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Radiological Assessment of Selected Borehole Water in Bori Metropolis, Rivers State, Nigeria

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Abstract
Evaluation of radiological hazards was carried out to assess the radionuclide content in borehole water from some randomly selected locations in Bori metropolis, Khana Local Government Area, Rivers State. A total of twenty water samples were collected into sterilized sample containers (50 cl). The collected samples were well packed, stored in a refrigerator (4°C) for twenty-four hours, and transported to the Centre for Energy Research and Development (CERD) laboratory, Obafemi Awolowo University, Ile-Ife, for analysis. Results indicated that radionuclides present in the borehole water and their mean activity concentrations are: ^{40}K (137.16±7.64), ^{232}Th (2.14±0.41), and ^{238}U (5.61±0.91) Bql^{-1}. Mean annual effective dose, annual effective dose equivalent, annual gonad dose equivalent, and radium equivalent are 9.605 nGyh^{-1}, 11.777mSvy^{-1}, 69.343 Bql^{-1}, and 19.25 Bql^{-1} respectively. Mean external hazard index, internal hazard index, representative gamma index, and excess lifetime cancer risk are (0.052), (0.067), (0.149) mSvy^{-1}, and 41.218 E-3 respectively. Mean activity concentration of ^{40}K and ^{232}Th exceeded reference limits of 10 and 0.1 Bql^{-1} respectively, while ^{238}U was within refence limit of 10 Bql^{-1}. The borehole water across the sample locations is harmful and unsafe for human consumption because all radiological hazards studied exceeded the reference limits (UNSCEAR, 2000). It is recommended that safe water supplies be provided for the inhabitants of the study area.

Keywords: Containers, Assessment, Consumption, Energy, Metropolis.

Introduction

Radionuclides are always present in the environmental media (air, water and soil or sediments) via naturally occurring radioactive materials (NORMs) (Okoro et al., 2025), and technologically enhanced naturally occurring radioactive materials (TENORM) in various proportions or amounts (Doyin et al., 2016). Some of the radionuclides present in the environment occur naturally in the earth's crust and living organisms while others are due to anthropogenic activities such as oil and gas exploration, mining and water treatment (Paul et al., 2022). The naturally occurring radioactive materials include uranium (^{235}U and ^{238}U), found in the in the water, soil, and rocks beneath the earth; uranium decay series such as radium (^{226}Ra and ^{228}Ra) and radon (^{222}Rn and ^{220}Rn) present in the groundwater, and mineral ores (Ononugbo & Tutumeni, 2016). Others are thorium (^{232}Th), also present in the soil, and rocks beneath the earth, potassium (^{40}K) found in the water, soil, food as well as in human body. Water is very essential for the overall survival of humans and other living organisms (Chifu et al., 2016; Igbudu & Briggs-Kamara, 2023; Zarma et al., 2024). Some of the sources of water for domestic (cooking, washing and drinking) as well as industrial purposes are supplied from underground (boreholes and hand dug wells) and surface water (rivers, streams and oceans) (Dankawu et al., 2021). Underground water sources contain some amounts of radionuclides (Zarma et al., 2024), which are released from the rocks beneath the earth. The presence of radioisotopes in underground water supplies poses serious health implication such as cataracts, infertility, gastrointestinal disease and cancer of the brain, pancreas, liver and lungs (Ononugbo & Anyalebechi, 2017) on its consumers.

Generally, access to portable (safe and clean) water is very crucial to every citizen, and constitutes the right of a citizen. The primary source of water for domestic purposes in Bori is the borehole. This borehole water source is considerably better alternative source of drinking water than the well water, even though the former is not entirely free from radiological contamination from naturally occurring and or man-made activities. This is because the borehole is drilled more dipper into the ground, and its water are usually cleaner, clearer because they have less surface contamination than the well water. Generally, human activities such as improper waste disposal practices, bunkering activities within the adjoining communities, as well as the activities of pipeline vandals and its resultant oil spillage, have contributed in increasing the chances of contamination of underground water with radioactive materials (Abba et al., 2020). Ingestion of this borehole water with very high level of radioisotopes over a long period of time can result in serious health effects (cancer, genetic mutations and other radiation induced ill health. Furthermore, in Bori, there is no available data on the radiological assessment of natural radionuclides in underground (borehole and well) water. This means that the inhabitants of the metropolitan city may be exposed unknowingly to some hazardous radiological substances present in the water. This also contributed towards the inability of policy makers to make informed decision concerning water quality improvement within the city. This knowledge gap gave rise to the need to determine the level of radioisotopes in borehole water in Bori metropolis. The aim of this study is to assess the natural radioactivity as well as the radiological hazard indices in water from some selected boreholes in Bori metropolis, Khana Local Government Area, Rivers State.

Presently, there are available literatures on natural radioactivity and radiological assessment studies in other parts of Ogoniland (Eleme, Tai, Gokana and Khana Local Government Areas) and its adjoining communities like Andoni, but there is no recorded literature on natural radioactivity in underground water in Bori metropolis hence, the need for this study. Some of the available studies on surface and underground water include the study conducted by Ononugbo & Ndodo (2019) to assess the annual effective dose and lifetime cancer risks as a result of natural radioactivity in well water in Tai local Government Area, Rivers State. The study highlighted that the mean activity concentration of the radioelements (^{40}K, ^{226}Ra and ^{228}Ra(^{232}Th) and the mean radium equivalent in the water are 25.90, 19.21, 18.50 Bql^{-1}, and 54.43 Bql^{-1}respectively. Their study further revealed that the activity concentration of the radionuclides in the well water exceeded the safe limit of 10.0, 10.0 and 1.0 Bql^{-1} respectively, while the mean radium equivalent was within permissible limit. However, the results of their study indicated that the well water sources are radiologically polluted and unsafe for human consumption. A research study by Irunkwor et al. (2022a), revealed that the activity concentration of uranium in surface water (river and creek) as well as underground water (borehole and hand-dug well) in the study areas ranged from 2.42±0.45 to 12.77±1.12 Bql^{-1} while the uranium mass concentration values ranged from 97.52±18.13 to 514.71±45±14 µgl^{-1}. Their study further indicated that the values of mass concentration of uranium obtained from the three sample locations were reportedly above the recommended safe limit. Their study revealed that the cancer mortality and morbidity levels were within permissible limit while the chemical toxicity (lifetime daily dose and hazard quotient) were reportedly above the permissible limits, indicating that the water supplies from the three sample locations are radiologically unsafe for consumption.

A research study carried out by Aman et al. (2023), revealed that the mean activity concentration of radioelements (^{40}K, ^{226}Ra and ^{232}Th) are 55.30±4.26, 22.80±4.03, and 79.76±9.17 Bql^{-1} respectively. The mean values of radium equivalent (Raeq), external hazard index (H_{ex}), internal hazard index (H_{in}), absorbed dose (D), annual effective dose (AED), annual gonad dose equivalent (AGDE) and excess lifetime cancer risk (ELCR) are 142.71 Bql^{-1}, 0.385 mSvyr^{-1}, 0.451 mSvy^{-1}, 63.11 nGyh^{-1}, 0.08 mSvy^{-1}, 426.14 mSvy^{-1}, and 0.27 E-3. According to Aman et al. (2022), all the radiological indices considered in their study exceeded the international permissible limit hence, the water supplies are reportedly unsafe for consumption. The study by Agaja & Ajisafe (2013) revealed that the mean concentration of the radioisotopes (^{226}Ra, ^{232}Th and ^{40}K) in surface water are 3.2±0.2 Bql^{-1}, 3.1± 0.4 Bql^{-1} and 12.31±0.1 Bql^{-1} respectively, and 2.1±0.2 Bql^{-1}, 0.9± 0.2 Bql^{-1} and 4.9±0.6 Bql^{-1} for underground water, while the radium equivalent ranged from 4.35Bql^{-1} to 12.66 Bql^{-1}. The study further revealed that mean activity concentration of ^{232}Th and ^{40}K exceeded the recommended limit, but the mean activity concentration of ^{226}Ra, as well as external and internal hazard indices were within recommended limit. This according to the study, revealed that the water samples were reportedly not heavily polluted radiologically. Okoro et al. (2025) highlighted that mean activity concentration of ^{40}K, ^{232}Th and

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^{238}U are 29.68 3.61 and 3.23 Bql^{-1} respectively. The values of ^{40}K and ^{232}Th according to Okoro et al. (2025), are above the recommended limits of 10.0 and 0.1 Bql^{-1} respectively, while the mean activity concentration of ^{238}U (3.23 Bql^{-1}) was within safe limit of 10.0 Bql^{-1}. Other radiological indices like absorbed dose, external hazard index, annual gonad dose equivalent, excess lifetime cancer risk, and radium equivalent were reportedly above their recommended limits, indicating that the water was radiologically polluted and unsafe for human consumption.

Igbudu et al. (2025) in their study revealed that mean activity concentrations of ^{40}K, ^{232}Th and ^{238}U are 71.51, 2.73 and 9.67 Bql-1 respectively. The study further revealed that mean values of absorbed dose, annual effective dose equivalent and annual gonad dose equivalent, radium equivalent, and excess lifetime cancer risk were reported to be 8.94 nGyh^{-1}, 10.96 mSvy^{-1} and 62.73 Bql^{-1}, 19.11 Bql-1 and 37.88 E-3 respectively. According to Igbudu et al. (2025), the well water sources are not suitable for human consumption since all radiological parameters considered apart from ^{238}U, exceeded their various recommended safe limits. Zarma et al. (2024) revealed that the mean activity concentration of the radionuclides ^{226}Ra, ^{232}Th and ^{40}K in borehole, surface and well water samples are 57.05, 40.31, 193.60 Bql^{-1}; 82.09, 23.0, 199.4 Bql^{-1}, and 87.65, 38.82 and 215.70 Bql^{-1} respectively. The study further highlighted that the mean vales of absorbed dose in borehole, surface and well water are 58.78, 60.10, and 72.94 nGyh^{-1} respectively; the mean values of total annual effective dose in borehole, surface and well water samples are 0.08, 0.08 and 0.09 respectively; the mean values of radium equivalent activity are in borehole, surface and well water samples are 129.6, 130.4 and 159.8 Bql^{-}1, and the mean value of total cancer risks in borehole, surface and well water samples are 3.18E-06, 3.25E-06 and 3.91E-06 respectively. The study revealed further that the mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K are higher than the recommended safety limits of 10.0, 0.1 and 10,0 Bql^{-1} (UNSCEAR, 2000) respectively; mean values of absorbed dose in surface and well water are higher than their recommended safe limits, while that for borehole water was within the recommended safe limit. The mean values of total annual effective dose and radium equivalent activity in borehole, surface and well water samples are below recommended safety limit while the total lifetime cancer risk in borehole, surface and well water are all below recommended safe limits by (WHO, 2017; UNSCEAR, 2000). Zarma et al. (2024) concluded borehole, surface and well water in the study area are not good for human consumption and recommended regular and periodic radiological monitoring of the water supplies.
Similar research study carried out by Dangari et al. (2025), revealed that the mean activity concentration of the radionuclides: ^{238}U, ^{232}Th and ^{40}K are 2.91, 1.63, and 55.31 Bql^{-1} in spring water; 2.70, 1.63, and 69.12 in borehole water; and 2.82, 1.48 and 66.25 Bql^{-1} I well water. The mean values of absorbed dose and total annual effective dose cancer risk in spring, bore and well water samples are 4.21, 5.11, 4.81nGyhr^{-1}; and 0.00574, 0.00694 and 0.0065 respectively. The mean values of radium equivalent activity and total cancer risk in spring water, borehole and well water s are 8.72, 10.35 and 9.78 Bql^{-1} and 3.22E-09, 3.9E-6 and 3.66E-09 respectively. Dangari et al. (2025) further revealed that the mean activity concentration of the radionuclides in all water supplies in the study area is above the recommended safe limit; the mean values of the absorbed dose, radium equivalent activity, total annual effective dose, and total cancer risk were all lower than the recommended safe limits by (UNSCEAR, 2000; WHO, 2017) across the three sources of water. The study concluded that the water supplies in the study area are good for human consumption, but recommended that the inhabitants should ensure constant or periodic radiological monitoring of the water supplies.

Materials and Methods

Study Area

The study was carried out in Bori metropolis, the Headquarters of Khana Local Government Area, Rivers State. Bori is located in the South-South geopolitical zone as well as in the Niger Delta region, Nigeria, at coordinates 4 40′ 34″ and 7º 21′ 54″. Bori is a city that serves as the administrative and commercial center, as well as the ancient headquarters of the Ogoni people. Bori shares some boundaries with other Ogoni communities, as well as other neigbouring communities outside Ogoni. Towards the North of Bori lies Tai Local Government Area, Andoni and Opobo/Nkoro Local Government Areas lie on the South of Bori, Gokana Local Government Area lies on the east of Bori while Oyibo and Eleme Local Government Areas lie on the West of Bori. Bori is a metropolis, hence the occupation of its residents are civil service and trading, but the occupation of residents of its adjoining communities are basically crop cultivation such as yam, cassava, plantain and vegetables, as well as fishing from nearby rivers and streams. Furthermore, Ogoniland, including Bori, is endowed with abundant and rich natural resources such as crude and natural gas deposits. The activities of multinational companies operating in the area was put to a halt many years ago due to environmental and political issues while the bunkering and illegal oil refining activities are still ongoing, despite the government advocacy and campaign, These activities contributed to series of environmental issues such as

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pollution and contamination of the environmental media (water, air and soil/sediments). The major sources of drinking water in Bori metropolis are mainly borehole water, with a few hand-dug for cooking, bathing and washing.

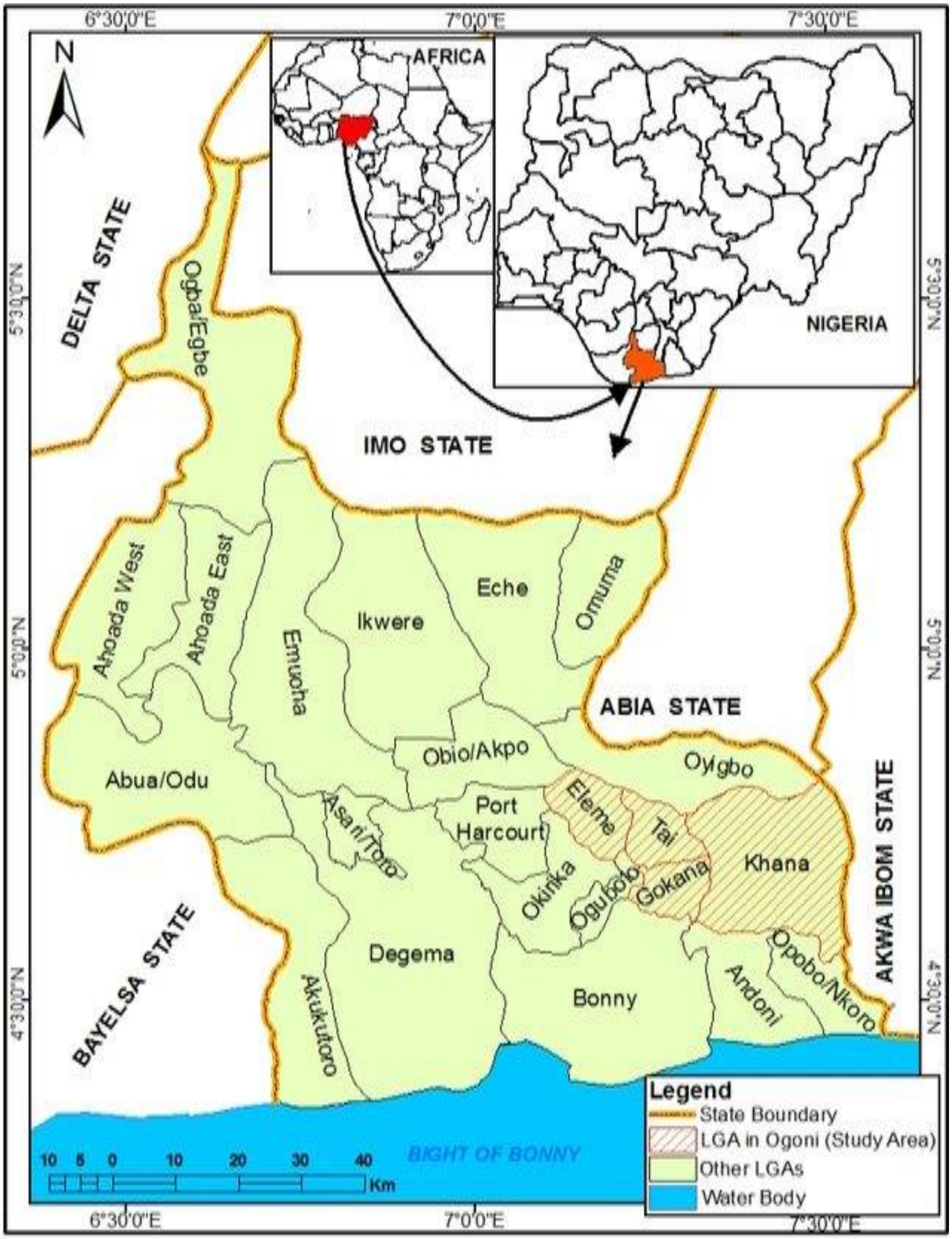

Fig. 3.1: Map of Rivers State showing the Local Government of Study Area

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Materials

The materials used in this study include a sterilized plastic bottle (50 cl), which was used to collect borehole water samples, and a sterilizing agent such as alcohol or bleach, used to sterilize the bottles to avoid been contaminated with other contaminants. Other materials are geographic positioning system (GPS) used to locate the coordinates of the

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sampling points, Cesium 137 or Cobalt-60 used to calibrate radiation detection instrument, a pair of hand gloves, safety goggles, and laboratory coat used as personal protective instruments against any hazardous substances, filter papers to remove suspended particulate matter in the borehole water samples prior to analysis, data sheet and logbooks were used to record the co-ordinates of sampling locations, instrument calibration and other details; cello tape used to label the sample containers against their respective sampling points, and Sodium Iodide (NaI) gamma-ray spectrometer used to analyze the water samples with a view to revealing the radionuclides present in the borehole water samples.

Methods

Twenty sterilized plastic bottles were washed thoroughly with the aid of detergents. The bottles were thereafter rinsed about three times with the use of distilled water. At each sampling point, the borehole water sample was used to rinse the plastic bottle before collection into the container. Each sample container was labeled against the sample location, and ice cooled at a temperature of about 4^{o}C before been transported to the Centre for Energy Research and Development (CERD) Laboratory, Obafemi Awolowo University (OAU), Ile-Ife, Osun State, for analysis. The samples were allowed for a minimum of 28 days before analysis. A computer program connected to the gamma-ray detector helped to determine the activity concentration or the number of radionuclides in the borehole water samples after subtracting the decay corrections.

Radiological Hazard Parameters

The knowledge of radiological hazard parameters in a given water sample helps to determine the potential health risks in humans as a result of the presence of some radioisotopes (^{40}K, ^{232}Th, ^{222}Ra, ^{226}Ra, ^{232}U or ^{238}U) and their daughter products, in water sample. Some of the common indices used in radiological studies include:

Activity Concentration

The activity concentration, measured in Bql^{-1}, is a quantity that measures the amount of radioactive decay that is present in any given volume of water sample. It was obtained using eq. (1): (Avwiri et al., 2014; Igbudu et al., 2023):

$$A_c.Conc = \frac{N_a}{P_\gamma (M_S/V) E_\gamma\, T_c} \qquad (1)$$

where**:**

$A_c.Conc =$ Activity Concentration; $N_a =$ Net peak area of a peak at energy; $E_\gamma =$ Efficiency of the detector for a γ-energy of interest; $V =$ Volume of water sample; $T_c =$ Total counting time; and $P_\gamma =$ Abundance of the γ-line in a radionuclide.

Annual Effective Dose (E)

Absorbed Dose (A_D)

This refers to the amount of ionizing radiation energy that is deposited in human tissues, and evaluates the potential biological effect caused to the human organs. It is measured in nGyh^{-1}, was estimated using Eq. (2): Eke & Emelue, 2019; Mbonu & Ben, 2021; Samaila & Tampul, 2021):

$$\mathbf{A_D} = 0.462\, A_C(U) + 0.604\, A_C(Th) + 0.0417\, A_C(K) \qquad (2)$$

where: A_C(U), A_C(Th), and A_C(K) are respective activity concentrations of 232-U, 232-Th, and 40-K, and the values: 0.462, 0.604, and 0.0417 are respective conversion factor for 232-U, 232-Th, and 40-K.

Annual Effective Dose Equivalent (AEDE)

This is a measure of the total dose of radiation from all radiation exposure pathways via ingestion of borehole water samples into the body for a period of one year. The annual effective dose equivalent, measured in milli-Sievert per year, was determined using eq. (3): Sowole & Egunjobi, 2019):

$$\text{AEDE} = A_D \times 8760\ \text{hr} \times 0.2 \times 0.7\ (\text{Sv/Gy}) \times 10^{-6} \qquad (3)$$

where**:** A_D = Absorbed dose(nGyh^{-1}); $8760 =$ Total hour per year; 0.7 = Dose conversion factor (Sv/Gy); and $0.2 =$ Occupancy factor for outdoor measurement.

Annual Gonad Dose Equivalent (AGDE)

This is a measure of total doses of radiation in which a human's gonad cell such as testes or ovaries absorbs over a period of one year. This is very important as it helps to protect reproductive health population genetics. The value of annual gonad dose equivalent is estimated using eq. (4): (Darko et al., 2011; Eke & Emelue, 2019):

$$AGDE = 3.09\, A_c(U) + 4.18\, A_c(Th) + 0.314\, A_c(K) \qquad (4)$$

where: $A_c(U)$, $A_c(Th)$, and $A_c(K)$ represent activity concentration of the radioisotopes: ^{232}U, ^{232}Th and ^{40}K respectively while 3.09; 4.18 and 0.314 are their respective conversion factor.

Radium Equivalent (Raeq)

This is a radiological hazard used to represent the sum total of radioactivity due to the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in any given material based on their relative gamma-ray hazards. It can be estimated using eq. (5): (Avwiri et al., 2014; Eke & Emelue, 2019):

$Raeq \quad A_c(U) + 1.43\, A_c(Th) + 0.077\, A_c(K)$ (5)

where: $A_c(U)$, $A_c(Th)$, and $A_c(K)$ represent activity concentration of the radioelements: 232-U, 232-Th and 40-K respectively.

External Hazard Index (H_{ext}):

The external hazard index (H_{ex}) is a measure of the level of radiological risk of the samples to the immediate environment. The external hazard was estimated using eq. (6): (Darko et al., 2011):

$H_{ex} = [0.00270\, A_c(U) + 0.00386\, A_c(Th) + 0.0002079\, A_c(K)] \leq 1$ (6)

Internal Hazard Index (H_{int}):

The internal hazard index was estimated using eq. (7): (El-Afifi & Awwad, 2005; Darko et al., 2011), and its value must be less than unity:

$H_{in} = [0.00540\, A_c(U) + 0.00386\, A_c(Th) + 0.0002079\, A_c(K)] \leq 1$ (7)

Representative Gamma Index (Iγ):

This is a measure of gamma radiation hazard associated with the natural radionuclide in any given investigated under investigation. It helps to identify materials of potential health concern when used in public places. The representative gamma index is given by eq. (8): (Avwiri et al., 2012):

Iγ = $[0.00666\, A_c(U) + 0.01\, A_c(Th) + 0.00066\, A_c(K)] \leq 1$ (8)

Excess Lifetime Cancer Risk

This measures the tendency or probability of individual to develop cancer in a lifetime because of specific exposure above the cancer risk the individual would initially have due to exposure from other causes. It is estimated from Eq. (9): (Sowole & Egunjobi, 2019):

ELCR = AEDE × LE × RF (9)

where: $AEDE =$ Annual effective dose equivalent; $LE =$ Life expectancy of approximately 70 years; $RF =$ Risk factor per Sievert (Sv^{-1}), approximately 0.05 for stochastic effect for general public.

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Results

Table 1 represents the sample locations and the corresponding coordinates, activity concentration of radioisotopes as well as the pH of the borehole water samples. Table 2 represents the estimated radiological hazards. Figures 1, 2 and 3 represent the activity concentration of ^{40}K, ^{232}Th and ^{238}U respectively across the sample locations while Fig. 4 represents a pie chart of mean activity concentration of the radionuclides, and Fig. 5 represents the mean estimated radiological hazard indices in the borehole water and the WAV.

Table 1: Activity concentration of radionuclides ^{40}K, ^{232}Th and ^{238}U in Borehole Water in Bori Metropolis, Rivers State.

Sample Locations	Sample Code	Location		Activity Concentration (Bql^{-1})			
		Latitude	Longitude	^{40}K	^{232}Th	^{238}U	pH
Engr. Campus	B1	4^0 40′19.34″	7^0 22′ 9.62″	67.62 ± 6.08	1.71 ± 0.06	5.68 ± 2.18	8. 35
Management Campus	B2	4^0 40′ 10.49″	7^0 22′19.49″	133.27±5.18	2.89 ± 0.01	4.07 ± 0.81	8. 40
Poly Road	B3	$4^0$40′10.83″	7^0 22′ 16.04″	97.21 ± 6.11	4.29 ± 1.10	6.64 ± 1.80	8. 20
T.T.C Road	B4	4^0 41′24.55″	7^0 22′ 15.82″	109.15 ± 9.12	1.47 ± 0.13	4.11 ± 1.18	7. 75
St. Joseph Church Bori	B5	4^0 40′ 8.54″	7^0 22′ 16.05″	149.72 ± 8.18	1.55 ± 0.28	3.51 ± 0.08	8. 00
Prince Layout	B6	4^0 40′ 11.21″	7^0 22′ 14.63″	112.83 ± 7.03	1.15 ± 0.22	2.65 ± 1.12	6. 95
Nkpee Strret	B7	4^0 40′ 5.89″	7^0 22′ 6.48″	101.22 ± 7.03	3.15 ± 0.22	4.34 ± 0.01	6. 90
Abanee Strret	B8	4^0 40′ 8.10″	7^0 22′ 0.37″	99.99 ± 8.81	1.56 ± 0.24	7.16 ± 1.80	6. 60
Monokpo Street	B9	4^0 40′ 1.92″	7^0 21′ 56.12″	113.86 ± 8.28	1.76 ± 0.58	7.18 ± 1.68	7. 25
Keenpoly Campus	B10	4^0 40′ 0.94 ″	7^0 21′ 56.51″	210.50 ± 10.12	2.06 ± 0.27	6.59 ± 1.14	6. 55
Boue/Kaa Road	B11	4^0 40′ 1.47 ″	7^0 21′ 49.55″	214.67 ± 4.45	1.19 ± 0.12	9.54 ± 0.98	7. 4
Ka-Bori	B12	4^0 40′10.10″	7^0 22′ 12.66″	139.75 ± 8.15	3.23 ± 1.38	3.41 ± 0.03	6. 9
Gokana Street	B13	$4^0$40′ 25.43″	7^0 21′ 51.32″	176.14 ± 6.66	1.72 ± 0.18	5.02 ± 0.58	6. 1
Boue Road	B14	$4^0$40′ 23.72″	7^0 21′ 52.93″	131.98 ± 6.12	2.81 ± 0.01	4.69 ± 1.11	6. 3
Mayor Street	B15	$4^0$40′ 26.75″	7^0 22′ 3. 50″	150.59 ± 8.58	1.23 ± 0.21	4.13 ± 0.88	5. 9
Mayor/Poly Road	B16	4^0 40′26.32″	7^0 22′ 7. 02″	126.58 ± 8.23	1.23 ± 0.90	5.73 ± 1.06	7. 3
Kenule Street	B17	4^0 40′28.45″	7^0 22′ 9. 66″	119.78 ± 7.08	2.17 ± 0.11	7.68 ± 0.03	7. 5
Prince Igbara Street	B18	4^0 40′13.04″	7^0 22′ 12.68″	187.65 ± 8.78	3.16 ± 0.60	7.16 ± 0.30	6. 8
Maakoro Street	B19	4^0 40′ 2.52 ″	7^0 22′ 6. 32″	117.93 ± 10.10	2.31 ± 0.44	5.29 ± 0.22	6. 8
Bank Road	B20	4^0 40′10.23″	$7^0$21′ 0. 96″	182.84 ± 9.98	2.13 ± 0.78	7.62 ± 1.161	6. 8
Min.				$\mathbf{67.62 \pm 6.08}$	$\mathbf{1.15 \pm 6.08}$	$\mathbf{2.65 \pm 1.12}$	
Max				$\mathbf{214.67 \pm 4.45}$	$\mathbf{4.29 \pm 1.10}$	$\mathbf{9.54 \pm 0.98}$	
Mean				$\mathbf{137.16 \pm 7.636}$	$\mathbf{2.14 \pm 0.415}$	$\mathbf{5.61 \pm 0.91}$	
WAV				**10**	**0.1**	**10**	

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Table 2: Estimated Radiological Hazard Due to Ingestion of Radionuclides (^{40}K, ^{232}Th and ^{238}U) in Borehole Water in Bori Metropolis, Rivers State

Sample Code	D ($nGyh^{-1}$)	AEDE ($mSvy^{-1}$)	AGDE (Bql^{-1})	Raeq (Bql^{-1})	H_{ex} ($mSvy^{-1}$)	H_{in} ($mSvy^{-1}$)	I_{γ} ($mSvy^{-1}$)	ELCR (E-3)
B1	6.481	7.947	45.932	1.333	0.036	0.051	0.100	27.814
B2	9.182	11.258	66.503	1.846	0.050	0.061	0.145	39.403
B3	9.711	11.908	68.974	2.026	0.055	0.073	0.152	41.678
B4	7.343	9.001	53.118	1.462	0.039	0.051	0.115	31.503
B5	8.801	10.792	64.337	1.725	0.046	0.055	0.117	37.772
B6	6.624	8.118	48.424	1.333	0.035	0.042	0.104	28.413
B7	8.133	9.970	58.361	1.664	0.045	0.057	0.128	34.895
B8	8.421	10.326	60.042	1.709	0.046	0.065	0.130	36.141
B9	9.132	11.197	65.295	1.846	0.050	0.070	0.141	39.189
B10	13.071	16.029	95.071	2.574	0.069	0.087	0.204	56.101
B11	14.081	17.267	101.859	2.777	0.075	0.101	0.218	60.434
B12	9.353	11.466	67.919	1.879	0.050	0.060	0.148	40.131
B13	10.701	13.122	78.009	2.104	0.051	0.064	0.147	45.927
B14	9.374	11.491	67.679	1.887	0.047	0.062	0.135	40.218
B15	8.934	10.951	65.188	1.748	0.054	0.059	0.153	38.328
B16	8.672	10.632	62.593	1.723	0.071	0.090	0.204	37.212
B17	9.851	12.080	70.413	2.001	0.048	0.062	0.137	42.281
B18	13.042	15.992	94.255	2.613	0.067	0.087	0.194	55.972
B19	8.762	10.743	63.032	1.767	0.047	0.058	0.140	37.600
B20	12.431	15.244	89.861	2.474	0.057	0.076	0.168	53.354
Min.	**6.481**	**7.947**	**45.932**	**1.333**	**0.035**	**0.042**	**0.100**	**27.814**
Max	**14.081**	**17.267**	**101.859**	**2.777**	**0.075**	**0.101**	**0.218**	**60.434**
Mean	**9.605**	**11.777**	**69.343**	**1.925**	**0.052**	**0.067**	**0.149**	**41.218**
SD	**2.098**	**2.574**	**15.304**	**0.407**	**0.011**	**0.015**	**0.033**	**9.009**
WAV	**1.0**	**0.1**	**1.0**	**37.0**	**≤ 1**	**≤ 1**	**≤ 1**	**0.29**

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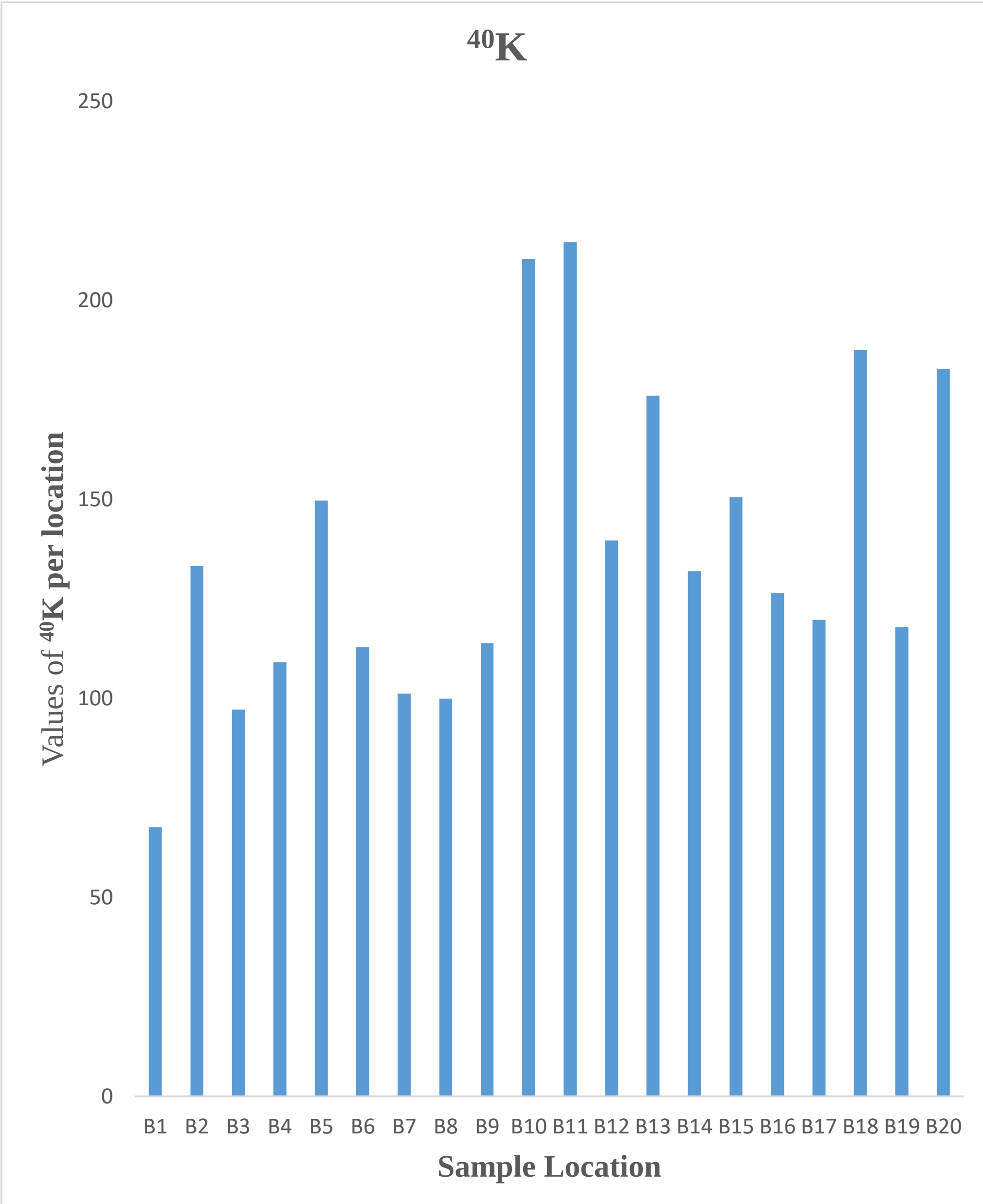

Fig. 1: Activity Concentration (^{40}K) in the Borehole Water Across the Sample Locations

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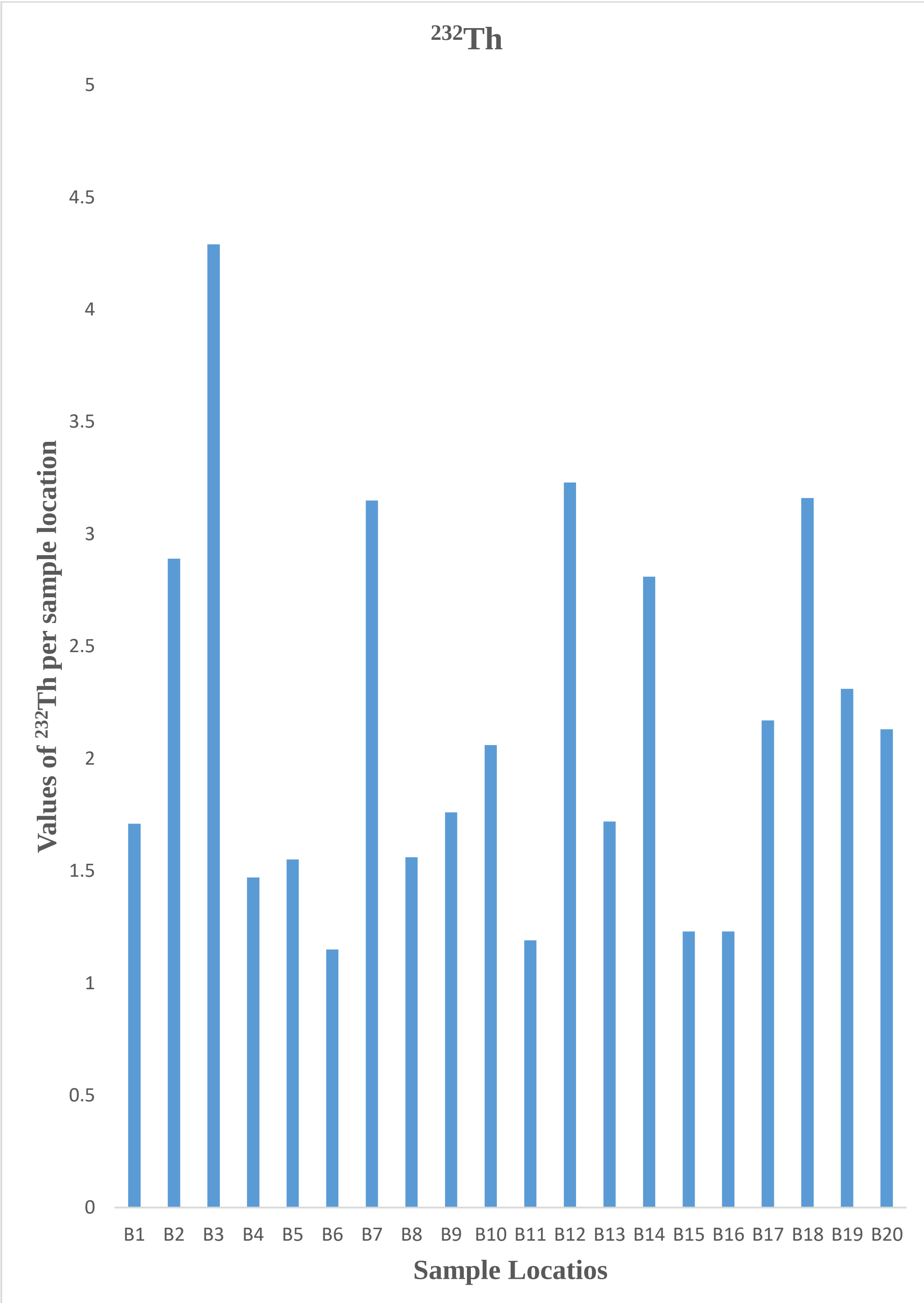

Fig. 2: Activity Concentration (^{232}Th) in the Borehole Water Across the Sample Locations

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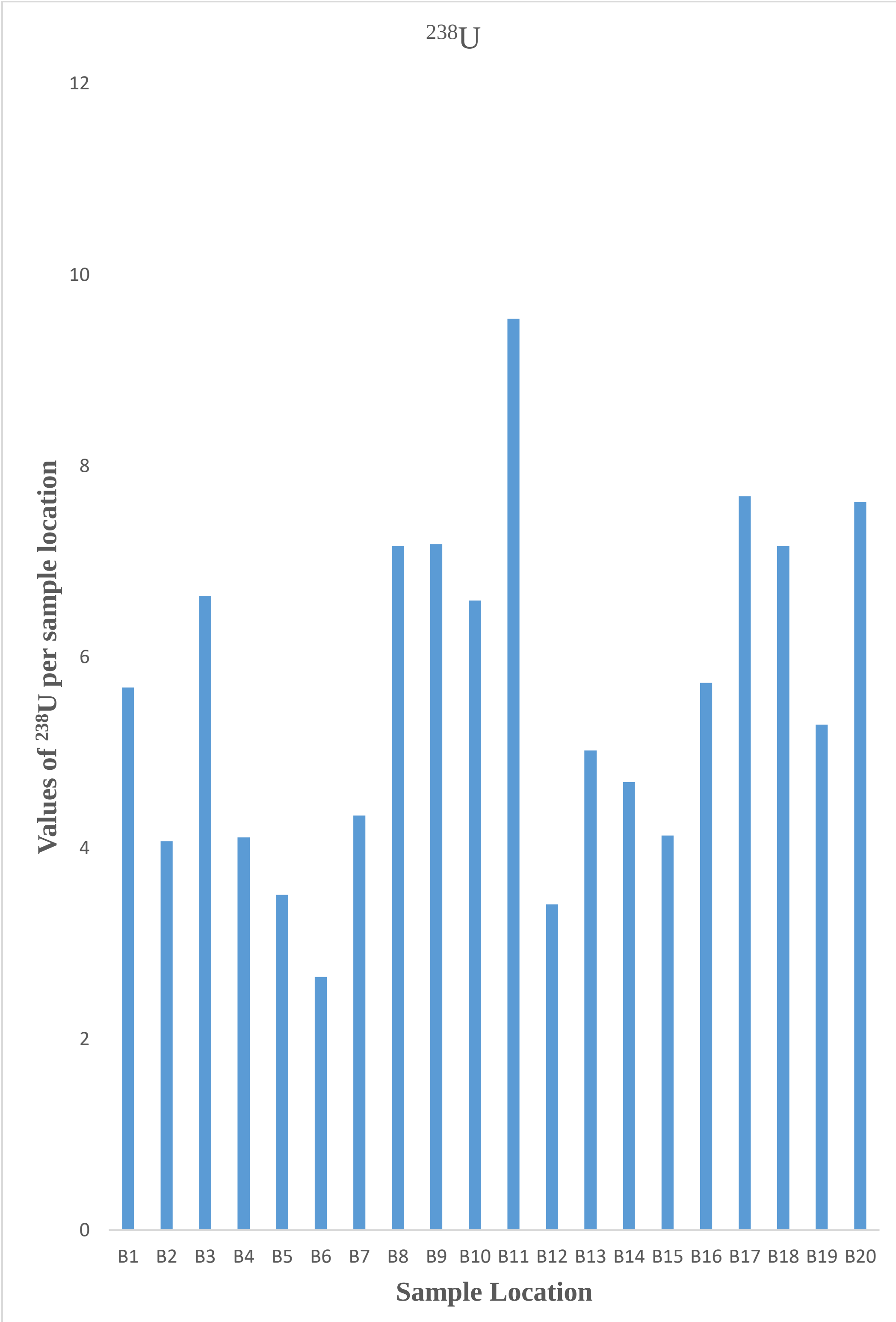

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Fig. 3: Activity Concentration (^{238}U) in the Borehole Water Across the Sample Locations

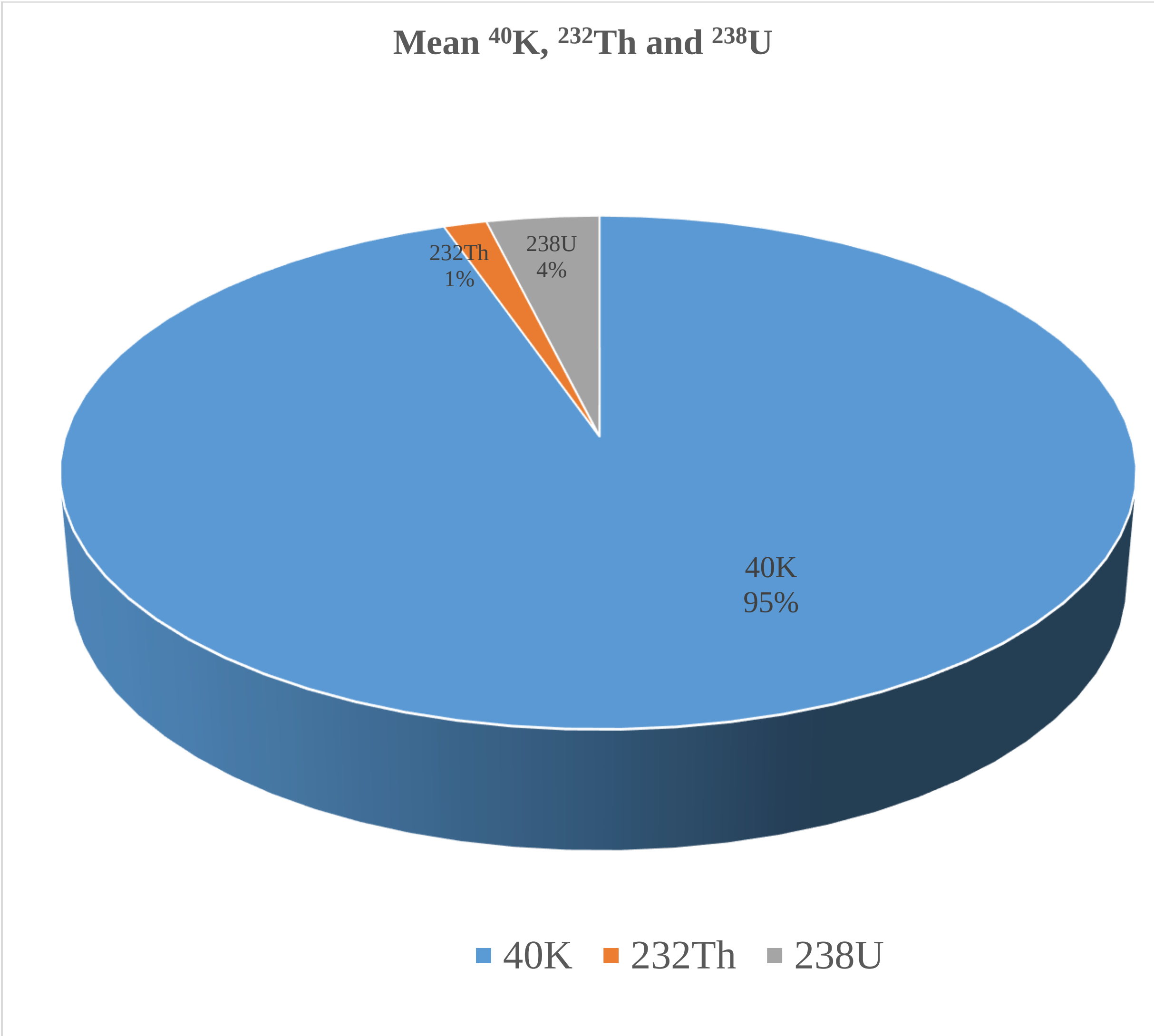

Fig. 4: Mean Values of Activity Concentration of 40K, 232-Th and 238-U

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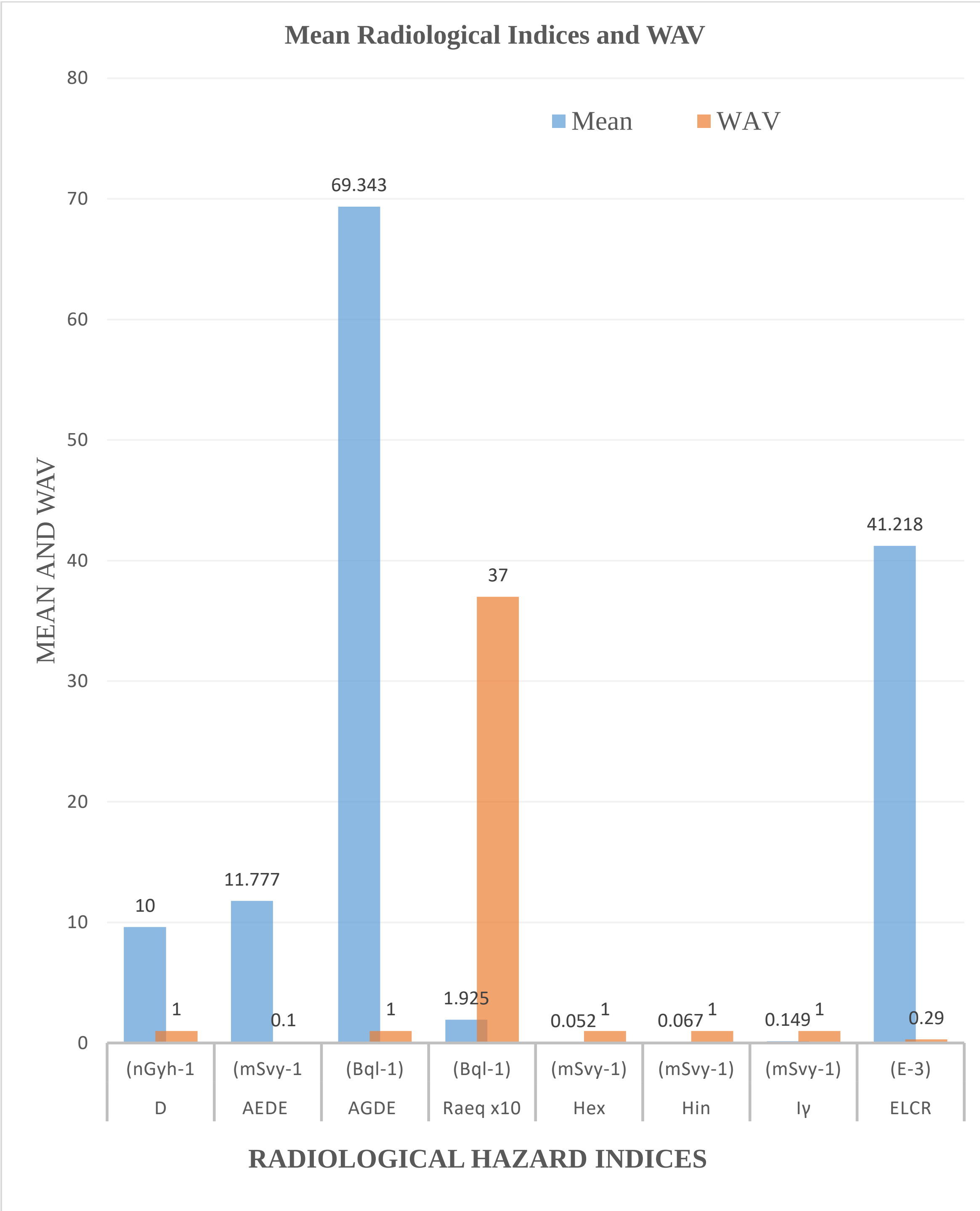

Fig. 5: Mean Radiological Hazard Indices and the WAV

Discussion

This study focuses on the determination of radiological hazard indices associated with intake of borehole water collected from Bori metropolis. The radioisotopes ^{40}K, ^{232}Th and ^{238}U present in the borehole water were detected with the aid of NaI gamma-ray spectrometer.

Activity Concentration

The results (Table 1) revealed that average values of activity concentration of the radioelements: ^{40}K, ^{232}Th, and ^{238}U are 137.16±7.636, 2.14±0.415, and 5.61±0.91 Bql^{-1} respectively. The lowest value of activity concentration of ^{40}K (67. 62±6.08 Bql^{-1}) occurred in sample location B1, while the lowest values of ^{232}Th (1.15±0.22 Bql^{-1}) and ^{238}U (2.65±1.12 Bql^{-1}) were both recorded in location B6. The highest values of ^{40}K (214.67±4.45Bql^{-1}), ^{232}Th (4.29±1.10 Bql^{-1}) and ^{238}U (9.54±0.98 Bql^{-1}) were recorded in B11, B3, and B11 respectively. Results in Table 2 and Fig. 4 indicated that the average activity concentration of ^{40}K and ^{232}Th exceeded their world average values of 10.0 and 0.1 Bql^{-1} respectively while that of ^{238}U was within the WAV (10 Bql^{-1}) (UNSCEAR, 2000). The findings in this study revealed that the mean activity concentration of ^{40}K (67. 62±6.08 Bql^{-1}) was found to be higher than: 25.90 Bql^{-1} recorded in Ononugbo & Ndodo (2019); 55.30 Bql^{-1} recorded in Aman et al. (2022); 12.31 Bql^{-1} (surface water) and 4.90 Bql^{-1} (underground water) in Agaja & Ajisafe (2013); 29.68 Bql^{-1} recorded in Okoro et al. (2022), 71.51 Bql^{-1} recorded in Igbudu et al. (2025); and 55.31 Bql^{-1} recorded in Dangari et al. (2025), but lower than 196.6 recorded in Zarma et al. (2025). Conversely, the mean activity concentration of ^{232}Th (2.14) in this study was found to be lower than 18.50 Bql^{-1} recorded in Ononugbo & Ndodo (2019); 79.76 Bql^{-1} recorded in Aman et al. (2022); 3.1±0.4 Bql^{-1} recorded in Agaja & Ajisafe (2013); 3.61 Bql^{-1} recorded in Okoro et al. (2022); 9.67 Bql^{-1} recorded in Igbudu et al. (2025); 40.31 Bql^{-1} recorded in Zarma et al. (2025), but higher than 1.63 Bql^{-1} recorded in Dangari et al. (2025), The results further indicated that the borehole water in Bori metropolis are not suitable for drinking since they contained some radiological substances which are harmful and damaging to human health.

Absorbed Dose

The results in Table 2 indicated that the values of absorbed dose ranged from 6.481 to 14.081 $nGyh^{-1}$, and average value of absorbed dose was found to be 9.605 $nGyh^{-1}$. This value far exceeded the world average value of 1.0 $nGyh^{-1}$ (UNSCEAR, 2000). This result revealed that the borehole water is not good for drinking because of the harmful radiological substance found in it. This radiological substance has the ability to cause disease like cancer of the brain, tumur, pancreas (Ononugbo & Anyalebechi, 2017).

Annual Effective Dose Equivalent (AEDE)

The value annual effective dose equivalent ranged from 7.947 to 17.267 $mSvyr^{-1}$, with a mean value of 11.777 $mSvyr^{-1}$. The comparison between the mean AEDE and the WAV in Fig. 5 revealed that the mean annual effective dose equivalent was higher than the reference limit of 0.1 $mSvy^{-1}$ (UNSCEAR, 2000). This finding agreed with the 10.96 $mSvy^{-1}$ value obtained in Igbudu et al. (2025). The results further indicated that the water is not safe for drinking because it contained some radiological hazards that can damage some human cells of it consumers.

Annual Gonad Dose Equivalent (AGDE)

The results (Table 2) revealed that minimum value of AGDE was 45.93 Bql^{-1}, obtained in the Engineering Campus of Ken Saro-Wiwa Polytechnic, Bori, while the maximum value (101.86 Bql^{-1}) was recorded in a borehole water located along Boue/Kaa road. Results further indicated that the mean AGDE was 69.34 Bql^{-1}. A comparison of mean AGDE and WAV revealed that the later was found to be 98.56 percent higher than the internationally recommended safety limit of 1.0 $mSvy^{-1}$. This result agrees with the studies conducted by Aman et al. (2022) and Igbudu et al. (2025), which recorded high mean value of AGDE above the WAV (UNSCEAR, 2000). The results also showed that the borehole water poses serious danger to the inhabitants of the study area.

Radium Equivalent (Raeq)

Results (Table 2) showed that the lowest value of radium equivalent (13.33 Bql^{-1}) was recorded in Engineering Campus as well as in Prince layout, Bori, while its highest value (27.77 Bql^{-1}) was obtained along Boue/Kaa road. The results further indicated that mean radium equivalent value was found to be 19.25 Bql^{-1}. The mean radiological hazards (Fig. 5), indicated that the world average value of radium equivalent (370 Bql^{-1}) was higher than its value in this study. The results implied that the radium equivalent is this study was within permissible limit, but there might be the tendency of it increasing over time, if not properly treatment. This finding agreed with Aman et al. (2022), Agaja & Ajisafe (2013), Okoro et al. (2025), and Igbudu et al. (2025) with values of radium equivalent lower than internationally recommended safe limit.

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External Hazard Index (H_{ex})
The value external hazard index ranged from 0.035 mSvy^{-1} to 0.075 mSvy^{-1}, with a mean value of 0.052 mSvy^{-1} (Table 2). Figure 5 indicated that external hazard index in this study is within safe limit (≤1), and the water is less harmful. This result agreed with the study by Aman et al. (2022).
Internal Hazard Index (H_{in})
Results (Table 2) indicated that the lowest and highest values of internal hazard index (0.042 mSvy^{-1} and 0.101 mSvy^{-1}) were obtained in B6 and B11 respectively, with a mean value of 0.067 mSvy^{-1}. Results indicated that mean value of internal hazard index is within permissible limit of ≤1 mSvy^{-1}. Based on this radiological index, the bore hole water is safe and less harmful to consumers. However, there might the tendency of increased internal hazard index due to prolonged use of borehole water without adequate treatment.
Representative Gamma Index (Iγ)

Results (Table 2) indicated that the value of representative gamma index ranged from 0.100 mSvy^{-1} to 0.218 mSvy^{-1}, with mean value of 0.149 mSvy^{-1}. This mean value was found to be within permissible limit of ≤1.0 mSvy^{-1}. Again, based on this radiological hazard index, the borehole water is safe for human consumption.
Excess Lifetime Cancer Risk.
The minimum and maximum values of ELCR were found to be 27.814 E-3 and 60.43 E-3 respectively (Table 2). Results (Fig. 5) revealed that mean ELCR exceeded the world reference value of 0.29 E-3 (UNSCEAR, 2000). The finding agreed with Irunkwor et al. (2022), Okoro et al. (2025), and Igbudu et al. (2025), with mean values of ELCR higher than the WAV. However, the study disagreed with Aman et al. (2022) with a mean value of ELCR within permissible limit.
Conclusion
This study focused on radiological assessment of some selected borehole water in Bori metropolis, Rivers State, Nigeria. Borehole water samples were collected from some randomly selected locations within the metropolis, treated and analyzed in the laboratory using Sodium Iodide (NaI) spectrometer. The values of the activity concentration obtained with the aid of NaI were used to estimate the radiological hazard indices using appropriate mathematical relations.
Results revealed that mean activity concentration of 40-K and 232-Th exceeded their reference limits of 10.0 and 0.1 Bql^{-1} respectively, while that of 238-U was within permissible limit of 10.0 Bql^{-1}. Mean absorbed dose, AEDE, AGDE, and ELCR exceeded their individual reference limits of 1.0 nGyh^{-1}, 0.1 mSvy^{-1}, 1.0 Bql^{-1}, and 0.29 E-3 respectively (UNSCEAR, 2000). Mean Raeq, H_{ex}, H_{int}, and I**γ** were found to be within the internationally recommended safety limits of 370 Bql^{-1}, ≤1.0 mSvy^{-1}, ≤1.0 mSvy^{-1} and ≤1.0 mSvy^{-1} respectively. The findings revealed that the selected borehole water supplies are not suitable for drinking. This is because the they contained some radiological substances which are likely to cause harm to human beings who depend on them for domestic purposes. Such health effects include cataracts and damage to internal organ (Ononugbo et al., 2013), anaemia, leucopoenia as well as kidney and lung diseases (Aliyu et al., 2015; Jegede et al., 2017).

Recommendations
1. There should be regular or periodic radiological monitoring of borehole water supplies within the study area to ascertain changes in the concentration of radioisotopes.
2. There should be community-based health awareness advocacy and enlightenment campaigns for the inhabitants of the study area to educate on the potential health effects associated with intake of borehole water containing radiological substances.
3. Further research work should be carried out on borehole water in other locations not captured in this study, as well as on other sources of underground water supplies.

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