

Soil radioactivity and radiotoxic risks of uranium in drinking water. A case study of Jos Plateau, Nigeria

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Abstract

Protection and assessment of any radiation pollution resulting from the use and disposal of radioactive materials to the large extent depend on the knowledge of natural radioactivity level of an environment. This work determined the activity concentration of terrestrial radionuclides ²²⁶Ra, ²³²Th and ⁴⁰K in top soil samples of Jos Plateau using high resolution HPGe detector. Inductive Coupled Plasma (ICP) Mass Spectrometer was used to determine the chemical concentrations of uranium (²³⁸U) in drinking water samples collected from the area. The activity concentration of ²²⁶Ra varied between 34±1 and 1006±18 Bq/kg, 67±2 and 1695±37 Bq kg⁻¹ for ²³²Th and between 67±4 and 2465±45 Bq/kg for ⁴⁰K. Chemical concentration of ²³⁸U in water samples was found to vary from 1.4 to 35 µg/ L. The values of radiological risks due to radioactivity and chemical risks of mortality and morbidity due concentration of ²³⁸U in drinking water were estimated. The risk values for some samples are found to be within safe limits provided by health and environmental protection agencies (ICRP, WHO and USEPA). The radiometric data could be useful for geochemical exploration and diagnosis and prognosis of uranium persuaded diseases for the local inhabitants in the study area.

Keywords: Soil; Radioactivity; Uranium; Radiotoxic risk; ICP-Mass spectroscopy

1. Introduction

Living organisms are always expose to a substantial amount of gamma radiation dose as much as 1 Sv due to natural radioactivity mainly from terrestrial sources [1]. Natural radioactivity in the environment comes from two sources; namely the terrestrial sources from the decay series of primordial radionuclides ²³⁸U and ²³²Th and the non-decay series of ⁴⁰K; and that of extra-terrestrial (cosmic) sources [2]. The former are distributed in varying concentration in all types of soils, rocks,

plants, sand and water which are significantly influenced by local geology, rainfall and a geographical conditions of a particular region [3-4]. It has been reported that granitic type of igneous rock contains substantial amount of radioactive materials such as Thorite, Monazite and trace amounts of Xenotime and rutile compared to limestone, gypsum and chalk which are of sedimentary origin [5].

Drinking water contains natural radionuclides such as uranium in dissolved form as a result of water passing through and over rocks formations [6] and interaction at water –aquifer bearing rocks interface. Chemical and radiological concentrations of uranium in groundwater are therefore determine by the bedrock formation hosting the aquifer. Uranium and its daughter products are important contributors to natural environmental radiation exposure. Since ingestion is a major path way for internal irradiation, apart from inhalation of radon, measurement of radioactivity in drinking water is very much relevant in assessing the contribution of these radionuclides to environmental radiation hazards. Thus, the concentration of radionuclides in drinking water of an area is a function of the Th and U contents in the aquifer, the geochemical properties of the aquifer solids, and the half-lives of each isotope [7]. Uranium enters groundwater by dissolution of aquifer solids, by direct recoil across the liquid-solid boundary during its formation by radioactive decay of its parent in the solid and by desorption [7]. For surface water, the uranium content is usually very low and standard water treatment methods are known to remove ^{238}U . When humans ingest uranium, about 20% is absorbed into the bloodstream which is initially distributed to soft tissues and bone, but its retention is mainly in growing bone [8-9]

Worldwide increase in energy demand and technological advancements have led to the use, transportation and disposal of radioactive materials. The risk of abuse and accidents are also high, consequently our natural environment is becoming more vulnerable to radioactive pollution by radioactive sources due to these practices. Moreover, safe and clean drinking water is one of the seventeen sustainable development goals (SGDs) to achieve by the United Nation (UN) as its new international agenda to transform the world and promote development [10]. Specially, for most of Nigerian environment, the level of natural radioactivity have not been established, and effort has not been made to carry out an extensive measurement program to cover the entire country [1]. Furthermore, clean water for drinking and domestic uses has become a challenging task to achieve and probably could be seen as luxury.

To establish reference data and for assessing the extent of possible environmental pollutions by the above mentioned practices, basic natural radiometric data in soil and drinking water must be known. As an effort to address this issues, this study aimed to determine the natural environmental radioactivity levels in soil and to evaluate the chemical and radiological quality of drinking water in Jos plateau, Nigeria.

2. Materials and methods

2.1 The Study Area

The study area is regionally located on Jos Plateau in the north central part of Nigeria between the latitudes of $8^{\circ}30'$ - $10^{\circ}24'$ north of the equator and longitudes of $9^{\circ}20'$ - $9^{\circ}30'$ of Greenwich meridian and covers nine local government areas (LGAs) of Plateau state. It has a total land mass area of $15,038 \text{ km}^2$ and a population of 1,933, 505[11].

2.2 The geology of the area

The area is made of eight geological types classified under three geological groups namely; the basement complex, younger granites and volcanic rocks as executively studied by Falconer [12]. About 50% of Jos Plateau is underlain by basement complexes such as migmatite-gneiss-quartzite, in some places the basement complex is intruded by Precambrian to the late Paleozoic Pan-African granite (Older Granite), diorite, charnockite. Intrusions of younger granites is also associated with the basement complex. Volcanic rocks such as basalts and rhyolites are found to overlie or cut across the younger granites formation as well as the basement complex. The volcanic rocks have been believed to be formed during the Tertiary period (Older basalts) and Quaternary period (Newer basalts) [13]. Table 1 gives the names of the geological formations in the study area while Figure 1 gives the digitalised map of the formations.

Table 1: Types of geological formations in the study area

Geology code	Type of formation
G1	Basement complex
G2	Biotite
G3	Older granite
G4	Rhyolite
G5	Older basalts
G6	New basalts
G7	Sandstone, clay and shale
G8	Younger granites

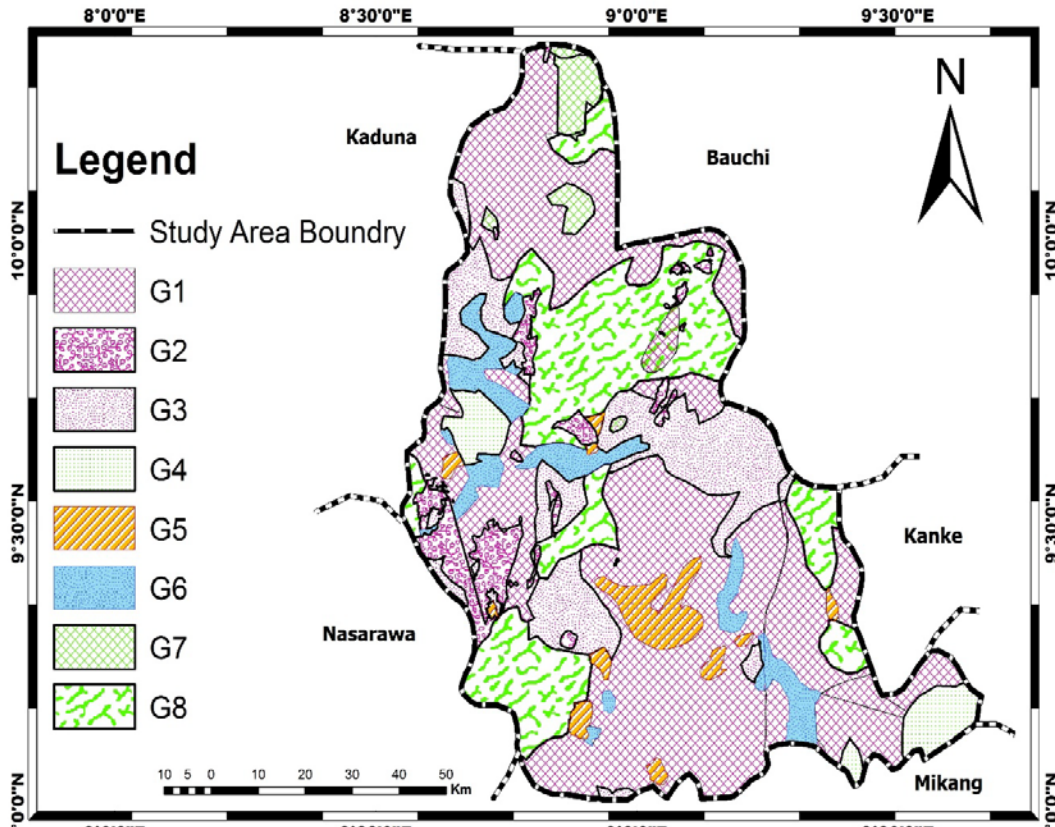


Fig. 1: Geological formations of the study area

2.3 Soil sampling and preparation

A total of 102 soil samples were collected across the geological formations and away from public structures to avoid contribution from non-natural sources using soil sampler at a depth of 10 cm. Each sample was sealed in a sampling polyethylene bag, firmly tied and properly labelled to avoid cross contamination of samples; and stored for further processing. Sampling points were recoded with GPS device as shown in Figure 2. In the laboratory, samples were cleared off stones, weeds, organic matter and other debris, then oven dried at 105 °C to a constant weight before grinding. They were later crushed to fine powder and packed into cylindrical containers of uniform size which suited the optimal soil mass of 350 g for the spectrometric analysis of bulk soil samples [14]. These containers were sealed and stored for 30 days, which allow radium and its short-lived daughters to reach secular equilibrium before the analysis. The geometry and configuration were maintained throughout the analysis. Identical containers were also used to pack IAEA reference materials (RGK-1, RGTh-1, and RGU-1) sealed and stored as previously.

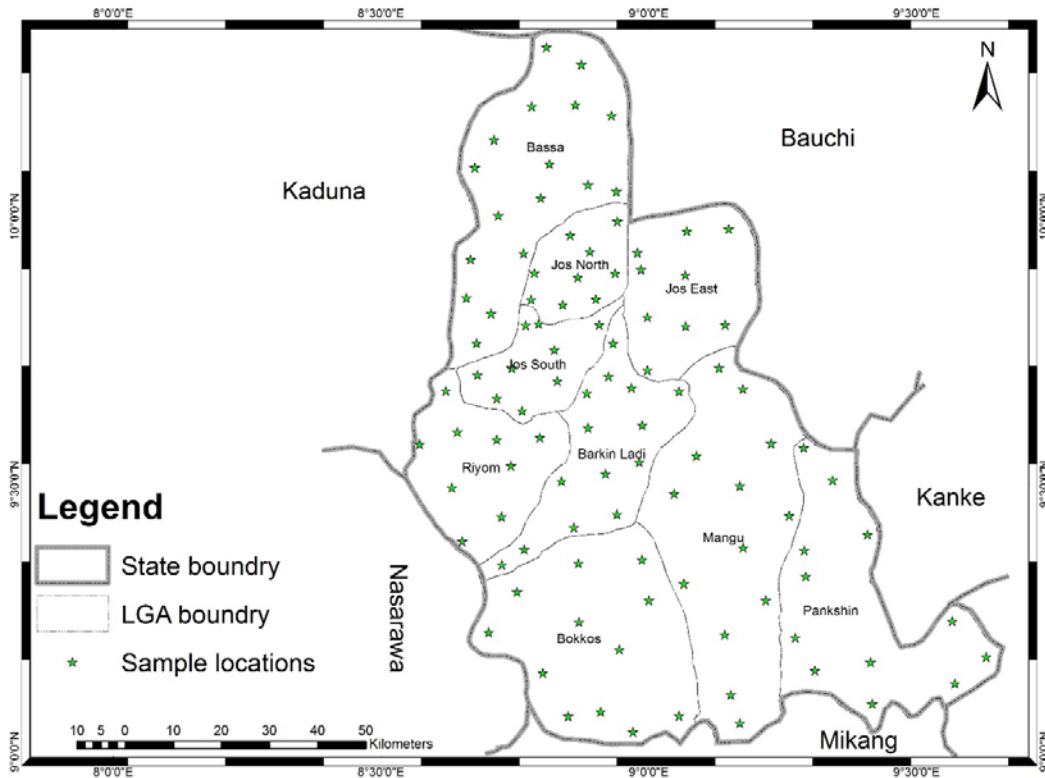


Fig. 2: Soil sampling locations

2.4 Gamma spectrometry analysis

Gamma spectrometry was employed for the measurement of the soil samples. Each sample was counted for 21, 600 s (6 hrs) using a counting system consisting of coaxial high purity germanium (HPGe) detector. The detector has a resolution of 1.8 keV and 20% efficiency at 1333 keV of ⁶⁰Co which is capable enough of distinguishing the gamma ray energies of the radionuclides of interest. The measured photo peaks were acquired and analysed using Genie 2000 (VI.3) software manufactured by Canberra. Point sources were used for energy calibration whereas a mixed source was used for the efficiency calibration in the same geometry as the soil samples. Standard IAEA reference materials (RGK-1, RGTh-1, and RGU-1) were counted for quality assurance. To strip out the radiation from background emission, an empty beaker was counted for the same length of time. At equilibrium, the energy peaks considered for analysis of the measured gamma-ray spectra are: ²¹⁴Pb (352 keV) and ²¹⁴Bi (609), for ²²⁶Ra and ²⁰⁸Tl (583.1 keV) and ²²⁸Ac (911.2 keV), for ²³²Th and direct energy emission of 1461.8 keV by ⁴⁰K was used to determine its activity concentration. The experiment was conducted at the Nuclear Laboratory, University of Technology, Malaysia. The specific activity concentration for each radionuclides was calculated using the following expression [15].

$$A_c = \frac{S}{t_a} + \frac{100}{\epsilon_i} + \frac{100}{y} + \frac{1}{q} \times k \quad (1)$$

where A_c is specific activity concentration of the radionuclide, S is the net area of the peak, t_a is the live time in second, ε_i is the efficiency in % for the energy line considered, y is the absolute transition probability of the specific gamma ray. The collective uncertainties (σ_{A_c}) of A_c is given by

$$\sigma_{A_c} = A_c \times 100 \times \sqrt{\left(\frac{\sigma_s}{S}\right)^2 + \left(\frac{\sigma_{\varepsilon_i}}{\varepsilon_i}\right)^2 + \left(\frac{\sigma_q}{q}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2} \quad (2)$$

where σ_s is the uncertainty in the net area, σ_y is the uncertainty in branching ratio while σ_{ε_i} is the uncertainty in the efficiency with the energy line.

2.5 Water sampling and preparation

A total of fifty one (51) groundwater samples, each of 1 litre, were collected from public water sources (borehole and hand dug wells) in clean airtight plastic bottles to prevent the escape of radon gas. Samples were stabilized by adding 5 ml of nitric acid (HNO_3) to avoid precipitation, and transported to laboratory for further preparation. Sampling sources was spread across all the geological formations of the area. Coordinate of each sampling source was also recorded using GPS device. In the laboratory, samples were filtered through Whatman filter paper. About 10 ml of each sample was placed in a test tube and stored in a refrigerator for analysis.

2.6 Radiological risks evaluation

2.6.1 Radium equivalent

Radionuclides are not uniformly distributed in soil, radium equivalent (Ra_{eq}), is defined to compare the activities of a material that contains different amount of ^{226}Ra , ^{232}Th and ^{40}K . It is assumed that 259 Bq kg^{-1} of ^{232}Th , 370 Bq kg^{-1} of ^{226}Ra and 4810 Bq kg^{-1} of ^{40}K produce the same γ - ray dose rate in air. Radium equilibrium was computed using the relation given by [16].

$$\text{Ra}_{\text{eq}} = ^{226}\text{Ra} + 1.43^{232}\text{Th} + 0.077 ^{40}\text{K} \quad (3)$$

2.6.2 External hazard index

Radiological suitability of any material for construction purposes is assess by external hazard index. For inhabitants leaving in a buildings provides with doors and windows, external hazard index has been proposed by some authors as follows [17].

$$H_{\text{Ext}} = \frac{A_{\text{Ra}}}{740} + \frac{A_{\text{Th}}}{518} + \frac{A_{\text{K}}}{9620} \leq 1 \quad (4)$$

where, A_{Ra} , A_{Th} and A_{K} represent the activity concentration of ^{226}Ra , ^{232}Th and ^{40}K , respectively.

2.7 Inductive coupled plasma mass spectrometry

Inductive Coupled Plasma Mass Spectrometry is relatively new method for multi-elemental analysis and ideal for water samples. The instrument can detect element below 0.1 ng L^{-1} . The method used for analysing radionuclide in this study has been accredited according to ISO standard 17025(European Standard EN ISO/IEC 17025:2000)[18]. Chemical concentration of ^{238}U in the groundwater samples were determined using Perkin Elmer ICP-MS instrument, model NexION350X at the Analytical Chemistry Laboratory, Universiti of Technology Malaysia. ICP-MS data was collected using Syngistix software (version 2.2). The results are reliable because of their triplicates which were comparable to each other. Standard calibration solutions provided by Perkin Elmer were run at beginning and at the end of the sequence of the samples.

The chemical concentration of uranium in part per million (ppm) was determined by comparing the intensity of the measured ^{238}U with the plotted calibration curve as per equation 5.

$$C_i(\text{ppm}) = \frac{I_i C_s}{I_s} \quad (5)$$

where, C_i is the chemical concentration in the sample, I_i is the intensity of ^{238}U in the sample, C_s is the concentration of ^{238}U for the standard, and I_s is the intensity of ^{238}U for the standard. The uncertainty associated with this measurement was calculated using equation 6:

$$\sigma_{C_i} = C_i \times \sqrt{\left(\frac{\sigma_{I_i}}{I_i}\right)^2 + \left(\frac{\sigma_{C_s}}{C_s}\right)^2 + \left(\frac{\sigma_{I_s}}{I_s}\right)^2} \quad (6)$$

2.8 Mortality and morbidity cancer risks assessment of uranium in groundwater

The purpose of radiological assessment in groundwater is to evaluate the risks associated with the ingestion of a given radioelement through drinking water over the lifetime of an individual. Mortality and morbidity cancer risks (R) associated with the intake of a given radionuclide is defined by equation 7:

$$R = r \times I \quad (7)$$

where r represents the risk coefficient of the ingested radionuclide and I is the per capita activity intake of the radionuclide. The mortality and morbidity risk coefficient for uranium is given by $1.13 \times 10^{-9} \text{ Bq}^{-1}$ and $1.73 \times 10^{-9} \text{ Bq}^{-1}$, respectively [19].

2.9 Toxicity risk of uranium in groundwater

Toxicity risk of a radionuclide is defined as the lifetime average daily dose (LADD in the unit of $\mu\text{g kg}^{-1} \text{ day}^{-1}$) of the element through the ingestion of drinking water. Mathematically given as [20].

$$LADD = \frac{EPC \times IR \times EF \times LE}{BW \times AT} \quad (8)$$

where EPC represents the exposure point of concentration ($\mu\text{g L}^{-1}$), IR means water ingestion rate (2 litres of water per day) according to WHO [19]. EF is the exposure frequency (350 days year $^{-1}$), LE is the life expectancy which is given as 45.5 years for average Nigerian according to report by WHO [21]. AT is the average time (i.e. average life time expectancy in days given by $365 \times 45.5 = 16607.5$ days) and BW is the body weight (70 kg for average Nigerian).

The extent of harms from toxic risk is indicated by hazard quotient (HQ):

$$HQ = \frac{LADD}{R_f D} \quad (9)$$

where $R_f D$ is reference dose and is recommended to be $0.6 \mu\text{g kg}^{-1} \text{ day}^{-1}$ by WHO [20].

2.10 Geostatistical analyses

The data set on the activity concentration of the terrestrial radionuclides plus the coordinates for all data points were used in plotting digital maps for the spatial distribution of ²²⁶Ra, ²³²Th and ⁴⁰K for the area. The geostatistical data analysis was performed using a mapping software ArcGIS (version 10.3) provided by ESRI [22]. Ordinary Kriging interpolation method for its advantages over other interpolation methods, was chosen. Kriging geostatistical technique interpolate based on the theory of regionalized variables which states that observations close to each other shows spatial autocorrelation and are more alike than those that are far apart [23]. The technique is unbiased method of interpolation which operate based on the Semivariogram function defined as half the averaged squared difference between paired data values separated by a distance interval [24].

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z(X_i) - Z(X_i + h)\}^2 \tag{10}$$

where $\gamma(h)$ represent the Semivariogram, $N(h)$ is the number of sample points $Z(X_i)$ is the value of activity concentration of the radionuclides or dose rate measured at sample position X_i , h is the distance between the sample points.

3. Results and discussion

3.1 Radioactivities of ²²⁶Ra, ²³²Th and ⁴⁰K

The descriptive statistics of the activity concentrations of the natural terrestrial radionuclides ²²⁶Ra, ²³²Th and ⁴⁰K in soil samples obtained using Statistical Package for Social Science (SPSS) software is shown in Table 2. The activity concentration of ²²⁶Ra varied from 34±2 to 1006±8 Bq kg⁻¹, 16±1 to 1695±37 Bq kg⁻¹ for ²³²Th and from 67±4 to 2465±45 Bq kg⁻¹ for ⁴⁰K, with mean values of 186±15, 627±39 and 1056±57 Bq kg⁻¹, respectively.

Table 2: Descriptive statistics of the activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K.

Statistics	²²⁶ Ra (Bq kg ⁻¹)	²³² Th (Bq kg ⁻¹)	⁴⁰ K (Bq kg ⁻¹)
Mean	186	627	1056
Std. Error of mean	15	39	57
Std. Deviation	152	401	580
95% confidence interval of mean	156-215	548-705	942-1169
Median	140	591	964
Minimum	34	16	67
Maximum	1006	1695	2465
Geometric mean	148	472	858
Harmonic mean	121	265	598

Range	34-1006	16-1695	67-2465
Kurtosis	9.73	-0.18	-0.51
Std. error of kurtosis	0.47	0.47	0.47
Skewness	2.75	0.69	0.40
Std. error of skewness	0.23	0.23	0.23
Freq. distribution	Log-normal	Normal	Normal

The activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K for each LGA is presented in Table 3. The activity concentrations of ^{226}Ra and ^{232}Th have their highest mean values in Bokokos and Barkin Ladi LGAs, respectively whereas highest mean activity concentration of ^{40}K was observed in Jos south. The mean values were found to distinctly exceed their corresponding world reference values of 35, 40 and 400 Bq kg^{-1} for ^{226}Ra , ^{232}Th and ^{40}K , respectively. These results were used to evaluate radiological health risk parameters for the area.

Table 3: Activity concentration of radionuclides in soil samples for each LGA

LGA	N	^{226}Ra (Bq kg^{-1})		^{232}Th (Bq kg^{-1})		^{40}K (Bq kg^{-1})	
		Mean	Range	Mean	Range	Mean	Range
Barkin Ladi	16	287±5	67-516	1096±15	610-1627	1210±13	699-1887
Bassa	15	166±3	99-297	568±7	311-1183	1086±15	595-1494
Bokokos	8	356±2	93-1006	829±4	199-1415	1583±5	927-2352
Jos East	9	139±4	91-245	446±6	280-738	744±6	327-1152
Jos North	15	141±3	57-194	611±7	250-1361	922±8	307-1545
Jos South	9	241±5	48-494	923±6	227-1563	1896±12	1492-2465
Mangu	11	123±2	40-291	348±5	38-889	558±4	245-1104
Pankshin	11	99±4	34-253	307±8	16-1090	596±16	67-1672
Riyom	8	164±3	55-487	670±9	67-1695	962±12	248-2188
Overall mean		186	34-1006	627	16-1695	1056	67-2465

Since background gamma radiation dose rate depends on the activity concentration of the terrestrial radionuclides ^{226}Ra , ^{232}Th and ^{40}K in soil. Results of the activity concentration was used to estimate the background gamma dose rate of the area due to these radionuclides. The contribution of each radionuclide is shown in Figure 3. The Figure indicates that, the largest portion (74%) comes from ^{232}Th followed by ^{238}U and the least (9%) comes from ^{40}K . This outcome agrees with the results of Masok, Masiteng [25] in the region. This may be linked to the granitic-basement complex formations which constitute the largest formation of the region. However, the result is in contrast with lower background areas where ^{40}K was found to contribute the largest [26, 27].

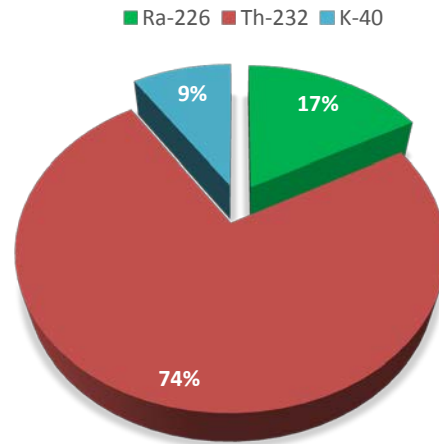


Fig. 3: Percentage contribution of ^{226}Ra , ^{232}Th and ^{40}K to gamma dose rate.

3.2 ICP-MS Results

The results of the chemical concentration of ^{238}U in groundwater samples was found to varied from 1.4 measured in hand-dug well water and $35 \mu\text{g L}^{-1}$ measured in borehole with water sample with a mean value of $13.15 \pm 1.2 \mu\text{g L}^{-1}$. Table 4 presents the chemical concentrations of ^{238}U in groundwater for different bearing aquifers. The mean activity concentration of ^{238}U varied between $9.43 \mu\text{g L}^{-1}$ noted in G7 (Sandstone, clay and shale) and $18.33 \mu\text{g L}^{-1}$ noted in G1 (Basement complex). This is in consistent with a similar work conducted by Abdurabu, Saleh [28]. Higher concentration of ^{238}U observed in the basement complex may be due to chemical compositions of uranium in this rock, uranium solubility, the nature of contact between granitic intrusions, uraniferous minerals and groundwater [29]. Lower values in water sample from hand-dug well compared to boreholes, this concurred with the statement of de Oliveira, Mazzilli [7]. However, these values are well below the range of values observed in many published works about the concentration of uranium in drinking water. Health and radiation protection agencies have set a safe chemical limit of uranium in drinking water which would not lead to any significant health risk due to drinking water that contains uranium. World Health Organisation [20] and United State Environmental Protection Agency [30] have recommend $15 \mu\text{g L}^{-1}$ and $30 \mu\text{g L}^{-1}$ as safe limit of U in drinking water for human beings, respectively. It could be seen from the results obtained in Table 4, some water samples contained uranium exceeding the recommended limits. This agreed with a similar work conducted by Jibiri, Alausa [31] for the same area.

Chemical to activity concentration conversion factor of $0.0245 \text{ Bq} \mu\text{g}^{-1}$ for natural uranium was used to convert the results to activity concentration. Activity concentration of uranium in water samples was found to range from $0.034 - 0.856 \text{ Bq L}^{-1}$ with overall mean of 0.322 Bq L^{-1} . The values of activity concentration for different geological formation are presented in Table 5. Uranium activity concentration in virtually all the water samples are below the radiological safe limit of 1 Bq L^{-1} recommended by WHO [32] in drinking water. Thus, the water is radiologically safe for drinking.

Table 4: Chemical concentration of ^{238}U in water samples for each geological formation

Geology	N	Mass concentration of ^{238}U ($\mu\text{g L}^{-1}$)			95% Confidence interval for mean
		Mean	Std. error	Range	
G1	7	18.33	0.15	9-30	15.34 -20.87
G2	5	12.03	0.05	1.4-28	10.22 -13.98
G3	7	10.68	0.13	2.8-14.4	7.8 -12.04
G4	5	12.33	0.07	7-19	10.45 - 14.78
G5	7	17.82	0.11	4.5-35	0.24-14.07
G6	7	15.83	0.06	4.1-31	148- 16.23
G7	7	9.43	0.04	2-20	7.78 - 12.87
G8	6	15.80	0.05	5-34	13.23 - 17.43

Table 5: Activity concentration of ^{238}U in water samples for each geological formation

Geology	N	Activity concentration of uranium (Bq L^{-1})			
		Mean	Std. error	Min.	Max.
G1	7	0.449	0.004	0.221	0.735
G2	5	0.295	0.001	0.034	0.69
G3	7	0.262	0.003	0.069	0.353
G4	5	0.302	0.002	0.172	0.466
G5	7	0.437	0.003	0.110	0.858
G6	7	0.388	0.001	0.100	0.759
G7	7	0.231	0.001	0.049	0.490
G8	6	0.387	0.001	0.123	0.833

3.3 Radium equivalent (Ra_{eq})

The mean Ra_{eq} is estimated to be 1163 Bq kg^{-1} which is higher than maximum limit of 370 Bq kg^{-1} to keep annual radiation dose below 1.5 mGy [33]. The higher values of Ra_{eq} observed in this study are due to the higher concentration of ^{232}Th measured in the area. Thus, the use of local soil for building materials should be discouraged to avoid radiation related diseases.

3.4 External hazard index (H_{Ext})

The average value of external hazard index is found to be 1.6 which exceed unity as recommended by [4]. The average value is found to be lower than 2.03 for Eastern Desert of Egypt [34] and higher than 0.84 for Xiazhuang Granite area in China [35].

3.5 Mortality and morbidity cancer risk of uranium in groundwater

The average values of cancer mortality and morbidity risk were found to be 6.09×10^{-6} and 9.41×10^{-6} , respectively. When compared to other results, cancer mortality risk is found to be distinctly higher than the value reported by Omeje and Wagiran [36] in Gossa, North-central Nigeria and lower than 2.54×10^{-4} reported by Amakom and Jibiri [37] in Ogun state of Nigeria. The mean cancer morbidity is found to be higher than 2.55×10^{-8} reported by Omeje and Wagiran [36] and lower than 3.39×10^{-4} reported by Amakom and Jibiri [37]. However, both the mortality and morbidity risks in this study are generally lower than acceptable limit of 10^{-3} for radiological risk as recommended by USEPA [38].

3.6 Toxicity risk of uranium

The average chemical toxicity risk for individual was evaluated to be $3.63 \times 10^{-1} \mu\text{g kg}^{-1} \text{day}^{-1}$. The value obtained in this study is lower than $0.81 \mu\text{g kg}^{-1} \text{day}^{-1}$ obtained by Sharma, Kumar [6] in India; and is higher than $6 \times 10^{-3} \mu\text{g kg}^{-1} \text{day}^{-1}$ given by Omeje and Wagiran [36] at Dei-Dei, Nigeria. The permissible limit of LADD given by WHO is $1.0 \mu\text{g kg}^{-1} \text{day}^{-1}$ [20]. This shows that the average value of this study is within the permissible limit.

The hazard quotient (HQ) in this study is obtained to be 0.605 which is lower than 0.68 obtained in India by Sharma, Kumar [6]. According to WHO, reference dose (R_fD) is 0.6. In this study, seven water samples have their HQ value exceeding the acceptable limit. This implies some levels of health risks associated with uranium in drinking water mainly due to the chemical toxicity risk [20].

3.7 Spatial distribution maps of ^{226}Ra , ^{232}Th and ^{40}K

The result of the activity concentration of the terrestrial radionuclides was used to plot a digital maps for the spatial distribution of ^{226}Ra , ^{232}Th and ^{40}K for this work. Spatial distribution of ^{226}Ra is shown in Figure 4. Elevated spots can be observed in Bokokos LGA with relatively higher concentration areas in Mangu, Pankshin and Riyom LGAs. Activity concentration of ^{232}Th was higher in spots around Jos South, Barkin Ladi and in Pankshin LGAs with the most elevated spot found in Jos South (Figure 5). Higher activity concentration of ^{40}K was noted in some locations around Pankshin, Mangu and Riyom LGAs as shown in Figure 6.

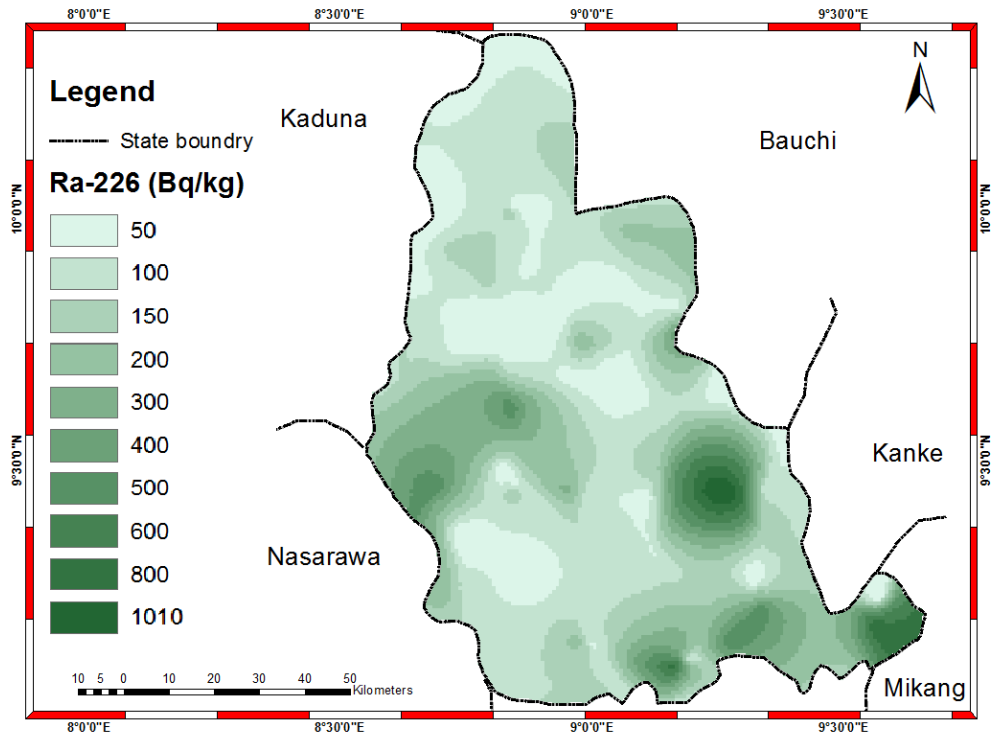


Fig. 4: Spatial distribution map of ²²⁶Ra concentration

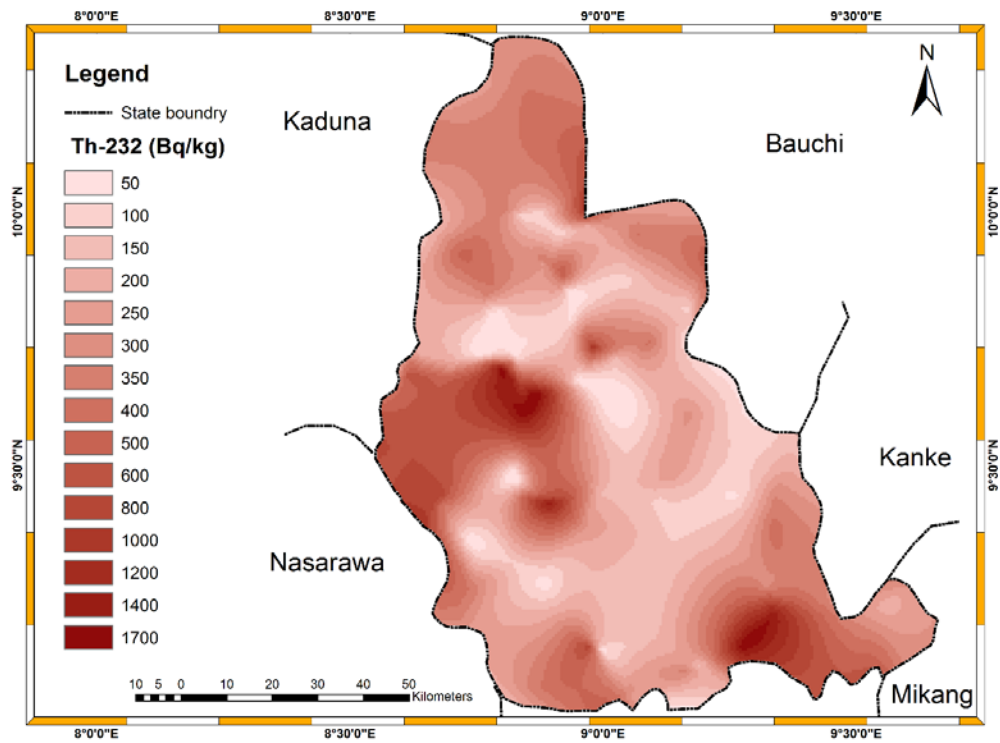


Fig. 5: Spatial distribution of ²³²Th concentration

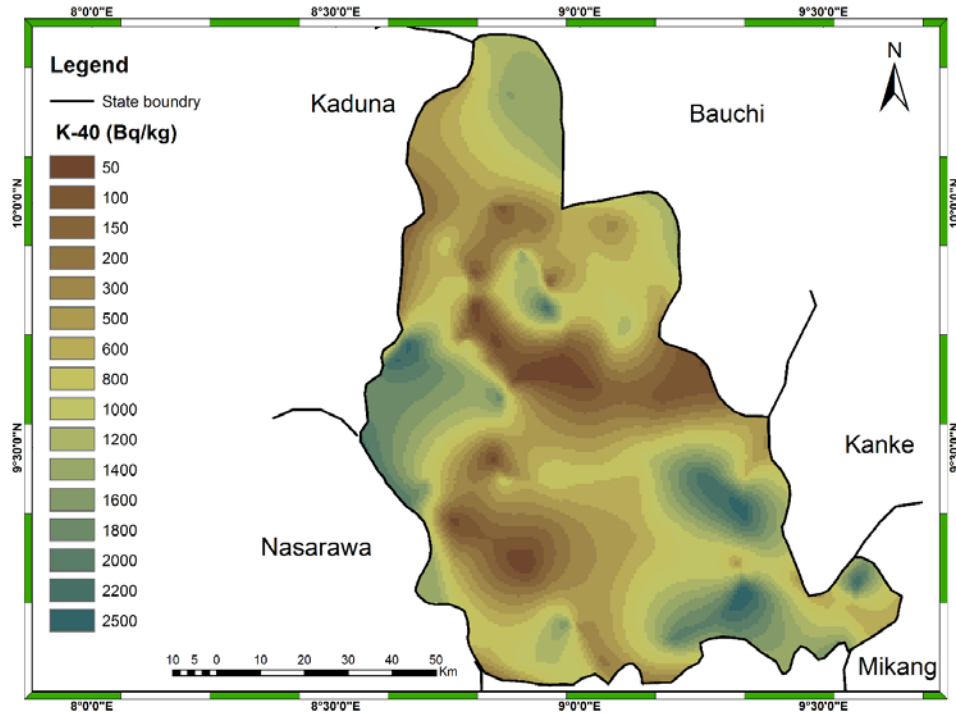


Fig. 6: Spatial distribution of ^{40}K concentration

4. Conclusion

Activity concentrations of natural terrestrial radionuclides ^{226}Ra , ^{232}Th and ^{40}K were determined in soil samples collected across eight geological formations of Jos Plateau. The results show that the mean activity concentration of the terrestrial radionuclides exceed their mean reference values obtained worldwide and ^{232}Th was found to significantly contribute to the total radioactivity of the area. Radium equivalent and external hazard index were found to exceed their global recommended limits. Chemical concentration ^{238}U in some drinking water samples was found to exceed permissible limit provided by WHO and USEPA. Human risks due to ingestion of groundwater was from chemical toxicity of ^{238}U as heavy metal rather than radiological risk. Therefore, this work, provides a yardstick for the monitoring and evaluation of any future radiological contamination in the environment due the local and international releases of radioactive materials. The results also represents a useful radiometric data that could be of vital importance in radio-epidemiological assessment, diagnosis and prognosis of uranium-induced diseases to the local population in of the area.

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