Measurement of natural radioactivity and dose rate assessment of terrestrial gamma radiation in the soils of Karibib and Okahandja, Namibia

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ABSTRACT

The activity concentrations of the naturally occurring radionuclides ^{238}U, ^{232}Th and ^{40}K in soil samples taken from the towns of Okahandja and Karibib in Namibia have been determined by gamma-ray spectroscopy using an HPGe detector. The average activity concentrations of ^{238}U, ^{232}Th and ^{40}K in Karibib are $29.4 \pm 5.8\,\mathrm{Bq/kg}$, $49.0 \pm 8.6\,\mathrm{Bq/kg}$, and $824.3 \pm 153.5\,\mathrm{Bq/kg}$ while they are $40.9 \pm 8.6\,\mathrm{Bq/kg}$, $57.9 \pm 19.4\,\mathrm{Bq/kg}$, and $562.4 \pm 125.4\,\mathrm{Bq/kg}$ respectively in Okahandja. Most of these values are much higher than the corresponding worldwide average values. These activity concentrations were used to calculate different radiological parameters in order to evaluate the associated health hazard. The value of $9.5 \times 10^{-2}\,\mathrm{mSv/y}$ obtained for the mean effective dose rate in both towns is far below the permissible limit of $1.0\,\mathrm{mSv/y}$ recommended by the ICRP and implies that there is no significant radiation hazard in the towns. Also, the values of $163.0\,\mathrm{Bq/kg}$ and $167.1\,\mathrm{Bq/kg}$ obtained for the average radium equivalent activity ($\mathrm{Ra_{eq}}$) in the towns and the corresponding values obtained for the average external hazard index ($\mathrm{H_{ex}}$) are much below their maximum permissible limits thus confirming that radiological hazard is negligible in the towns.

1 Introduction

Human beings are exposed to naturally occurring ionising radiation at all times [1, 2]. The main natural contributors to external exposure from gamma rays are the radionuclides ^{238}U, ^{232}Th and ^{40}K in the soil [3–5]. High concentrations of these radionuclides in the soil will result in high background radiation which is a health hazard as it may increase the risk of cancer. Consequently, the determination of the activity concentrations of these primordial radionuclides in the soils of different towns and countries as well as the corresponding radioactivity levels has been of interest to many scientists worldwide [6–9]. Namibia is one of the countries in which there is interest in radioactivity levels especially because there is a wealth of mineral resources, including uranium, in the country and therefore the concentrations of primordial radionuclides in the soil may be high in some towns or areas leading to a high background radiation level [2, 6, 10]. It is therefore desirable to determine the concentrations of the primordial radionuclides ^{238}U, ^{232}Th and ^{40}K in the soils of important towns in Namibia and thereby obtain a baseline data of environmental radioactivity that will serve as a reference in future. The towns of Karibib and Okahandja are important towns in mineral-rich western and central Namibia.

Okahandja is about 70 km north of Windhoek at latitude 21°59′S and longitude 16°55′E and it is known as the "garden town" of Namibia. The Von Bach dam that supplies water to the city of Windhoek is close to the town

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and the National Institute for Educational Development (NIED) is situated in the town. Many foreign and local tourists pass through Okahandja on their way to the coastal cities of Swakopmund and Walvis Bay. Okahandja is particularly important to the Herero tribe as they gather annually in the town in August to commemorate their fallen heroes and thereby temporarily increase the population of the town in August. Karibib (21°56′17″S 15°51′16″E) is about 100 km from Okahandja on the B2 road to Walvis Bay. It is almost halfway between Windhoek and the western coastal towns of Namibia and it is the gateway to the coastal towns. This town is therefore an ideal overnight or refreshment stop-over for both foreign and local tourists travelling to the western coast of Namibia. It is well known for its marble and granite deposits. Also, the Navachab gold mine is near the town and many workers of the gold mine live in Karibib. There is therefore interest in the determination of the natural radioactivity in the soils of Karibib and Okahandja. Furthermore, earlier studies on soil radioactivity in the Walvis Bay-Henties Bay coastal region in western Namibia have shown a trend in which the concentration of the radionuclide ^{40}K in the soils of the towns increases with decreasing latitude [2]. It is of interest to find out if the trend will continue to Karibib and Okahandja.

The aim of this study was to determine the concentrations and distributions of the primordial radionuclides ^{238}U, ^{232}Th and ^{40}K in soil samples collected from across the towns of Karibib and Okahandja and use the data to find the background radiation levels of the two towns and also calculate the associated radiation hazard indices. The results obtained will reveal whether or not the two towns are in areas of normal or high background radiation. Furthermore, the results will contribute to the baseline data of environmental radioactivity in Namibia and also confirm whether or not the earlier trend, in which the concentration of ^{40}K in the soils of some towns increases with decreasing latitude, continues to Karibib and Okahandja.

2 Sample collection and measurement procedure

A total of 50 soil samples were collected from ten geographical areas in each of the two towns as shown in Figure 1 and listed in Table 1. In each geographical area, soil samples were collected at five sites across the area. In order to avoid secondary soils, all the sites chosen were away from roads, buildings, railway lines and rivers. The samples were collected at a depth of about 2 cm - 5 cm below the surface of the soil. All the samples were dried under laboratory temperature, and were subsequently passed through a 2 mm mesh screen to obtain a fine textured soil and to ensure that the radionuclides present in a sample are uniformly distributed. 500 g of each sample were carefully weighed and placed in a 500 ml air-tight polythene bottle similar to those of the reference materials and sealed. These sealed bottles were then stored for a month to ensure that radioactive equilibrium is established between ^{226}Ra and ^{232}Th and their progeny before they were counted in the gamma spectrometry detector system.

A well-shielded and calibrated vertical Canberra HPGe detector was used to measure the gamma-ray spectra for the soil samples. The calibration was done using reference materials provided by the International Atomic Energy Agency (IAEA) namely RGU-1, RGTh-1 and RGK-1. In order to obtain good results, the same geometry and counting time of 10800 seconds were used for the reference materials and for the samples. Details of the measurement procedure have been discussed elsewhere [11]. The gamma transition energy of 0.609 MeV of ^{214}Bi was used to determine the concentrations of ^{238}U while the gamma transition energy of 0.911 MeV of ^{228}Ac was used to determine the concentrations of ^{232}Th and ^{40}K activity was determined from the 1.460 MeV gamma-line. These concentrations were subsequently used to calculate the absorbed dose rate and the annual effective dose rate due to the radionuclides in each sample. The resulting data were used to calculate the mean absorbed dose rate and the mean annual effective dose rate for the two towns. Furthermore, the concentrations were used to calculate different radiation hazard indices.

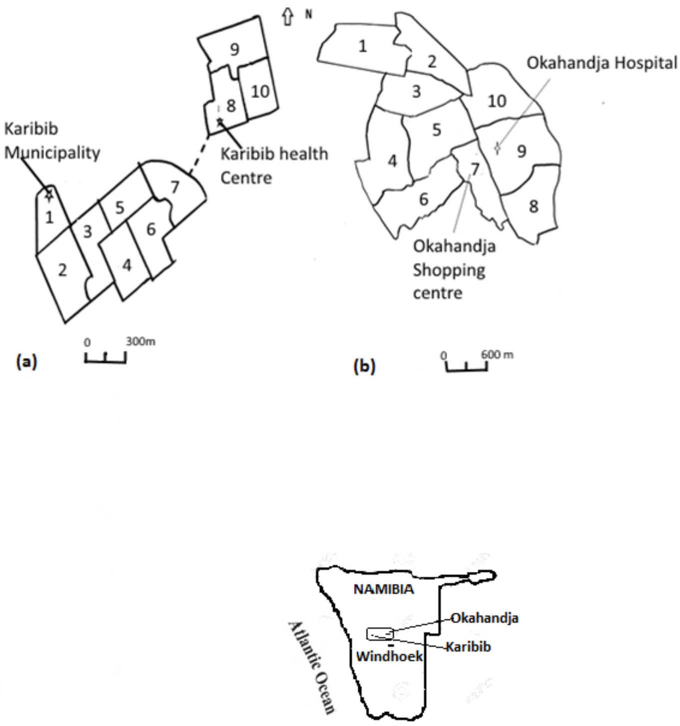


Figure 1: Map showing the areas where soil samples were collected in (a) Karibib and (b) Okahandja. The insert is the map of Namibia showing the locations of Karibib and Okahandja.

Table 1: Geographical areas where soil samples were collected in Karibib and Okahandja.

Town	Area	Name	Town	Area	Name
Okahandja	1	Veddersdal / Okahandja (ext. 1) area.	Karibib	1	Karibib Town area
	2	Okahandja (ext. 2) area.		2	Natis/ Police area
	3	Okahandja (ext. 6) area.		3	Third / Fourth St area
	4	Nau-aib Proper area.		4	Heim Graben St/ 2nd St area
	5	Okahandja (ext. 8) area.		5	Ok Stores/ Gemstone area
	6	Okahandja (ext. 9/ 10) area.		6	Country Club area
	7	Okahandja (ext. 1/ 7) area.		7	Tommy's Lodge area
	8	Okahandja (ext. 4) area.		8	Karibib Health Centre area
	9	Okahandja Proper area.		9	Libertine Amadhila St/ Kapupa Rd area
	10	NIED /Okahandja Country club area.		10	Ebenezer Primary School area

3 Results and Discussion

3.1 Radionuclide concentrations in Karibib

The activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the soil samples collected from each of the ten geographical areas in Karibib (Figure 1(a)) and their average values for the different areas are summarized in Table 2 and shown in Figure 2(a). As could be observed in the Table and Figure, the activity concentration of ^{238}U is highest in area No.2 with an average of 32.7 ± 2.1 Bq/kg (and varies from 31.0 to 36.2 Bq/kg) but lowest in area No.6 with an average of 26.1 ± 3.3 Bq/kg (and varies from 21.6 to 29.5 Bq/kg). The average activity concentration of ^{238}U from all the soil samples across the town of Karibib is 29.4 ± 5.8 Bq/kg as shown in Table 2 (column 2, bottom row). This value is lower than the worldwide average activity concentration of 35 Bq/kg for ^{238}U in soil [1].

Similarly, the activity concentration of ^{232}Th is highest in area No.3 with an average of 55.4 ± 6.1 Bq/kg (and varies from 45.3 to 61.6 Bq/kg) while it is lowest in area No.8 with an average of 40.9 ± 11.6 Bq/kg (and varies from 29.0 to 54.7 Bq/kg) as could be observed in Figure 2(a). Also, the average activity concentration of 232Th from all the samples across Karibib is 49.0 ± 8.6 Bq/kg as could be observed in Table 2. These results show that the average activity concentration of ^{232}Th in the soil of Karibib is higher than the worldwide average activity concentration of 30 Bq/kg reported by UNSCEAR [1].This observation is in contrast to that made on ^{238}U in which the average activity concentration of ^{238}U is lower than the worldwide average. In the case of ^{40}K, its activity concentration is highest in area No.10 with an average of 1007.4 ± 108.8 Bq/kg (and varies from 815.8 to 1079.0 Bq/ kg) but it is lowest in area No.3 with an average of 704.2 ± 87.1 Bq/kg (and varies from 579.0 to 784.2 Bq/kg). However, while the average activity concentration of ^{40}K is lowest in area No. 3, the average activity concentration of ^{232}Th is highest in area No.3 as could be observed in Figure 2(a). The average activity concentration of ^{40}K from all the samples collected across Karibib is 824.3 ± 153.5 Bq/kg which is more than double the worldwide average activity concentration of 400 Bq/kg [1]. As could be seen in Figure 2(a) the activity concentration of ^{40}K (in each of the geographical areas) is much greater than those of ^{238}U and ^{232}Th, while the activity concentration of ^{232}Th is higher than that of ^{238}U. It therefore follows that, among the three primordial radionuclides, ^{40}K has the highest activity concentration while ^{238}U has the lowest activity concentration in the soil of Karibib. These results are consistent with those obtained in some other towns in western Namibia [2].

3.2 Radionuclide concentrations in Okahandja

The activity concentrations of ^{238}U, ^{232}Th and ^{40}K determined in the soil samples collected from each of the ten geographical areas in Okahandja (Figure 1(b)) and their average values for the different areas are summarized in Table 3 and shown in Figure 2(b). As could be observed in the Table and Figure, the activity concentration of ^{238}U is highest in area No. 7 with an average of 50.6 ± 3.8 Bq/kg (and varies from 44.7 to 54.8 Bq/kg) but lowest in area No.1 with an average of 31.3 ± 5.8 Bq/kg (and varies from 25.9 to 40.9 Bq/kg). The average activity concentration of ^{238}U from all the soil samples collected across the town of Okahandja is 40.9 ± 8.6 Bq/kg as shown in Table 3. This value is greater than the worldwide average activity concentration of 35 Bq/kg [1].

The activity concentration of ^{232}Th is also highest in area No.8 with an average value of 85.3 ± 38.6 Bq/kg (and varies from 38.5 to 138.8 Bq/kg) but, interestingly, it is lowest in area No.1 (as in the case of ^{238}U) with an average value of 44.4 ± 15.2 Bq/kg (and varies from 34.6 to 71.2 Bq/kg) as shown in Table 3. The average activity concentration of ^{232}Th from all the soil samples collected across the town of Okahandja is 57.9 ± 19.4 Bq/kg. This value is greater than the worldwide average activity concentration of ^{232}Th which is 30 Bq/kg [1]. The activity concentration of ^{40}K is highest in area No.7 with an average value of 656.8 ± 55.6 Bq/kg (and varies from 579.0 to 726.3 Bq/kg) and lowest in area No.4 with an average value of 348.4 ± 33.5 Bq/kg (and varies from 307.4 to 382.6 Bq/kg) as shown in Figure 2(b). In fact, the average value of ^{40}K in area No.7 is almost double that in area No.4.

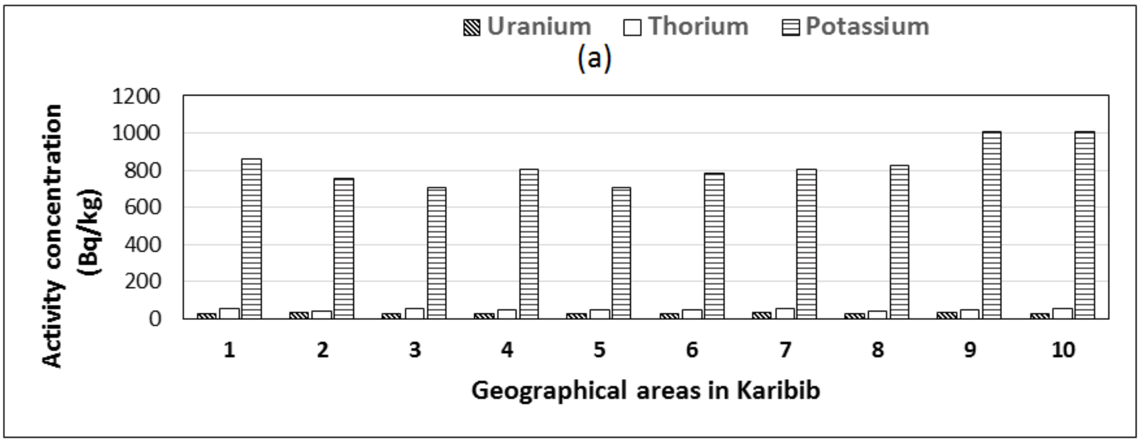
Table 2: Average (± standard deviation) activity concentrations of ^{238}U, ^{232}Th and ^{40}K in different geographical areas of Karibib. (The corresponding range of values is given in parentheses.)

Area	Radionuclide concentration (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
1	30.3 ± 7.1 (24.4 - 42.3)	53.1 ± 5.2 (43.8 - 56.9)	857.9 ± 104.4 (736.8 – 994.7)
2	32.7 ± 2.1 (31.0 - 36.2)	43.8 ± 5.3 (36.9 - 49.0)	753.7 ± 60.2 (694.7 - 821.1)
3	26.2 ± 4.2 (21.2 – 30.7)	55.4 ± 6.1 (45.3 – 61.6)	704.2 ± 87.1 (579.0 – 784.2)
4	30.3 ± 6.5 (23.1 - 39.0)	47.8 ± 5.6 (39.1 - 53.7)	801.1 ± 109.2 (621.1 – 879.0)
5	27.8 ± 5.2 (20.5 – 34.0)	45.7 ± 9.1 (39.1 – 60.7)	707.4 ± 74.8 (605.3 – 805.3)
6	26.1 ± 3.3 (21.6 – 29.5)	48.3 ± 7.8 (38.4 – 55.9)	783.2 ± 67.3 (731.6 – 884.2)
7	30.9 ± 10.8 (14.3 – 43.1)	51.9 ± 14.6 (33.1 – 69.9)	801.1 ± 240.1 (505.3 – 1168.4)
8	27.8 ± 7.5 (19.8 – 39.5)	40.9 ± 11.6 (29.0 – 54.7)	822.1 ± 206.9 (621.1 – 1058.0)
9	31.9 ± 3.3 (27.6 - 36.4)	49.9 ± 2.5 (46.5 - 52.5)	1005.3 ± 57.5 (926.3 - 1057.9)
10	30.6 ± 4.2 (25.9 - 36.5)	53.1 ± 6.3 (43.5 - 60.4)	1007.4 ± 108.8 (815.8 - 1079.0)
Average of all samples	**29.4 ± 5.8 (14.3 – 43.1)**	**49.0 ± 8.6 (29.0 – 69.9)**	**824.3 ± 153.5 (505.3 – 1168.4)**

As could be seen in Table 3 the average activity concentration of ^{40}K from all the soil samples is 562.4 ± 125.4 Bq/kg. This average activity concentration of ^{40}K is higher than the worldwide average activity concentration of 400 Bq/kg [1]. It is apparent from Figure 2(b) that the activity concentration of ^{40}K is much larger than those of ^{238}U and ^{232}Th while the activity concentration of ^{232}Th is greater than that of ^{238}U across all the ten geographical areas of Okahandja. It therefore follows that, among the three primordial radionuclides, ^{40}K has the highest activity concentration in Okahandja while ^{238}U has the lowest activity concentration in the town.

3.3 Comparison of activity concentrations in Karibib and Okahandja

The mean activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the soil samples collected from the towns of Karibib and Okahandja are summarised in Tables 2 and 3 (bottom row), and shown in Figure 3(a). As could be seen in



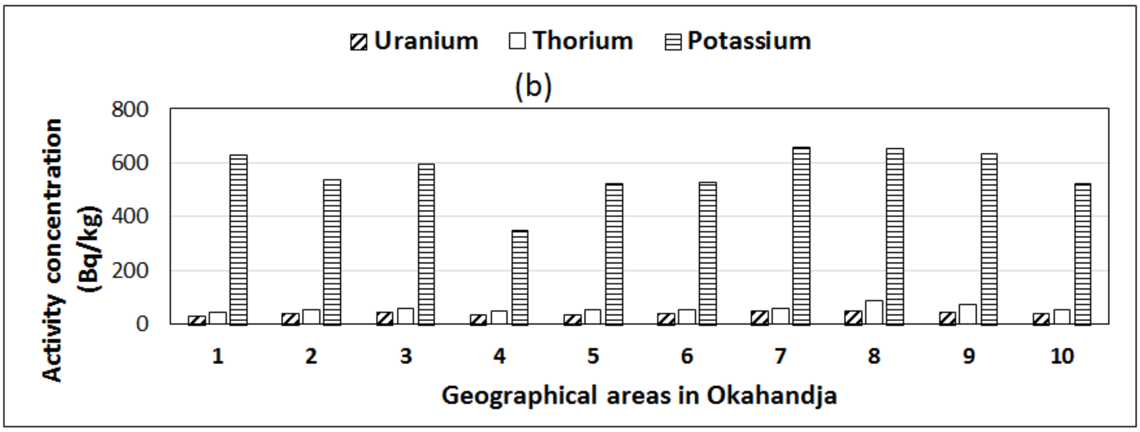


Figure 2: The mean activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the ten geographical areas of (a) Karibib and (b) Okahandja

the Figure, the average activity concentration of ^{238}U is higher in Okahandja (with a value of 40.9 ± 8.6 Bq/kg) than in Karibib (with a value of 29.4 ± 5.8 Bq/kg). In fact, the activity concentration of ^{238}U in Okahandja is 1.4 times that of Karibib. Also, the average activity concentration of ^{232}Th is higher in Okahandja (with a value of 57.9 ± 19.4 Bq/kg) than in Karibib (with a value of 49.0 ± 8.6 Bq/kg). In contrast to the higher concentrations of ^{238}U and ^{232}Th in Okahandja, the average concentration of ^{40}K is much higher in Karibib (with a value of 824.3 ± 153.5 Bq/kg) than in Okahandja (with a value of 562.4 ± 125.4 Bq/kg). Also, the activity concentration of ^{40}K is much higher than those of ^{238}U and ^{232}Th in both towns. Similarly, in both towns, ^{238}U has the lowest activity concentration among the three primordial radionuclides.

3.4 Comparison of the activity concentrations of ^{40}K in Karibib and Okahandja with those measured in some other towns in western Namibia.

A comparison of the mean activity concentrations of ^{40}K in the soils of Karibib and Okahandja with those determined by some researchers in the soils of three major towns and a holiday settlement in the same part of

Table 3: Average ($\pm$ standard deviation) activity concentrations of ^{238}U, ^{232}Th and ^{40}K different geographical areas of Okahandja. (The corresponding range of values is given in parentheses.)

Area	Radionuclide concentrations (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
1	31.3 ± 5.8 (25.9 - 40.9)	44.4 ± 15.2 (34.6 - 71.2)	628.6 ± 167.2 (445.3 - 857.9)
2	38.7 ± 3.5 (35.3 -43.2)	54.9 ± 3.4 (46.2 - 63.7)	535.5 ± 42.5 (470.5 - 573.7)
3	43.4 ± 5.1 (35.3 - 48.4)	58.7 ± 20.6 (46.3 - 95.3)	593.4 ± 150.9 (460.5 - 815.8)
4	34.7 ± 2.1 (29.7 - 40.0)	47.6 ± 7.5 (39.1 - 57.1)	348.4 ± 33.5 (307.4 - 382.6)
5	37.3 ± 6.3 (30.2 - 44.7)	51.7 ± 8.7 (41.9 - 63.2)	523.4 ± 92.1 (420.0 - 657.9)
6	40.8 ± 7.6 (32.0 - 47.3)	51.8 ± 11.2 (37.9 - 63.4)	526.5 ± 37.2 (474.2 - 573.7)
7	50.6± 3.8 (44.7 - 54.8)	58.4 ± 13.3 (46.8 - 72.9)	656.8 ± 55.6 (579.0 - 726.3)
8	50.1 ± 12.5 (41.0 - 71.7)	85.3 ± 38.6 (38.5 - 138.8)	651.2 ± 120.0 (482.1 - 768.4)
9	44.6 ± 8.5 (32.6 - 51.0)	72.2 ± 14.1 (55.7 - 88.5)	635.3 ± 78.5 (513.2 - 726.3)
10	37.8 ± 6.7 (29.3 - 44.2)	54.2 ± 8.8 (43.0 – 64.0)	524.7 ± 87.4 (417.9 - 636.8)
Average of all samples	**40.9 ± 8.6 (25.9 - 71.7)**	**57.9 ± 19.4 (34.6 - 138.8)**	**562.4 ± 125.4 (307.4 - 857.9)**

Namibia is shown in Figure 3(b) [2]. The three towns and a settlement are Walvis Bay, Swakopmund, Usakos and Wlotzkasbaken. All the three towns and Karibib and Okahandja are on the popular B2 road and next to each other in western Namibia. These five towns (Walvis Bay, Swakopmund, Usakos, Karibib and Okahandja) and the settlement (Wlotzkasbaken) are at different latitudes, and earlier studies have shown an increase in the average activity concentration of ^{40}K with decreasing latitude in the three major towns and holiday settlement (Walvis Bay, Swakopmund, Usakos and Wlotzkasbaken) as could be observed in Figure 3(b)(i-iv) [2].

However, the increase in the activity concentration of ^{40}K with decreasing latitude does not extend to Karibib and Okahandja as could be observed in Figure 3(b)(i - vi). As could be seen in the figure, the average activity

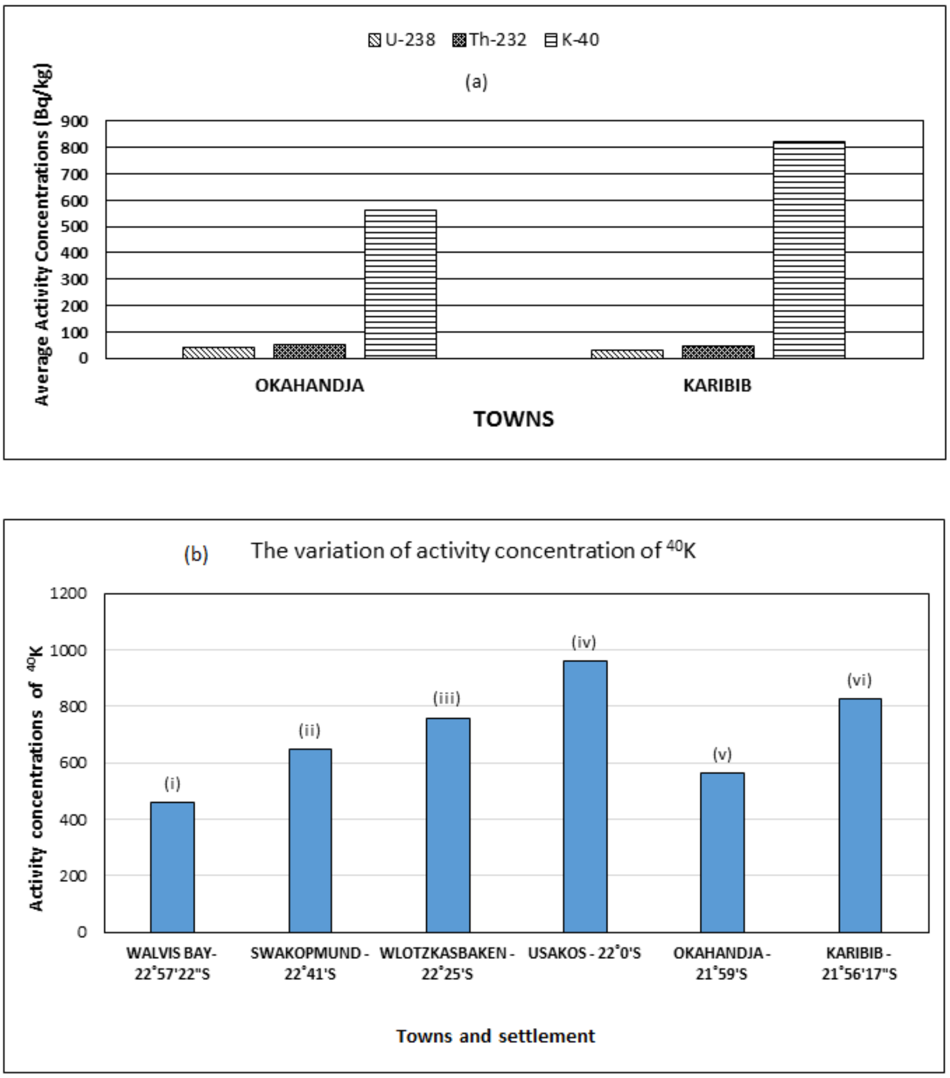


Figure 3: Comparison of the mean activity concentrations of (a) ^{238}U, ^{232}Th and ^{40}K in the towns of Karibib and Okahandja and (b) ^{40}K in five towns and a holiday settlement in western Namibia. (The towns and settlement are arranged in decreasing latitude but not to scale.)

concentration of ^{40}K increases from one town to another (decreasing latitude) until it is maximum at Usakos, and it is subsequently smaller in Okahandja and Karibib. It therefore follows that the observed increase in the average activity concentration of ^{40}K with decreasing latitude in some towns in western Namibia cannot be generalised to all the towns in the area.

3.5 Dose rates and hazard indices in Karibib.

The absorbed dose rates in air, at 1 m above the ground, due to the radionuclides at each of the sites where samples were collected were calculated using the expression [1, 4, 12]

$$D(\mathrm{nGy/h}) = 0.462C_U + 0.604C_{Th} + 0.0417C_K \tag{1}$$

where C_U, C_{Th}, C_K are the activity concentrations of ^{238}U, ^{232}Th and ^{40}K respectively in each sample.

The resulting annual effective dose was calculated using the conversion coefficient from absorbed dose in air to effective dose, $0.7\,\mathrm{Sv\,Gy^{-1}}$, and an outdoor occupancy factor 0.2 proposed by UNSCEAR, 2000 [1]. The mean absorbed dose rates in air in the ten geographical areas of Karibib are shown in Table 4, column 2. As could be observed in the Table, the mean absorbed dose rate is highest in area No.10 with an average value of 88.2 ± 7.3 nGy/h while it is lowest in area No.5 with an average value of 69.9 ± 1.3 nGy/h. The relatively high value of the mean absorbed dose rate in area No.10 is not surprising since the same area has a relatively high concentration of ^{40}K as discussed in section 3.1 and shown in Table 2 (column 4). The average absorbed dose rate from all the ten geographical areas in Karibib is 77.6 ± 10.9 nGy/h as shown in Table 4. This value is much higher than the reported worldwide average value of 51 nGy/h [1].

Table 4 (column 3) and Figure 4(a) show the mean annual effective dose in each of the ten geographical areas of Karibib. As could be observed in the Table and Figure, the corresponding mean annual effective dose is also highest in area No.10 with a value of 0.108 ± 0.009 mSv while it is lowest in area No.5 with a value of 0.086 ± 0.002 mSv. These results are also not surprising since area No.10 and area No.5 respectively have the highest and lowest absorbed dose rates. The average annual effective dose from all the ten geographical areas of Karibib is 0.095 ± 0.013 mSv which is much below the maximum permissible annual effective dose of 1.0 mSv recommended for the public by the ICRP [13]. This result implies that the town of Karibib has normal background radiation.

A radiological index that represents the activity levels of ^{238}U, ^{232}Th and ^{40}K as a single quantity is the radium equivalent activity ($\mathrm{Ra_{eq}}$) which is given by the expression

$$\mathrm{Ra_{eq}} = C_U + 1.43C_{Th} + 0.077C_K \tag{2}$$

where are the activity concentrations of ^{238}U, ^{232}Th and ^{40}K respectively. In applying equation (2) to the concentrations in Table 2, it was assumed that there was secular equilibrium between ^{238}U and ^{226}Ra. The maximum value of radium equivalent activity is 370 Bq/kg [1]. Another widely used hazard index (reflecting external exposure) is the external hazard index, $\mathrm{H_{ex}}$, which is defined as

$$\mathrm{H_{ex}} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \tag{3}$$

The value of $\mathrm{H_{ex}}$ must be less than unity for radiation hazard to be negligible [14].

The mean radium equivalent activity and the external hazard index in the ten geographical areas of Karibib are presented in Table 4 (columns 4 and 5) and shown in Figure 4(b and c). As could be seen in Figure 4(b), the mean radium equivalent activity is highest in area No.10 with an average value of 184.1 ± 15.3 Bq/kg while it is lowest in area No.5 with an average value of 147.6 ± 3.9 Bq/kg. The average radium equivalent activity from all the ten geographical areas in Karibib is 163.0 ± 22.6 Bq/kg as shown in Table 4. This value is much below the maximum permissible limit of 370 Bq/kg so that radiation hazard is negligible in Karibib [1]. Similarly, the highest external hazard index is in area No.10 with an average value of 0.50 ± 0.04 while it is lowest in area No.5 with an average value of 0.40 ± 0.01 as could be observed in Figure 4(c). The average external hazard index from all the ten geographical areas is 0.44 ± 0.06. This value is less than unity thus confirming that radiation hazard is negligible in Karibib as observed earlier in this section.

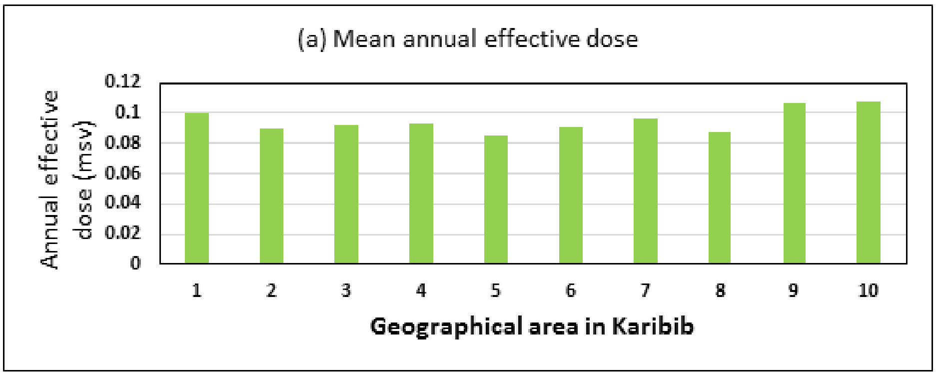
3.6 Dose rates and hazard indices in Okahandja

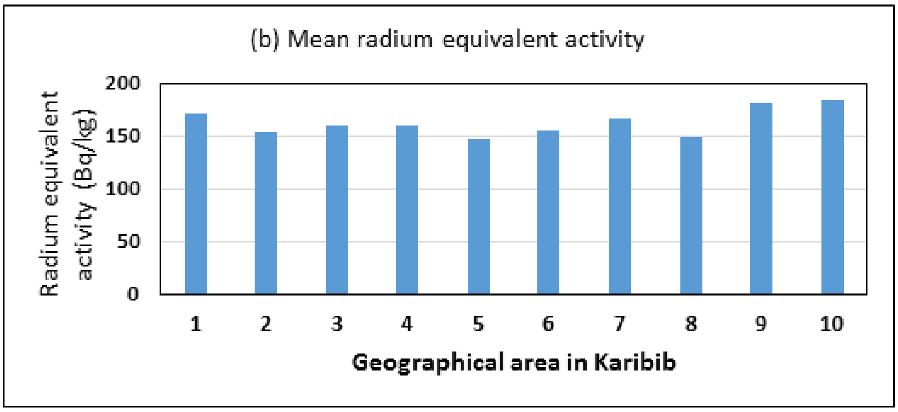
The mean absorbed dose rates in air and the corresponding mean annual effective doses in the ten geographical areas of Okahandja are presented in Table 5 (columns 2 and 3). As could be seen in the Table, the mean absorbed

Table 4: Mean absorbed dose rate, annual effective dose, radium equivalent activity and external hazard index in different geographical areas in Karibib. (The corresponding range of values in each geographical area is given in parentheses.)

Area	Absorbed dose rate (nGy/h)	Annual effective dose (× 10^{-2} mSv)	Radium equivalent activity (Ra_{eq}) (Bq/kg)	External hazard Index (H_{ex})
1	81.8 ± 8.9 (70.7 - 93.9)	10.0 ± 1.1 (8.7 – 11.5)	172.2 ± 18.4 (148.2 - 196.7)	0.47 ± 0.05 (0.40 - 0.53)
2	73.0 ± 1.4 (70.5 - 74.2)	8.9 ± 2.0 (8.6 – 9.1)	153.3 ± 3.2 (148.6 - 156.9)	0.41 ± 0.01 (0.40 -0.42)
3	74.9 ± 5.7 (67.6 - 80.7)	9.2 ± 0.7 (8.3 – 9.9)	159.7 ± 11.8 (145.5 - 172.1)	0.44 ± 0.03 (0.39 - 0.46)
4	76.3 ± 8.3 (67.4 - 84.5)	9.4 ± 1.0 (8.3 – 10.4)	160.3 ± 17.2 (140.4 - 177.9)	0.43 ± 0.05 (0.38 - 0.48)
5	69.9 ± 1.3 (68.6 - 71.4)	8.6 ± 0.2 (8.4 – 8.8)	147.6 ± 3.9 (143.6 - 153.9)	0.40 ± 0.01 (0.39 - 0.42)
6	73.9 ± 7.5 (62.5 - 84.2)	9.1 ± 0.9 (7.8 – 10.3)	155.5 ± 16.6 (132.8 - 177.3)	0.42 ± 0.04 (0.36 - 0.48)
7	78.9 ± 19.6 (67.6 - 110.8)	9.7 ± 2.4 (7.7 – 13.6)	166.7 ± 40.9 (129.7 - 232.9)	0.45 ± 0.11 (0.35 - 0.63)
8	71.8 ± 18.1 (54.9 - 94.1)	8.8 ± 2.2 (6.7 – 11.5)	149.5 ± 37.9 (114.5 - 196.8)	0.40 ± 0.01 (0.31 - 0.53)
9	86.8 ± 3.6 (83.6 - 92.6)	10.6 ± 0.4 (10.2 – 11.4)	180.7 ± 7.3 (174.8 - 192.9)	0.49 ± 0.02 (0.47 - 0.52)
10	88.2 ± 7.3 (79.6 - 97.7)	10.8 ± 0.9 (9.8 – 12.0)	184.1 ± 15.3 (168.0 - 204.8)	0.50 ± 0.04 (0.45 - 0.55)
Average of all samples	**77.6 ± 10.9 (54.9 - 110.8)**	**9.5 ± 1.3 (6.7 – 13.6)**	**163.0 ± 22.6 (114.5 - 232.9)**	**0.44 ± 0.06 (0.31 - 0.63)**

dose rate is highest in area No. 8 with an average value of 101.8 ± 32.7 nGy/h while it is lowest in area No. 4 with an average value of 59.3 ± 6.1 nGy/h. The average absorbed dose rate from all the ten geographical areas is 77.3 ± 18.0 nGy/h. This value is higher than the reported worldwide average of 51 nGy/h [1]. Similarly, the corresponding mean annual effective dose is highest in area No.8 with an average value of 0.125 ± 0.04 mSv while it is lowest in area No.4 with an average value of 0.073 ± 0.007 mSv as could be seen in Figure 5(a). These results are not surprising since area No.8 and area No.4 respectively have the highest and lowest mean absorbed dose rates. The average annual effective dose from all the ten geographical areas is 0.095 ± 0.022 mSv as could be seen in Table 5. This average value is far below the maximum permissible annual dose of 1.0 mSv and implies





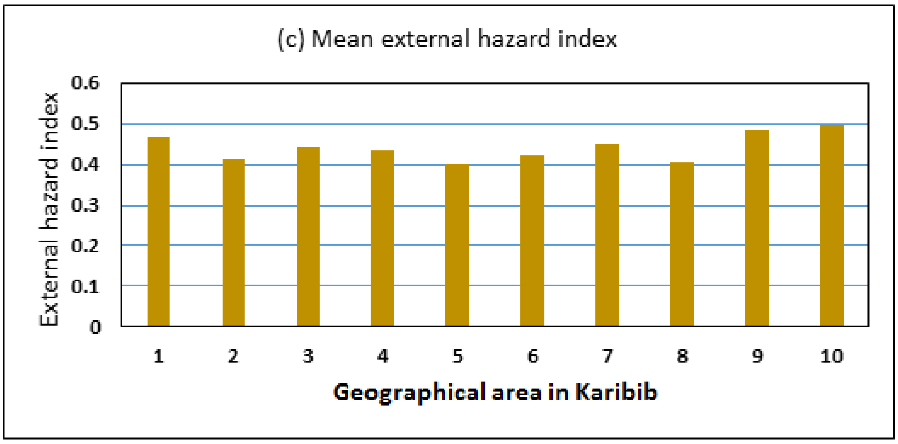


Figure 4: The mean (a) annual effective dose (b) radium equivalent activity and (c) external hazard index in the ten geographical areas of Karibib.

that the town of Okahandja, like the town of Karibib, has a normal background radiation.

The mean radium equivalent activity ($\mathrm{Ra_{eq}}$) and the mean external hazard ($\mathrm{H_{ex}}$) index in the ten geographical areas of Okahandja are presented in Table 5 (columns 4 and 5) and shown in Figure 5(b and c). As could be

Table 5: Mean absorbed dose rate, annual effective dose, radium equivalent activity and external hazard index in different geographical areas in Okahandja. (The corresponding range of values in each geographical area is given in parentheses.)

Area	Absorbed dose rate (nGy/h)	Annual effective dose (× 10^{-2} mSv)	Radium equivalent activity (Ra_{eq}) (Bq/kg)	External hazard index (H_{ex})
1	67.5± 15.3 (51.8 -91.9)	8.3 ± 1.1 (6.3 – 11.3)	143.2 ± 33.3 (110.5- 198.2)	0.39 ± 0.09 (0.30 - 0.54)
2	73.4± 7.3 (63.8 - 81.2)	9.0 ± 0.9 (7.8 – 10.0)	158.5 ± 16.2 (137.6 - 176.4)	0.44 ± 0.53 (0.37 -0.48)
3	80.3 ± 16.7 (66.6 - 108.2)	9.8 ± 2.1 (8.2 – 13.3)	173.1± 37.5 (142.7 - 237.0)	0.47± 0.10 (0.39 - 0.64)
4	59.3 ± 6.1 (52.2 - 66.9)	7.3 ± 0.7 (6.4 -8.2)	129.7 ± 13.8 (113.1 - 146.8)	0.35 ± 0.04 (0.31 - 0.40)
5	70.3 ± 11.4 (58.4 - 86.3)	8.6 ± 1.4 (7.2 – 10.6)	151.45-± 24.5 (126.3 - 185.8)	0.41± 0.07 (0.34 - 0.50)
6	72.2 ± 10.3 (60.0 - 80.0)	8.9 ± 3.0 (7.4 – 9.8)	155.5 ± 23.6 (127.7 - 173.9)	0.42 ± 0.06 (0.34 - 0.47)
7	86.0 ± 7.6 (79.2 - 94.8)	10.5 ± 0.9 (9.7 – 11.6)	184.6 ± 18.5 (168.5 - 205.8)	0.50 ± 0.05 (0.46 - 0.56)
8	101.8 ± 32.7 (67.2 - 148.8)	12.5 ± 4.0 (8.2 – 18.2)	222.2 ± 74.1 (142.3 - 329.0)	0.60 ± 0.20 (0.38 - 0.89)
9	90.7 ± 13.5 (72.9 - 104.9)	11.1 ± 1.6 (8.9 – 12.9)	196.8 ± 29.7 (157.8- 229.1)	0.53 ± 0.08 (0.43 - 0.62)
10	72.1 ± 8.8 (56.9 - 79.1)	8.8 ± 1.1 (7.0 - 9.7)	155.8± 19.5 (122.9 - 172.2)	0.42 ± 0.05 (0.33 - 0.47)
Average of all samples	**77.3 ± 18.0 (51.8 - 148.8)**	**9.5 ± 2.2 (6.3 – 18.2)**	**167.1 ± 40.1 (110.5 - 329.0)**	**0.45 ± 0.11 (0.3 - 0.9)**

observed in Figure 5(b), the radium equivalent activity is highest in area No.8 with an average value of 222.2 ± 74.1 Bq/kg while it is lowest in area No.4 with an average value of 129.7 ± 13.8 Bq/kg. The average radium equivalent

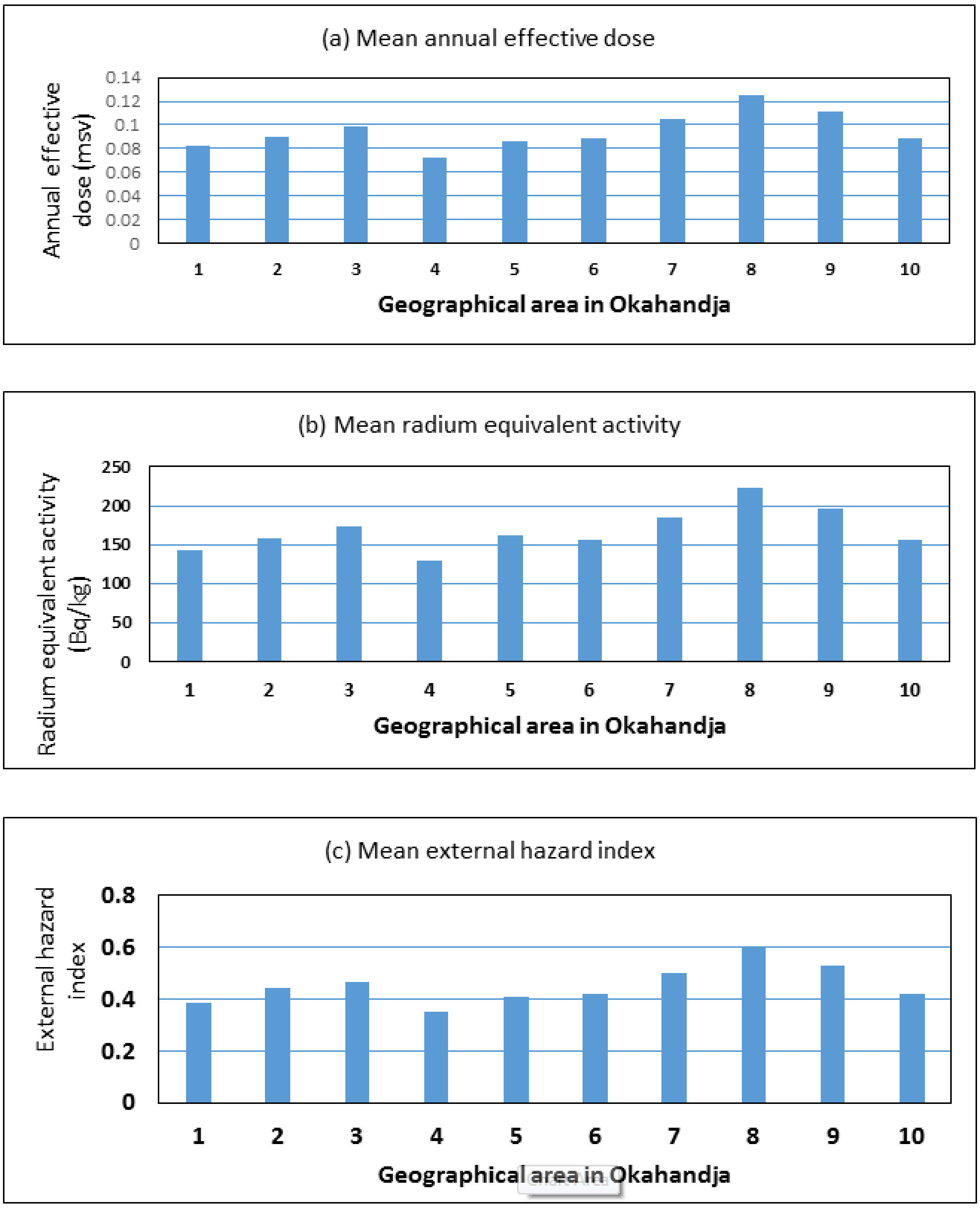


Figure 5: The mean (a) annual effective dose (b) radium equivalent activity and (c) external hazard index in the ten geographical areas of Okahandja.

activity from all the ten geographical areas is 167.1 ± 40.1 Bq/kg. This value is far below the maximum of 370 Bq/kg stated earlier in section 3.5. Similarly, the highest external hazard index is in area No.8 with an average value of 0.60 ± 0.2 while it is lowest in area No.4 with an average value of 0.35 ± 0.04 as could be seen in Figure 5(c). The average external hazard index from all the ten geographical areas is 0.45 ± 0.11 which is far less than unity [14]. The relatively low average values of $\mathrm{Ra_{eq}}$ and $\mathrm{H_{ex}}$ confirm that the town of Okahandja, like the town of Karibib, has a normal background radiation.

Conclusion

The activity concentrations of the primordial radionuclides ^{238}U, ^{232}Th and ^{40}K in soil samples collected from the towns of Karibib and Okahandja and the associated radiation hazard have been studied. With the exemption of the average activity concentration of ^{238}U in the soil samples of Karibib, the average activity concentrations of the radionuclides in the soil samples are higher than the worldwide average values. The average activity concentration of ^{238}U in the soil samples of Karibib is lower than the worldwide average value. However, the corresponding effective dose rates in both towns are below the maximum limit of 1.0 mSv/y recommended by ICRP for the public. Furthermore, the average values obtained for the radium equivalent activity, $\mathrm{Ra_{eq}}$, and the external hazard index, $\mathrm{H_{ex}}$, in the towns are below their respective maximum permissible limits thus confirming that the two towns do not have high background radiation so that radiological hazard is negligible in the towns. The trend in which the average activity concentration of ^{40}K in the soils of some towns in western Namibia increases with decreasing latitude does not continue to Karibib and Okahandja.

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