UMYU Scientifica, Vol. 3 NO. 1, March 2024, Pp 080 – 087
https://doi.org/10.56919/usci.2431.009
ISSN: 2955 – 1145 (print); 2955 – 1153 (online)
A periodical of the Faculty of Natural and Applied Sciences, UMYU, Katsina

ORIGINAL RESEARCH ARTICLE

Radon Levels and Risk Assessment due to its Ingestion and Inhalation from Groundwater of Lapai, North-Central Nigeria

Sadiq Umar[1]*, Abdulsamad Asuku[2], Abdullahi Muhammad[1], Munirat Bashir[1], Ibrahim Kuta Suleiman[1] and Khadijah Abdullahi[1].

[1]Department of Physics, Ibrahim Badamasi Babangida University, PMB 11, Lapai, Nigeria.
[2]Center for Energy Research and Training, PMB 1014, Zaria, Nigeria.

ARTICLE HISTORY

Received August 15, 2023.
Accepted January 17, 2024.
Published February 22, 2024.

KEYWORDS

Radon gas, decay correction, alpha emitter, water contamination

ABSTRACT

Radon exposure through ingestion or inhalation from groundwater can be a significant public health concern due to its carcinogenic effects. This study assessed the health risks of radon exposure from groundwater in Lapai, Nigeria, using a Rad7 detector to measure radon concentration levels. The measured concentrations ranged from 5.36 ± 0.22 BqL^{-1} to 0.52 ± 0.06 BqL^{-1} with an average value of 2.82 ± 0.14 BqL^{-1}. The annual effect dose due to ingestion of Radon obtained varies in the range of 2.76 to 28.34 µSva^{-1}, 1.02 to 10.43 µSva^{-1}, and 1.33 to 13.69 µSva^{-1} for infants, children, and adults, respectively. While the effective dose per year from inhalation of Radon released from water by adults has values in the range of 1.31 to 13.50 µSva^{-1}. Radon levels were within permissible limits of UNSCEAR and USEPA, and the annual effective doses from inhalation and ingestion were within WHO's safe range. Nonetheless, monitoring is advised, especially during the rainy season when contamination levels may increase.

INTRODUCTION

An area of increasing attention in public and environmental health research is drinking water quality. Radon (^{222}Rn) is a colorless, odorless, and inert alpha-emitting gas soluble in water and absorbed by underground water when released from surrounding soil and rocks. Its concentration in underground water depends on factors such as temperature, type of surrounding rock formation, and environmental pollution (Nagaraja *et al*., 2019; Nakasone *et al*., 2021; Yong *et al*., 2021). In addition, the radon concentration in groundwater is subject to seasonal variations, with concentration levels becoming highin summer, highest in autumn, and lowest in winter (Nakasone *et al*., 2021). The ingestion of Radon dissolved in water and its inhalation when released from water constitute dose contributions to the stomach and lungs, respectively. However, an estimated 90 percent of the radon dose from groundwaterin humans is due to inhalation rather than ingestion (UNSCEAR, 2000). Also, no research findings have shown a conclusive link between radon ingestion in the stomach and stomach cancer (UNSCEAR, 2000). However, exposure through inhalation from Radon released from the water poses a potential health risk, as lung cancer is a public health threat associated with radon exposure from groundwater (Darby *et al*., 2005; Hadkhale *et al*., 2022).

In most parts of Nigeria, there is little or no adequate public water supply system that provides access to potable water. In addition, there is an increasing demand for portable water, driven mostly by population growth and urbanization. This has given rise to an interest in research focusing on drinking water quality in Nigeria. There are quite a good number of researchesconducted on the radon concentration levels and its associated health risks due to ingestion and inhalation from portable water in Nigeria (Kolo *et al*., 2023; Oni *et al*., 2021; Shu'aibu *et al*., 2021). However, previous research studies on the water quality level of the Lapai community (the study area) have largely focused on heavy metal assessment and other parameters (Boko *et al*., 2021; Oladipo *et al*., 2011). No literature references radon content and its associated risks due to radon ingestion and inhalation from groundwater sources in the community. This makes the present study a pioneering work for the community.

Interestingly, the Lapai community does not have an active pipe-borne public water supply system. Residents rely on groundwater from hand-dug wells and hand-

Correspondence: Sadiq Umar. Department of Physics, Ibrahim Badamasi Babangida University, PMB 11, Lapai, Nigeria. ✉ sadiqmx@gmail.com.

How to cite: Umar, S., Asuku, A., Muhammad, A., Bashir, M., Suleiman, I. K., & Abdullahi, K. (2024). Radon Levels and Risk Assessment due to its Ingestion and Inhalation from Groundwater of Lapai, North-Central Nigeria. *UMYU Scientifica*, 3(1), 80 – 87. https://doi.org/10.56919/usci.2431.009

pumped or motorized boreholes as sources of potable water supply. The community is situated in sedimentary and basement complex formations, which can be sources for radon ingress into underground water. Against this backdrop, it is imperative to ascertain the radon exposure levels in the community's groundwater. The current research is aimed at monitoring the dissolved radon concentrationlevels in groundwater sources and assessing the health risks due to ingestion and inhalation of Radon from the groundwater sources of the community for different age groups.

MATERIALS AND METHODS

Study area

Lapai is a West African community located in Niger State, North-Central region of Nigeria. It is the administrative headquarters of the Lapai local government area. It has latitudinal and longitudinal coordinates of 9°3'1.1" N, 6°33'40.72" E and 9°1'45.81" N, 6°35'23.51" E (see Figure 1).

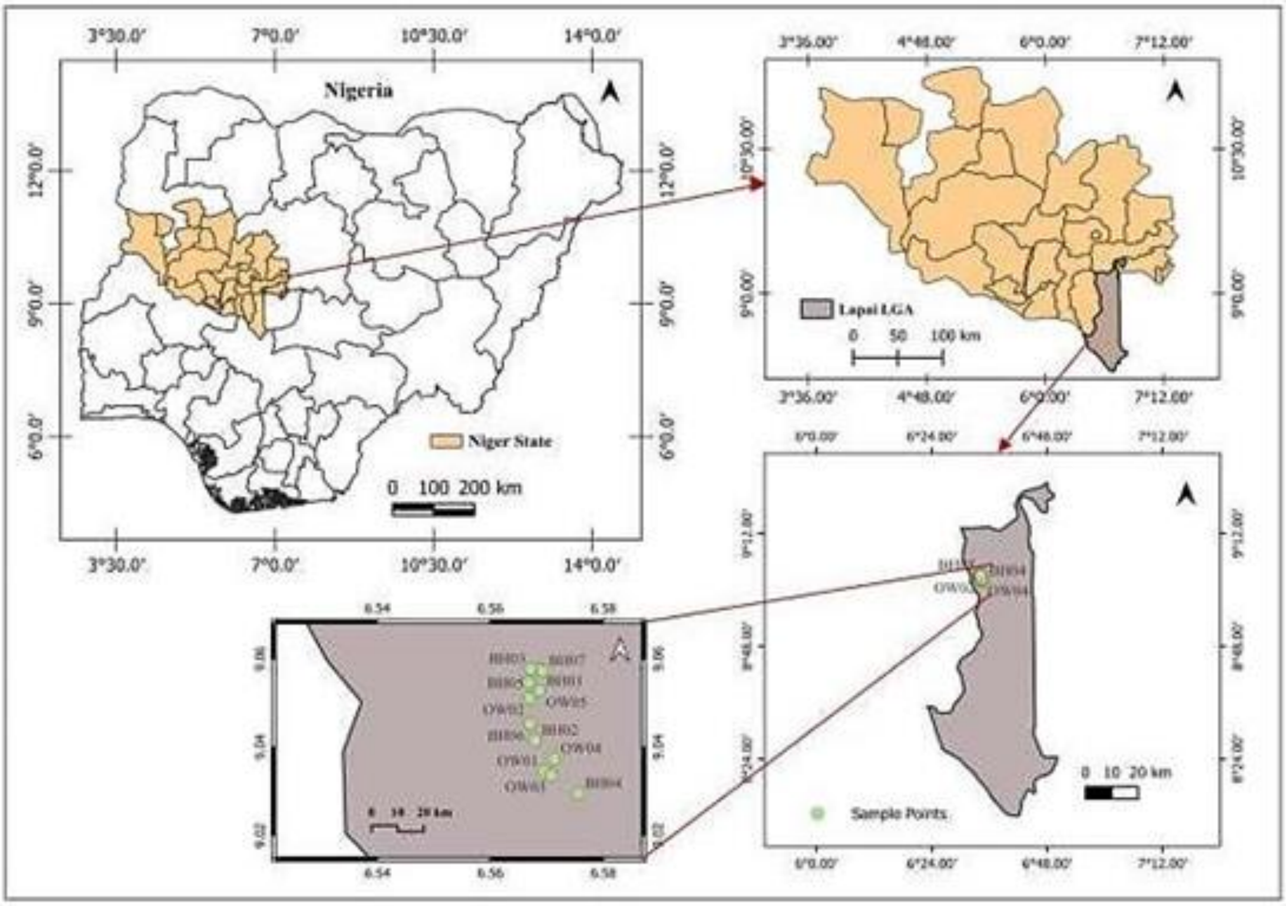

Figure 1. Map of the study area showing sampling points, developed using QGIS open software version 3.30.0

The community is situated on two existing geological formations: the sedimentary rocks, which constitute about 10 percent, and the basement complex, which covers about 90 percent of the community (Tsepav *et al.*, 2021). The basement complex comprises petro-lithological units: Migmatite – gneisses, schists, and older granites. The sedimentary rocks comprise the Bida Sandstone and the Enagi Formation, mainly sandstones, siltstones, and claystone (George Obaje *et al.*, 2020; Tsepav *et al.*, 2021). Lapai has a minimum mean annual temperature of 21 ^{0}C, recorded around July to December. It has a maximum temperature of about 34 ^{0}C between March and April. And mean annual temperature in the range of 27 ^{0}C – 30 ^{0}C. It has elevations from 35 m to 574 m above sea level.

Lapai also has two seasons: the rainy season, which usually appears from April to October, and the dry season, also known as the harmattan season, which usually lasts from November to March.

Materials

The materials used in this study included the Durridge Rad7 detector (0716) available at the Ahmadu Bello University Center for Energy Research and Training (CERT), Nigeria. German GPS tool (etrex 10) available at the Department of Geology, Ibrahim Badamasi Babangida University, Nigeria, distilled water from chemistry laboratory, Ibrahim Badamasi Babangida University, Nigeria.

Sample Collection and Preparation

Water samples were collected from a total of twelve (12) hand-dug wells (HDWs) and hand-pumped boreholes (HPBs) located in the study area. Five (5) HDWs and seven (7) HPBs were randomly selected based on their proximity to human settlements. Water samples from the HDWs were collected using a bailer, whereas samples from the HPBs were collected directly from the tap head after pumping for 15 min. The water samples were collected in December during the dry (harmattan) season and were carefully collected while avoiding bubble formation in 350 ml airtight plastic container bottles that had been rinsed with distilled water. The bottles were filled to the brim before being covered to minimize Radon escape from the water sample.

The samples were labelled with unique identifiers that included sampling points and sample source types while noting the date and time of collection. The GPS coordinates of the sampling points were measured using a Garmin (etrax 10) GPS device, and the longitudes and latitudes were recorded. The depths of the wells and boreholes were estimated and recorded as well. The samples were transported to the CERT laboratory for radon measurement.

Sample Description

A detailed description of the collected water samples is provided in Table 1. The longitudinal and latitudinal coordinates are shown in degree-minutes-second (DMS).

Table 1. Description of the collected sample

Sampling Area	Sampling Points		Sample Code	Water Source
	Longitude	Latitude		
Efu Alaji	6° 34' 07.60"	9° 3' 15.00"	BH 01	Borehole
Anguwan Malle	6° 34' 04.60"	9° 2' 28.50"	BH 02	Borehole
Anguwan Alaji Dadi	6° 34' 01.80"	9° 3' 15.00"	BH 03	Borehole
Efu Maiyaki Prison	6° 33' 32.30"	9° 1' 53.60"	BH 04	Borehole
State Lowcost	6° 34' 00.70"	9° 3' 06.00"	BH 05	Borehole
Bani Road	6° 34' 01.20"	9° 2' 39.30"	BH 06	Borehole
Zaria Street	6° 34' 09.20"	9° 3' 13.70"	BH 07	Borehole
Angwan Hausawa	6° 34' 10.05"	9° 2' 08.15"	OW 01	Open well
Tanko Ilimi	6° 34' 01.00"	9° 2' 56.00"	OW 02	Open well
Muhammadu Jauro	6° 34' 15.00"	9° 2' 05.60"	OW 03	Open well
Federal Lowcost	6° 34' 16.90"	9° 2' 16.50"	OW 04	Open well
Baban Kogi	6° 34' 07.40"	9° 3' 00.80"	OW 05	Open well

Sources of water are from hand-dug well (open well) and hand-pumped boreholes (borehole)

Measurement of radon concentration

Radon measurements were conducted using a Durridge Rad7 solid-state alpha detector equipped with a RAD H_2O Accessory. The water sample was carefully transferred into a 250 ml Rad H_2O vial from airtight container bottles used to collect the samples to avoid bubble formation in the sampling vial. The Rad7 detector was connected to its vial in a closed loop, where radon separation from the water sample occurred, and the gas was released into the air in the closed air loop that formed the aeration system. The Rad7 equipment was purged to remove residual radon gas from the measuring chamber before measurement (Durridge-Company, 2015).

Radon was extracted from the water sample by continuous air circulation through the water in the loop until equilibrium was reached. The extracted Radon decayed into a polonium-218daughter nucleus, and alpha particles emitted by the short-lived radon-decay daughter nucleus were detected and counted by the solid-state detector of the Rad7. The detector converts the count into an electrical signal whose strength is dependent on the energy of the emitted alpha particles. The radon concentration reading was displayed by the Rad7 display (Durridge-Company, 2015). The Rad7 detector produced results after 30 min of measurement. The measurement was repeated four times, and the mean reading was recorded for accuracy.

Decay correction

The radon measurement was not made on-site, so time elapsed between the collection of the samples and measurement in the CERT laboratory. To get an estimate of what the radonconcentration in the collected water samples would have been at the time of sampling, decay correction was made using the correction factor, $[exp(-\lambda t)] - 1$, which is related to the measured laboratory radon concentration, C (in unit BqL^{-1}) as

$$C = C_0[exp(-\lambda t)] \quad (1)$$

where C_0 (in unit BqL^{-1}) is the true radon concentration in the water sample(s) and represents the radon concentration if the measurements were made immediately at the sampling point, where t is the time between sampling and laboratory measurements (in days), and λ is the radon decay constant, $= \ln 2/t_{1/2}$; where $t_{1/2}$ is the half-life of Radon in units per day (d^{-1}) (Ajiboye *et al.*, 2022).

Annual effective dose estimation

Table **2**. Representative age grouping used in the present study based on the United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR (2000) recommendations

Age range [years	Age Categories	Water Consumption[La^{-1}]
1 - 2 years	Infants	230
8 - 12 years	Children	330
>17 years	Adults	730

The annual effective dose from the ingestion of water was calculated from the equation.

$$AED_{ing} = C_{Rn}.W_{ing}.F \quad (2)$$

where AED_{ing} is the annual committed dose (in unit μSvy^{-1}), and C_{Rn} is the measured radon concentration of the water samples in unit Becquerel per litre (BqL^{-1}), W_{ing} is the water consumption (intake) per year in the unit (La^{-1}) for different age groups (see Table 2). And, F is the dose conversion factor of Radon, which is 23, 5, and 3.5 $nSvBq^{-1}$ for infants, children, and adults, respectively (Mamun & Alazmi, 2022).

The determination of the annual effective dose due to radon inhalation from water release,

AED_{inh} (in μSva^{-1}) was made using the following equation

$$AED_{inh} = C_{Rn} \times R_{aw} \times O \times F_{eq} \times DCF \quad (3)$$

where R_{aw} is the air-to-water radon concentration ratio (10^{-4}), O is the average indoor occupancytime per human (7000 ha^{-1}), $F_{eq}$is the equilibrium factor between Radon and its decay products (0.4), and DCF is the dose conversion factor for radon exposure (9.0×10^{-9} $Sv/Bqhm^{-3}$) (Mamun & Alazmi, 2022).

RESULTS AND DISCUSSION

Radon concentration

The radon concentration levels in all 12 samples, the annual effective doses for ingestion in infants, children, and adults, and the annual effective dose for inhalation in adults are shown in Table 3. The radon concentration in the water samples collected across the selected wells and boreholes ranged from 5.36 ± 0.22 BqL^{-1} to 0.52 ± 0.06 BqL^{-1} with an average concentration of 2.82 ± 0.14 BqL^{-1}. Most water samples from open wells showed higher radon concentrationsthan borehole sources. The highest radon concentration was measured in water samples from open-well samples collected from the well water of Mahmud Jauro (sample OW03), and the water sample with the lowest radon concentration was found in the water samples collected from the open well of the Baban Kogi (sample OW05) area. All measured values were below the maximum contaminant level of 11.1 BqL^{-1} (300 pCi/L) for Radon in drinking water recommended by the United States Environmental Protection Agency (USEPA) and the 4 – 40 BqL^{-1} benchmark of the UNSCEAR (UNSCEAR, 2008; US-EPA, 1999). It signifies low health risk due to radon exposure for the community. This finding is important to regulatory bodies and researchersas it could contribute to the foundation of evidence-based policy construction in environmental and public health management, and it is critical to future investigations, including groundwater radon mapping and the exploration of seasonal variational effects on groundwater radon concentrations of the Lapai town.

In comparison to other research findings, the obtained concentration values are similar to thevalues in the range of 2.64 ± 0.80 BqL^{-1} to 0.60 ± 0.37 BqL^{-1} obtained for drinking water samples of Ogbomosho, Southwestern Nigeria (Oni & Adagunodo, 2019). However, the obtained concentration levelsare relatively low in contrast to some of the values in the range of 2.1 ± 0.7 BqL^{-1} to 27.9 ± 2.5 BqL^{-1} and 2.8 ± 1.1 BqL^{-1} to 39.5 ± 1.5 BqL^{-1} that was obtained respectively for open well and borehole groundwater samples of the Bosso community, North-Central Nigeria (Kolo *et al.*, 2023). The two communities share the same geology; hence, the disparity in values could be attributed to the seasonal difference since the measurements for the groundwater of Bosso were made during the rainy season when concentration levels are usually at their peak (Nakasone *et al.*, 2021) as opposed to the present research where the samples were collected in the dry season when the concentration of Radon is likely low.

The effect of sampling water depth on radon concentration levels was examined. There was no observable indication of the effect of depth on the concentration levels. The highest and lowest concentration values were obtained from well water at shallow depths. Both high and low concentration values were observed for both shallow and relatively deep water sources. This indicates the need for a comprehensive study/understanding of the radon transport mechanism within the groundwater system of the Lapai community.

The results of the present study are compared with those obtained for radon concentration levels from studies of groundwater samples from other regions of the world, as shown in Table 4.The values obtained are in agreement with the results from other countries.

Table **3**. Radon levels and annual effective doses of the water samples for both HDWs and HPBs

Sample Code	**Radon Concentration[BqL^{-1}]**	**Water Source Depth [m]**	**AED for Ingestion[μSv a^{-1}]**			**AED for inhalation[μSv a^{-1}]**
			Infants	**Children**	**Adults**	
BH01	2.74 ± 0.24	145.0	14.49	5.33	7.00	6.90
BH02	1.95 ± 0.11	137.0	10.32	3.80	4.98	4.91
BH03	1.56 ± 0.13	115.0	8.26	3.04	3.99	3.93
BH04	1.30 ± 0.07	130.0	6.90	2.54	3.33	3.28
BH05	5.07 ± 0.13	75.0	26.83	9.87	12.96	12.78
BH06	1.82 ± 0.25	120-140	9.62	3.54	4.64	4.58
BH07	3.12 ± 0.12	120-140	16.53	6.08	7.98	7.87
OW01	2.34 ± 0.07	5.0	12.39	4.56	5.99	5.90
OW02	4.68 ± 0.18	6.0	24.75	9.11	11.95	11.79
OW03	5.36 ± 0.22	5.5	28.34	10.43	13.69	13.50
OW04	3.39 ± 0.08	12.0	17.93	6.60	8.66	8.54
OW05	0.52 ± 0.06	5.0	2.76	1.02	1.33	1.31
Mean	**2.82 ± 0.14**	145.0	**14.93**	**05.49**	**07.21**	**7.11**
Max.	**5.36 ± 0.22**	137.0	**28.34**	**10.43**	**13.69**	**13.50**
Min.	**0.52 ± 0.06**	115.0	**02.76**	**01.02**	**01.33**	**1.31**

Table 4. Comparison of radon concentration levels in portable water for different regions of the world

Reference(s)	Country-Region	Radon concentration[BqL^{-1}]
Current study	Lapai-Nigeria	0.52 – 5.36
(El-Araby *et al.*, 2019)	Jazan-Saudi Arabia	1.65 – 3.82
(Rotich *et al.*, 2020)	Bureti-Kenya	4.57 - 22.56
(Aydin & Söğüt, 2019)	Adiyaman-Turkey	0.32 - 0.71
(Faella *et al.*, 2020)	Cilento-Italy	3.0 – 45.0
(Yong *et al.*, 2021)	Urumqi-China	0.28– 0.75

Annual effective dose

The risk posed by the ingestion of water samples of the Lapai community was evaluated for three different age groups as specified in Table 2, and the values obtained vary in the range of 2.76 to 28.34 μSva^{-1}, 1.02 to 10.43 μSva^{-1}, and 1.33 to 13.69 μSva^{-1} for infants, children, and adults respectively. These values are below the world average of 300 μSva^{-1} (UNSCEAR, 2000) and below the 100 μSva^{-1} limit of the World Health Organization (WHO, 2017). As expected, the calculated annual effective doses for infants were relatively higher than those for children and adults. This is consistent with the observations of (Mamun & Alazmi, 2022). The obtained results showed a significant difference between the doses estimated for infants and children age groups. The dose in infants is almost three times higher than that in children, although water consumption is lower in infants. The dose values for the infant age group were approximately twice those in adults. However, the dose difference between children and adult age categories was not relatively significant. This disparity in estimated dose values emphasizes the need to monitor risk assessments based on age grouping.

As shown in Table 3, the annual effective dose due to inhalation of Radon released from water by adults has values of 1.31 to 13.50 μSva^{-1}. These values are below the world average of 1260 μSva^{-1} (WHO, 2017). The values obtained for the present study's annual effective dose due to inhalation were approximately the same as those of the annual effective dose due to adult ingestion. This finding is consistent with the observations of Mamun & Alazmi, 2022.. The obtained values were below the recommended limit of 100 μSva^{-1} of the WHO (WHO, 2017). There was a direct linear correlation between the annual effective dose due to ingestion and inhalation in adults with an R-square value of 1 (see Figure 2).

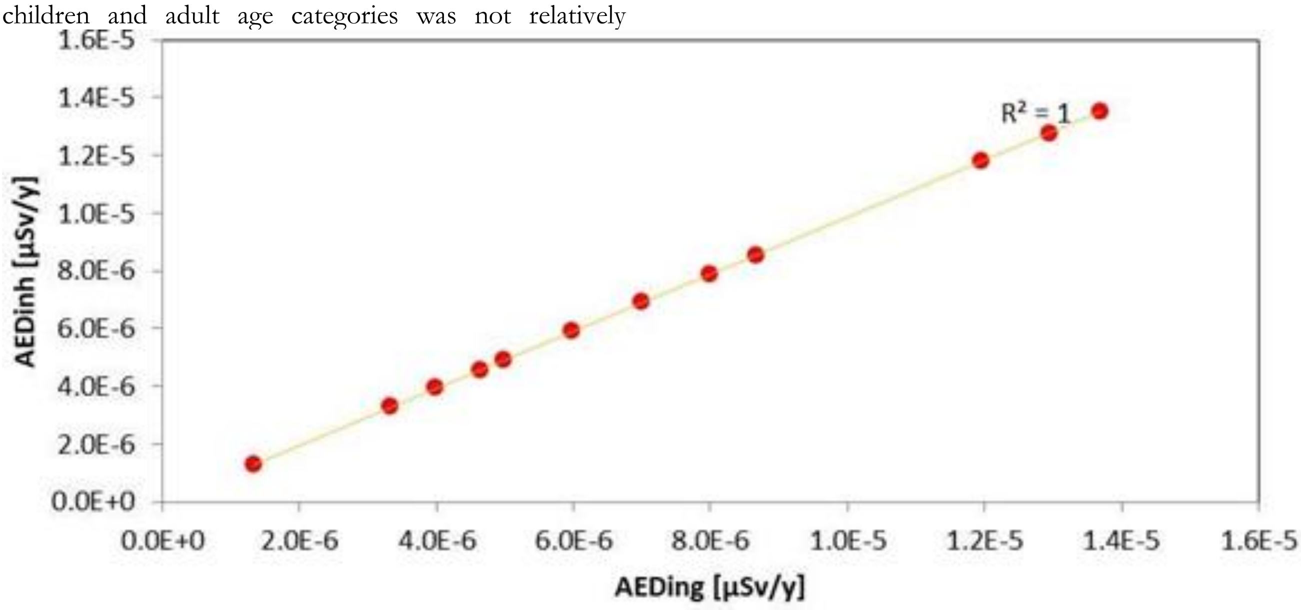

Figure 2. Correlation between the annual effective dose due to ingestion and inhalation in adults

CONCLUSION

The research found that major drinking water sources in the Lapai community do not suffer immediate radon-associated public health hazards. This is because the values obtained for radon concentration levels in wells and borehole samples of the community and the estimated dose due to radon exposure from the groundwater do not exceed the US-EPA, WHO, and UNSCEAR recommended maximum permissible levels. However, constant monitoring is prescribed becauseelevated radon concentrations may manifest in the water samples, especially during the rainy season, and the continuous consumption of such water will expose the consumer to an increased risk of cancer. There was no observable trend between the radon concentrations and the depth of the groundwater sources. The data obtained in this study can be used for groundwater radon concentration level mapping of the study area and its environs. In addition, the data from this research could be useful in assessing the effect of sampling season, sampling container material, and storage time on the water radon concentration levels of the community.

ACKNOWLEDGMENT

The authors wish to thank the residents of the Lapai community for their cooperation during sample collection and Umar Aliyu Ba-Kano of the Department of Physics, Ibrahim Badamasi Babangida University, Lapai, Nigeria, for his assistance during the depth estimation of the water sources considered in this study.

REFERENCES

Ajiboye, Y., Isinkaye, M. O., Badmus, G. O., Faloye, O. T., & Atoiki, V. (2022). Pilot groundwater radon mapping and the assessment of health risk from heavy metals in drinking water of southwest, Nigeria. *Heliyon*, *8*(2), e08840. **[Crossref]**

Aydin, M., & Söğüt, Ö. (2019). Measurement of radon gas activity concentrations in drinking water in the city center of Adıyaman, Turkey. *Radiation Protection and Environment*, *42*(1), 10. **[Crossref]**

Boko, U. H., Saidu, M., Yakubu, N., Hassana, S. R., Awwal, A., & Mohammed, H. (2021). Concentrations and health risk assessment of selected heavy metals in drinking water sources, food, and soils of Lapai. *Journal of Environmental Science, Toxicology and Food Technology*, *15*(6), 36–44. **[Crossref]**

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J. M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., … Doll, R. (2005). Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 European case-control studies. *BMJ*, *330*(7485), 223. **[Crossref]**

Durridge-Company. (2015). *RAD7 Radon Detector User Manual*. Drurrige Radon Instrumentation, USA.

El-Araby, E. H., Soliman, H. A., & Abo-Elmagd, M. (2019). Measurement of radon levels in water and the associated health hazards in Jazan, Saudi Arabia. *Journal of Radiation Research and Applied Sciences*, *12*(1), 31–36. **[Crossref]**

Faella, E., Mancini, S., Guida, M., Cuomo, A., & Guida, D. (2020). Alpha Spectrometry of Radon Short-Lived Progeny in Drinking Water and Assessment of the Public Effective Dose: Results from the Cilento Area, Province of Salerno, Southern Italy. *Materials*, *13*(24), 5840. **[Crossref]**

George Obaje, N., Bomai, A., Dabai Moses, S., Ali, M., Aweda, A., Japhet Habu, S., Idris-Nda, A., Isah Goro, A., & Waziri, S. (2020). Updates on the Geology and Potential Petroleum System of the Bida Basin in Central Nigeria. *Petroleum Science and Engineering*, *4*(1), 23. **[Crossref]**

Hadkhale, K., Atosuo, J., & Putus, T. (2022). Groundwater radon exposure and risk of lung cancer: A population-based study in Finland. *Frontiers in Oncology*, *12*, 935687. **[Crossref]**

Kolo, M. T., Olarinoye, O., Salihu, S. O., Ugwuanyi, H. A., Onuche, P., Falade, O., & Chibueze, N. (2023). Annual Effective Dose and Excess Lifetime Cancer Risk due to Ingestion and Inhalation of Radon in Groundwater of Bosso Community Minna, North-Central Nigeria. *Journal of the Nigerian Society of Physical Sciences*, 896. **[Crossref]**

Mamun, A., & Alazmi, A. S. (2022). Investigation of Radon in Groundwater and the Corresponding Human-Health Risk Assessment in Northeastern Saudi Arabia. *Sustainability*, *14*(21), 14515. **[Crossref]**

Nagaraja, M., Sukumar, A., Dhanalakshmi, V., & Rajashekara, S. (2019). Factors Influencing Radon (²²²Ra) Levels of Water: An International Comparison. *Journal of Geoscience and Environment Protection*, *07*(05), 69–80. **[Crossref]**

Nakasone, S., Ishimine, A., Shiroma, S., Masuda, N., Nakamura, K., Shiroma, Y., Ooka, S., Tanaka, M., Kato, A., Hosoda, M., Akata, N., Yasuoka, Y., & Furukawa, M. (2021). Temporal and Spatial Variation of Radon Concentrations in Environmental Water from Okinawa Island, Southwestern Part of Japan. *International Journal of Environmental Research and Public Health*, *18*(3), 998. **[Crossref]**

Oladipo, M. O. A., Njinga, R. L., Baba, A., & Mohammed, I. (2011). Contaminant evaluation of major drinking water sources (boreholes water) in Lapai metropolis. *Advances in Applied Science Research*, *2*(6), 123–130.

Oni, E. A., & Adagunodo, T. A. (2019). Assessment of radon concentration in groundwater within Ogbomoso, SW Nigeria. *Science, Technology and Research: Keys to Sustainable Development*, *1299*. **[Crossref]**

Oni, E. A., Adagunodo, T. A., Adegbite, A. A., & Omeje, M. (2021). Determination of Radon gas in bottled and sachet water in Ile-Ife, Nigeria. *IOP Conference Series: Earth and Environmental Science*, *655*(1), 012092. **[Crossref]**

Rotich, C. K., Hashim, N. O., Chege, M. W., & Nyambura, C. (2020). Measurement of Radon Activity Concentration in Underground Water of Bureti Sub-County of Kericho County Kenya. *Radiation Protection Dosimetry*, *192*(1), 56–60. **[Crossref]**

Shu'aibu, 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. *Radiation Physics and Chemistry*, *178*, 108934. **[Crossref]**

Tsepav, M. T., Badeggi, A. Y., George, O. N., Tanko, U. Y., & Ibbi, I. S. (2021). On the Use of Electrical Resistivity Method in Mapping Potential Sources and Extent of Pollution of Groundwater Systems in Lapai Town, Niger State, Nigeria. *Journal of Physics: Theories and Applications*, *5*(1), 18. **[Crossref]**https://doi.org/10.20961/jphystheor-appl.v5i1.51563

UNSCEAR (Ed.). (2000). *Sources and effects of ionizing radiation: United Nations Scientific Committee on the Effects of Atomic Radiation: UNSCEAR 2000 report to the General Assembly, with scientific annexes*. United Nations.

UNSCEAR. (2008). *Sources and Effects of Ionizing Radiation: UNSCEAR 2008 Report to the General Assembly with Scientific Annexes, Volume I.*

US-EPA. (1999). *National Primary Drinking Water Regulations; Radon-222*. United State Environmental Protection Agency.

WHO. (2017). *Guidelines for Drinking Water Quality: Fourth edition incorporating the first addendum*. World Health Organization.

Yong, J., Liu, Q., Wu, B., Hu, Y., & Feng, G. (2021). Assessment of radiation dose hazards caused by Radon and its progenies in tap water by the human dosimetric model. *Journal of Water and Health*, *19*(6), 933–945. **[Crossref]**