International Journal of Mechanical Engineering and Technology (IJMET)
Volume 10, Issue 01, January 2019, pp. 1897-1920, Article ID: IJMET_10_01_187
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=10&IType=1
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

INVESTIGATION OF DRILLERS' EXPOSURE TO NATURAL RADIOACTIVITY AND ITS RADIOLOGICAL RISKS IN LOW LATITUDE REGION USING NEUTRON ACTIVATION ANALYSIS

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ABSTRACT

Radiation originates from anthropogenic, primordial, and cosmogenic sources. The impact of radiation through anthropogenic and cosmogenic sources is negligible to the environment while the primordial radioactivity is widely distributed in the earth and its environs. This radioactive material and its Byproducts are found mainly in diverse geological formations around us. Inadequate access to public water supply in Abuja has forced more than 80 percent of the population of about 5 million to drill private boreholes. Nigerian drillers are unaware of high concentrations of radioactivity present in granitic rocks which vary with depth. The radioactivity of 226Ra as well as 232Th decay chains for the lithological rock samples could be at equilibrium considering the age as well as the isotopic mass proportion which is assumed to be equal to its natural isotope. Neutron Activation Analysis (NAA) is adopted for this study with the aim of minimizing sample size as well as less counting rate in order to estimate the radioactivity concentration in rock samples. Two boreholes are drilled in Abuja in order to randomly collect the rock samples from three different layers of each site. All the samples were duplicated for each radionuclide examination, resulting to twelve samples in all. The results showed that the activity concentrations of 226Ra, 232Th and 40K in the two sites were in the order 232Th > 226Ra > 40K. 226Ra and 232Th possess activity concentration greater than

the world's average while 40K activity is less than the world's average. The radiological risks estimated showed that more than half of the parameters used nearly exhibited greater values than the global average values. It is, therefore, concluded that Abuja is underlain by rocks of low potassic value. If the drillers do not take caution about the geologic formation of the subsurface and apply necessary precautions before the commencement of any borehole drilling, over – exposure to these -radiation may pose unquantifiable health risks to them

Keywords: Drillers, Boreholes, Granitic rocks, Natural radioactivity, Radiological risks, Neutron Activation Analysis, Abuja.

Cite this Article: Maxwell OMEJE, Theophilus Aanuoluwa ADAGUNODO, Sayo Akinloye AKINWUMI, Olusegun Oladotun ADEWOYIN, Emmanuel Sunday JOEL, Wagiran HUSIN and Suhaimi Hamzah MOHD, Investigation of Drillers' Exposure to Natural Radioactivity and its Radiological Risks in Low Latitude Region using Neutron Activation Analysis, *International Journal of Mechanical Engineering and Technology*, 10(1), 2019, pp. 1897-1920.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=1

1. INTRODUCTION

Understanding the different levels of radiation and radionuclide distributions in any environment is vital for evaluating the effects of radiation exposure to man as a result of cosmogenic, human, and terrestrial activities. Exposure to radiation can be from either external sources (outside the body) or internal sources (food consumed, air inhaled, or water consumed) or both [1]. Natural radioactivity occurs in diverse domains (e.g. soils, water, plants, rocks, air, and animals) and it consists of those that have their origin from parent bedrocks (i.e. the series radionuclides led by ^{238}U and ^{232}Th, and the natural ^{40}K) during the formation of the earth [1, 2]. All rocks possess radionuclides in different quantities; the concentration in each rock depends on its geological composition. Belivermis *et al*. [3] reported that the radiation emissions' effect is a function of the thickness and types of the over-lining soil, chelating agents, physicochemical properties, rock types and its diverse usage. Other terrestrial sources are ^{235}U series, ^{138}La, ^{87}Rb, ^{137}Cs (as a result of weapon testing), ^{176}Lu, and so on [1].

One of the features that cannot be averted on earth is the exposure to ionizing radiation [4]. The ionizing radiation emanating from the environment is an ever-present form of exposure to radiation. The risks of exposure of these radiations to human health are of great concern in environmental Geophysics and health Physics. Some of the health risks associated with over exposure to radioactivity and inhalation of radionuclides include: acute leucopoenia, chronic lung diseases, necrosis of the mouth and anemia [5]. Exposure to Radium could lead to cataract, teeth fracture, anemia, and cancer of different types, while hepatic, pancreas, kidney, bone and lung cancers as well as leukemia could be associated with exposure to thorium [5 – 6]. These diseases are triggered by γ-radiation, which propagates efficiently through long distances in air and affects humans [7]. Radiation can be the result of emission of energy in the form of electromagnetic waves or as moving subatomic particles, predominantly high-energy particle which lead to ionization. Radiation can also occur in two distinct forms which could be natural or artificial. Uranium (U) and Thorium (Th) contribute mostly to natural radiation from high energy cosmic rays that could be found in rock, water, soil, plant, air, and so on. Meanwhile, artificial radiation is produced through man-made nuclear or atomic pollution [8]. Adequate knowledge of natural radioactive elements helps in

environmental studies and data interpretation from man-made pollution of the environment [9]. Radioactive elements in rocks are disintegrated into radionuclides which are transferred into the soil by rain. However, due to high content of radionuclides in igneous rocks it possesses higher radiation levels than sedimentary rocks most especially granitic rocks [10 – 11].

The major sources of exposure of man to radioactivity are radionuclides of ^{238}U and ^{232}Th. The geological contents of uranium and thorium are necessary in analysis and solving geochemistry exploration problems [12 – 13]. Uranium is four times lower in abundance than thorium in the earth's crust because the igneous rocks that are of granitic origin are extremely enriched in thorium than uranium, that is, on the average of 5 part per million of uranium to 15 part per million of thorium [14 – 16]. Potassium (K) makes similar contributions as uranium and thorium because of high content of rocks with acidity [14 – 16]. Therefore, the mean concentration of external incident gamma radiation of ^{238}U, ^{232}Th and ^{40}K is 35, 30 and 400 $BqKg^{-1}$ respectively [17]. World Health Organization (WHO) estimated that in 2008, 7.6 million people died globally as a result of various types of cancer diseases. It was projected that about 13 million people would die by 2030 if no precaution was taken. The analysis further showed that over one hundred thousand Nigerians are diagnosed with cancer yearly with a death record of about eighty percent of those diagnosed. Nigeria's death ratio of four out of five affected persons is one of the highest in the world. Thus, it is the duty of environmental and health scientists to assess the concentrations of these naturally occurring radionuclides in an environment in order to sensitize people about the risks associated with its over-exposure. Therefore, this study aims to investigating the level of exposure of drillers involved in borehole drilling (through inhalation) to natural radioactivity in Abuja and consequently estimating its associated radiological risks.

2. THE STUDY AREA AND ITS GEOLOGY

The two sites used for this study are located in Abuja, Nigeria with the coordinates of latitude 9^o 6′ 52″ north, longitude 7^o 15′ 39″ east and latitude 9^o 6′ 16.7″ north, longitude 7^o 16′ 26″ east respectively. Abuja, low latitude region (Fig. 1a) is situated on the central basement complex of Nigeria (Fig. 1b). Abuja's geology has been covered extensively in the literature by Oyawoye [18], McCurry [19], Black *et al*. [20], Ajibade *et al*. [21], Rahaman [22] and so on. Abuja falls on the modified crystalline basement rocks of Africa [23]. The geology of Abuja in relationship with its groundwater potentials was revisited not quite long by Abam and Ngah [24]. They affirm that the rocks are chiefly composed of granite, mica schists, gneisses, feldspathic schists, migmatites, and hornblende. The fracture and joints in the area trend in two distinct patterns which are: NE – SW and NW – SE. The drainage and water flow patterns are solely controlled by these fracture system [24]. Nevertheless, slight quantity of Nupe's Cretaceous sandstone deposits transpire to the southern part of the Federal Capital Territory (FCT) between Abaji and Kwali which extends to Rubochi and share with Nassarawa state's border. Likewise, metasediments have been mapped also in the south (i.e. west of Kusaki) as well as northern part of Abuja (east of Takushara) which trend in NNE – SSW [24 – 25]. Amphibolite schists and mica schists have also been noticed very close to Buze and Kasaki villages.

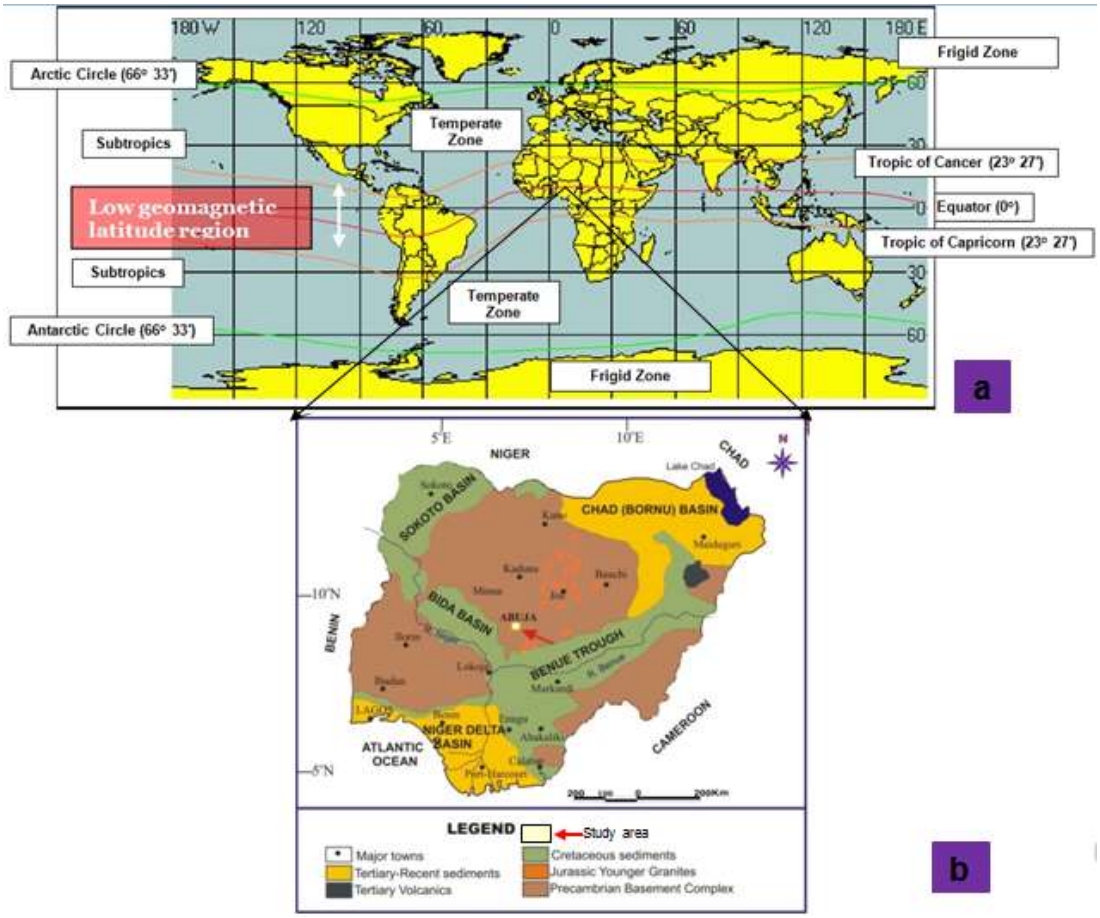

Figure 1a The world map showing the low latitude region (modified from [49]). **b** Nigerian geological map revealing Abuja, the study area (adapted from [50]).

3. MATERIALS AND METHODS

3.1. Sample Collection

The geophysical survey involving Vertical Electrical Sounding with the engagement of Schlumberger configuration was employed in order to locate the aquiferous zone [26]. VES was adopted here due to its simplicity as well as its prevalence in groundwater investigation especially in basement complex [27 – 29]. VES explores the vertical variation of subsurface, thereby revealing fluid's presence in the subsurface [30 – 31]. This method is used to find the suitable sites where the boreholes are drilled for sample collection according to layer variations. The VES types for site one and site two are H-type and A-type respectively. The field interpretations of these two VES stations were used to predict the drilling depths of 80 and 60 m for the two boreholes. Drilling rig of 25 ton capacity coupled with compressor of 30 ton capacity were used to drill at site one (80 m) and site two (60 m) in Abuja, Nigeria. Three major lithologic rock formations were randomly considered for each borehole at varying depths in this study. The depths at which the samples were taken and their respective lithology descriptions are presented in Table 1 while the lithology logs of the two sites are presented in Fig. 2.

Table 1 Lithological sequence and descriptions of the collected samples

Site One (latitude 9^o 6′ 52″ north, longitude 7^o 15′ 39″ east)				**Site Two (latitude 9^o 6′ 16.7″ north, longitude 7^o 16′ 26″ east)**			
Sample's identifier	Depth (m)	Thickness (m)	Description of its lithology	Sample's identifier	Depth (m)	Thickness (m)	Description of its lithology
S1Lx–A S1Lx–B	5.0–9.0	4.0	Feldspar with silty sand, revealing blackish to grey colour	S2Lx–A S2Lx–B	0 - 7.0	7.0	Sandy clay interbedded with gravel, revealing brownish ash colour
S1Ly–A S1Ly–B	35.0 – 46.5	11.5	Fine to coarse sand revealing blackish pebble to grey	S2Ly–A S2Ly–B	29.0-36.4	7.4	Clayey sand with fine grain size that intercalates with darkish ash feldspar
S1Lz–A S1Lz–B	46.5–71.7	25.2	Fine to medium grained sand of blackish to grey colour, turning to whitish formation at depth ≥ 69 m	S2Lz–A S2Lz–B	51.0-61.1	10.1	Micaceous gravel sand of fine to medium coarse composition, showing darkish to grey colour

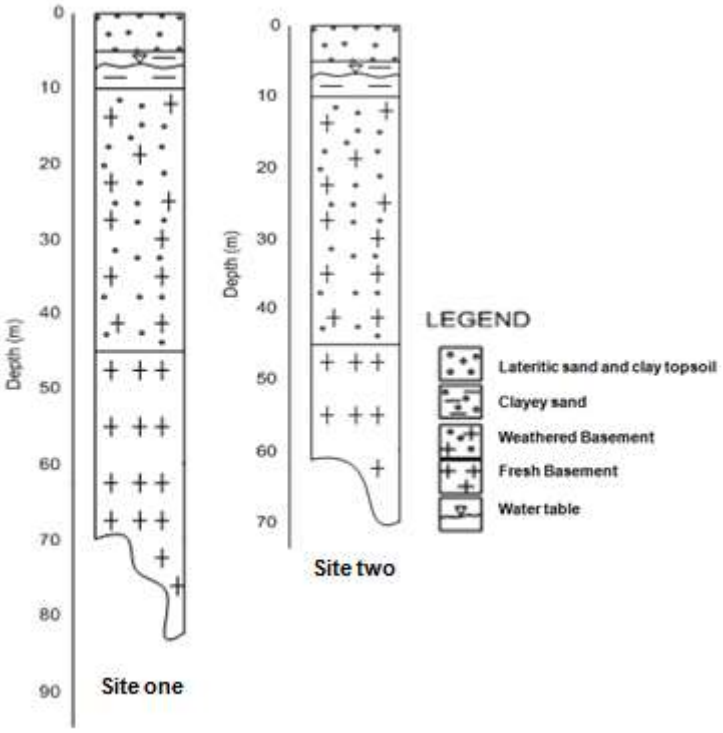

Figure 2 Lithology logs of site one and site two.

3.2. Neutron Activation Analysis (NAA) Method

In NAA, the analysis through nuclear reaction is achieved by bombarding the samples with neutron [32]. The two products that are adequately measured using this technique are the imperceptibly released radiation upon neutron capture and the induced radioactivity when they decay provided that the new nuclei are radioactive elements. NAA is a nuclear process that is used to determine the elements' concentrations in a very large amount of materials. This technique has come to limelight since its approval in 2008 [32] and has a vast applications in Chemistry, Geology, Geophysics, Archaeology, Environmental Impact Assessment, Forensic Science as well as Medicine. NAA is mostly preferred to be used for samples with high contents of radionuclides to several methods because of its non-destructive, very simple and fast method of analysis.

This present study is conducted by randomly collecting dual samples from each layer in three different lithological sequences from each site for their natural radioactivity reference concentrations. Site one samples were collected at 7, 40 and 70 m depths while site two samples were collected at 7, 35 and 60 m depths (towards the base of each lithological domain). All the prepared samples were duplicated for each radionuclide examination, resulting to twelve overall samples. The reduction of sample size was made to approximately 0.2 g in a polyethylene vials for irradiation. For the analysis of potassium, it was irradiated with a little, ultra-pure aluminum wire with variance in neutron flux which was measured and recorded. For uranium analysis, a 3 percent variation in the neutron flux without wire was assumed which is approximately the experimental mean calculated from several characterization experiments. The analysis of thorium did not involve flux wires due to the length of the irradiation and the rotation motion of samples in the reactor. All the standards

reference materials and the samples were concurrently irradiated. The processes of the experimental analysis and nuclides formed are presented in Table 2. The procedures used to determine uranium, thorium and potassium concentrations from the sample are in line with the documented records of [33-35]. In order to assess the overall effect of activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K to drillers in Abuja, Nigeria, six (6) quantities (radium equivalent activity, annual gonnadal equivalent dose, external hazard index, gamma index, annual effective dose equivalent, and excess lifetime cancer risk) are calculated based on the procedures from the literature [1, 7, 36-37, 51].

Table 2 The NAA procedures in this study and nuclides formed by Neutron capture

NAA procedures					**Nuclides formed by Neutron capture (adapted from [48])**				
Nuclide Experiment	Analysis Method	Power Rating	Irradiated Time	Decay Time	Element	Isotope	Production	Half-life (days)	Energy (keV)
Uranium	Epithermal	100 kW	2 mins.	10-20 mins.	Uranium	^{239}Np	^{238}U (n, γ, β$^-$)	2.34	277.9
Thorium	Thermal	750 kW	6 hrs	2 weeks	Thorium	^{233}Pa	^{232}Th (n, γ, β$^-$)	27.4	312.17
Potassium	Epithermal	500 kW	5 mins.	24 hrs	Potassium	^{56}Mn	^{40}K(n, γ)	12.8	1524.5

4. RESULTS AND DISCUSSION

Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K

The activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in the samples analyzed varied from 6.2 ± 0.01 to 161 ± 8.0Bqkg^{-1}, 87.2 ± 4.4 to 283 ± 14.2Bqkg^{-1}, and 0.017 ± 0.001 to 0.136 ± 0.007Bqkg^{-1} respectively. The average values of ^{226}Ra, ^{232}Th, and ^{40}K in site one and site two are 107.22 and 37.97 Bqkg^{-1}, 205.18 and 102.05 Bqkg^{-1}, 0.1308 and 0.0383 Bqkg^{-1} respectively as shown in Table 3. Apart from the activity concentrations of ^{40}K from the two sites that manifested very low values, ^{226}Ra and ^{232}Th activity values were greater than the world's average based on UNSCEAR [38] and Qureshi*et al* [7] yardsticks as shown in Table 3. The results of this study corroborated that of Bea [16] which showed that for an igneous rock with a granitic origin, radium ~ uranium is less abundant than thorium. In site one and site two, radium is less abundant than thorium by the factors of 1.9 and 2.7 respectively. The lithologic description of the highest activity concentration of 161 ± 8.0 Bqkg^{-1} for ^{226}Ra found in site one layer eleven-A (S1Lz-A) composed of fine to medium grained sand of blackish to grey colour, turning to whitish formation at depth ≥ 69 m was interpreted as migmatite-gneiss complex. The lowest activity concentration value of 6.2 ± 0.01 Bqkg^{-1} for ^{226}Ra constituted feldspar with silty sand, revealing blackish to grey colour for site one layer 7-A (S1Lx-A), clayey sand with fine grain size that intercalates with darkish ash feldspar for (S2Ly-A and S2Ly-B) and Micaceous gravel sand of fine to medium coarse composition, showing darkish to grey colour for site two layer nine (S2Lz-A and S2Lz-B) boreholes. The blackish content found in all the samples that attributed to lower value of ^{226}Ra could be the effect of micaceous sandstone at such depth. The sum of all the activity concentrations ranged from 99.23 to 444.13 Bqkg^{-1}. The average values of the total activity concentrations (^{226}Ra + ^{232}Th + ^{40}K) of site one 312.53 Bqkg^{-1} and site two 140.16 Bqkg^{-1} were below the world average

value of 420 $Bqkg^{-1}$ as reported by UNSCEAR [38] and Qureshi *et al* [7]. Generally, the activity concentrations in the two sites are in the order $^{232}Th > ^{226}Ra > ^{40}K$. The $^{232}Th/^{40}K$ and $^{226}Ra/^{40}K$ presented in Table 4 are comparatively higher than the world's average of 0.067. The $^{226}Ra/^{232}Th$ ratio in its case is lower than the world's average value of 1. This implies that the rocks in Abuja are composed of low pottasic values. Qureshi *et al*. [7] reported that samples having unusual higher activity concentration could be granitic in composition. The unusual activity concentration of ^{226}Ra, ^{232}Th from the two sites and geologic formation of Abuja confirmed this claim. However, plots of the radioactivity concentrations of these naturally occurring radionuclides and their ratios are presented in Figs. 3a – g. The mean comparison of this study with the global mean value was done in order to determine the safety of drillers in Abuja, Nigeria.

This study is further compared with Landsberg *et al*. [35] who carried out their analyses in rocky flat soil samples of Texas, USA using NAA. It was noted that the ^{226}Ra site one result of this study is distinctly higher by a factor of 3.91, ^{232}Th by a factor of 2.56 and ^{40}K by a factor of 2.0 (though both studies reported low concentrations of ^{40}K from their samples). The concentrations of ^{226}Ra varied from 0.5 to 12.9 ± 0.6 μgg^{-1}in site one with the highest value of 12.9 ± 0.6 μgg^{-1}obtained in Layer eleven (S1Lz-A). For ^{232}Th, the highest concentration was found in the same layer eleven with a depth of about 80 m with a value of 47.4 ± 2.4 μgg^{-1}. Lower values of ^{40}K were reported in both studies but the highest value of ^{40}K was recorded in layer ten (S1Ly-A) with a value of $3.70 \pm 0.05 \mu gg^{-1}$. The values for site one and the results of Landsberg *et al*. [35] were presented in Table 5. In site two, the concentrations of ^{226}Ra varied from 0.5 to 8.1 ± 0.4 μgg^{-1} with the highest value of 8.1 ± 0.4 μgg^{-1} noted in Layer one (S2Lx-A). When compared with the value of 3.30 ± 0.28 μgg^{-1}obtained in Landsberg *et al*. [35] using the same approach, the present work is half times lower. For ^{232}Th, the highest concentration was found in layer nine (S2Lz-A) with a depth of about 60 m with a value of 29.9 ± 1.5 μgg^{-1}. In contrast with Landsberg *et al*. [35] with a value of 18.51 ± 0.39 $\mu gg^{-1}$for ^{232}Th in rocky flat soil measured in Texas, this present work is distinctly higher by a factor of 1.62. Lower values of ^{40}K were equally reported in both studies. In this study, the highest value of ^{40}K reported in layer ten (S2Lz-A) with a value of 1.64 ± 0.04 μgg^{-1} is 0.89 lower than the value of ^{40}K reported by Landsberg *et al*. [35]. The values for site two and Landsberg *et al*. [35]'s work were presented in Table 6.

Table 3 Activity concentration of radionuclides ($Bqkg^{-1}$)

Site one				**Site two**			
Sample ID	^{226}Ra	^{232}Th	^{40}K	Sample ID	^{226}Ra	^{232}Th	^{40}K
S1Lx-A	<6.2	92.9 ± 4.6	0.126 ± 0.006	S2Lx-A	101 ± 5.0	95.0 ± 4.7	0.018 ± 0.001
S1Lx-B	Nill	Nill	Nill	S2Lx-B	102 ± 5.1	87.2 ± 4.4	0.017 ± 0.001
S1Ly-A	97.9 ± 4.9	181 ± 9.0	0.134 ± 0.007	S2Ly-A	<6.2	99.3 ± 5.0	0.035 ± 0.002
S1Ly-B	136 ± 6.8	192 ± 9.6	0.136 ± 0.007	S2Ly-B	<6.2	93.8 ± 4.7	0.037 ± 0.002
S1Lz-A	161 ± 8.0	283 ± 14.2	0.125 ± 0.006	S2Lz-A	<6.2	122 ± 6.1	0.059 ± 0.003
S1Lz-B	135 ± 6.7	277 ± 13.8	0.133 ± 0.007	S2Lz-B	<6.2	115 ± 5.8	0.064 ± 0.003
Mean	107.22	205.18	0.1308	Mean	37.9666	102.05	0.038333

Global Mean	25*	25*	370*	Global Mean	25*	25*	370*

***** represents UNSCEAR [38]

Table 4 Radioactivity ratios in the study area ($Bqkg^{-1}$)

Site one					Site two				
Sample ID	$^{226}Ra/^{40}K$	$^{232}Th/^{40}K$	$^{226}Ra/^{232}Th$	$^{226}Ra + ^{232}Th + ^{40}K$	Sample ID	$^{226}Ra/^{40}K$	$^{232}Th/^{40}K$	$^{226}Ra/^{232}Th$	$^{226}Ra + ^{232}Th + ^{40}K$
S1Lx-A	49.206	737.302	0.067	99.226	S2Lx-A	5611.111	5277.778	1.063	196.018
S1Lx-B	-	-	-	-	S2Lx-B	6000.000	5129.412	1.170	189.217
S1Ly-A	730.597	1350.746	0.541	279.034	S2Ly-A	177.143	2837.143	0.062	105.535
S1Ly-B	1000.000	1411.765	0.708	328.136	S2Ly-B	167.568	2535.135	0.066	100.037
S1Lz-A	1288.000	2264.000	0.569	444.125	S2Lz-A	105.085	2067.797	0.051	128.259
S1Lz-B	1015.038	2082.707	0.487	412.133	S2Lz-B	96.875	1796.875	0.054	121.264
Mean	819.725	1568.654	0.523	312.531	Mean	990.435	2662.174	0.372	140.055
Global Mean	0.067*	0.067*	1*	420*	Global Mean	0.067*	0.067*	1*	420*

***** represents UNSCEAR [38]

Table 5 Comparing the NAA Concentrations of ^{226}Ra, ^{232}Th (μgg^{-1}), and K (%) from Site One Borehole Samples with NAA Values by Landsberger *et.al*. [35].

Sample ID	**Concentrations in Abuja, Nigeria (present study).**			**Concentrations Reported by Landsberger *et.al.* [35] for Rocky Flat Soil in Texas, USA.**		
	^{226}Ra (μgg^{-1})	^{232}Th (μgg^{-1})	K (%)	^{226}Ra (μgg^{-1})	^{232}Th (μgg^{-1})	K (%)
S1Lx-A	<0.5	22.9 ± 1.1	3.48± 0.03	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S1Lx-B	Nil	Nil	Nil	Nil	Nil	Nil
S1Ly-A	7.9 ± 0.4	44.6 ± 2.2	3.70 ± 0.05	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S1Ly-B	10.9 ± 0.5	47.4 ± 2.4	3.75 ± 0.05	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S1Lz-A	12.9 ± 0.6	47.4 ± 2.4	3.47 ± 0.03	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S1Lz-B	10.8 ± 0.5	68.2 ± 3.4	3.69 ± 0.04	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20

Table 6 Comparing the NAA Concentrations of ^{226}Ra, ^{232}Th (μgg^{-1}), K (%) from Site Two Borehole Samples with NAA Values by Landsberger *et.al.* [35].

Sample ID	Concentrations in Abuja, Nigeria (present study).			Concentrations Reported by Landsberger *et.al.* [35] for Rocky Flat Soil in Texas, USA		
	^{226}Ra (μgg^{-1})	^{232}Th (μgg^{-1})	K (%)	^{226}Ra (μgg^{-1})	^{232}Th (μgg^{-1})	K (%)
S2Lx-A	8.1 ± 0.4	23.4 ± 1.2	0.5± 0.01	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S2Lx-B	8.2 ± 0.4	21.5 ± 1.1	0.46 ± 0.01	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S2Ly-A	<0.5	24.5 ± 1.2	0.96± 0.02	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S2Ly-B	<0.5	23.1 ± 1.2	1.03 ± 0.02	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S2Lz-A	<0.5	29.9 ± 1.5	1.64± 0.04	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20
S2Lz-B	<0.5	28.4 ± 1.4	1.77 ± 0.04	3.30 ± 0.28	18.51 ± 0.39	1.84 ± 0.20

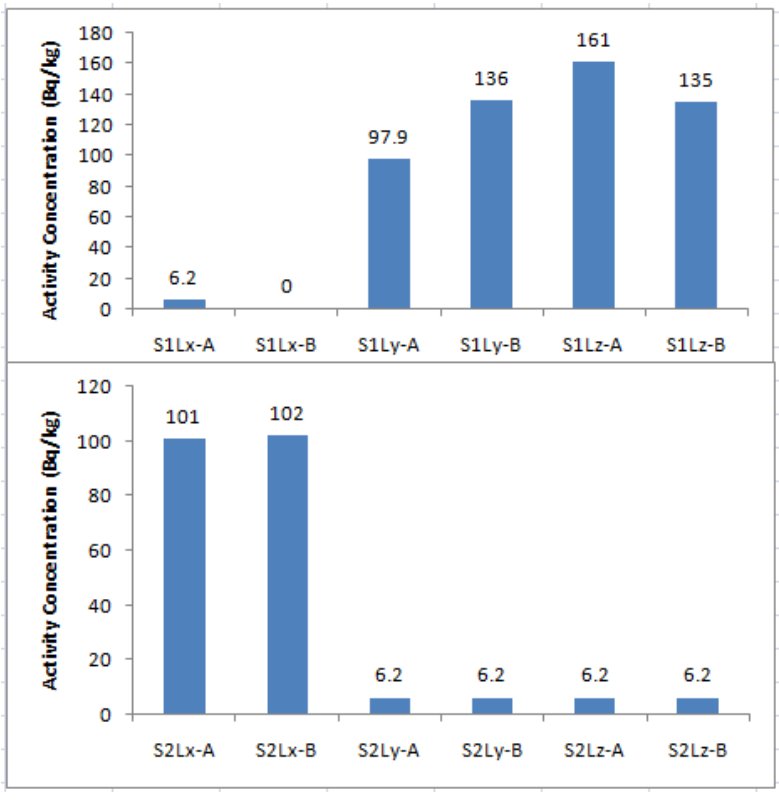

Figure 3a Activity concentration of ^{226}Ra.

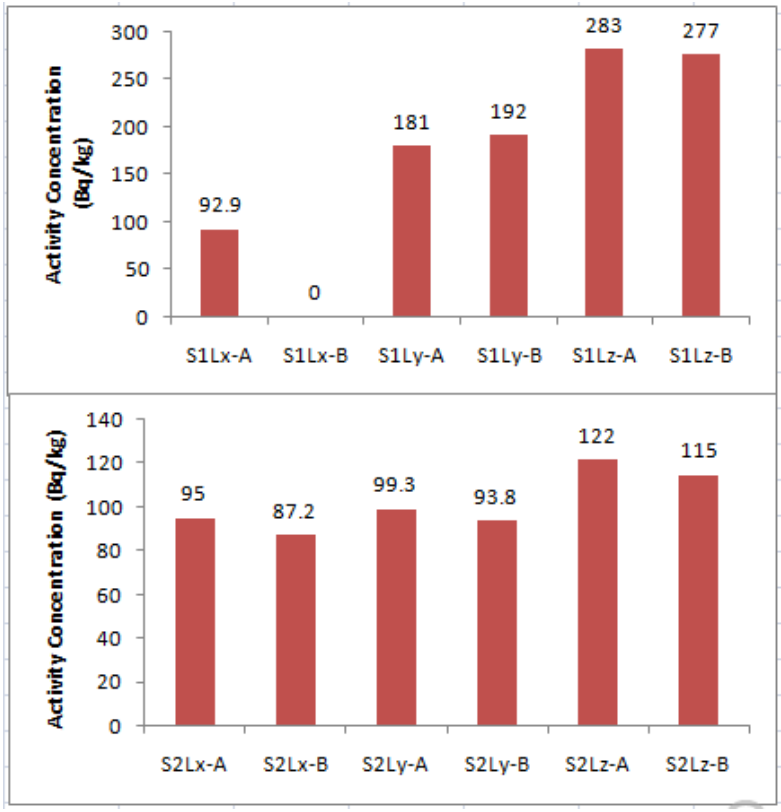

Figure 3b Activity concentration of ^{232}Th.

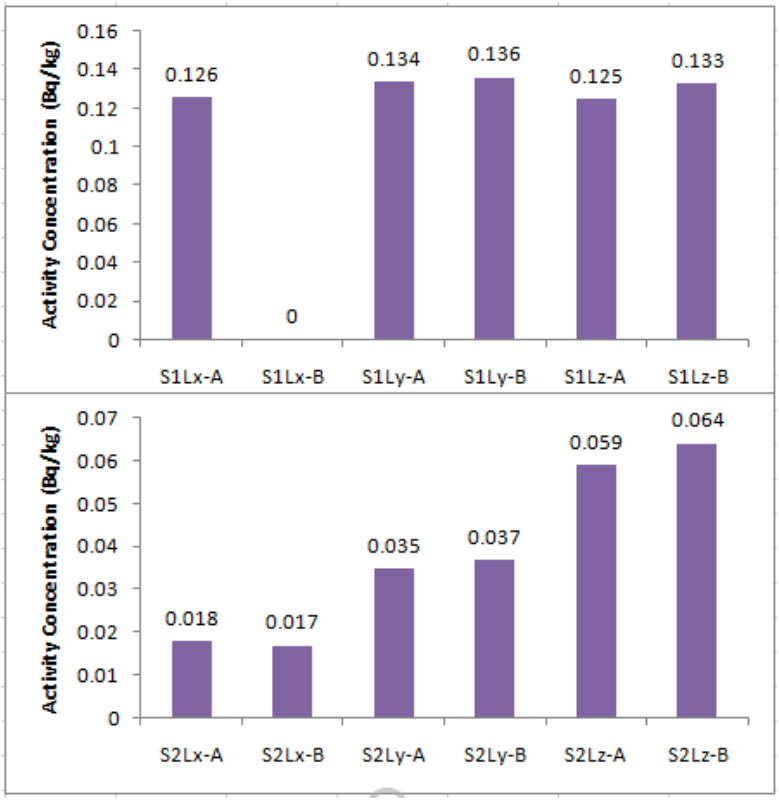

Figure 3c Activity concentration of ^{40}K

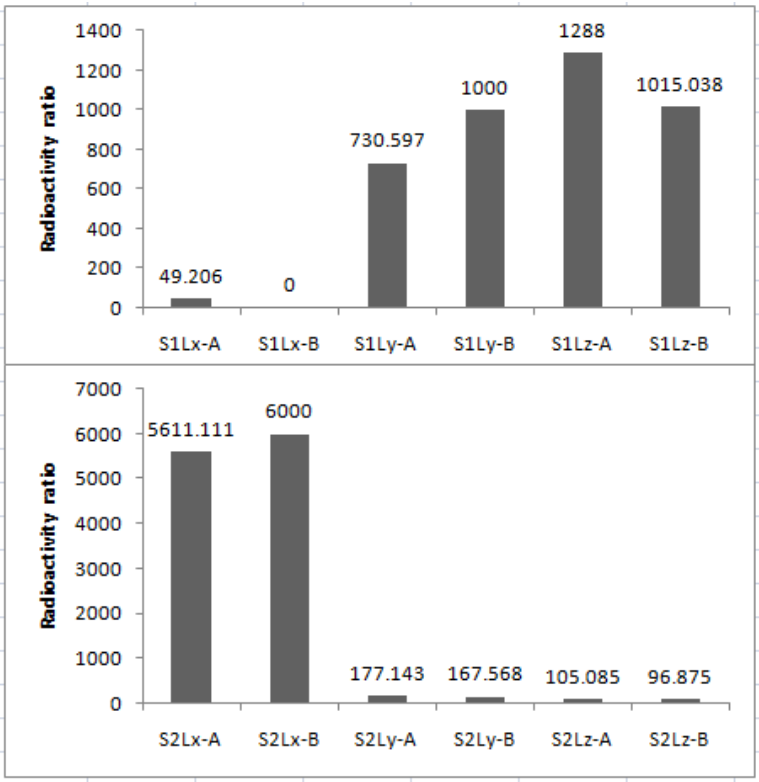

Figure 3d Ratio of Ra-226 to K-40 activity concentrations.

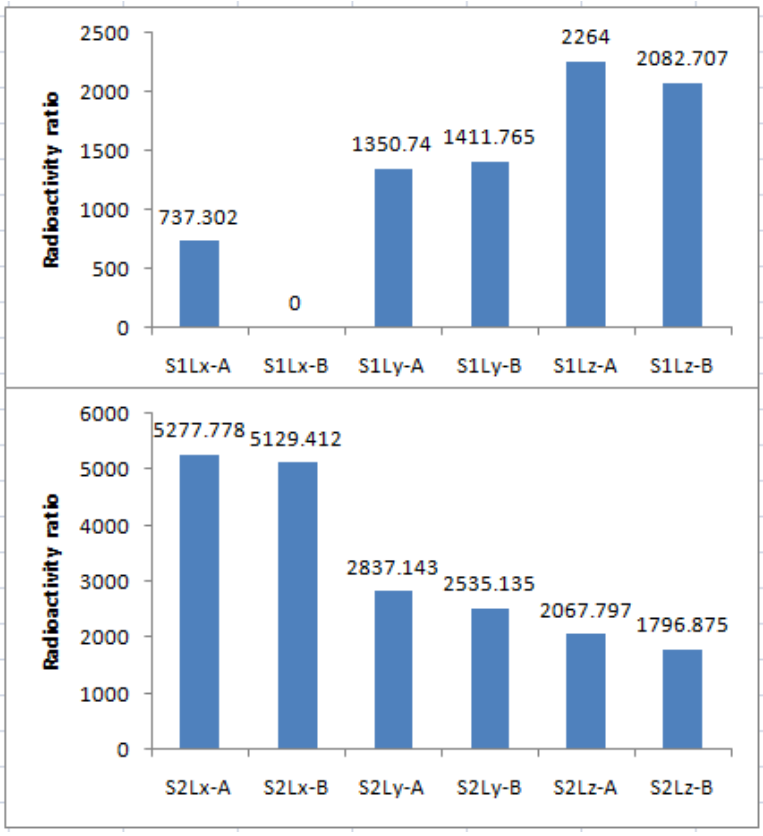

Figure 3e Ratio of Th-232 to K-40 activity concentrations.

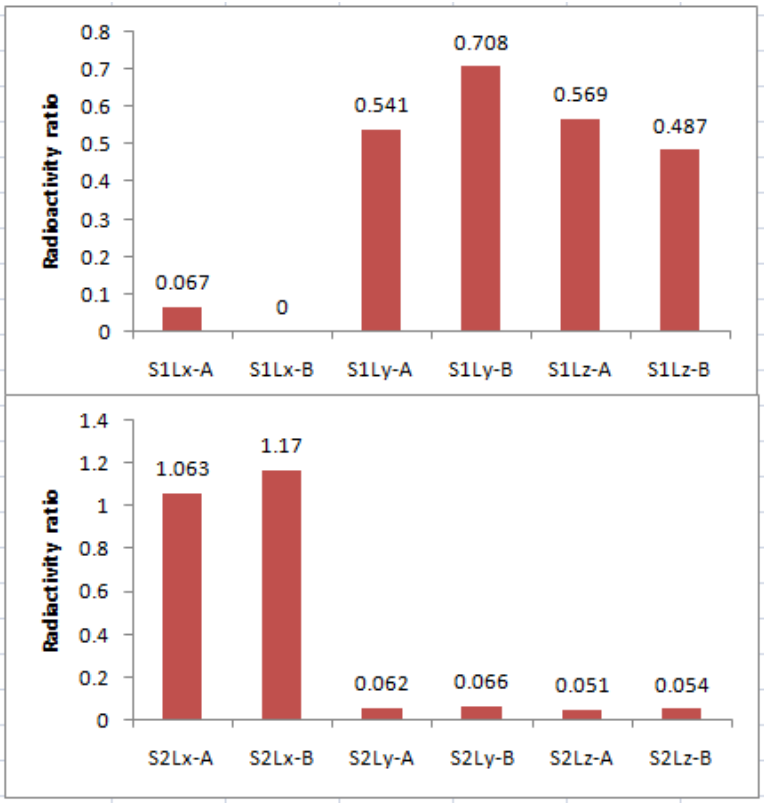

Figure 3f Ratio of Ra-226 to Th-232 activity concentrations.

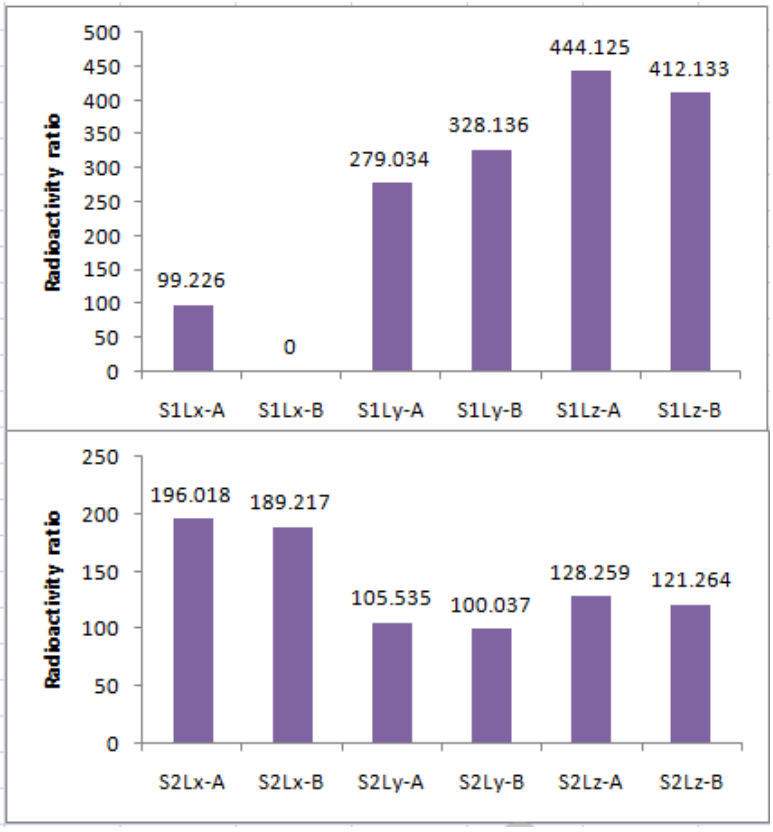

Figure 3g Total activity concentrations.

4.1. Radiological Risks Estimation

Six (6) parameters were estimated in order to justify the safety of the drillers in Abuja, Nigeria. The parameters are: radium equivalent activity, annual gonnadal equivalent dose, external hazard index, gamma index, annual effective dose equivalent, and excess lifetime cancer risk.

4.2. Radium Equivalent Activity Index

The γ-doses emission of ^{226}Ra, 232Th, and ^{40}K differs even if they are of the same quantity in a material. The radiological hazard risk exposure of these ^{226}Ra, ^{232}Th and ^{40}K from different layers to borehole drillers is useful to estimate the index called the radium equivalent activity, Ra_{eq}. The Ra_{eq} is the weighted sum of activities of ^{226}Ra, 232Th, and ^{40}K in a material. This is assumed that 1 Bqkg^{-1} of ^{226}Ra, 1.43Bqkg^{-1} of ^{232}Th and 0.077 Bqkg^{-1} of ^{40}K produce the same gamma dose rate [1, 39 – 40]. This index is given in Equation (3) as:

$$Raeq = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (3)$$

where,

A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K respectively.

The maximum Ra_{eq} from the borehole lithological samples must be less than 370 Bqkg^{-1}for safe exposure [38] so as to keep the external dose lower than1.5 mSvy^{-1}. It is a criterion limit and the activity within the recommended safety limit for industry. It can be observed that the value of 400.63 Bqkg^{-1} is recorded in site one of this study. This is higher than the recommended value by a factor of 1.1. In site two, the value of 183.90 Bqkg^{-1} is far less than the average safety value of 370 Bqkg^{-1}. Details of the estimated radium equivalent activity and other risks with their global average activity are presented in Table 7. The variations of Ra_{eq} in the two sites with the world's average are shown in Fig. 4a.

4.3. The External Absorbed Dose Rate

The outdoor external absorbed dose rate (D_{Ex}) at 1 m above the ground level is computed from the γ-radiation arising from ^{226}Ra, 232Th, and ^{40}K assumed to be uniformly dispensed in the ground. For the conversion of γ-radiation emanating from ^{226}Ra, 232Th, and ^{40}K, the facts of 0.436 nGy h^{-1} Bq^{-1} kg^{-1} for ^{226}Ra, 0.599 nGy h^{-1} Bq^{-1} kg^{-1} for ^{232}Th, and 0.0417 nGy h^{-1} Bq^{-1} kg^{-1} for ^{40}K were employed for estimation of D_{Ex}. The conversion factors have been considered from literature of Beck [41], Akinloye *et al*. [1], Avwiri *et al*. [36], Qureshi *et al*. [7], Isola *et al*. [37] and Adagunodo et al. [51]. Jacob *et al*. [42] and Akinloye *et al*. [1] reported that, "^{137}Cs, ^{90}Sr, ^{87}Rb, ^{138}La, ^{176}Lu, and ^{235}U decay series have negligible contributions to the total dose emanating from the environment background" .The D_{Ex} is estimated using Equation (4) as given by European Commission (1999).

$$D_{Ex} = 0.436A_{Ra} + 0.599A_{Th} + 0.0417A_k \text{ (nGy h}^{-1}\text{)} \quad (4)$$

The average outdoor external absorbed doses due to the existence of ^{226}Ra, 232Th, and ^{40}K in site one and site two are 169.66 and 77.68 nGy h^{-1} respectively. The two values are higher than the world's average value of 59 nGy h^{-1} [43] by the factors of 2.86 and 1.30 respectively. Details of the estimated outdoor external absorbed doses due to the existence of ^{226}Ra, 232Th, and ^{40}K are presented in Table 7. The variations of D_{Ex} in the two sites with the world's average are shown in Fig. 4b.

4.4. Annual Gonnadal Equivalent Dose

The gonad (organ that produces gametes; ovary or testis), the bone surface cells, and the activity bone marrow are regarded as organs of interest according to UNSCEAR [38]. This is necessary because borehole drilling requires the drillers to actively stay on the site at least for a day in a favourable terrain. Therefore, the annual gonnadal equivalent dose (AGED) is estimated using Equation (5) as given by Avwiri *et al*. [36] and Adagunodo et al. [51].

$$\text{AGED (Sv yr}^{-1}) = 3.09A_{Ra} + 4.18A_{Th} + 0.314A_K \quad (5)$$

Where A_{Ra}, A_{Th}, and A_K are the radioactivity concentration of ^{226}Ra, 232Th, and ^{40}K respectively.

The estimated AGED for the two sites are 1180 and 543.9 Sv yr^{-1}. These values surpass the world's average AGED value by the factors of 3.96 and 1.81. Layer-by-layer estimates of AGED in the two sites are presented in Table 7 with their variations shown in Fig. 4c.

4.5. External Hazard Index

The gamma ray radiation hazards index due to the specified radionuclides were assessed by external radiation hazard and was calculated using Equation (6) according to UNSCEAR [43].

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (6)$$

where,

$A_{Ra} \sim A_U$, A_{Th} and A_K are the average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1} respectively.

For the radiation hazard to be acceptable, it is recommended that the H_{ex} be less than unity. The estimated H_{ex} for site one borehole is 1.1. This is higher than the recommended value of ≤ 1. Site two borehole however, has H_{ex} of 0.5. This is lower than the recommended value of $\leq$ 1 [43]. Layers' estimated values for the two sites are presented in Table 7 with their deviation from the global average shown on Fig. 4d.

4.6. Gamma Index Representation

Gamma index is used to evaluate the γ-radiation hazard related to the natural radionuclide in the particular samples under investigation. It could also be used as a measure to identify the radiological safe materials or samples when human are being overexposed to them. The gamma index representation (I_{yr}) is estimated using Equation (7) as presented by OECD [39], Avwiri *et al*. [36] and Adagunodo et al. [47].

$$I_{yr} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \quad (7)$$

From the two sites, the average values of 2.77 and 1.27 Sv yr^{-1} were estimated. These values are greater than the world's average value of 1 Sv yr^{-1}by the factors of 2.8 and 1.3 as reported by Avwiri [36]. Details of the gamma index representation of Abuja are presented in Table 7 with its variation with the world's average value shown in Fig. 4e.

4.7. Annual Effective Dose Equivalent

The outdoor annual effective dose equivalent received by human is estimated from the outdoor external dose rate (D_{Ex}), occupancy factor which is defined as the level of human occupancy in an area in proximity with radiation source; is given as 20% of 8760 hours in a year, and the conversion factor of 0.7 Sv Gy^{-1} which is used to convert the absorbed does in

air to effective dose [43 – 44]. The annual effective dose equivalent is estimated using Equation 8.

$$AEDE = D_{Ex}\ (nGy\ h^{-1}) \times 20\%\ of\ 8760\ hr \times 0.7\ (Sv\ Gy^{-1}) \times 10^{-3} \quad (8)$$

At site one, the value of AEDE ranges from 0.072 (S1Lx-A) to 0.294mSv y^{-1} (S1Lz-A) with an average of 0.208mSv y^{-1}. The AEDE of the second site ranges from 0.072 (S2Ly-B) to 0.124 $mSvy^{-1}$ (S2Lx-A) with an average of 0.095 $mSvy^{-1}$. The mean values from the two sites surpass the world's average value of 0.07 mSv y^{-1} by the factors of 2.97 and 1.36 respectively. Details of all the samples are recorded in Table 7 with its variation with the world's average value shown in Fig. 4f.

4.8. Excess Lifetime Cancer Risk

The excess lifetime cancer risk (ELCR) is estimated from the annual effective dose equivalent using Equation (9). The higher the ELCR, the higher the AEDE since they are directly proportional.

$$ELCR = AEDE \times LE \times RF \quad (9)$$

where LE is the life expectancy which is given as 66 years and RF, a fatal risk factor per Sievert is given as 0.05 Sv^{-1} [45].

We show in Table 7 that the estimated mean of ELCR from the two sites (0.687×10^{-3} and 0.314×10^{-3}) are greater than the world's mean value of 0.29×10^{-3} by the factors of 2.37 and 1.08 respectively. From the literature, ELCR due to γ-radiation have been estimated from different part of the world but overall mortality and lifetime cancer risk has not been related to the population of an area having unusual high value of ELCR [7, 11, 46]. Nevertheless, Taskin *et al*. [11] and Adagunodo et al. [5 – 6, 47, 51] reported that, "long exposure to radium and thorium through inhalation pose health challenges to human beings among which are: chronic disease, cancer of various types, kidney diseases, bone weakening, tumors, sterility, and above all death". Since it has been reported by the world health organization that Nigeria has the highest record of cancer related diseases in Africa. Therefore, people are advised to refrain or take caution in an environment with high concentration of radium and thorium. Figure 4g shows the plot of ELCR on the two sites which reveals the extremely high variation to that of global average.

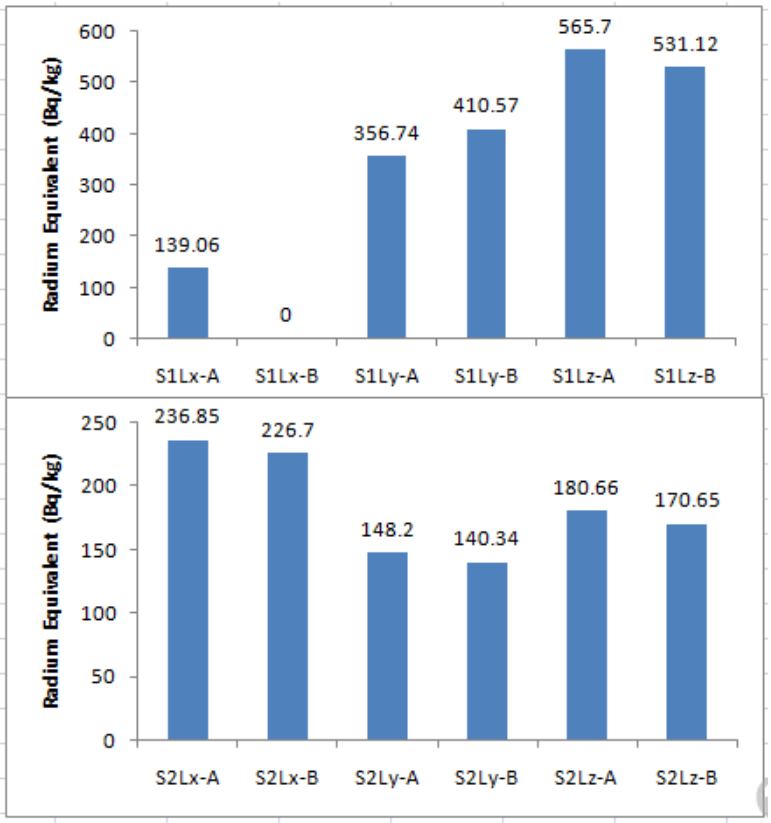

Figure 4a Radium equivalent activity index of the two sites

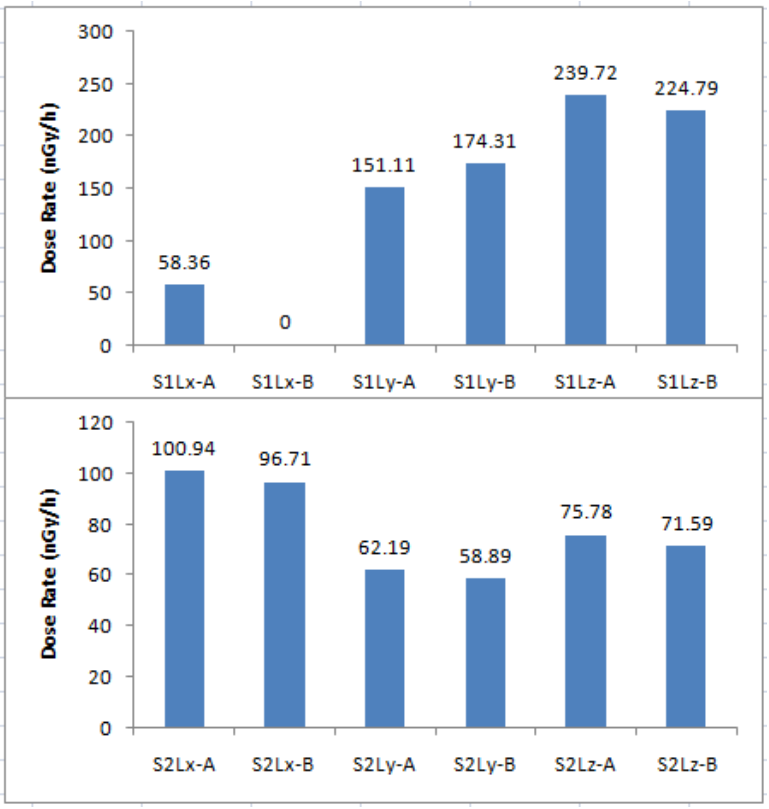

Figure 4b The external absorbed dose rate of the two sites

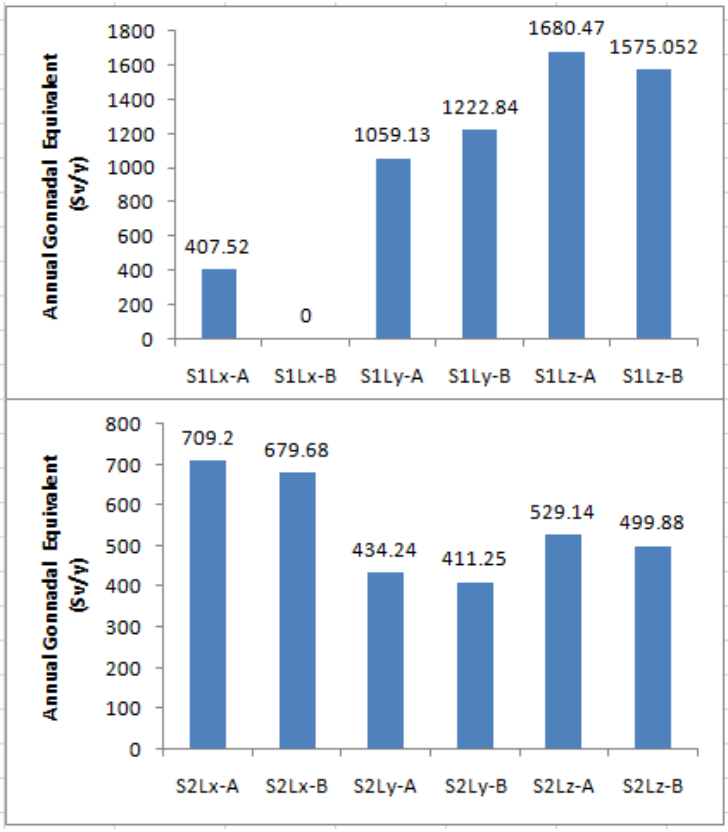

Figure 4c Annual gonnadal equivalent dose of the two sites

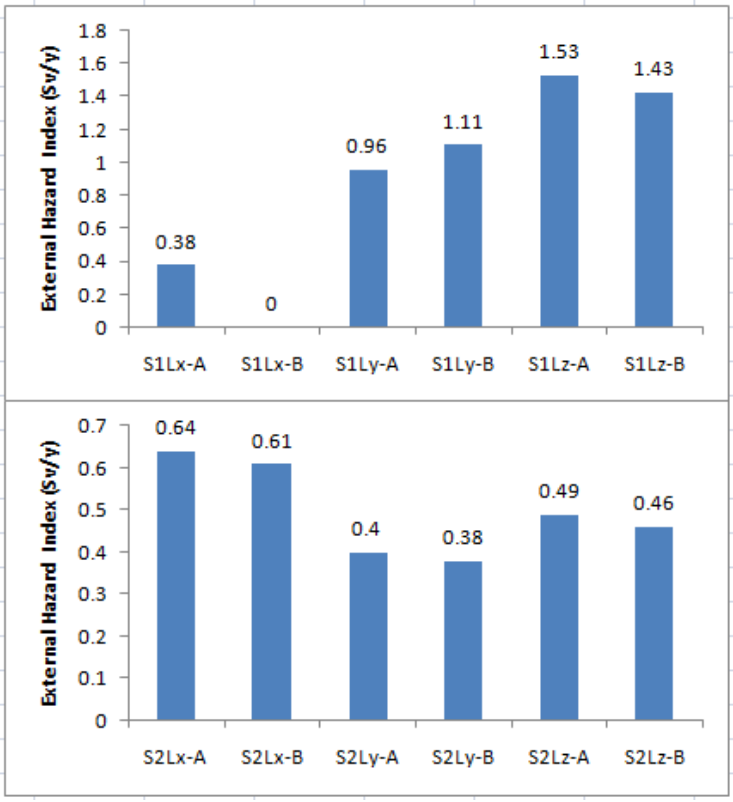

Figure 4d External hazard index of the two sites

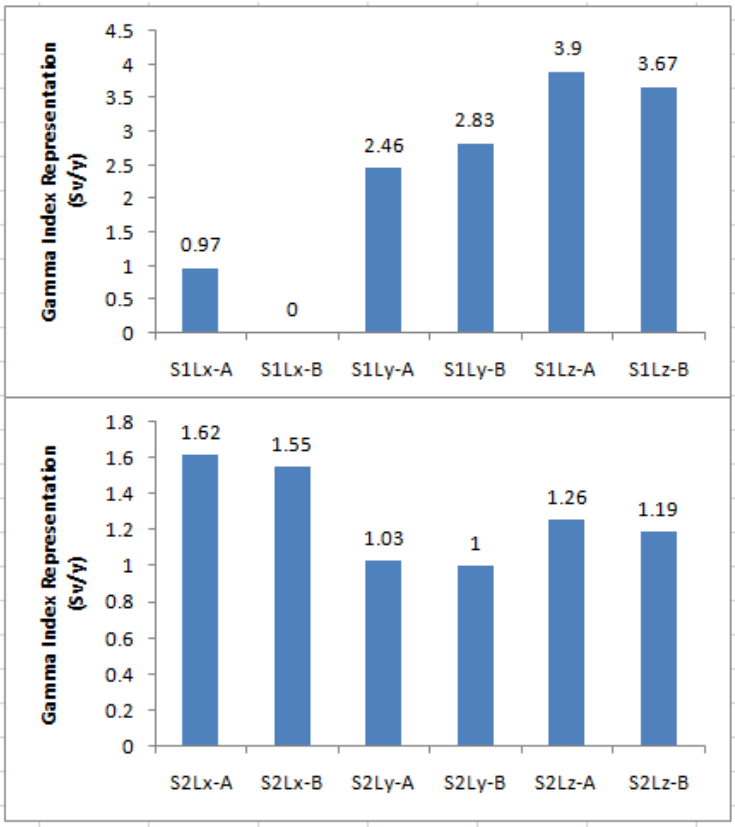

Figure 4e Gamma index representation of the two sites

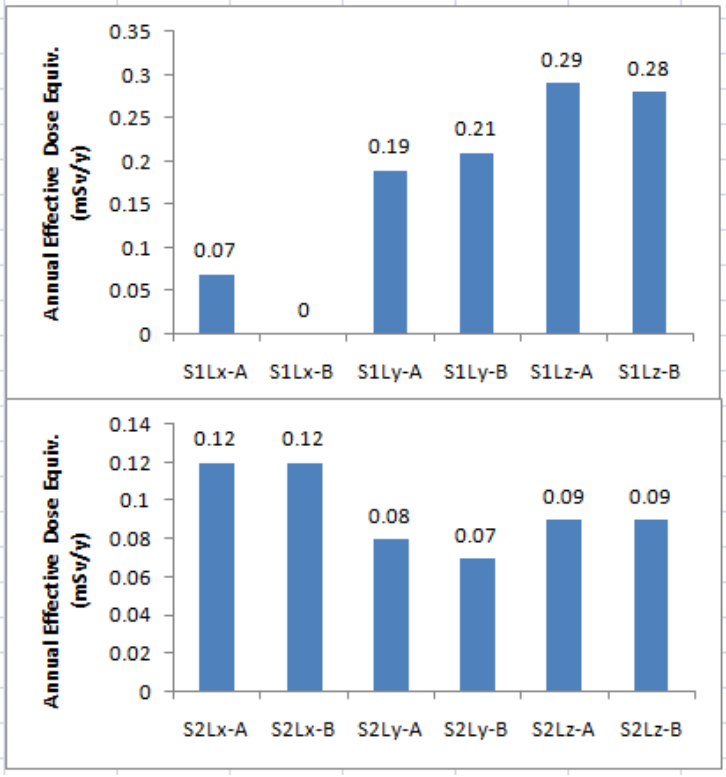

Figure 4f Annual effective dose equivalent of the two sites

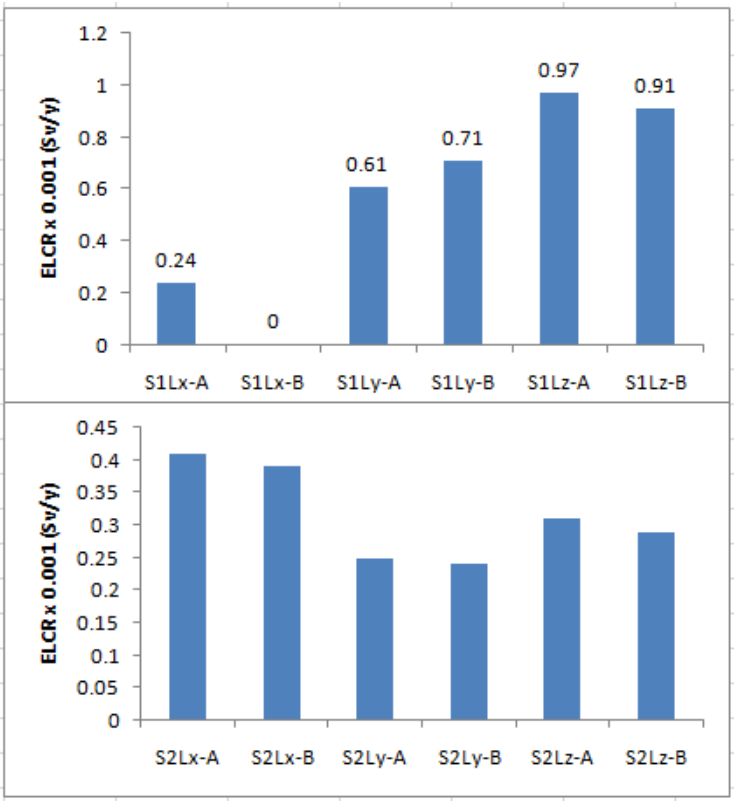

Figure 4g Excess lifetime cancer risk of the two sites

Table 7 Estimated radiological risks

Sample ID	D_{Ex} (nGy h^{-1})	Ra_{eq} (Bqkg^{-1})	H_{ex} (Svy^{-1})	AEDE (mSvy^{-1})	AGED (Svy^{-1})	I_{yr} (Svy^{-1})	ELCR x 10^{-3} (Svy^{-1})
Site one							
S1Lx-A	58..36	139.06	0.38	0.07	407.52	0.97	0.24
S1Lx-B	---	---	---	---	---	---	---
S1Ly-A	151.11	356.74	0.96	0.19	1059.13	2.46	0.61
S1Ly-B	174.31	410.57	1.11	0.21	1222.84	2.83	0.71
S1Lz-A	239.72	565.70	1.53	0.29	1680.47	3.90	0.97
S1Lz-B	224.79	531.12	1.43	0.28	1575.052	3.67	0.91
Mean	169.66	400.64	1.08	0.21	1189.003	2.77	0.69
Global Mean	59**	370***	1**	0.07**	300****	1****	0.29*****
Site two							
S2Lx-A	100.94	236.85	0.64	0.12	709.20	1.62	0.41
S2Lx-B	96.71	226.70	0.61	0.12	679.68	1.55	0.39
S2Ly-A	62.19	148.20	0.40	0.08	434.24	1.03	0.25
S2Ly-B	58.89	140.34	0.38	0.07	411.25	1.0	0.24
S2Lz-A	75.78	180.66	0.49	0.09	529.14	1.26	0.31
S2Lz-B	71.59	170.65	0.46	0.09	499.88	1.19	0.29
Mean	77.68	183.90	0.50	0.10	543.90	1.27	0.31

Global Mean	59**	370***	1**	0.07**	300****	1****	0.29*****

****** represents UNSCEAR [43], *** represents UNSCEAR [38]

**** represents Adagunodo *et al*. [51], ***** represents Taskin *et al*. [11]

5. CONCLUSION

This study demonstrated the efficacy of using NAA to determine the natural radioactivity in randomly collected rock samples of borehole logs at two locations in Abuja. This was done in order to determine the level of exposure of drillers to γ-radiation through inhalation and to estimate the risks associated with their over-exposure. The estimated risks revealed that over half of the samples analyzed exhibited unusual mean values greater than the world's average value. The rocks in Abuja are enriched in granitic composition which exhibited higher activity concentration of radium and thorium with low potassic value. Since 80% of inhabitants of Abuja in Nigeria and suburbs rely on private boreholes for water supply, the risk due to long exposure to these radionuclides may pose hazard health risk on drillers more than the benefits they received from borehole drilling. Therefore, it is recommended that the drillers should employ the use of dusk mask to reduce the level at which these radioactive materials are inhaled.

ACKNOWLEDGEMENT

The authors would like to thank the management of Covenant University for supporting this present study financially to this point. Also, thanks to both Universiti Teknologi Malaysia Grant Scheme Project number: Q.J130000.2526.03H65 and Nuclear Malaysia Agency for the analysis of samples for this research. The authors appreciate Maxico Hydrosolution Consult for the geosurvey and drilling of boreholes for step by step data acquisition below ground level.

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