Radionuclide concentrations and radiation hazard assessment in the soil of Otjiwarongo, Namibia

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ARTICLE INFO

Article history:
Received: 9 August 2021
Received in revised form: 13 September 2021
Accepted: 27 September 2021
Published: 25 February 2022
Edited by KC Chinsembu

Keywords:
Natural radioactivity
Soil
Gamma spectroscopy
Otjiwarongo
Namibia

ABSTRACT

The natural radioactivity and associated hazards in soil samples collected from ten geographical areas in the town of Otjiwarongo, Namibia, have been studied by gamma-ray spectroscopy with an HPGe detector. The mean activity concentrations of the primordial radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ in the ten areas was found to vary from 37.6 ± 7.4 Bq/kg to 97.8 ± 46.2 Bq/kg for $^{238}\mathrm{U}$, from 81.9 ± 16.7 Bq/kg to 852.8 ± 533.0 Bq/kg for $^{232}\mathrm{Th}$ and from 498.7 ± 55.7 Bq/kg to 807.1 ± 94.5 Bq/kg for $^{40}\mathrm{K}$. Most of these mean activity concentrations, especially those of $^{232}\mathrm{Th}$, are much higher than the corresponding worldwide average values. In order to evaluate the associated health hazard, the activity concentrations were used to calculate different radiological parameters. The values obtained for the mean radium equivalent activity (Ra_{eq}) in some areas are above the maximum permissible limit. Also, the values obtained for the mean external hazard index (H_{ex}) in some areas are above the corresponding maximum permissible limit. However, the mean effective dose rates in the ten areas vary from 0.11 ± 0.01 mSv y^{-1} to 0.73 ± 0.43mSv y^{-1} which are all below the maximum permissible limit of 1.0 mSv y^{-1}. These results imply that radiation hazard is negligible in the town of Otjiwarongo.

1 Introduction

Unstable nuclei exist in the soil where they emit ionizing radiation and thereby contribute to natural background radiation. Such nuclei are the primordial radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ and human beings are continuously exposed to the background radiation (Khan, 2010; Oyedele *et al.*, 2008). If the concentrations of the radionuclides in the soil are high, the background radiation will be high and it could pose a health hazard by increasing the risk of cancerous diseases (UNSCEAR, 1993; Midzi *et al.*, 2019).

Consequently, the determination of the activity concentrations of primordial radionuclides and the resulting radioactivity levels in the soils of different towns and countries have been of interest to many scientists worldwide (Shimboyo & Oyedele, 2015; Faanu *et al.*, 2011; Ahmed & El-Arabi, 2005). In Namibia, there is interest in radioactivity levels because there are many uranium deposits and mineral resources in the country and therefore the activity concentrations of primordial radionuclides may be high in the soils of some important towns resulting in unwanted high background radiation. One such town is Otjiwarongo.

The town of Otjiwarongo has a population of more than 21 000 and is situated about 240 km north of Windhoek. The town is an important service centre for the surrounding commercial farms and is a convenient base for day

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 http://istjn.unam.na/index.php/istjn; http://repository.unam.na/handle/11070/790 ISSN: 2026-7673; eISSN: 2026-8653/c 2022 ISTJN.

trips to the Waterberg Plateau Park and the well-known dinosaur footprints on the farm Otjihaenamaparero. The opening of the B2Gold Namibia mine and a Cement Plant near the town should boost the economy of the town and increase the population of the town. More importantly, the town is known for tourism and it is the main gate-way between the southern and northern parts of Namibia.

The objective of this study was to determine the activity concentrations and distributions of the primordial radionuclides $^{40}\mathrm{K}$, $^{232}\mathrm{Th}$, and $^{238}\mathrm{U}$ in the soil of Otjiwarongo and use the results obtained to find background radiation levels across the town and calculate different radiation hazard indices. The study will reveal whether or not the town of Otjiwarongo is in an area of normal or high background radiation. Also, the study will contribute to the baseline data of environmental radioactivity in Namibia.

2 Materials and methods

Sample collection and measurement procedures

The town of Otjiwarongo was divided into ten geographical areas as shown in Figure 1 and five soil samples were collected across each area giving a total of fifty samples. All the sites chosen were away from roads, buildings, railway lines, industrial or agricultural sites and rivers. Each sample collected was about 1kg, and was placed in a plastic bag which was labelled according to the geographical area from which it was collected. The samples were subsequently transported to the Nuclear Physics Laboratory at the University of Namibia (UNAM), Windhoek, and dried under laboratory temperature as well as sieved through a 2 mm mesh screen. 500 g of each sample was carefully weighed and placed in a 500 mL polythene bottle. All the bottles were then tightly sealed and stored at room temperature for about four weeks for the radionuclides to attain secular equilibrium with their progeny before taking measurements.

The soil samples were placed, one at a time, on a calibrated and well-shielded vertical Canberra High Purity Germanium (HPGe) detector and the gamma-ray spectra of the radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the samples were measured. The same geometry and counting time of 10800 seconds used for the samples were also used for measurement on the reference materials RGU-1, RGTh-1 and RGK-1 donated by the International Atomic Energy Agency (IAEA) for radionuclide analysis. The experimental procedure followed in the calibration of the detector has been described elsewhere (Kapofi, 2019). For both the samples and reference materials, the activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ were respectively determined from the gamma transition energies of 0.609 MeV of $^{214}\mathrm{Bi}$, 0.911 MeV of $^{228}\mathrm{Ac}$ and 1.460 MeV of $^{40}\mathrm{K}$. The activity concentrations were in turn used to calculate absorbed dose rates, effective dose rates and different radiation hazard parameters.

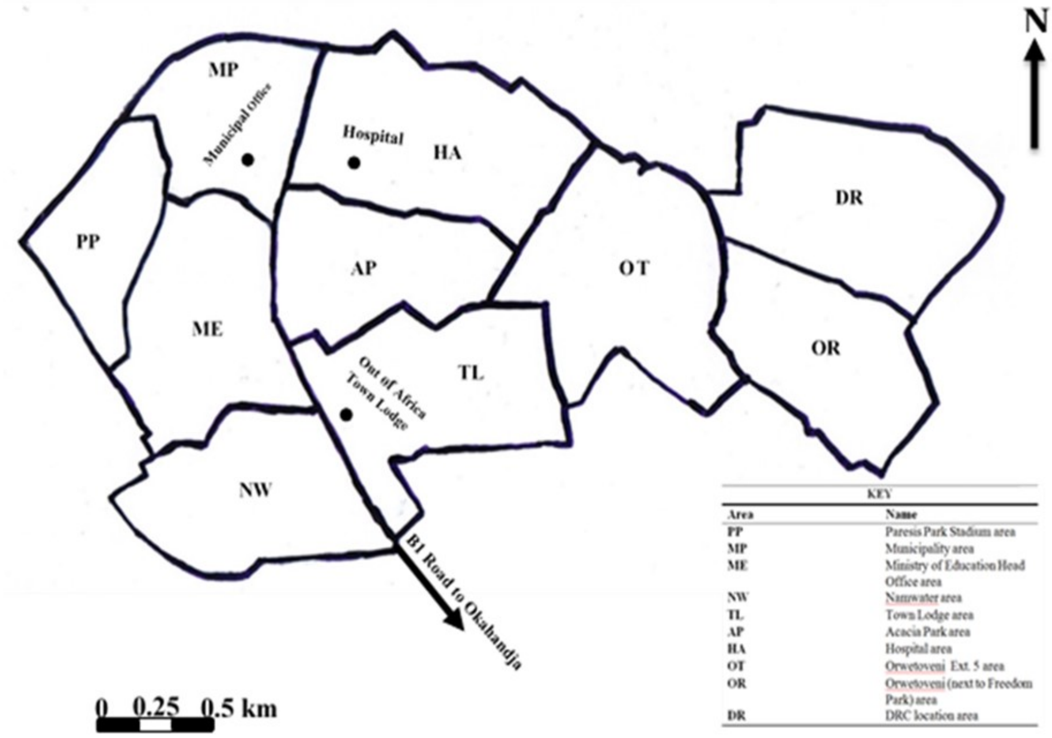


Figure 1: A map showing the geographical areas where soil samples were collected in Otjiwarongo

3 Results

Activity concentrations

The mean activity concentrations of the primordial radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ in the soil samples collected from the ten geographical areas of the town of Otjiwarongo are presented in Table 1 and shown in Figure 2. The range of activity concentrations of the radionuclides in each area is also shown in the Table.

Table 1: Mean activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in different geographical areas of Otjiwarongo. The range of values are given in parenthesis

Area	Mean activity concentration (Bq/kg)		
	$^{238}\mathrm{U}$	$^{232}\mathrm{Th}$	$^{40}\mathrm{K}$
PP	$\mathbf{46.9 \pm 10.1}$ (36.8 - 60.4)	$\mathbf{99.9 \pm 29.2}$ (70.5 - 135.6)	$\mathbf{543.1 \pm 49.1}$ (478.6 - 596.9)
MP	$\mathbf{37.6 \pm 7.4}$ (25.4 - 44.2)	$\mathbf{88.0 \pm 43.4}$ (38.6 - 144.7)	$\mathbf{498.7 \pm 55.7}$ (411.2 - 556.1)
ME	$\mathbf{42.0 \pm 8.5}$ (30.8 - 54.2)	$\mathbf{98.1 \pm 27.3}$ (68.9 - 135.7)	$\mathbf{510.3 \pm 43.8}$ (457.7 - 571.4)
NW	$\mathbf{37.8 \pm 3.2}$ (32.2 - 40.0)	$\mathbf{89.0 \pm 26.9}$ (71.9 - 136.3)	$\mathbf{562.2 \pm 40.4}$ (520.4 - 627.6)
TL	$\mathbf{40.3 \pm 6.6}$ (29.9 - 45.0)	$\mathbf{96.5 \pm 25.6}$ (58.3 - 119.7)	$\mathbf{573.5 \pm 25.7}$ (551.0 - 602.0)
AP	$\mathbf{47.0 \pm 9.2}$ (36.0 - 58.2)	$\mathbf{146.1 \pm 55.7}$ (97.4 - 227.5)	$\mathbf{554.1 \pm 35.5}$ (515.3 - 596.9)
HA	$\mathbf{41.0 \pm 6.7}$ (33.7 - 49.1)	$\mathbf{81.9 \pm 16.7}$ (61.2 - 103.8)	$\mathbf{517.4 \pm 13.6}$ (501.0 - 535.7)
OT	$\mathbf{46.0 \pm 15.8}$ (27.2 - 64.5)	$\mathbf{222.0 \pm 107.2}$ (88.6 - 334.4)	$\mathbf{698.0 \pm 52.2}$ (642.9 - 760.2)
OR	$\mathbf{97.8 \pm 46.2}$ (32.3 - 153.5)	$\mathbf{852.8 \pm 533.0}$ (200.0 - 1397.0)	$\mathbf{807.1 \pm 94.5}$ (693.9 - 882.7)
DR	$\mathbf{56.4 \pm 11.6}$ (45.8 - 72.9)	$\mathbf{275.1 \pm 113.5}$ (163.4 - 429.0)	$\mathbf{794.6 \pm 77.7}$ (709.2 - 898.0)
Mean	$\mathbf{49.3 \pm 23.1}$	$\mathbf{204.9 \pm 278.2}*$	$\mathbf{604.3 \pm 119.5}$

*This value reflects the high degree of non-uniformity in the distripution of $^{232}\mathrm{Th}$ across the town.

As could be observed in the Table, the mean activity concentration of $^{238}\mathrm{U}$ varies from 37.6 ± 7.4 Bq/kg in the MP area to a high value of 97.8 ± 46.2 Bq/kg in the OR area. Also, the mean activity concentration of $^{232}\mathrm{Th}$ varies from a value of 81.9 ± 16.7 Bq/kg in the HA area to a very high value of 852.8 ± 533.0 Bq/kg in the OR area. Similarly, the mean activity concentration of $^{40}\mathrm{K}$ varies from a high value of 498.7 ± 55.7 Bq/kg in the MP area to a very high value of 807.1 ± 94.5 Bq/kg in the OR area. These results show that the mean activity concentrations of $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ are relatively high across the ten geographical areas and they are higher than the corresponding world-wide mean values of 45 Bq/kg and 420 Bq/kg, respectively. In particular, the mean activity concentration of $^{232}\mathrm{Th}$ in the OR area is very high and very much higher than its world-wide mean value. As could be observed in Figure 2 (column 9), the OR area has the highest mean activity concentrations of the three radionuclides. With the exemption of the OR area, the mean activity concentration of $^{40}\mathrm{K}$ is the highest among the radionuclides in all the areas. In contrast, $^{238}\mathrm{U}$ has the lowest activity concentrations among the radionuclides in all the areas. However, the mean activity concentrations of $^{238}\mathrm{U}$ in the areas are higher than the world-wide mean value of 33 Bq/kg (UNSCEAR, 2000).

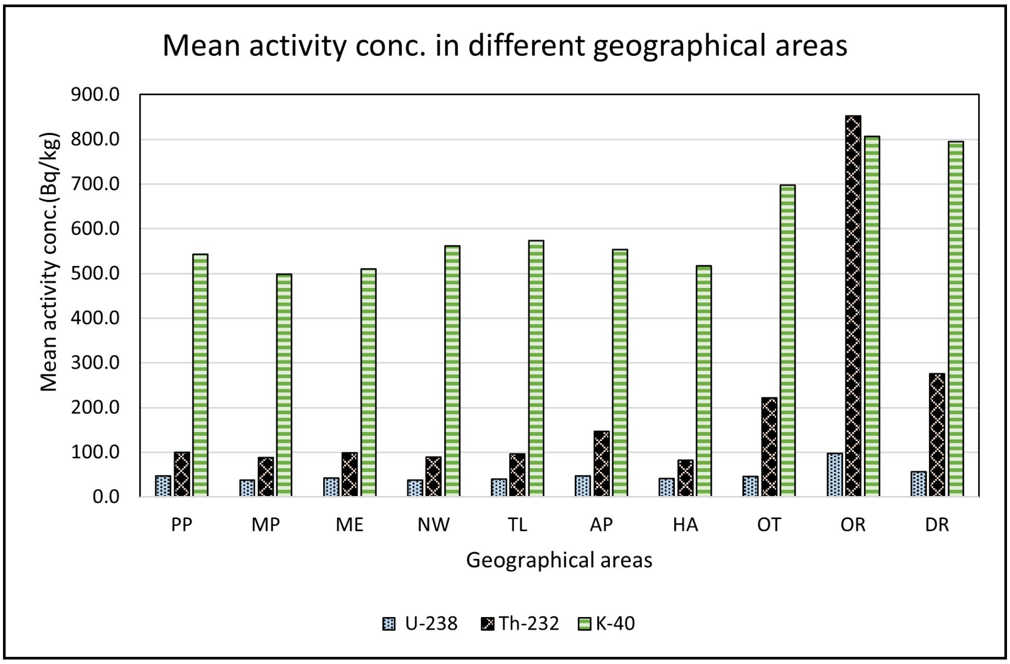


Figure 2: The mean activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ in the ten geographical areas of Otjiwarongo

Dose rates and radiation hazards

The absorbed dose rates in air, at 1 m above the ground, due to the activity concentrations of radionuclides at each of the sites where samples were collected were calculated using the expression (Shimboyo *et al.*, 2016):

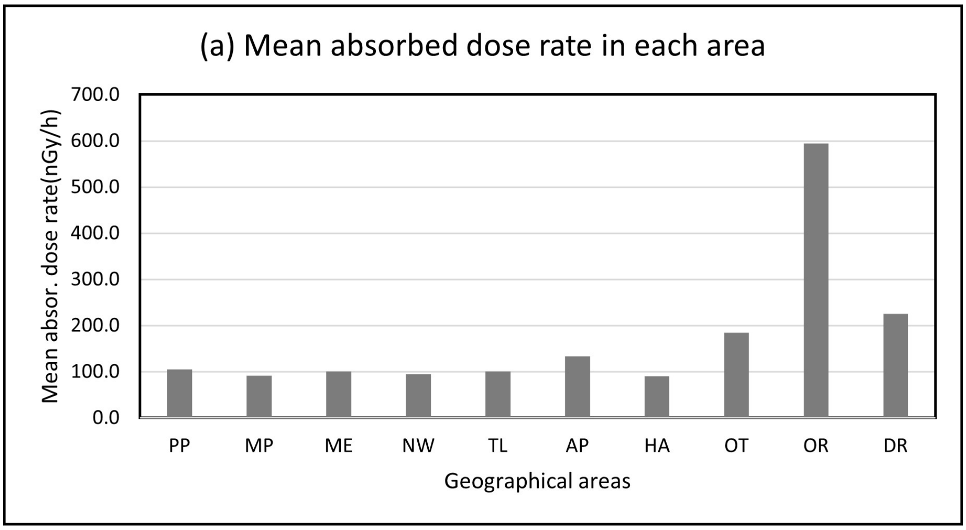
$$D = 0.462\, A_U + 0.604\, A_{Th} + 0.417\, A_K \tag{1}$$

where D is the dose rate (nGy h^{-1}) at 1m above the ground and A_U, A_{Th} and A_K are the activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ in Bq/kg, respectively. Also, the annual effective dose was calculated using the conversion coefficient from absorbed dose in air to effective dose, 0.7 Sv Gy^{-1}, and an outdoor occupancy factor 0.2 (UNSCEAR, 2000). The mean absorbed dose rate in the ten areas varies from a low value of 90.0 ± 13.7 nGy h^{-1}, at HA to a high value of 593.9 ± 347.2 nGy h^{-1} at OR as could be seen in Table 2 and Figure 3(a). This shows that the highest mean absorbed dose rate, 593.9 ± 347 nGy h^{-1}, is several times the world average of 60 nGy h^{-1} (UNSCEAR, 2000).

Also, the mean annual effective dose varies from a low value of 0.11 ± 0.02 mSv y^{-1} at HA , to a high value of 0.73 ± 0.43 mSv y^{-1} at OR as shown in Table 2 and Figure 3(b). This implies that the mean effective dose rates calculated for all geographical areas are below the maximum permissible limit of 1.0 mSv y^{-1} recommended by the International Commission on Radiological Protection (ICRP). Hence, all the effective dose rates obtained are considered to be within acceptable levels.

Table 2: Mean absorbed dose rate and annual effective dose in different geographical areas of Otiwarongo (The range of values are given in parenthesis)

Area	Mean absorbed dose rate (nGy /h)	Mean annual effective dose (mSv)
PP	$\mathbf{104.7 \pm 19.9}$ (84.9 - 129.7)	$\mathbf{0.13 \pm 0.02}$ (0.11 - 0.16)
MP	$\mathbf{91.3 \pm 31.9}$ (52.2 - 130.0)	$\mathbf{0.11 \pm 0.04}$ (0.06 - 0.16)
ME	$\mathbf{99.9 \pm 22.2}$ (76.0 - 130.8)	$\mathbf{0.12 \pm 0.03}$ (0.09 - 0.16)
NW	$\mathbf{94.7 \pm 19.4}$ (83.1 - 126.9)	$\mathbf{0.12 \pm 0.02}$ (0.10 - 0.16)
TL	$\mathbf{100.8 \pm 19.6}$ (72.9 - 117.9)	$\mathbf{0.12 \pm 0.02}$ (0.09 - 0.14)
AP	$\mathbf{133.0 \pm 39.4}$ (97.0 - 188.3)	$\mathbf{0.16 \pm 0.05}$ (0.12 - 0.23)
HA	$\mathbf{90.0 \pm 13.7}$ (73.8 - 100.6)	$\mathbf{0.11 \pm 0.02}$ (0.09 - 0.12)
OT	$\mathbf{184.4 \pm 74.3}$ (99.7 - 255.9)	$\mathbf{0.23 \pm 0.09}$ (0.12 - 0.31)
OR	$\mathbf{593.9 \pm 347.2}$ (164.7 - 951.5)	$\mathbf{0.73 \pm 0.43}$ (0.20 - 1.17)
DR	$\mathbf{225.4 \pm 77.1}$ (149.8 - 330.2)	$\mathbf{0.28 \pm 0.09}$ (0.18 - 0.40)
Mean	$\mathbf{171.7 \pm 180.1}$	$\mathbf{0.21 \pm 0.22}$



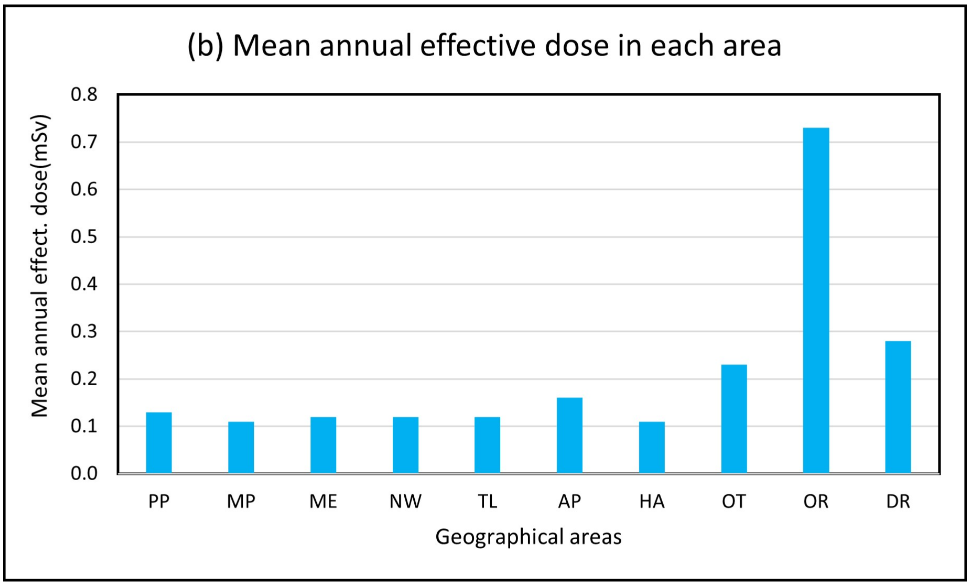


Figure 3: The mean (a) absorbed dose rates and (b) effective dose rates in different geographical areas of Otjiwarongo

The hazard indices which are normally used to indicate the level of exposure are also calculated. One of these indices is the radium equivalent activity (Ra$_{eq}$) given by the following equation (Midzi *et al.*, 2019):

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{2}$$

Where A_{Ra}, A_{Th} and A_K are respectively activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in Bq/kg and it is assumed that there is secular equilibrium between $^{238}\mathrm{U}$ and $^{226}\mathrm{Ra}$ (same activity concentration). The maximum value of the radium equivalent activity is 370 Bq/kg. Another index is the external hazard index (H_{ex}) which is given by (Shimboyo *et al.*, 2016):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{3}$$

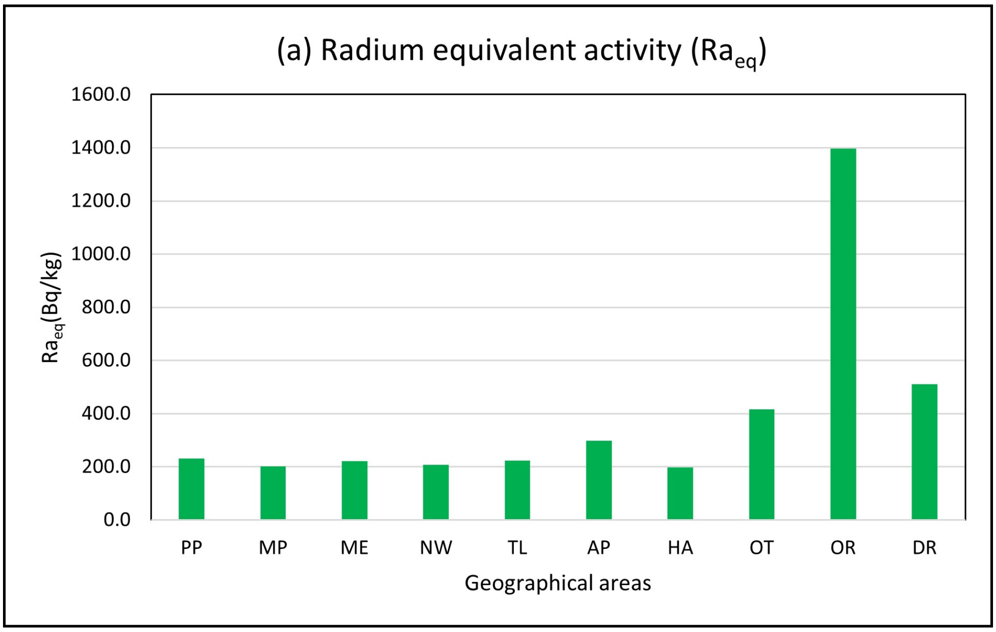
Where,A_{Ra}, A_{Th} and A_K are as defined earlier and it is assumed that there is secular equilibrium between $^{238}\mathrm{U}$ and $^{226}\mathrm{Ra}$. The value of Hex must be less than unity for radiation hazard to be negligible.

The mean Radium equivalent activity (Ra$_{eq}$) and mean external hazard index (H_{ex}) in different geographical areas are shown in Table 3.

Table 3: Mean Radium equivalent activity and external hazard index in different areas of Otjiwarongo. (The range of values are given in parenthesis)

Area	Mean Radium equivalent activity (Ra_{eq})	Mean external hazard index (H_{ex})
PP	$\mathbf{231.6 \pm 46.0}$ (185.0 - 291.1)	$\mathbf{0.6 \pm 0.1}$ (0.5 - 0.8)
MP	$\mathbf{201.8 \pm 73.7}$ (112.3 - 291.8)	$\mathbf{0.6 \pm 0.2}$ (0.3 - 0.8)
ME	$\mathbf{221.5 \pm 50.8}$ (166.5 - 292.3)	$\mathbf{0.6 \pm 0.1}$ (0.5 - 0.8)
NW	$\mathbf{208.4 \pm 44.8}$ (181.7 - 283.1)	$\mathbf{0.6 \pm 0.1}$ (0.5 - 0.8)
TL	$\mathbf{222.4 \pm 45.6}$ (157.3 - 262.0)	$\mathbf{0.6 \pm 0.1}$ (0.4 - 0.7)
AP	$\mathbf{298.5 \pm 91.6}$ (215.0 - 427.9)	$\mathbf{0.8 \pm 0.3}$ (0.6 - 1.2)
HA	$\mathbf{197.9 \pm 31.5}$ (160.4 - 223.5)	$\mathbf{0.5 \pm 0.1}$ (0.4 - 0.6)
OT	$\mathbf{417.2 \pm 173.2}$ (216.9 - 586.1)	$\mathbf{1.13 \pm 0.47}$ (0.6 - 1.6)
OR	$\mathbf{1379.5 \pm 815.7}$ (371.8 - 2219.1)	$\mathbf{3.7 \pm 2.2}$ (1.0 - 6.0)
DR	$\mathbf{511.0 \pm 179.8}$ (334.8 - 755.5)	$\mathbf{1.4 \pm 0.5}$ (0.9 - 2.0)
Mean	$\mathbf{388.9 \pm 426.7}$	$\mathbf{1.1 \pm 1.2}$

The mean Radium equivalent activity (Ra_{eq}) varies from a relatively low value of 197.9 ± 31.5 Bq/kg at HA to a high value of 1379.5 ± 815.7 Bq/kg at OR as could be seen in Table 3 and Figure 4(a). Similarly, the mean external hazard index (H_{ex}) varies from a relatively low value of 0.5 ± 0.1 at HA to a high value of 3.7 ± 2.2 at OR as could be observed in Table 3 and Figure 4(b). These results show that the OR area has the highest mean Radium equivalent activity (Ra_{eq}) and mean external hazard index (H_{ex}) while the HA area has the lowest Ra_{eq}, and H_{ex} as could be seen in Figures 4(a) and (b). These results are not surprising as the OR area has the highest mean activity concentrations of radionuclides and the HA area is one of the areas with low mean activity concentrations of radionuclides as could be observed in Table 1 and Figure 2. The relatively high values of 1379.5 ± 815.7 Bq/kg and 3.7 ± 2.2 obtained for Ra_{eq} and H_{ex} respectively in the OR area are much above the corresponding maximum permissible values of 370 Bq/kg and 1. However, the mean values of Ra_{eq} and H_{ex} in most of the other areas in the town are below the maximum permissible values.



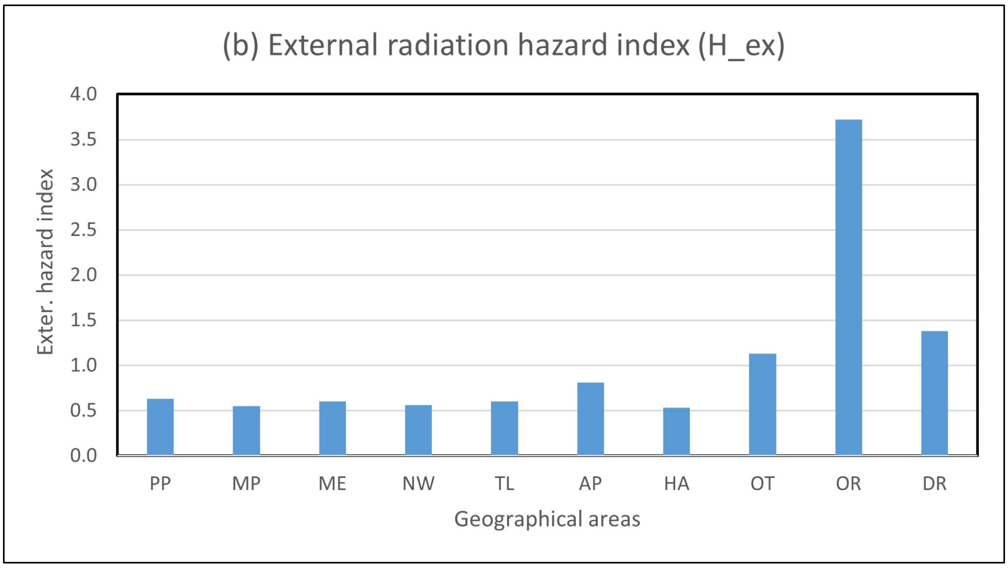


Figure 4: (a) Mean radium equivalent activity and (b) mean external hazard index in Otjiwarongo

4 Discussion

The mean activity concentrations of the primoidial radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soils of the different geographical areas of the town of otjiwarongo are higher than the corresponding world-wide average values. Also, the mean activity concentration of some of the radionuclides (e.g. $^{232}\mathrm{Th}$) in some areas (e.g. OR) are more than double those of the other areas (e.g. MP) thus indicating that the distribution of radionuclides in the soil of the town is not uniform. Similar observation of the non-uniformity of radionuclide distributions in the soils of different towns in Namibia have been made (Shimboyo *et al.*, 2016).

While the mean activity concentration of $^{40}\mathrm{K}$ is always higher than those of the other radionuclides in some other studies (Oyedele *et al.*, 2008), the mean activity concentration of $^{232}\mathrm{Th}$ in the OR area is higher than that of $^{40}\mathrm{K}$. The highest mean absorbed dose rate in the ten geographical areas, 593.9 ± 347.2 nGy h^{-1}, is much higher than the worldwide average value, 60 nGy h^{-1} (UNSCEAR, 2000). However, the mean effective dose rates calculated for the ten areas are below the maximum permissible limit of 1.0 mSv y^{-1} recommended by the International Commission on Radiological Protection (ICRP). This result implies that the town has a normal background radiation.

The activity concentrations were also used to calculate the radium equivalent activity (Ra$_{eq}$) and external hazard index (H_{ex}). The mean radium equivalent activity (Ra$_{eq}$) varies from 197.9 ± 31.5 Bq/kg in the HA area to a high value of 1379.5 ± 815.7 Bq/kg in the OR area. This high value is far above the maximum permissible limit of 370 Bq/kg. Similarly, the mean external hazard index (H_{ex}) varies from 0.5 ± 0.1 at HA to a high value of 3.7 ± 2.2 at OR. This high value is above the maximum permissible limit of 1. However, the mean values of Ra$_{eq}$ and H_{ex} in most of the areas in the town are below the corresponding maximum permissible values. Also, the mean effective dose rates calculated for each area of the town are below the maximum permissible limit of 1.0 mSv y^{-1}. These results imply that the town of Otjiwarongo has normal background radiation.

5 Conclusion

The activity concentrations of the primordial radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$, in the soil of the town of Otjiwarongo have been determined and used to calculate radiological parameters such as effective dose rate, radium equivalent activity (Ra$_{eq}$) and external hazard index (H_{ex}). The mean activity concentrations of the radionuclides in ten different geographical areas of the town are higher than the corresponding world-wide average values. Also, the mean activity concentrations of some radionuclides in some areas is double that in other areas. The mean values obtained for the radium equivalent activity in some areas are above the maximum permissible limit. Similarly, the mean values obtained for the external hazard index (H_{ex}).in some areas are above the maximum permissible limit. However, the mean values calculated for the effective dose rate in the areas are all lower than the corresponding maximum permissible limit of 1.0 mSv y^{-1} thus implying that the town of Otjiwarongo has normal background radiation level.

Acknowledgements

The authors wish to thank the University of Namibia (UNAM), the Ministry of Health and Social Services (MHSS) and the Municipality of Otjiwarongo for supporting the project in various forms. Appreciation is also extended to the International Atomic Energy Agency (IAEA) for providing the equipment and reference materials used in the project.

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