Annual effective dose from ^{222}Rn in groundwater of a Nigeria University campus area

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Abstract

Radon, the heaviest among the noble gases in the periodic table of element is a radioactive nuclide that is naturally available in rocks, soil and water. It has become the subject of many research efforts in recent years due to its leading role in causing cancer. In this study, a total of 68 groundwater samples were collected and assayed using alpha spectrometry with RAD7 radon detector with RAD-H₂O accessories manufactured by DurrIDGE CO (USA). The ^{222}Rn concentration measured were in the range of 0.6–36.2 Bq L⁻¹ with an average of 13.33 Bq L⁻¹, 7.0–41.5 Bq L⁻¹ with mean value 23.3 Bq L⁻¹ and 0.6–27.4 Bq L⁻¹ with an average value of 7.4 Bq L⁻¹ for hand dug wells (HDW), hand pumped boreholes (HPB) and motorized boreholes (MBH), respectively. About 54, 86 and 15% of samples from the HDW, HPB and MBH, respectively, exceeded the parametric reference level of 11.1 Bq L⁻¹ suggested by United State of America Environmental Protection Agency but lower than the permissible limit of 100 Bq L⁻¹ by World Health Organization (WHO) and European Union. The average annual effective doses resulting from inhalation and ingestion of radon in water obtained for the three groundwater sources are less than recommended limits by WHO and ICRP. The data obtained from this study are comparable with similar studies conducted in Nigeria and other parts of the world as reported in literature. Continuous radon monitoring in drinking water and indoor environment is however recommended for the study area.

Keywords Radon · Groundwater · University campus · Annual effective dose · Natural radionuclides

Introduction

Radionuclides are natural constituents of rock, soil and water which make up our environment. Man being the product of the environment gets radiation exposure through inhalation of both outdoor and indoor air, consumption of food and water and direct exposure from the ground or through dermal contact (Abd El-mageeb et al. 2011; Moreno et al. 2014). The largest fraction of the exposure of humans to radiation from natural sources comes from radon gas (WHO 2004). Radon is a highly radioactive noble gas which has no odor, color or taste, and it is of radiological concern because of the danger it poses when inhaled or ingested due to its immediate radioactive daughters which are alpha emitters (El-Gamal

and Hosny 2008; Ononugbo and Avwiri 2018). It is released from decay of radium, which is also a bi-product of the natural disintegration of uranium. Radon, whose half-life is 3.8 days, emanates from rocks and soil. It has the tendency to accumulate in enclosures such as underground mines and indoor spaces. ^{214}Po and ^{218}Po which are the radioactive daughters of ^{222}Rn decay through alpha emissions and account for about 90% of the total radiation dose received by man due to radon exposure (Badhan et al. 2010; Yalcin et al. 2011). It is noted as the foremost cause of lung cancer among non-smokers. Radon studies have been the subject of many regional, national and international research efforts due to its activity, natural occurrence and the risks to public health (Akawwi 2014; Isinkaye and Ajiboye 2017; Oni and Adagunodo 2019; Ogundare and Adekoya 2015; Kalip et al. 2018; El-Araby et al. 2019; Duggal et al. 2020). Water is an essential item to human life and a very significant parameter for environmental, geological and radiological studies. The occurrence of radionuclides in groundwater poses a number of health risks, particularly when the radionuclides are

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deposited in the human body through the consumption of water sourced from high background radiation environment (Tajudeen 2006). The concentrations of radon dissolved in groundwater is a function of various parameters such as the characteristics of the aquifer, residence time of water within the aquifer, water–rock interaction, mineral content of the bedrock, etc. (Choubey and Ramola 1997). Determination of radon contents in groundwater have been carried out in connection with hydro-geological, geological and radiological health hazard studies by different researchers (Gillmore et al. 2000; Popit and Vaupotič 2002; Skeppström and Olofsson 2007; Bem et al. 2014; Przylibski and Gorecka 2014; Hao et al. 2015; Smith and Voutchkov 2017; Ina'cio et al. 2017; Ferreira et al. 2018; Girault et al. 2018). Many of those studies have reported strong correlations between radon concentration and the geology of a given environment. Consumption of water which contains enhanced activity concentrations of ^{222}Rn could raise the effective dose received by man and increase the risk of lung and gastric cancer (Rožmarić et al. 2012).

Due to the inadequate supply of pipe borne water, the practice of drilling deep wells and boreholes as major sources of drinking water has been in practice for close to four decades in the study area. Three types of groundwater sources are common in the area. These are; hand dug wells (HDW), hand pumped boreholes (HPB) and motorized boreholes (MBH). The hand dug wells are the most common sources usually fitted with moveable covers. The hand pumped wells are borehole projects mostly executed with the Millennium Development Goal (MDG) initiatives, while the motorized boreholes are usually fitted with submersible motorized pumps and piped directly for household of workplace uses. The aim of this study therefore was to measure the concentrations of ^{222}Rn in drinking water from different groundwater sources in the study area and to determine the annual effective doses of radon ingested and inhaled by groundwater consumers in the area. It is expected that the results of radon measurements obtained in this study will complement other data which have hitherto served as baseline. It is also envisaged that the results will serve as database for future work and policy formulation on ^{222}Rn concentration in groundwater for Nigeria.

Materials and methods

Study area

Ekiti State University and its environs is located at the outskirts of Ado Ekiti in Ekiti State (Fig. 1). The Study area lies within latitude $7^{\circ} 42' 30''$ and $7^{\circ} 44' 0''$ N and longitude $5^{\circ} 15' 0''$ and $5^{\circ} 16' 0''$ E. Due to the inadequacy of students' hostels, majority of the University students patronize

privately built hostels located around the University campus as well an agrarian community which is about 2 km to the University campus. The target population therefore includes the student and the staff of the University together with the dwellers of the adjoining town and villages around the campus. Water samples were collected from the work areas, hostels and lodges. Most of the hostels are built as one room self-contained with bathroom and toilet inclusive. The rooms are usually not well ventilated, which may lead to excessive accumulation of dissolved radon from groundwater used in showers into the indoor spaces of the dwellings. The geology of Ado-Ekiti where the University is located belongs to the basement complex rock (igneous rock) of South Western Nigeria. (Omotoyinbo and Okafor 2008). The rock sequence includes the granitic and charnockitic rocks, the quartzite series, gneisses and migmatites (Olajuyigbe 2010).

Sampling and experimental analysis

A total of 68 groundwater samples were collected for analysis. The samples were collected from three different groundwater sources namely, hand dug wells (HDW), hand pumped boreholes (HPB) and motorized boreholes (MBH). The samples consist of 48 water samples from hand dug wells collected using water bailer, seven from hand-pumped boreholes collected directly after pumping and 13 from motorized boreholes collected from taps after pumping and storing in storage tanks. Google map was employed to obtain the coordinates of each location as shown in Tables 1, 2 and 3. The sampling area includes the University main campus, opposite of the University gate, Satellite hostel's environment and Iworoko Ekiti as shown in Fig. 1. Standard water sampling procedures were employed in collecting the samples. The water samples were collected using the 250 ml vial associated with Durrige RAD-H₂O. The bottles were gently and completely filled to avoid agitations that could lead to the loss of radon gas. The collected samples were taken to the laboratory where measurements were carried out using a factory calibrated radon detector (RAD7) coupled to RAD-H₂O accessories (Ajiboye et al. 2018). The detector is located in the Radioanalytical Research Laboratory of Physics Department, Ekiti State University, Ado Ekiti, Nigeria.

The setup of the RAD7 detector with the RAD-H₂O accessories used for the measurements is shown in Fig. 2. The setup consists of four parts; (1) the electronic RAD 7 detector, (2) the 250 mL vial containing water sample, (3) the desiccant tube supported by resort stand and (4) infrared enabled printer. The RAD7 setup utilizes a closed loop aeration arrangement where the air and water volumes are constant and independent of the rate of flow. The operation of the device consists of ejection of radon from the water sample using a bubbling kit, the ejected radon then enters a hemisphere chamber through air circulation

Fig. 1 Location map of the study area showing the sampling points

and polonium nuclei are produced through the decay of radon. These are collected onto the silicon solid-state detector in a high electric field, which are then counted and estimated as concentration of radon in water sample through the in-built software (Durrige 2011). To ensure the reliability of the measurement methods and for quality

control purposes, each sample was analyzed automatically in four cycles with each cycle taking 5 min. Prior to this, the water is aerated for a period of 5 min with the aeration or bubbling kit. The aeration process releases about 95% of radon from the water sample and the radon concentration in the water is automatically measured by the RAD-7.

Table 1 Activity concentration, ingestion, inhalation and total annual doses from ^{222}Rn in groundwater from hand dug wells (HDW) in the study area

Location	Sample code	Longitude	Latitude	Radon concentration (Bq L^{-1})	Ingestion dose ($\mu\text{Sv year}^{-1}$)	Inhalation dose ($\mu\text{Sv year}^{-1}$)
Solidarity hostel	HDW-1	5° 15' 15.5" E	7° 42' 36.9" N	4.0±0.8	10.2	12.6
Easy lodge	HDW-2	5° 15' 9.2" E	7° 43' 2.7" N	6.5±1.1	16.6	20.5
Omobola hostel	HDW-3	5° 15' 10.6" E	7° 43' 13.9" N	2.7±0.7	6.9	8.5
State house	HDW-4	5° 14' 49.4" E	7° 43' 13.0" N	2.9±0.7	7.4	9.1
Junkay hostel	HDW-5	5° 14' 9.4" E	7° 43' 12.7" N	3.0±0.7	7.7	9.5
Old faculty of science	HDW-6	5° 15' 2.3" E	7° 42' 37.1" N	13.5±1.5	34.5	42.6
Alexander hostel	HDW-7	5° 15' 4.7" E	7° 43' 9.1" N	2.9±0.7	7.4	9.1
Living large	HDW-8	5° 15' 4.7" E	7° 43' 9.1" N	1.6±0.5	4.1	5.0
Covenant hostel	HDW-9	5° 15' 5.0" E	7° 43' 10.2" N	2.2±0.6	5.6	6.9
Gods grace Hostel	HDW-10	5° 15' 15.3" E	7° 43' 4.1" N	4.2±0.8	10.7	13.2
CASOR	HDW-11	5° 14' 51.8" E	7° 43' 48.7" N	1.3±0.5	3.3	4.1
Dorcas hostel	HDW-12	5° 15' 47.2" E	7° 42' 48.7" N	12.8±1.5	32.7	40.4
Higherground hostel	HDW-13	5° 15' 49.9" E	7° 42' 49.6" N	11.9±1.4	30.4	37.5
St George hostel	HDW-14	5° 15' 50.6" E	7° 42' 45.8" N	8.7±1.3	22.2	27.4
Option hostel	HDW-15	5° 15' 10.2" E	7° 42' 33.1" N	28.5±2.2	72.8	89.9
Shiloh hostel	HDW-16	5° 15' 32.9" E	7° 42' 20.1" N	34.0±2.4	86.9	107.2
New faculty of art	HDW-17	5° 15' 5.8" E	7° 42' 31.7" N	13.4±1.5	34.2	42.3
College of medicine 1	HDW-18	5° 15' 22.1" E	7° 42' 27.0" N	6.1±1.0	15.6	19.2
College of medicine 3	HDW-19	5° 15' 23.9" E	7° 42' 26.3" N	8.8±1.2	22.5	27.8
Christ villa	HDW-20	5° 15' 25.0" E	7° 43' 49.2" N	20.3±3.8	51.9	64.0
Savannah villa	HDW-21	5° 15' 21.0" E	7° 43' 43.0" N	13.6±3.2	34.7	42.9
Campus villa	HDW-22	5° 15' 20.7" E	7° 43' 46.0" N	0.8±0.9	2.0	2.5
Koko mansion 1	HDW-23	5° 15' 39.4" E	7° 43' 42.4" N	14.8±3.3	37.8	46.7
Authority villa	HDW-24	5° 15' 34.5" E	7° 43' 55.8" N	33.2±5.1	84.8	104.7
Vineyard of comfort	HDW-25	5° 15' 33.1" E	7° 43' 56.1" N	18.3±3.7	46.8	57.7
Shonibare villa	HDW-26	5° 15' 30.0" E	7° 43' 59.9" N	17.8±3.6	45.5	56.1
New Bahamas	HDW-27	5° 15' 28.3" E	7° 44' 0.1" N	28.4±4.6	72.6	89.6
Eminent hostel	HDW-28	5° 15' 27.9" E	7° 44' 2.1" N	36.2±3.8	92.5	114.2
Pitosin	HDW-29	5° 15' 26.6" E	7° 44' 0.2" N	16.7±1.2	42.7	52.7
Mighty villa	HDW-30	5° 15' 25.5" E	7° 43' 58.7" N	25.0±0.8	63.9	78.8
Modupe villa	HDW-31	5° 15' 3.8" E	7° 44' 0.2" N	12.8±4.6	32.7	40.4
Equilibrium villa	HDW-32	5° 15' 28.9" E	7° 44' 0.2" N	11.0±1.1	28.1	34.7
Concept villa	HDW-33	5° 15' 28.4" E	7° 44' 4.5" N	21.7±1.4	55.4	68.4
A-Jay villa	HDW-34	5° 15' 30.8" E	7° 44' 4.0" N	16.1±1.0	41.1	50.8
Define favor	HDW-35	5° 15' 27.0" E	7° 44' 2.8" N	22.7±2.6	58.0	71.6
Harmony villa	HDW-36	5° 26' 8.3" E	7° 72' 79.3" N	3.6±1.8	9.2	11.4
God's Own villa	HDW-37	5° 26' 17.5" E	7° 72' 84.8" N	23.5±4.4	60.0	74.1
Cool paradise	HDW-38	5° 26' 26.4" E	7° 72' 76.5" N	26.1±4.6	66.7	82.3
Koko mansion 2	HDW-39	5° 26' 8.6" E	7° 72' 84.6" N	25.3±4.4	64.6	79.8
Sharon lounge	HDW-40	5° 26' 16.5" E	7° 72' 90.8" N	13.5±3.2	34.5	42.6
St Felicia villa	HDW-41	5° 26' 16.6" E	7° 72' 97.2" N	15.5±3.4	39.6	48.9
Jewel camp	HDW-42	5° 26' 8.3" E	7° 72' 79.7" N	14.4±3.2	36.8	45.4
Diamond place	HDW-43	5° 26' 16.5" E	7° 72' 91.7" N	0.6±0.7	1.5	1.9
City villa	HDW-44	5° 26' 6.2" E	7° 72' 74.1" N	12.0±2.9	30.7	37.8
Mirror palace	HDW-45	5° 26' 59.6" E	7° 72' 82.4" N	10.8±1.7	27.6	34.1
Zenith hostel	HDW-46	5° 26' 50.3" E	7° 72' 81.0" N	4.3±1.2	11.0	13.6
Peaceful castel	HDW-47	5° 26' 60.9" E	7° 72' 86.6" N	8.3±1.4	21.2	26.2
Olympus hostel	HDW-48	5° 26' 64.7" E	7° 72' 6.7" N	3.5±0.6	8.9	11.0

Table 1 (continued)

Location	Sample code	Longitude	Latitude	Radon concentration (Bq L ⁻¹)	Ingestion dose (μSv year ⁻¹)	Inhalation dose (μSv year ⁻¹)
Mean				13.3 ± 9.7	34.1	42.0

Table 2 Activity concentration, ingestion, inhalation and total annual doses from ²²²Rn in groundwater from hand pumped boreholes (HPB) in the study area

Location	Sample code	Longitude	Latitude	Radon concentration (Bq L ⁻¹)	Ingestion dose (μSv year ⁻¹)	Inhalation dose (μSv year ⁻¹)
EKSU health centre	HPB-1	5° 15' 7.7" E	7° 42' 52.1" N	30.7 ± 2.3	78.4	96.8
Old faculty of art	HPB-2	5° 15' 5.8" E	7° 42' 55.1" N	41.5 ± 2.7	106.0	130.9
West end hostel	HPB-3	5° 15' 38.8" E	7° 42' 33.4" N	15.8 ± 1.7	40.4	49.8
Aduralere model high school	HPB-4	5° 15' 29.1" E	7° 43' 58.6" N	31.3 ± 4.9	80.0	98.7
Possibility lodge	HPB-5	5° 15' 32.3" E	7° 43' 59.6" N	25.3 ± 4.4	64.6	79.8
Obafunke lodge	HPB-6	5° 15' 28" E	7° 44' 1.9" N	7.0 ± 4.0	17.9	22.1
Our villa hostel	HPB-7	5° 15' 30.4" E	7° 42' 3.0" N	11.8 ± 0.4	30.1	37.2
Mean				23.3 ± 12.3	59.6	73.6

Table 3 Activity concentration, ingestion, inhalation and total annual doses from ²²²Rn in groundwater from motorized boreholes (MBH) in the study area

Location	Sample code	Longitude	Latitude	Radon concentration (Bq L ⁻¹)	Ingestion dose (μSv year ⁻¹)	Inhalation dose (μSv year ⁻¹)
UBA bank	MBH-1	5° 14' 56.4" E	7° 42' 58.6" N	0.8 ± 0.4	0.17	0.02
Access bank	MBH-2	5° 15' 0.2" E	7° 42' 48.1" N	2.6 ± 0.7	0.55	0.065
New faculty of education	MBH-3	5° 15' 4.7" E	7° 42' 32.4" N	5.9 ± 1.0	1.24	0.15
Faculty of education extension	MBH-4	5° 15' 4.8" E	7° 42' 32.3" N	11.6 ± 1.4	2.44	0.29
Postgraduate college	MBH-5	5° 15' 12.4" E	7° 42' 24.8" N	10.2 ± 1.3	2.14	0.26
EKSU water (raw)	MBH-6	5° 15' 28.3" E	7° 42' 50.6" N	27.4 ± 2.2	5.75	0.69
EKSU water (bottled)	MBH-7	5° 15' 28.3" E	7° 42' 50.6" N	8.5 ± 1.2	1.79	0.21
College of medicine 2	MBH-8	5° 15' 21.0" E	7° 42' 23.6" N	0.6 ± 0.3	0.13	0.02
New faculty of science	MBH-9	5° 15' 1.7" E	7° 42' 36.4" N	7.1 ± 1.1	1.50	0.18
Melodia hostel	MBH-10	5° 15' 2.7" E	7° 43' 6.6" N	1.5 ± 0.5	0.32	0.038
RCF EKSU	MBH-11	5° 15' 7.9" E	7° 43' 3.7" N	0.9 ± 0.4	0.19	0.023
Eminado lounge	MBH-12	5° 26' 30.5" E	7° 72' 79.3" N	9.6 ± 6.7	2.02	0.24
Portable villa hostel	MBH-13	5° 25' 64.1" E	7° 73' 10.5" N	10.1 ± 0.4	2.12	0.25
Mean				7.4 ± 7.3	19.0	23.5

After a 30 min period, the printer prints out a summary of results consisting of the average radon reading from the four cycles counted. This procedure takes into consideration the calibration of the RAD7, the sample vial volume, time lapse for the analysis and the total volume of the closed air loop. The detector has a sensitivity ranging from 10 pCi L⁻¹ to 400,000 pCi L⁻¹. All the measurements were done following the ISO 13,164 protocol of test method using two-phase liquid scintillation counting for ²²²Ra in water (Isinkaye and Ajiboye 2017).

Estimation of annual effective dose

Human exposure to radiation from radon in water can be quantify through two main exposure pathways, which are ingestion and inhalation pathways. Ingestion occurs when water containing radon at given concentration is consumed while inhalation occurs when radon in water is released into the indoor air and inhaled. Though the accompanying hazard of ingested radon through water consumption is low compared to the hazard from inhalation of radon from air yet the

Fig. 2 Experimental setup of RAD7 detector with RAD-H₂O accessories used in this study

risk posed by this pathway cannot be ignored (Ina'cio et al. 2017). The average annual effective dose from ingestion and inhalation of radon in water is estimated in this work using Eqs. 1 and 2 (UNSCEAR 2000; Ajiboye et al. 2018):

$$AED_{ing} = C_{Rn} \times WCR \times DCF_{ing} \quad (1)$$

$$AED_{inh} = C_{Rn} \times R_{aw} \times EF \times OT \times DCF_{inh} \quad (2)$$

where $AED_{ingestion}$ and $AED_{inhalation}$ are the annual effective doses from ingestion and inhalation of radon in water, respectively, given in the unit of mSv year⁻¹, C_{Rn} is the radon concentration in water given in Bq L⁻¹, WCR is the water consumption rate given as 730 L year⁻¹ with the assumption that an average adult takes 2 L of water per day, DCF_{ing} is the dose conversion factor for ingestion, which is given as 3.5 nSv Bq⁻¹, R_{aw} is the ratio of radon released to air when water is used to radon in water and is given as 10⁻⁴, EF is equilibrium factor between radon and its progeny given as 0.4, OT is the average indoor occupancy time given as 7000 h year⁻¹ and DCF_{inh} is the dose conversion factor for inhalation of radon in air, which is given as 9 nSv h⁻¹ Bq L⁻¹.

Results and discussion

Radon concentration

Table 1 depicts the measured concentrations of ²²²Rn in groundwater samples collected from hand dug wells (HDW) within and in the adjoining residential areas of Ekiti State University, Ado Ekiti. From the Table, the concentration of ²²²Rn in the samples varied from 0.6 ± 0.1 to 36.2 ± 3.8

with an average of 13.3 ± 9.7 Bq L⁻¹. About 54% of the values were higher than the limit of 11.1 Bq L⁻¹ specified by USEPA, but within the recommended range of the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) and the European Union Commission (EU) of 4 – 40 Bq L⁻¹ and 100 Bq L⁻¹, respectively. Table 2 shows the activity concentrations of ²²²Rn in groundwater samples from hand pumped boreholes (HPB). As shown in the Table, activity concentrations of ²²²Rn ranged from 7.0 ± 4.0 to 41.5 ± 2.7 Bq L⁻¹ with a mean value of 23.1 ± 12.3 Bq L⁻¹. About 86% of the values were higher than the specified permissible level of the USEPA recommendation. One of the samples from this groundwater source gave a value that was higher than the range (4–40 Bq L⁻¹) of safe limit recommended by UNSCEAR but lower than 100 Bq L⁻¹ of the EU recommendation. Table 3 shows the activity concentrations of ²²²Rn in samples collected from motorized boreholes (MBH). As depicted in the Table, the values obtained ranged from 0.6 ± 0.3 to 27.4 ± 2.2 Bq L⁻¹ with a mean value of 7.4 ± 7.3 Bq L⁻¹. Approximately 15% of the values were higher than the limits of USEPA. This groundwater source presented the highest variability in the activity concentrations of ²²²Rn within the study area. This is exhibited by the high value of standard deviation associated with the mean value. From the result presented in Tables 1, 2 and 3, there is a considerable variation in the activity concentration of ²²²Rn between the HDW, HPB and MBH. The variation could be credited to diverse factors such as the characteristics and composition of the aquifer, radionuclides contents of the bed-rock, water residence time within the aquifer and the storage facilities, etc. (Gundersen et al. 1992; Choubey and Ramola 1997; Choubey et al. 1997). The highest average radon level was recorded in samples from hand pumped boreholes

(HPB). This may not be unconnected with the less aeration and casing of the borehole with concrete made from granitic materials which may lead to dissolution of more ^{222}Rn into the well water (Ademola and Ojeniran 2017; Ajiboye et al. 2018). Motorized boreholes give the lowest values of radon activity concentrations. This is possible as the water sourced from source is always piped directly to overhead storage

Fig. 3 Variations of the mean radon activity concentrations for the three groundwater sources and USEPA parametric value

facility from where is connected for household or office use. In most cases, the residence time of the water sample in the storage facility would have led to reduction in radon concentration due to radioactive decay. The variation of the mean radon activity concentrations among the three groundwater sources is presented in Fig. 3 with HPB showing mean value of two order of magnitude higher than the USEPA (1991) recommended limit of 11.1 Bq L^{-1} . Generally, most of the values recorded for ^{222}Rn in the study were higher than the recommended safe limit suggested by Nigerian Industrial Standard (NIS 2015; Khandaker et al. 2020) which is 0.1 Bq L^{-1} . This value has been a subject of debate among radiation protection specialists in Nigeria. Research works on radon measurement from different locations within the country is therefore essential to help the regulatory authorities to arrive at an acceptable and practical safe limit on radon in water for the country. The geology of the study area is prevalent with migmatite gneiss and granites. Wells and boreholes in areas with these rock types are known to contain intramontaneous groundwater with higher radon concentrations (Akerblom and Lindgren 1997). Table 4 shows the comparison of the results of this study to results of radon measurement in other locations around the world. As can be observed in the Table, the range of values obtained for the three groundwater sources in this study is comparable to range of values

Table 4 Comparison of activity concentrations of ^{222}Rn obtained in groundwater with results from other locations within and outside Nigeria

Location	Water type	Radon concentration (Bq/L)	References
Czech Republic	Hot spring	5.04	Girault et al. (2018)
Spain	Aquifer	12.85	Alonso et al. (2015)
Strzelin, Poland	Shallow wells	0.5–119.4	Przylibski et al. (2020)
Turkey	Tap	0.98–27.28	Büyüksulu et al. (2018)
India	Tap	0.27–5.4	Shilpa et al. (2017)
	Open well	0.24–9.82	
	Bore well	3.19–106.17	
Ghana	Bottled water	0.026–0.093	Opoku-Ntim et al. (2019)
Vietnam	Drilled wells	1.4	Hao et al. (2015)
Iran	Tap/wells/surface	16–23	Binesh et al. (2010)
Jamaica	Wells	18	Smith and Voutchkov (2017)
Saudi Arabia	Drinking water	2.47	El-Araby et al. (2019)
	Groundwater	2.95	
India	Hand pump wells	12.5–862	Duggal et al. (2020)
Bauchi, Nigeria	Well	4.92–82.89	Khandaker et al. (2020)
Ogbomoso, Nigeria	Ground water	1.86	Oni and Adagunodo (2019)
Delta, Nigeria	Drinking water	0.046–0.126	Ogundare and Adekoya (2015)
Ekiti, Nigeria	Groundwater	34.7	Ajiboye et al. (2018)
Ekiti, Nigeria	Drinking/groundwater	34.3	Isinkaye and Ajiboye (2017)
Ado-Ekiti, Nigeria	Well/borehole	13.59	Oni et al. (2014)
EKSU, Ado, Nigeria	HDW, HPB and MBH	0.6–41.5	Present Study

HDW = Hand Dug Wells, HPB = Hand Pumped Boreholes and MBH = Motorized Boreholes

reported in literature except for boreholes from India, which exhibited higher ranges.

Figure 4 shows the spatial distribution map of ^{222}Rn activity concentration for the study area. The map was developed with ArcGIS software version 10.1. As indicated in the map,

Fig. 4 Generated groundwater radon map for the study location

locations with radon activity concentrations in the excess of the USEPA recommended maximum permissible level are highlighted in red color. These areas include the University gate, EKSU water, University health Centre, College of Medicine to the old Faculty of Arts. The high concentrations of ^{222}Rn observed in Iworoko community is in agreement with a previous study (Ajiboye et al. 2018), which classified the community as a radon prone area.

Estimated annual effective dose

The calculated annual effective dose (ingestion and inhalation) for an average adult in the study area is given in Tables 1, 2 and 3. The ingestion dose obtained for hand dug wells (HDW) ranged from 1.5 to 92.5 $\mu\text{Sv year}^{-1}$ with a mean value of 34.1 $\mu\text{Sv year}^{-1}$, for hand pumped boreholes (HPB), the values ranged from 17.6 to 106.0 $\mu\text{Sv year}^{-1}$ with a mean of 59.6 $\mu\text{Sv year}^{-1}$ while for motorized boreholes (MBH), the values ranged from 1.5 to 70.0 $\mu\text{Sv year}^{-1}$ with a mean of 19.0 $\mu\text{Sv year}^{-1}$. For the inhalation dose, the values ranged from 1.9 to 114.2 $\mu\text{Sv year}^{-1}$ with a mean of 42.0 $\mu\text{Sv year}^{-1}$, 22.1 to 130.9 $\mu\text{Sv year}^{-1}$ with a mean of 73.6 $\mu\text{Sv year}^{-1}$ and 1.9 to 86.4 $\mu\text{Sv year}^{-1}$ for hand dug wells (HDW), hand pumped boreholes (HPB) and motorized boreholes (MBH), respectively. The highest total annual effective dose (256.9 $\mu\text{Sv year}^{-1}$) is obtained HPB while the lowest value of 3.4 $\mu\text{Sv year}^{-1}$ is obtained in both HDW and MBH. Even though the mean total annual effective doses for the three groundwater sources are lower than the 100 $\mu\text{Sv year}^{-1}$ recommended as the maximum permissible dose by WHO (2004) except HPB with 133.2 $\mu\text{Sv year}^{-1}$, all the three sources presented highest values which are some order magnitudes higher than the recommended maximum permissible dose.

Conclusion

In this study, groundwater samples were collected from hand dug wells, hand pumped boreholes and motorized boreholes for analysis to determine the activity concentrations of ^{222}Rn within the environment of Ekiti State University, Ado Ekiti, Nigeria. The mean radon activity concentrations determined for HDW, HPB and MBH are 13.3 ± 9.7 , 23.1 ± 12.3 and $7.4 \pm 7.3 \text{ Bq L}^{-1}$, respectively. All the mean values are higher than the USEPA recommended parametric value of 11.1 Bq L^{-1} for drinking water except motorized boreholes. Dissolved radon may therefore be a major contributor to indoor radon in dwellings of the study area. All the mean annual effective doses calculated for the three groundwater sources are lower than the 100 $\mu\text{Sv year}^{-1}$ recommended as the maximum permissible dose for drinking water by WHO. Even though the

area may be safe as far as dose incur from radiation exposure from ingestion and inhalation of radon in groundwater is concern, it is recommended that continuous radon monitoring of the drinking water in the area be carried out from time to time. The results of this study will serve as baseline for future studies and help regulatory authorities to generate guidelines on radon concentration.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethical conduct No human or animal subject was used in this study as such no ethical compliance to declare.

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