http://dx.doi.org/10.5455/sf.95355

Science Forum (Journal of Pure and Applied Sciences)

journal homepage: www.atbuscienceforum.com

Concentration of radon and other elements in groundwaters of the Jos and Bukuru younger granite aquifers

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ABSTRACT

The Jos-Bukuru crystalline rocks have high radioactivity, but not much is known about the concentration of radon in the waters of its aquifers. In this work, the activity concentrations of radon-222 (^{222}Rn) were investigated from 20 water samples collected at different locations within the Jos-Bukuru area. The analysis of radon was done using liquid scintillation counter. A total of 15 out of the 20 water samples were analyzed for anions and cations. The anions (SO_4^{-2} and Cl^-) were analyzed using a multiparameter and HCO_3^- by titration. The cations (major ions, trace elements, and rare earth elements were analyzed using inductively coupled plasma mass spectrometry. Radon concentration in groundwater of the study area ranges from 1.62 to 24.55 Bq/l with a mean value of 15.62 Bq/l. only 25% of the water sources had radon above the 10 Bq/l recommended by the WHO. These values were obtained within the Jos and Bukuru boitite younger granite aquifers. The variation in radon content in water is the result of: (1) the actual use of the wells in the area such as extraction of groundwater which increases the groundwater circulation thereby decreasing the radon content and (2) bad well constructions with inflow of surface water, and (3) bedrock geology. Radon behaved independently with regard to the major ions and some of the trace elements but showed a positive but not significant relationship with uranium and some of the rare earth elements indicating a possible contribution of these elements to the concentration of radon in the waters. The annual effective doses due to ingestion of ^{222}Rn in water for the three categories of people vary from 0.038, 0.077, and 0.271 mSv/y for adults, children, and infants, respectively. These are within the recommended limits of 0.1 mSv/y for adults and children but high for infants. The composition of the groundwaters in the area is dominated by natural water–rock interactions while other areas were highly impacted by anthropogenic sources. On the basis of total dissolved solids, all the samples are within the range of desirable to permissible for drinking.

ARTICLE INFO

Article history:
Received 10 July 2021
Received in revised form
01 August 2021
Accepted 02 August 2021
Published 12 October 2021
Available online 12 October 2021

KEYWORDS

Bukuru
Crystalline rocks
Radioactivity
Radon-222 (222 Rn)

1. Introduction

One of the most important contributors of radioactivity in groundwater is radon. It has three different isotopes, but only radon-222 (^{222}Rn), with a half-life of 3.82 days, formed within the uranium chain by the decay of ^{226}Ra, is of interest as the others are very short-lived (Somlai, 2007).

Human exposure to a high concentration of radon for a long period has significant health effects ranging from respiratory functional changes to cancer of the lungs and stomach and gastrointestinal tract (Beir, 1999; Kendal and Smith , 2002).

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Studies on radon in groundwater have been carried out globally (Binesh et al., 2010; Byong and Chang, 2019; Idriss et al., 2011; Marques et al, 2004; Otwoma and Mustapha , 1998; Vikas et al., 2012).

In Nigeria, groundwater samples from various locations have been investigated (Akinnagbe et al., 2018; Emmanuel and Theophillus, 2019; Garba et al., 2013; Gbadebo et al., 2021; Joseph et al., 2018; Kalip et al., 2018; Olise et al., 2016; Pauline et al., 2021)

The Jos-Bukuru younger granites have been studied in detail with regard to their radioactivity and were found to contain high radioactive elements (Solomon, 2005). While much is known about the radioactivity of these rocks, nothing has been done about the concentration of radon in waters of the aquifers of the younger granites of the Jos and Bukuru areas. The aim of this study was to determine the concentration of radon and other elements in the groundwater of the Jos and Bukuru crystalline aquifers.

2. Methodology

2.1. Description of the study area

The study area falls within parts of Jos North, Jos South, and Jos East Local Government Area of Plateau state, Nigeria (Fig. 1). It lies between Latitudes 8°50′ to 9°59′ and Longitudes 9°45′ to 9°58′.

The Jos Plateau is known for its topographically high points as well as low areas and hosts over 80% of the jurassic younger granite rocks in Nigeria. The younger granites of the Jos–Bukuru area have been studied extensively (Bowen et al., 1976; Ike, 1983; Macloeod et al.,1971; Turner, 1976) because they were recognized as the source of rich alluvial cassiterite deposits. The most striking petrographic feature of the whole province is the overwhelmingly acid nature of the rocks and the similarity of the rock types found in all areas. Over 95% of the rocks are classified as acidic with basic rocks forming the remaining 5%. Many of the rocks have strongly *alkaline* to *peralkaline* compositions, others are *aluminous* to *peraluminous*. More than 50 complexes of the younger granites occur in Nigeria varying from <2 to >25 km in diameter (Kinnaird et al., 1981) and occur as ring dykes with a total area of about 7,500 km^2 with individual massifs varying from 1,000 km^2 to <1 km^2.

2.2. Sampling and analytical methods

A total of 15 water samples were collected with three (one for radon, cations, and anions) samples collected from each location. The locations of each sampling site were taken using the global positioning system. Field parameters (electrical conductivity, pH, temperature, and total dissolved solids (TDS) were measured with a HACH field kits.

A 250 ml plastic container was used in collecting the water samples. The sample bottle was first rinsed with the water to be collected and thereafter, the water sample was collected. Care was taken in the collection of the sample to avoid air bubbles and to avoid the outgassing of ^{222}Rn gas. Also, boreholes were pumped and allowed to flow each for at least 2 minutes before samples were collected in order to ensure that fresh samples were obtained. Each collected sample was properly labeled using a tape and permanent marker and the time of sample collection was noted. The samples were immediately sent to the laboratory for analysis to avoid the decay of ^{222}Rn with half-life of 3.8 days.

Radon was analyzed using liquid scintillation counter (Tri-Card LSA 1,000) at the Center for Energy Research and Training, Ahmadu Bello University Zaria, Kaduna, Nigeria. 10 ml of each sample was added into a vial containing 10 ml of toluene-based cocktail (scintillator) using a hypodermic syringe. The vials were tightly capped and shaken vigorously for 3 minutes to extract ^{222}Rn in the water phase into the organic scintillator. In a similar manner, a blank sample for the background was prepared using distilled water that has been kept in a glass bottle for at least 21 days. The prepared samples were allowed to stand undisturbed for at least 3 hours each in order for ^{222}Rn and its alpha decay products attain equilibrium before counting.

Sulfate was analyzed using Multi Ion Parameter Hanna U.S.A Model 721. Chloride and bicarbonate by titration methods at the University of Jos, Department of Geology. Major, trace, and rare earth elements were analyzed with the inductively coupled plasma optical emission spectroscopy at the Bureau Veritas Minerals Laboratory, Canada.

3. Results and Discussion

3.1. Physicochemical parameters in the study area

Physico-chemical parameters of the Jos – Bukuru crystalline aquifers are presented in Table 1. With a pH range of 7.3–8.9 most of the samples (53.33%) are slightly alkaline to alkaline in nature. The TDS values ranged from 6 to 275 mg/l, with an average of 98.47 mg/l. 26.67% of the water in the study area have TDS values above 100 mg/l (Table 2) and electrical conductivity ranging from 13 to 558 µS/cm indicating waters in the area to be fresh.

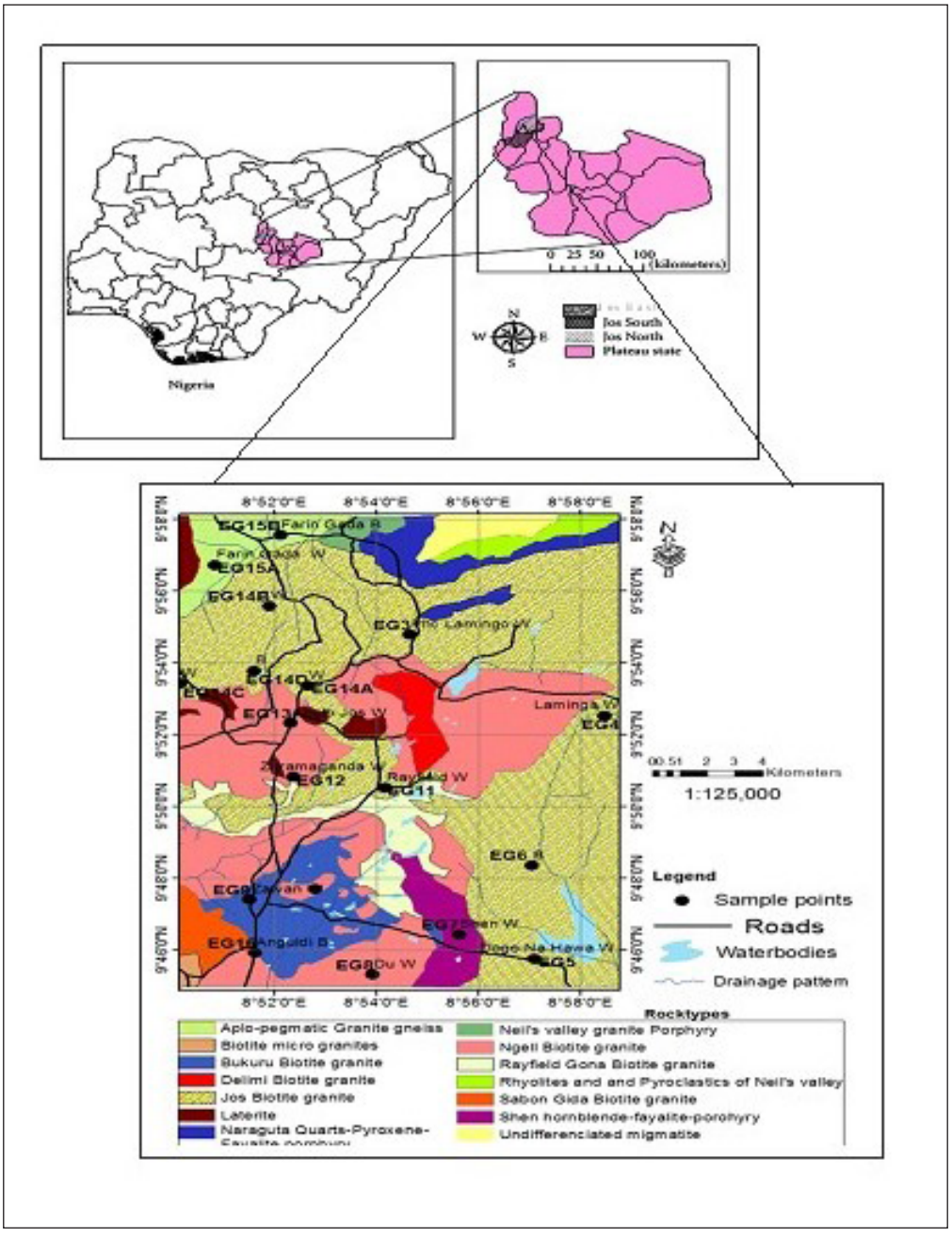

Figure 1. Location map of the study area.

The concentration of the cations is in the order of Na > Ca > K > Mg and the anions are in the order of Cl > HCO_3 > SO_4. These ions also correlated well with TDS (Table 2) which indicates that they are responsible for TDS in the waters (Table 2). This order of abundance of the ions and their close association in the waters accounting for 43.59% of the variance indicates rock water interaction as the major control on the chemistry of the water. The high concentration of chloride could not have come from the crystalline rocks, as the micas that hosts the chloride contained traces of them (Macleod et al., 1971). Hence, anthropogenic inputs are the likely source from which chloride in the waters was sourced. Radon shows a negative correlation with pH, TDS, EC, and the other major ions in water except uranium indicating independent behaviors of radon with respect to all the parameters in water. The positive correlation of uranium and radon and their close association in factor 2 accounting for 20.65% of the variance means that uranium is responsible for the radon in the waters probably from accessory uranium-bearing minerals (Silver and Wright, 1975). Also,

Table 1. Physicochemical parameters, uranium, and radon.

S/N	Sample no.	Latitude	Longitude	ELEVATION (M)	TDS	TEMP (°C)	E. C	pH	Ca	Mg	Na	K	HCO_3^-	Cl^-	SO_4^{-2}	U	Rn
1.	EG 01	N09°59′33.3″	E008°54′30.2″	1,085	110	27	227	8.9	20.88	8.03	21.81	2.24	18.18	20.00	2.60	0.08	ND
2.	EG 02	N10°00′05.1″	E008°54′24.9″	1,059	79	27	159	8.2	14.96	7.33	17.25	2.72	39.39	10.00	3.70	0.01	ND
3.	EG 03	N09°54′45.8″	E008°54′41.0″	1,314	6	27	13	7.4	0.88	0.08	1.95	0.88	8.08	5.00	2.60	0.01	ND
4.	EG 04	N09°52′51.6″	E008°58′54.0″	1,326	8	26	17	7.3	1.02	0.14	2.31	2.04	8.08	5.00	7.50	0.08	4.96
5.	EG 05	N09°48′27.6″	E008°57′04.7′′	1,250	83	27	168	5.7	8.44	1.79	14.16	11.78	12.12	25.00	2.60	0.88	16.12
6.	EG 06	N09°48′23.3″	E008°57′03.3″	1,239	70	26	142	6.4	7.77	1.58	15.63	11.8	4.04	20.00	2.60	0.5	24.69
7.	EG 07	N09°46′27.2″	E008°55′37.4″	1,267	114	26	229	6.8	8.7	1.84	32.38	19.99	8.08	45.00	3.70	0.01	1.62
8.	EG 08	N09°45′36.1″	E008°53′21.8″	1,303	275	25	558	7.3	25.82	4.88	79.26	38.92	12.12	65.00	2.60	1.91	ND
9.	EG 09	N09°45′51.2″	E008°52′41.3″	1,293	11	25	23	7.3	1.34	0.16	2.46	2.63	8.08	10.00	3.70	0.04	24.55
10.	EG 10	N09°47′41.6″	E008°52′49.4″	1,296	25	25	51	6.8	3.04	0.34	7.28	4.46	8.08	15.00	2.60	4.47	21.83
11.	EG 11	N09°50′31.5″	E008°54′12.5″	1,307	16	26	32	6.4	1.73	0.16	4.16	1.77	8.08	15.00	3.70	0.01	ND
12.	EG 12	N09°50′47.4″	E008°52′21.1″	1,286	16	25	35	6.7	0.52	<0.05	7.45	0.42	8.08	10.00	2.60	0.01	ND
13.	EG 13	N09°52′17.5″	E008°52′18.5″	1,285	191	25	25	6.9	21.11	2.2	61.74	15.77	12.12	65.00	2.60	0.75	ND
14.	EG 14	N09°54′00.0″	E008°51′52.7″	1,230	269	26	532	7.6	47.04	6.41	57.84	24.72	20.20	60.00	2.00	0.16	ND
15.	EG 15	N09°57′44.5″	E008°51′40.5″	1,127	39	26	79	7.7	12.97	4.43	57.21	5.92	16.16	65.00	6.80	0.09	ND

Table 2. Correlation matrix for hydrochemical components of groundwater.

	TDS	EC	PH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	U	Rn	Zn	Mn	Rb	Sr
TDS	1															
EC	0.867	1														
PH	0.163	0.219	1													
Ca	0.902	0.821	0.387	1												
Mg	0.596	0.639	0.715	0.765	1											
Na	0.853	0.677	0.195	0.773	0.541	1										
K	0.892	0.843	-112	0.673	0.324	0.812	1									
HCO_3	0.274	0.291	0.601	0.471	0.789	0.228	-002	1								
Cl	0.776	0.579	0.050	0.709	0.416	0.962	0.768	0.102	1							
SO_4	-415	-351	0.158	-317	-126	-087	-306	0.006	-046	1						
U	0.105	0.093	-225	-024	-140	0.087	0.216	-180	.074	-263	1					
Rn	-323	-243	-428	-366	-412	-415	-147	-392	-347	-124	0.416	1				
Zn	0.247	0.323	0.132	0.194	.275	0.034	0.172	-165	-014	-385	0.282	0.098	1			
Mn	0.159	-124	-552	0.031	-140	0.106	0.158	-190	0.176	-277	0.055	0.368	0.051	1		
Rb	0.607	0.563	-239	0.441	0.038	0.621	0.790	-202	0.680	-139	0.551	0.172	0.031	0.071	1	
Sr	0.729	0.670	0.611	0.875	0.952	0.706	0.455	0.658	.627	-164	-106	-420	0.271	0.010	0.206	1

Table 3. Factor analysis.

Components	Factor 1	Factor 2	Factor 3	Factor 4
TDS	0.946	0.213	0.018	096
EC	0.876	0.119	0.137	0.147
PH	0.370	-778	0.169	0.293
Ca	0.941	-067	0.062	-097
Mg	0.780	-513	0.256	-049
Na	0.892	0.155	-325	-016
K	0.805	0.485	-143	0.050
HCO_3	0.445	-673	0.101	-118
Cl	0.813	0.255	-413	-057
SO_4	-280	-346	-623	0.271
U	0.062	0.578	0.323	0.493
Rn	-415	0.544	0.346	0.020
Zn	0.232	0.145	0.752	0.134
Mn	0.004	0.504	0.077	-779
Rb	0.547	0.673	-218	0.357
Sr	0.880	-342	.150	-128
Eigen value	6.975	3.306	1.677	1.234
% variance explained	43.591	20.659	10.484	7.711
Cumulative % variance	43.591	64.251	74.735	82.446

the close association of uranium and rubidium in factor 2 (Table 3) indicates the same source, since both are formed lately in the magma. Rubidium substitute for potassium in feldspars and mica and uranium is concentrated at the felsic end of the series (Krauskopf and Bird, 1995). Strontium correlates positively with calcium, this is because strontium replaces carbonate minerals as fissure infillings and as coatings and partly because it replaces calcium in plagioclase feldspars (Byong and Chang, 2019). There is a likelihood

that strontium may be occurring as strontianite in the waters since it correlates positively with bicarbonate (Duo Li et al., 2021).

3.2. Concentration of trace elements and relationship with radon

Zinc, nickel, lithium, manganese, chromium, and cobalt show substantial concentration in the waters of the area (Table 4). Zinc ranges from 1.9 to 57.1 µg/l, Ni has concentration ranging from < 0.2 to 4.1 µg/l, Cr ranges from < 0.5 to 5.3 µg/l, Li varies from 0.6 to 16.8 µg/l, Mn from < 0.05 to 141.54 µg/l and Cu from <0.1 to 16.6 µg/l. All the other trace elements show 90% – 100% of their concentration below the detection limit. The correlation between the trace elements and radon and uranium is very poor (Table 5) indicating no relationship with radon and uranium. However, zinc correlates with copper and vanadium with copper. Although zinc and copper are chalcophile element and are not known to have their ores in the crystalline rocks, zinc might have substituted for either iron or magnesium in the silicate structure as they rarely do and copper may be from chalcopyrite which are common in greisens of the younger granite rocks (Macleod, 1971). Lithium, vanadium, and chromium are all lithophile element, hence their positive correlation to each other.

3.3. Concentration of rare earth elements (REE) and relationship with radon

The REE in the groundwater is presented in Table 6. The concentrations of Neodymium (Nd) vary between 0.05 and 57.87 µg/l, Lanthanum (La) content ranges from 0.06 to 76.54 µg/l, Samarium (Sm) displays a range of 0.02 to 12.43 µg/l Europium (Eu) concentration ranges from <0.01 to 1.47 µg/l. Among the heavy rare earth elements, Gadolium (Gd) ranges from <0.01 to 15.75 µg/l, Thulium (Tm) ranged from <0.01 to 2.00 µg/l, Ytterbium (Yb) ranges from <0.01 to 11.70 µg/l and Lutelium (Lu) ranges from <0.01 to 1.55 µg/l. The rare earth elements correlated well with each other except with Er. Probably the Er is the radioactive type which has a half-life ranging from 1 second (erbium—145)—9.4 days (erbium—169) and because they are unstable (Encyclopedia Britanica) they must have changed to some other forms. However, there exist correlation between the rare earth elements with radon although not so significant (Table 7). This may probably signify the contribution of some of the radioactive rare earth elements to radon concentration in the waters.

Table 4. Trace elements.

S/N	Sample nO.	B µg/l	Co µg/l	Cu µg/l	Fe µg/l	Mn µg/l	Mo µg/l	Zn µg/l	Cr µg/l	Ni µg/l	Se µg/l	V µg/l	Li ug/l	Sn µg/l	Ti µg/l
1.	EG 01	<5	<0.02	16.6	<10	0.61	0.8	57.1	4.5	<0.2	<0.5	8	16.8	<0.05	<10
2.	EG 02	<5	<0.02	<0.1	<10	<0.05	0.4	3.4	5.3	<0.2	<0.5	4.3	19.2	<0.05	<10
3.	EG 03	<5	<0.02	0.4	<10	0.1	<0.1	7.8	0.8	0.7	<0.5	<0.2	2.1	<0.05	<10
4.	EG 04	<5	0.04	0.4	269	0.44	<0.1	11.1	1.1	0.4	<0.5	0.3	3.3	<0.05	<10
5.	EG 05	<5	4.41	1.9	<10	141.54	<0.1	19.5	<0.5	4.1	1.7	<0.2	4.6	<0.05	<10
6.	EG 06	<5	3.26	14.4	<10	127.48	<0.1	30.2	0.5	1.7	<0.5	<0.2	2.2	<0.05	<10
7.	EG 07	7	<0.02	0.6	<10	0.24	<0.1	15.1	0.8	0. 8	<0.5	0.4	1.2	<0.05	<10
8.	EG 08	9	0.08	0.9	<10	0.13	0.4	33.5	1.5	0.4	<0.5	0.6	4.2	<0.05	<10
9.	EG 09	<5	0.03	0.9	<10	0.11	<0.1	10	<0.5	0.3	<0.5	<0.2	2.2	<0.05	<10
10.	EG 10	<5	<0.02	<0.1	<10	1.53	<0.1	28.6	0.7	<0.2	<0.5	<0.2	3.7	<0.05	<10
11.	EG 11	<5	0.02	0.2	<10	0.83	<0.1	33.5	<0.5	0.5	<0.5	<0.2	1.4	<0.05	<10
12.	EG 12	<5	<0.02	0.4	<10	<0.05	<0.1	7.2	<0.5	0.3	<0.5	<0.2	1.2	<0.05	<10
13.	EG 13	<5	1.05	0.5	<10	139.31	<0.1	13.1	0.8	1.5	0.5	0.3	1.1	<0.05	<10
14.	EG 14	14	0.46	2	<10	0.14	4.2	16.8	2.7	0.7	<0.5	2.6	0.6	<0.05	<10
15.	EG 15	<5	0.15	0.8	<10	0.79	0.2	1.9	1.7	1.2	<0.5	0.6	2.6	<0.05	<10

Table 5. Correlation matrix for trace elements.

	Cu	Mn	Mo	Zn	Cr	V	Li	Si	U	Rn
Cu	1									
Mn	0.262	1								
Mo	0.078	−0.193	1							
Zn	0.692	0.052	0.071	1						
Cr	0.312	−0.297	0.402	0.169	1					
V	0.567	−0.239	0.37	0.471	0.887	1				
Li	0.373	−0.162	−0.008	0.278	0.858	0.835	1			
Si	0.391	−0.307	0.169	0.277	0.911	0.898	0.949	1		
U	-0.128	0.055	−0.116	0.282	−0.159	−0.206	−0.075	−0.096	1	
Rn	0.22	0.368	−0.25	0.098	−0.411	−0.334	−0.169	−0.186	0.416	1

3.4. Distribution of radon in groundwater

The distribution of radon is shown on the map of the study area in form of bubble plots and as a histogram (Figs. 3 and 4). Over 60% of water sources in the area have radon values below detectable limit. The remaining water sources have radon ranging from 1.62 to 24.69 Bq/l (Table 4). These values compare well with values of radon recorded in other parts of the basement rocks of Nigeria (Emmanuel and Theophilus, 2019; Garba et al., 2013; Gbadebo et al., 2021; Jidele et al., 2020; Kalip et al., 2081) except that of Olise et al., 2016 whose values in groundwater was higher. The northern part of the study area has a lower concentration of radon compared to the southern part (Fig. 3). This concentration is irrespective of the rock type in the northern part of the study area. Two of the sources (Anguldi and Dogo Na Hawa) have concentrations ranging from 12.67 to 24.69 Bq/l. These areas have corresponding higher annual dose rates (Fig. 3)

4. Discussion

4.1. Geochemical implications of the crystalline aquifers

Although the younger granite aquifers have high radioactivity (Solomon 2005), the content of radon in the waters in groundwater in 60% of the sources are less than 10 Bq/l and greater than 10 Bq/l in 40% in the remaining sources. The distribution of these values < and > 10 Bq/l are irrespective of the rock type that constitute the aquifers. However, values greater than 10 Bq/l of radon are found in the southern portion of the study area. Some of the locations like Tudun wada, for example, showed concentrations BDL for the same rock type (Jos biotite) granite as against the very high contents of radon recorded for Dogo Na Hawa, which cannot simply be explained by the data presented on the generalized geological map of the area. The values obtained in this study, however, compare well with other crystalline aquifers in other parts of Nigeria.

Since radon concentrations in groundwater are fundamentally dependent on emanation coefficients and time related to its short half-life as they change through aquifers (Knutsson and Olofsson, 2002) this may be the case with radon concentration in the rocks that constitute crystalline aquifers of the Jos and Bukuru areas (Skeppström and Olofsson, 2007; Banks et al., 1998). The same lithological dependence has also been found in Norway (Banks et al., 1998). The reason for this is probably the abundance of uranium and thorium in acidic magmatic rocks, in combination with a more pronounced regular fracture pattern that increases the surface area for water -rock interaction. The correlation of radon and the major ions in water showed independent behavior of radon with regards to the major ions in water. This behavior was also reflected between radon and the trace elements. However, radon showed a positive correlation although not significant, with the rare earth element which indicates a possible contribution of the rare earth elements to radon concentration in the waters.

The positive correlation between radon and uranium although not significant indicates that most uraniferous minerals in the Jurassic granites occur as partial replacements in some accessory mineral phases such as monazite and apatite or in rock-forming minerals such as feldspars and micas (Choo, 2002 and Lee and Baik, 2009). Hence most of the uranium might have been converted to accessory minerals. This local lack of correlation between uranium and radon in bedrock and groundwater was similarly recorded in Helsinki, Finland (Asikainen and Kahlos, 1979).

Table 6. Rare earth elements.

S/N	Sample nO.	La µg/l	Sc µg/l	Nd µg/l	Y µg/l	Eu µg/l	Ce µg/l	Dy µg/l	Er µg/l	Gd µg/l	Pr µg/l	Sm µg/l	Yb µg/l	Tm µg/l	Tb µg/l	Lu µg/l	Ho µg/l	U µg/l	Rn Bq/l
1.	EG 01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	4.5	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.08	0
2.	EG 02	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	5.3	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0
3.	EG 03	0.02	<1	0.03	0.06	<0.01	<0.01	0.01	0.8	<0.01	<0.01	<0.02	0.01	<0.01	<0.01	<0.01	<0.01	0.01	0
4.	EG 04	0.8	<1	0.62	0.84	0.01	0.44	0.14	1.1	0.08	0.17	0.13	0.1	0.01	0.02	0.01	0.03	0.08	4.96
5.	EG 05	76.54	<1	57.87	136.37	1.47	16.35	20.58	<0.5	13.29	16.52	12.43	11.7	2	2.92	1.55	4.38	0.88	16.12
6.	EG 06	34.02	<1	17.28	29.33	0.28	6.04	3.26	0.5	1.93	5.45	2.76	1.53	0.26	0.5	0.2	0.73	0.5	24.69
7.	EG 07	0.71	<1	0.46	0.76	<0.01	0.02	0.08	0.8	0.06	0.11	0.06	0.05	<0.01	0.01	<0.01	0.02	0.01	1.62
8.	EG 08	0.56	<1	0.31	1.83	<0.01	<0.01	0.11	1.5	0.14	0.08	0.08	0.18	0.02	0.02	0.03	0.04	1.91	0
9.	EG 09	0.06	<1	0.05	0.23	<0.01	0.02	0.02	<0.5	0.01	0.01	<0.02	0.01	<0.01	<0.01	<0.01	<0.01	0.04	24.55
10.	EG 10	0.24	<1	0.1	0.39	<0.01	0.01	0.03	0.7	0.03	0.03	0.02	0.03	<0.01	<0.01	<0.01	<0.01	4.47	21.83
11.	EG 11	0.06	<1	0.06	0.1	<0.01	0.01	0.01	<0.5	0.01	0.01	<0.02	0.02	<0.01	<0.01	<0.01	<0.01	0.01	0
12.	EG 12	0.02	<1	0.03	0.05	<0.01	<0.01	<0.01	<0.5	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0
13.	EG 13	28.68	<1	13.37	27.56	0.16	4.39	2.46	0.8	1.72	3.84	2	1.22	0.22	0.35	0.17	0.54	0.75	0
14.	EG 14	0.07	<1	0.06	0.61	<0.01	<0.01	0.04	2.7	0.15	0.01	<0.02	0.28	0.03	<0.01	0.06	0.02	0.16	0
15.	EG 15	0.12	<1	0.2	0.3	<0.01	0.02	0.04	1.7	0.05	0.04	0.04	0.09	0.01	<0.01	0.02	0.01	0.09	0

Table 7. Correlation matrix for REE, uranium and radon.

	La	Nd	Y	Eu	Ce	Dy	Er	Gd	Pr	Sm	Yb	Tm	Tb	Lu	Ho	U	Rn
La	1																
Nd	0.985	1															
Y	0.968	0.996	1														
Eu	0.945	0.987	0.995	1													
Ce	0.994	0.997	0.988	0.974	1												
Dy	0.942	0.986	0.995	0.999	0.971	1											
Er	−307	−292	−281	−269	−299	−267	1										
Gd	0.940	0.985	0.995	0.999	0.969	1.000	-265	1									
Pr	0.988	1.000	0.994	0.984	0.999	0.982	−294	0.980	1								
Sm	0.963	0.995	0.999	0.998	0.986	0.997	−278	0.997	0.993	1							
Yb	0.929	0.979	0.992	0.998	0.962	0.999	−258	0.999	0.974	0.994	1						
Tm	0.930	0.980	0.992	0.998	0.963	0.999	−259	1.000	0.975	0.994	1.000	1					
Tb	0.944	0.987	0.996	1.000	0.973	1.000	−268	1.000	0.983	0.998	0.999	0.999	1				
Lu	0.927	0.978	0.991	0.997	0.961	0.999	−254	0.999	0.973	0.993	1.000	1.000	0.998	1			
Ho	0.944	0.987	0.996	1.000	0.973	1.000	−268	1.000	0.983	0.998	0.999	0.999	1.000	0.998	1		
U	0.064	0.064	0.070	0.064	0.059	0.066	−159	0.068	0.063	0.065	0.067	0.066	0.066	0.066	0.066	1	
Rn	0.399	0.375	0.344	0.351	0.397	0.334	−411	0.323	0.388	0.356	0.318	0.319	0.340	0.313	0.336	0.416	1

Table 8. Result of analysis of radon in groundwater of the study area.

S/N	Sample location	Sample no.	Latitude	Longitude	Elevation (M)	Rn (Bql^{-1})	AED (mSV/y)			Rock type
							Adult	Children	Infant	
1.	Kumga II	EG 01A	N09°59′33.3″	E008°54′30.2″	1,085	BDL	-	-	-	Naraguta quartz–fayalite–pyroxene porphry
2.	Kunga II	EG 02A	N10°00′05.1″	E008°54′24.9″	1,059	BDL	-	-	-	Undifferentiated migmatite
3.	PHC Lamingo	EG 03A	N09°54′45.8″	E008°54′41.0″	1,314	BDL	-	-	-	Jos biotite granite
4.	Lamingo	EG 04A	N09°52′51.6″	E008°58′54.0″	1,326	4.96	0.036	0.072	0.252	Ngell biotite granite
5.	Doga Na Hawa	EG 05A	N09°48′27.6″	E008°57′04.7″	1,250	16.12	0.118	0.236	0.826	Jos biotite granite
6.	Dogo Na Hawa	EG 06A	N09°48′23.3″	E008°57′03.3″	1,239	24.69	0.180	0.360	1.26	Jos biotite granite
7.	Timtim	EG 07A	N09°46′27.2″	E008°55′37.4″	1,267	1.62	0.012	0.023	0.084	Shen hornblende-fayalite-porphyry
8.	Du	EG 08A	N09°45′36.1″	E008°53′21.8″	1,303	BDL	-	-	-	Ngell biotite granite
9.	Zawan	EG 09A	N09°45′51.2″	E008°52′41.3″	1,293	24.55	0.179	0.358	1.253	Bukuru biotite granite
10.	Bukuru	EG 10A	N09°47′41.6″	E008°52′49.4″	1,296	21.83	0.159	0.319	1.113	Bukuru biotite granite
11.	Rayfield	EG 11A	N09°50′31.5″	E008°54′12.5″	1,307	BDL	-	-	-	Jos biotite granite
12.	Zaramaganda	EG 12A	N09°50′47.4″	E008°52′21.1″	1,286	BDL	-	-	-	Rayfield gona biotite granite
13.	Anglo Jos	EG 13A	N09°52′17.5″	E008°52′18.5″	1,285	BDL	-	-	-	Ngell biotite granite
14.	Tudun Wada A	EG 14A	N09°54′00.0″	E008°51′52.7″	1,230	BDL	-	-	-	Jos biotite granite
15.	Tudun Wada B	EG 14B	N09°54′02.3″	E008°51′50.4″	1,233	BDL	-	-	-	Jos biotite granite
16.	Tudun Wada C	EG 14C	N09°53′57.5″	E008°51′35.5″	1,264	BDL	-	-	-	Jos biotite granite
17.	Tudun Wada D	EG 14D	N09°53′53.9″	E008°51′35.0″	1,264	BDL	-	-	-	Jos biotite granite
18.	Farin Gada A	EG 15A	N09°57′44.5″	E008°51′40.5″	1,127	BDL	-	-	-	Aplopegmatitic granite gneiss
19.	Farin Gada B	EG 15B	N09°57′45.7″	E008°51′40.7″	1,127	BDL	-	-	-	Aplopegmatitic granite gneiss
20.	Anguldi	EG 16A	N09°45′50.1″	E008°51′39.7″	1,275	12.67	0.093	0.185	0.648	Bukuru biotite granite

BDL; below detectable limit.

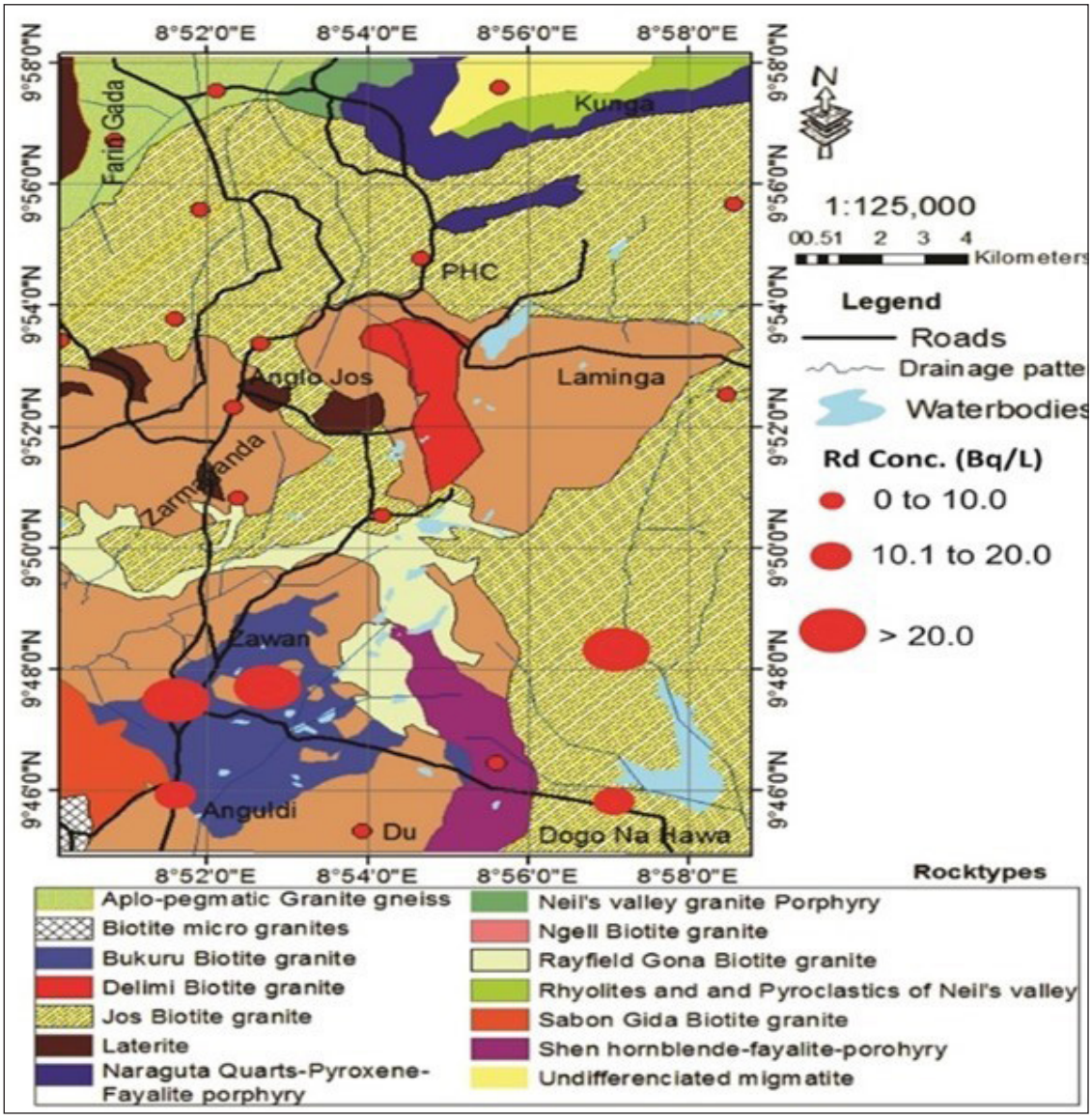

Figure 2. Radon distribution in the study area.

The actual use of the wells in the area is another variable of interest. Continuous extraction of groundwater, such as in permanent housing areas, increases the groundwater circulation which decreases the radon content. The technical installations must also be taken into consideration during water sampling since installations with the possibility of aeration (for example use of water tanks) give lower values than pressurized systems as well as bad well constructions with the inflow of surface water (Nilssen, 2001).

The combination of statistical and geochemical analysis provides useful assessment of controls over water composition and assists in the identification of possible anthropogenic influences. Results showed that the composition of the groundwaters in the area is dominated by natural water–rock interactions while other areas were highly impacted by anthropogenic sources. The best indicators for the present dataset are elevated electrical conductivity and increased concentrations of calcium, magnesium, sodium, potassium, and chloride ions. The dominant cation is Na^+ derived from weathering of silicate-rich rocks while chloride was derived from anthropogenic activities as the crystalline rocks contain only trace of chloride-bearing minerals. The accepted limit of TDS in drinking water is 1000 mg/l (WHO, 1993). On the basis of TDS, all the samples are within the range of desirable to permissible for drinking.

5. Summary and Conclusion

In this study, high concentration of radon in groundwater has been observed in some areas within the Jos – Bukuru crystalline aquifers. Values above 10 Bq/l

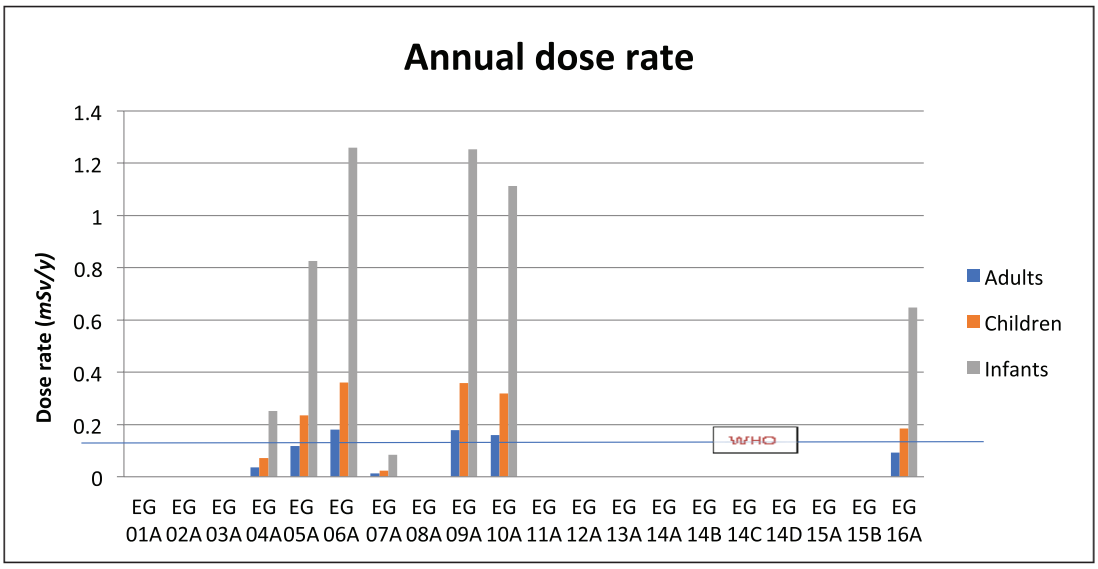

Figure 3. Plot showing annual dose rates for adults, children and infants.

were recorded for areas around the southern part of the study area such as Dogo Na Hawa, Shen, Zawan, Anguldi, and Bukuru. Radon values in this study compares well with data obtained from similar studies in crystalline aquifers in Nigeria. The variation in the concentration of radon may be the result of:

i) The actual use of the wells in the area such as extraction of groundwater which increases the groundwater circulation thereby decreasing the radon content.

ii) Bad well constructions with inflow of surface water and

iii) Bedrock geology.

Radon concentration must have been sourced from uranium and some of the rare earth elements owing to the positive correlation they exhibited. The composition of the groundwaters in the area is dominated by natural water–rock interactions while other areas were highly impacted by anthropogenic sources. On the basis of TDS, all the samples are within the range of desirable to permissible for drinking.

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