rn conc. (Bq/l)	ACED (mSv/y) to ICRP age groups					
	Long	Lat		3 months	1 yr	5 yr	10 yr	15 yr	Adult
Groundwater samples: Hand-dug wells in Bosso Community									
HDW 01	9° 38' 55"	6° 30' 54"	9.2 ± 2.2	0.009	0.012	0.014	0.016	0.028	0.034
HDW 02	9° 38' 41.6"	6° 30' 33.7"	20.5 ± 2.7	0.021	0.027	0.031	0.036	0.062	0.075
HDW 03	9° 39' 1.4"	6° 31' 35"	1.7 ± 0.6	0.002	0.002	0.003	0.003	0.005	0.006
HDW 04	9° 39' 2.4"	6° 31' 29"	14.9 ± 1.7	0.015	0.019	0.022	0.026	0.045	0.054
HDW 05	9° 39' 6.0"	6° 31' 28"	5.9 ± 1.1	0.006	0.008	0.009	0.010	0.018	0.022
HDW 06	9° 39' 7.2"	6° 31' 33"	6.2 ± 1.9	0.006	0.008	0.009	0.011	0.019	0.023
HDW 07	9° 39' 6.1"	6° 31' 29"	1.5 ± 0.6	0.002	0.002	0.002	0.003	0.005	0.005
HDW 08	9° 39' 34"	6° 31' 32.7"	12.8 ± 3.3	0.013	0.017	0.019	0.022	0.038	0.047
HDW 09	9° 39' 51.6"	6° 31' 48.5"	1.6 ± 0.3	0.002	0.002	0.002	0.003	0.005	0.006
HDW 10	9° 39' 12"	6° 31' 23"	23.8 ± 4.1	0.024	0.031	0.036	0.042	0.071	0.087
Min			1.5 ± 0.6	0.002	0.002	0.002	0.003	0.005	0.005
Max			23.8 ± 4.1	0.024	0.031	0.036	0.042	0.071	0.087
Mean			9.81 ± 1.85	0.010	0.013	0.015	0.017	0.029	0.036
Groundwater samples: Bore-holes in Bosso Community									
BHW 01	9° 39' 36.9"	6° 31' 52.7"	35.5 ± 2.9	0.036	0.046	0.053	0.062	0.107	0.130
BHW 02	9° 39' 34"	6° 32' 4.5"	15.8 ± 1.9	0.016	0.021	0.024	0.028	0.047	0.058
BHW 03	9° 39.7' 46"	6° 31' 44"	42.5 ± 3.1	0.043	0.055	0.064	0.074	0.128	0.155
BHW 04	9° 39' 8.1"	6° 31' 52"	25.0 ± 2.6	0.025	0.033	0.038	0.044	0.075	0.091
BHW 05	9° 38.7' 48"	6° 31' 38"	20.2 ± 2.2	0.020	0.026	0.030	0.035	0.061	0.074
BHW 06	9° 39' 59.7"	6° 31' 14"	25.7 ± 2.5	0.026	0.033	0.039	0.045	0.077	0.094
BHW 07	9° 39' 2.3"	6° 31' 7.7"	30.7 ± 2.8	0.031	0.040	0.046	0.054	0.092	0.112
BHW 08	9° 38.8' 51"	6° 30.8' 53"	14.8 ± 1.9	0.015	0.019	0.022	0.026	0.044	0.054
BHW 09	9° 38.7' 44"	6° 31' 57"	23.8 ± 2.6	0.024	0.031	0.036	0.042	0.071	0.087
BHW 10	9° 38' 38.9"	6° 31' 37"	13.8 ± 2.3	0.014	0.018	0.021	0.024	0.041	0.050
Min			13.8 ± 2.3	0.014	0.018	0.021	0.024	0.041	0.050
Max			42.5 ± 3.1	0.043	0.055	0.064	0.074	0.128	0.155
Mean			24.78 ± 2.48	0.025	0.032	0.037	0.043	0.074	0.090

The ACED for individual ICRP age groups is computed from the equation (Opoku-Ntim et al., 2019; Ravikumar and Somashekar, 2014):

$$ACED\ (Sv) = A_{Rn} \times DCF \times ACR \quad (2)$$

where, A_{Rn} is the radon activity measured in Bq/L, DCF is the dose conversion factor of 5.0×10^{-9} Sv/Bq and ACR is the water consumption rate provided in Table 1 for the respective age groups.

2.3.2. Committed effective dose to internal organs

Two principal human exposure pathways to radiation from waterborne radon are the ingestion and inhalation routes. The ingestion pathway involves direct consumption of radon-laden water which results in dose delivery to the stomach. The inhalation route involves breathing of waterborne radon that has been released into indoor air, resulting in dose delivery to the lungs. UNSCEAR (2000) outlines some basic coefficients by which the radiation hazard exposure suffered by humans from ingestion and inhalation of waterborne radon (i.e., the mean annual effective dose (ACED) due to ingestion and inhalation of waterborne radon) can be computed using the equations (Isinkaye et al., 2021; Shuaibu et al., 2021; UNSCEAR, 2000):

$$ACED_{ing}\left(mSv\ y^{-1}\right) = A_{Rn} \times C_W \times DCF_{ing} \quad (3)$$

$$ACED_{inh}\left(mSv\ y^{-1}\right) = A_{Rn} \times R_{AW} \times EF \times OF \times DCF_{inh} \quad (4)$$

where A_{Rn} is the radon activity in water (Bq/L), C_W is the annual water consumption for adults = 730 L/y, DCF_{ing} is the effective dose conversion coefficient for ingestion = 3.5 nSv/Bq, and DCF_{inh} if the dose conversion factor for exposure to radon in air = 9 nSv/h (Bq/L), R_{AW} is the ratio of radon-in-air to radon-in-water = 10^{-4}, EF is the equilibrium factor between radon and its progeny for indoor environment = 0.4, and OF is the average global indoor occupancy factor = 7000 h/year.

3. Results and discussion

^{222}Rn concentration in groundwater samples sourced from 10 hand-dug wells from the Bosso community are presented in Table 2. Also shown in Table 2 are the computed annual committed effective dose (ACED) to the individual ICRP age groups based on the estimated volume of water consumed by each age group per annum. Similarly, ^{222}Rn concentration in 10 borehole water samples in the Bosso community together with the respective ACED to the individual ICRP age groups are shown in Table 2. ^{222}Rn concentration in hand-dug wells ranged from 1.5 ± 0.6 to 23.8 ± 4.1 Bq/L with an average value of 9.81 ± 1.85 Bq/L,

Table 3
Comparison of radon concentration in groundwater from Bosso community with similar studies around the world.

Country	Water type	^{222}Rn conc. (Bq/l)	References
Mashhad, Iran	Groundwater	16.23	Binesh et al. (2012)
Malathahali lake area, India	Groundwater	11.43	Ravikumar and Somashekar (2014)
West bank, Palestine	Groundwater	0.64	Thabayneh (2015)
Iraq	Wells	2.84 ± 1.65	Al-Alawy and Hasan (2018)
Ekiti state, Nigeria	Wells and boreholes	34.7	Ajiboye et al. (2018)
Jazan, Saudi Arabia	Groundwater	1.74–4.32	El-Araby et al. (2019)
Coastal Kerala, India	Wells	0.12–4.35	Divya and Prakash (2019)
Southwestern Nigeria	Wells and boreholes	8.2–94.8	Oni and Adagunodo (2019)
Offinso, Ghana	Groundwater	0.06–0.16	Opoku-Ntim et al. (2019)
Gadau, Bauchi state, Nigeria	Wells and boreholes	38.32	Shuaibu et al. (2021)
Ekiti State University, Nigeria	Wells	13.33	Isinkaye et al. (2021)
Ekiti State University, Nigeria	Boreholes	23.3	Isinkaye et al. (2021)
Bosso Community, Nigeria	Wells	9.81	Present work
Bosso Community, Nigeria	Boreholes	24.78	Present work

Table 4
ACED to internal organs due to radon in groundwater samples (hand-dug wells and borehole) in the study area.

	Location coordinates			ACED (mSv/y)		
Sample ID	Long	Lat	^{222}Rn concentration (Bq/l)	Ingestion (Stomach)	Inhalation (lungs)	Whole body
Groundwater samples: Hand-dug wells in Bosso Community						
HDW 01	9° 38' 55"	6° 30' 54"	9.2 ± 2.2	0.0016	0.0232	0.0248
HDW 02	9° 38' 41.6"	6° 30' 33.7"	20.5 ± 2.7	0.0036	0.0517	0.0552
HDW 03	9° 39' 1.4"	6° 31' 35"	1.7 ± 0.6	0.0003	0.0043	0.0046
HDW 04	9° 39' 2.4"	6° 31' 29"	14.9 ± 1.7	0.0026	0.0375	0.0402
HDW 05	9° 39' 6.0"	6° 31' 28"	5.9 ± 1.1	0.0010	0.0149	0.0159
HDW 06	9° 39' 7.2"	6° 31' 33"	6.2 ± 1.9	0.0011	0.0156	0.0167
HDW 07	9° 39' 6.1"	6° 31' 29"	1.5 ± 0.6	0.0003	0.0038	0.0040
HDW 08	9° 39' 34"	6° 31' 32.7"	12.8 ± 3.3	0.0022	0.0323	0.0345
HDW 09	9° 39' 51.6"	6° 31' 48.5"	1.6 ± 0.3	0.0003	0.0040	0.0043
HDW 10	9° 39' 12"	6° 31' 23"	23.8 ± 4.1	0.0042	0.0600	0.0641
Min				0.0003	0.0038	0.0040
Max				0.0042	0.0600	0.0641
Mean				0.0017	0.0247	0.0264
Groundwater samples: Bore-holes in Bosso Community						
BHW 01	9° 39' 36.9"	6° 31' 52.7"	35.5 ± 2.9	0.0062	0.0895	0.0957
BHW 02	9° 39' 34"	6° 32' 4.5"	15.8 ± 1.9	0.0028	0.0398	0.0426
BHW 03	9° 39.7' 46"	6° 31' 44"	42.5 ± 3.1	0.0074	0.1071	0.1145
BHW 04	9° 39' 8.1"	6° 31' 52"	25.0 ± 2.6	0.0044	0.0630	0.0674
BHW 05	9° 38.7' 48"	6° 31' 38"	20.2 ± 2.2	0.0035	0.0509	0.0544
BHW 06	9° 39' 59.7"	6° 31' 14"	25.7 ± 2.5	0.0045	0.0648	0.0693
BHW 07	9° 39' 2.3"	6° 31' 7.7"	30.7 ± 2.8	0.0054	0.0774	0.0827
BHW 08	9° 38.8' 51"	6° 30.8' 53"	14.8 ± 1.9	0.0026	0.0373	0.0399
BHW 09	9° 38.7' 44"	6° 31' 57"	23.8 ± 2.6	0.0042	0.0600	0.0641
BHW 10	9° 38' 38.9"	6° 31' 37"	13.8 ± 2.3	0.0024	0.0348	0.0372
Min				0.0024	0.0348	0.0372
Max				0.0074	0.1071	0.1145
Mean				0.0043	0.0624	0.0668

while the concentration in borehole water samples varied between 13.8 ± 2.3 and 42.5 ± 3.1 Bq/L with a mean of 24.78 ± 2.48 Bq/L. About 40% of the total hand-dug well water samples and almost 100% of water samples from the borehole exceeded the USEPA (1991) prescribed minimum contaminant level (MCL) of 11.1 Bq/L. ^{222}Rn concentration in all the investigated underground water samples (hand-dug well and borehole) were however below the non-binding reference level of 100 Bq/L recommended by the European Union Commission (EU, 2001). ^{222}Rn concentration in groundwater sourced from boreholes is seen to be higher than the concentration in hand-dug well water samples. The variation observed in activity concentration of ^{222}Rn in the two groundwater sources may be due to the contents and composition of radionuclides in the basement rocks, resident time of water in the aquifer, and concrete casing of the borehole which allows for very minimum aeration within the borehole water (Ademola and Abdulkareem, 2019; Ajiboye et al., 2018).

A comparison of the findings of this research with similar studies from many parts of the world is presented in Table 3.

A comparison of the results of this study with similar studies in different parts of the world as seen in Table 3 showed that the average radon concentration in groundwater in the Bosso community is lower than that reported by Shuaibu et al. (2021) in Bauchi State, Nigeria, but in good agreement with the report of Isinkaye et al. (2021).

3.1. Annual committed effective dose (ACED)

Calculated annual committed effective dose (ACED) due to water ingested from the two investigated groundwater sources for ICRP age groups are presented in Table 2. Computed ACED for infants of 0–1 year age range represented as the ICRP age group of 3 months with an average water consumption rate of 200 L/yr, ranging between 15.0 and 23.80 μSv/y with a mean value of 9.81 μSv/y for hand-dug wells and 13.80–42.50 μSv/y with an average of 24.78 μSv/y. For the ICRP age group of 1–2 years with a water consumption rate of 260 L/y, computed ACED varied from 1.95 to 30.94 μSv/y with a mean value of 12.75 μSv/y for hand-dug wells and 17.94–55.25 μSv/y with an average of 32.21 μSv/y for the borehole. ICRP age groups of 5 years and 10 years with annual water consumption of 300 L and 350 L respectively, recorded mean ACED values of 14.72 μSv/y and 17.17 μSv/y for hand-dug wells and 37.17 μSv/y and 43.37 μSv/y for borehole water sources in sequence. Computed ACED for ages of 12–17 years which represent the ICRP age group of 15 years with an average water consumption rate of 600 L/y ranging from 4.50 to 71.40 μSv/y for hand-dug wells and 41.40–127.50 μSv/y for boreholes, with respective average values of 29.43 μSv/y and 74.34 μSv/y.

For those above 17 years of age which are termed adults according to the ICRP age group classification, with a water consumption rate of 730 L/y, calculated ACED varied from 5.48 to 86.87 μSv/y with a mean value of 35.81 μSv/y for hand-dug wells and 50.37–155.13 μSv/y with an average value of 90.45 μSv/y for boreholes. The computed mean dose rate for the entire ICRP age group ranging from 3 months to adult age, was below the world's precautionary limit of 1 mSv/y recommended for the public by the United Nations Scientific Committee on the Effect of Atomic Radiation and the World Health Organization. A critical look at the results in Table 2 shows that the computed ACED increases with an increase in age, the rate of water consumption, and radon activity concentration. Observed trend in the increasing order of ACED is adult >15 years > 10 years >5 years > 1 year >3 months. This decreasing trend is in agreement with the one reported by Ravikumar and Somashekar (2014).

3.2. Computed ACED for internal organs

The committed annual effective dose received by the stomach as a result of ingestion of waterborne radon and that received by the lungs via the inhalation pathway were computed and presented in Table 4. The ACED due to ingestion of waterborne radon from hand-dug wells (HDW) in the study area ranged between 3.0×10^{-4} and 4.2×10^{-3} mSv/y with an average value of 1.7×10^{-3} mSv/y. This value agrees with the world average annual effective dose of 0.002 mSv recommended by UNSCEAR (2000) for ingestion of waterborne. Similarly, ACED received by the lungs from inhalation of waterborne radon from HDW varied from 3.8×10^{-3} to 0.06 mSv/y with a mean value of 2.5×10^{-2} mSv/y. Whole-body dose as a result of ingestion and inhalation of waterborne radon and its daughters from hand-dug wells in the Bosso community varied between 0.004 and 0.064 mSv/y with an average value of 0.026 mSv/y (Table 4). Mean ACED received by the stomach from ingestion of waterborne radon in borehole water samples from the Bosso community is 4.3×10^{-3} mSv/y, while the dose imputed to the lungs from the inhalation pathway is 0.062 mSv/y. Thus, the average whole-body dose due to ingestion and inhalation of waterborne radon from boreholes in the Bosso community is 0.067 mSv/y (Table 4). Results presented in Table 4 show that about 93% of the whole-body dose due to waterborne radon from the groundwater sources (hand-dug wells and boreholes) in the Bosso community comes via the inhalation pathway.

This shows that the risk of radiation incidence due to waterborne radon among the population of the Bosso community is higher via the inhalation pathway. It also suggests that the bronchial epithelium and the general respiratory tracks have a higher tendency of becoming cancerous compared to cells of the walls of the stomach from radon exposure (Chew et al., 2021; Nasser et al., 2019) in drinking water. However, the average whole-body dose incurred from ingestion and inhalation of waterborne radon from hand-dug wells and boreholes in the Bosso community was found to be lower than the safety threshold of 0.1 mSv/y set by the European Union (EU, 2001) and World Health Organization (WHO, 2004).

4. Conclusion

Potable water from two groundwater sources in the Bosso community, Minna, Nigeria, was sampled and analyzed for their ^{222}Rn concentration. The average ^{222}Rn concentration in hand-dug wells and boreholes were 9.81 ± 1.85 Bq/L and 24.78 ± 2.48 Bq/L, respectively. Although potable water from boreholes recorded higher radon activity than those from hand-dug wells, the results were generally below the non-binding reference level set by the European Union commission. Computed ACED for the ICRP age groups increases with an increase in age, the rate of water consumption, and radium activity concentration. Mean whole-body committed effective dose due to ingestion and inhalation of waterborne radon from the two groundwater sources in the community were below the international safety threshold. Although the overall results of this pilot study do not pose any immediate radiological threat, continuous radon monitoring of the drinking water in the Bosso community should be carried out from time to time from the point of view of radiation protection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are available in the manuscript

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References

Ademola, J.A., Abdulkareem, A., 2019. Radon-222 assessment and estimation of annual effective dose in groundwater in lagos state, Nigeria. Radiat. Protect. Dosim. 185 (3), 320–325.

Ajiboye, Y., Isinkaye, M., Khanderkar, M., 2018. Spatial distribution mapping and radiological hazard assessment of groundwater and soil gas radon in Ekiti State, Southwest Nigeria. Environ. Earth Sci. 77 (14), 1–15.

Akinnagbe, D., Orosun, M., Orosun, R., Osanyinlusi, O., Yusuk, K., Akinyose, F., Olaniyan, T., Ige, S., 2018. Assessment of radon concentration of ground water in Ijero Ekiti. Manila Journal of Science 11, 32–41.

Ako, T.A., Onoduku, U.S., Salihu, H.D., Ejepu, S.J., Abdulfatai, I.A., 2013. Petrographic and structural analysis of exposed rocks of bishini sheet (block 2), North Central Nigeria. Canadian center of science and education. Earth Sci. Res. 2 (1), 143–155.

Ako, T.A., Onoduku, U.S., Oke, S.A., Essien, B.I., Idris, F.N., Umar, A.N., Ahmed, A.A., 2014. Environmental effects of sand and gravel mining on land and soil in luku, Minna, Niger state, North Central Nigeria. Universal Journal of Geosciences 2 (2), 42–49.

Al-Alawy, I., Hasan, A., 2018. Radon concentration and dose assessment in well water samples from karbala governorate of Iraq. J. Phys.: Conf. Ser. 1003, 012117. IBN AL-HAITHAM FIRST INTERNATIONAL SCIENTIFIC CONFERENCE 13–14 December 2017, Baghdad, Iraq.

Ali, S.E., Ako, T.A., Onoduku, U.S., Omang, B.O., Ejepu, J.S., 2018. Petrographic and phisico-mechanical characteristics of quartzite from the wolframite mine in zumba, northcentral Nigeria: implication for their use as construction materials. Minna. J. Geosci. 2 (2).

Balakrishnan, D., Jojo, P.J., Khandaker, M.U., 2021. Inhalation dose in the indoor environment of eloor industrial area, Kerala, India. Radiat. Phys. Chem. 188, 109655 https://doi.org/10.1016/j.radphyschem.2021.109655.

Binesh, A., Mowlavi, A., Mohammadi, S., 2012. Estimation of the effective dose from radon ingestion and inhalation in drinking water sources of Mashhad, Iran. Iran. J. Radiat. Res. 10 (1), 37–41.

Chew, M.T., Daar, E., Khandaker, M.U., Jones, B., Nisbet, A., Bradley, D.A., 2021. Low radiation dose to treat pneumonia and other inflammations. Br. J. Radiol. 94, 20201265.

Choubey, V., Ramola, R., 1997. Correlation between geology and radon levels in groundwater, soil and indoor air in Bhilangana Valley, Garhwal Himalaya, India. Environ. Geol. 32 (4), 258–262.

Choubey, V.M., Sharma, K., Ramola, R., 1994. Soil gas and indoor radon studies in Doon Valley, India. Nucl. Geophys. 8 (1), 49–54.

Divya, P., Prakash, V., 2019. Investigation on radon concentration in drinking water to assess the whole body dose and excess lifetime cancer risk along coastal Kerala, India. J. Radioanal. Nucl. Chem. 322 (1), 37–42.

Durridge, 2011. RAD7 Radon Detector—User Manual. Durridge Company Inc, Bedford.

El-Araby, Entesar H., Soliman, H.A., Abo-Elmagd, M., 2019. Measurement of radon levels in water and the associated health hazards in Jazan, Saudi Arabia. J. Radiat. Res. Appl. Sci. 12 (1), 31–36. In this issue.

EU, 2001. European Union Commission Recommendation on the protection of the public against exposure to radon in drinking water supplies. Office J Eur Commun L. 344, 85–88.

IAEA, 1996. International Atomic Energy Agency - International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources. Vienna Safety Series 115.

Isinkaye, M.O., Matthew-Ojelabi, F., Adegun, C.O., Fasanmi, P.O., Adeleye, F.A., Olowomofe, O.G., 2021. Annual effective dose from 222Rn in groundwater of a Nigeria University campus area. Appl. Water Sci. 11 (5), 1–10.

Kalip, A., Haque, M., Gaiya, S., 2018. Estimation of annual effective dose due to ingestion and inhalation of radon in groundwater from Kaduna, Nigeria. Phys Sci Int J 19 (3), 1–12.

Kendall, G.M., Smith, T., 2002. Doses to organs and tissues from radon and its decay products. J. Radiol. Prot. 22 (4), 389.

Momoh, O.L., Amadi, A.N., Abdulfatai, I.A., Omonanyi, Y.A., Onoduku, U.S., Onah, M., 2012. Exploration of groundwater within the mariam babangida girls science secondary school Minna North Central Nigeria using schlumberger vertical electrical sounding techniques. J. Sci. Math. Technol. Educ. 8 (3), 21–32.

Nasser, S.M., Khandaker, M.U., Bradley, D.A., Isinkaye, M.O., 2019. Evaluation of radon concentration in irrigation and drinking waters from the eastern part of Oman and estimation of effective doses to omanis. Radiat. Protect. Dosim. 184 (3–4), 422–425. https://doi.org/10.1093/rpd/ncz088.

Oke, S.A., Okeke, O.E., Amadi, N.A., Onoduku, U.S., 2009. Geotechnical properties of the subsoil for designing shallow foundation in some selected parts of chanchaga area, Minna, Nigeria. J. Environ. Sci. (China) 1 (1), 45–54.

Oni, E.A., Adagunodo, T.A., 2019. Assessment of radon concentration in groundwater within Ogbomoso, SW Nigeria. In: Paper Presented at the Journal of Physics: Conference Series.

Opoku-Ntim, I., Andam, A.B., Akiti, T.T., Flectcher, J., Roca, V., 2019. The annual effective dose of radon in groundwater samples for different age groups in Obuasi and Offinso in the Ashanti Region, Ghana. Environ. Res. Commun. 1 (10), 105002.

Pervin, S., Yeasmin, S., Khandaker, M.U., Begum, A., 2022. Radon concentrations in indoor and outdoor environments of atomic energy centre dhaka, Bangladesh, and concomitant health hazards. Front. Nucl. Eng. 1, 901818 https://doi.org/10.3389/fnuen.2022.901818.

Ramola, R., Singh, M., Sandhu, A., Singh, S., Virk, H., 1990. The use of radon as an earthquake precursor. Int. J. Radiat. Applic. Instrum., Part E. 4 (2), 275–287.

Ravikumar, P., Somashekar, R., 2014. Determination of the radiation dose due to radon ingestion and inhalation. Int. J. Environ. Sci. Technol. 11 (2), 493–508.

Shuaibu, H.K., Khandaker, M.U., Baballe, A., Tata, S., Adamu, M.A., 2021. Determination of radon concentration in groundwater of Gadau, Bauchi State, Nigeria, and estimation of effective dose. Radiat. Phys. Chem. 178, 108934.
Thabayneh, K.M., 2015. Measurement of 222Rn concentration levels in drinking water and the associated health effects in the Southern part of West bank–Palestine. Appl. Radiat. Isot. 103, 48–53.
UNSCEAR, 1993. Sources and effects of ionizing radiation. In: Report to General Assembly with Scientific Annexes. United Nations, New York.
UNSCEAR, 2000. Sources and effects of ionizing radiation. In: Report to General Assembly, with Scientific Annexes. United Nations, New York.
USEPA, 1991. United States Environmental Protection Agency - national primary drinking water regulations for radionuclides: notice of proposed rule-making. Fed. Regist. 56, 33050–33127.
WHO, 2004. World Health Organization - Guidelines for Drinking Water Quality, second ed. WHO, Geneva.
WHO, 2011. Guidelines for Drinking-Water Quality, fourth ed. World Health Organisation Geneva, Switzerland.