Radioprotection 2024, 59(3), 235–245
© A.E.A. Elzain *et al.*, Published by EDP Sciences, 2024
https://doi.org/10.1051/radiopro/2024018

Available online at:
www.radioprotection.org

ARTICLE OPEN ACCESS

Assessment of environmental radioactivity concentration and effective dose rates from radon gas exposure from water samples in Gezira State, Sudan

A.E.A. Elzain[1,2,*], R. Shady[2,3] and A.A. Yagob[4]

[1] Department of Physics, Kassala University, P. O. Box 266 Box 266, Sudan.
[2] Department of Physics, College of Science and Arts in Uglat Asugour, Qassim University, Uglat Asugour, Kingdom of Saudi Arabia.
[3] Department of Physics, faculty of Science, Tanta University, Tanta, Egypt.
[4] Department of Physical Sciences, College of Science, Jazan University, P.O.Box 114, Jazan 82817, Saudi Arabia.

Received: 17 December 2023 / Accepted: 24 May 2024

Abstract – A study was conducted in Gezira State, Sudan, to estimate the concentration of radon and the annual effective dose rate in water samples based on inhalation, ingestion, and age group. The study collected 26 samples from different locations. The results showed that the mean concentration of radon was 7.68 ± 1.07 Bq.l^{-1}, and the mean effective dose rate of radon released from water to indoor air was 19.17 ± 2.68 μSv.y^{-1}. The average effective dose rates calculated from ingestion, inhalation, and the total annual effective dose rate were 18.81 ± 2.63, 19.34 ± 2.71, and 38.15 ± 5.34 μSv.y^{-1}, respectively. The annual effective dose rates for infants, children, and adults were calculated to have mean values of 80.60 ± 11.27, 53.73 ± 7.51, and 38.38 ± 5.37 μSv.y^{-1}, respectively. The study found that 23.1% of the samples exceeded the maximum contamination level, while 76.9% were below the reference levels set by the USEPA, WHO, and EU. Despite the increase in radiation dose with age and consumption rates, the radiation dose from water was lower than the recommended limits set by UNSCEAR and WHO. Additionally, the bronchial epithelium received twice the radiation dose compared to the stomach walls.

Keywords: radon concentration / effective dose rate / RAD7 / water samples / different age groups

1 Introduction

Radon-222, a naturally occurring radioactive gas with the longest half-life (3.82 days), This isotope comes from the decaying chain of uranium-238. Water's radionuclide content is crucial as it can dissolve these elements during interactions with soil and rocks (Duong *et al.*, 2024). Environmental monitoring focuses on detecting natural radiation from radon and its offspring in air, soil, building materials and water (Idriss *et al.*, 2020; Elzain *et al.*, 2023). Radon-222, a chemical found in drinking water, can cause cancer by damaging the DNA of lungs and stomach cells and can also lead to stomach disorders and classified as the second leading cause of lung cancer (Riudavets *et al.*, 2022). Lung and stomach cancer are responsible for many annual cancer deaths and health problems in the USA and Europe (Darby *et al.*, 2006; Messier and Serre, 2016). Health organizations have established acceptable levels of radon and radium concentrations, with the US Environmental Protection Agency (USEPA) defining a radon concentration value of 11 Bq.l^{-1} to ensure safe drinking water through regulating drinking water quality with the Maximum Contaminant Level (MCL), the legal upper limit on material allowed in public water systems (USEPA, 2022). The concentration of radon in groundwater can vary over time due to factors like recharge dilution and pumping changes (WHO, 2011; ISO, 2023). The European Commission has recommended measures to address radon in drinking water, although the de-ionization of water can reduce radon concentrations in tube wells (EUC, 2001; Nakano *et al.*, 2020). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates the transfer coefficient of radon from water to indoor air to be 10^{-4}, and suggests radon concentration in water for human consumption from 4 to 40 Bq.l^{-1} (UNSCEAR, 2008). The World Health Organization (WHO) guidelines for drinking water quality do not provide recommended radon levels, but it is more appropriate to measure concentrations in indoor air; thus, public water supplies should control radon levels if they exceed the WHO guideline value of 100 Bq.l^{-1}(WHO, 2004). The EU Directive 2013/51/EURATOM sets limits on the concentration of radon

*Corresponding author: Abdelmoniem1@yahoo.com; 3954@qu.edu.sa

in water for human consumption (EUC, 2013). This study aims to evaluate and supplement previous research on radon health effects in Gezira State, Sudan, and other investigations in Africa, focusing on concentration levels, effective dose rates, and age groups (Traoré I. *et al.*, 2013; Elzain, 2014, 2015, 2016, 2023; Isinkaye and Ajiboye, 2017; Elzain *et al.*, 2019). The results can help identify potential health hazards associated with water use in the region.

2 Materials and methods

2.1 The study area

Gezira State is a densely populated region located in the east-central part of Sudan. Its coordinates are 14.5° N and 33.5° E (Fig. 1). The state's capital is Wad Madani, and it shares borders with Khartoum, Sinnar, White Nile, and Gedarif States. The northern and northeastern parts of Gezira State have a semi-arid climate, while the eastern and southern parts have a dry monsoon climate with a maximum mean temperature of 47°C. The area is primarily flat, with clay soil and small hills, and can be divided into three major units: highlands and isolated smaller mountains, clayey and sandy soil areas, and valleys (Wadis). These details were reported by UNDP in 2010, MOG in 1994, and studies by Sami *et al.* (2014) and Abdelgalili *et al.* (2019) (MOG, 1994; UNDP, 2010; Sami *et al.*, 2014; Abdelgalili *et al.*, 2019).

2.2 Evaluations of radon gas from water samples using the RAD7 H_2O technique

The RAD7 radon-in-air monitor was employed to measure the levels of radon in water samples and assess their quality by using the RAD H_2O technique. The test followed the Wat-250 protocols and began with the RAD7's internal air pump expelling radon-222 and measuring its activity concentration. The closed-loop aeration system and radon-in-air monitor completed the process within 30 min. The RAD7 was attached to 250-ml sample bottles, and a closed air loop was circulated through the water sample until the RAD-H_2O system achieved equilibrium. The RAD7 employed a passivated implanted planar silicon detector (PIPS) to detect alpha-decaying radon progeny ^{218}Po and ^{214}Po. After 30 min, the RAD7 created a summary report with the average radon reading (Durridge, 2023). Water samples' concentration levels can be determined using the following formula (Elzain, 2017):

$$C_{RnW} = C_{Rn} e^{-\lambda t}. \quad (1)$$

The (C_{RnW}) level from water is determined by measuring the radon concentration (C_{Rn}) using a RAD7 device. The time interval between sampling and testing is denoted by (t), while (λ) represents the decay constant, which is equivalent to 0.181 day^{-1}, given that the half-life is 3.83 days.

2.3 Calculation of the annual effective dose

Home radiation exposure is primarily due to radon concentrations and the effective dose rates of water released during daily tasks like dishwashing and showering (Nazaroff and Nero, 1988; Niculita-Hirzel *et al.*, 2021). The following formula can estimate the annual effective dose of radon released from water into the interior air due to regular household activities (UNSCEAR, 2000):

$$E(mSv{\cdot}y^{-1}) = C_{RnW} \times Q_f \times F_f \times R \times D \times 8760. \quad (2)$$

C_{RnW} is the radon concentration in water, Q_f is the indoor occupation factor with the value of 0.8, E_f is the equilibrium factor that equal to 0.4, R: is the ratio of radon in air to water = 10^{-4}, D is the conversion factor of 9 nSv. (h.Bq.m^{-3})$^{-1}$ and 8760 is the number of hours annually.

Radon in water enters the body through ingestion and inhalation, exposing the stomach and lungs. Annual effective doses can be calculated using UNSCEAR parameters (UNSCEAR, 2000). The amount of water consumed impacts the annual mean exposure doses through ingestion. Additionally, radon-222 can leak into indoor air during household chores. The annual mean exposure doses of radon-222 in water for ingestion (E_{wIng}) and inhalation (E_{wInh}) were calculated using UNSCEAR 2000 parameters (UNSCEAR, 2000):

$$E_{Ing}(\mu Sv{\cdot}y^{-1}) = C_{RnW} \times C_W \times D, \quad (3)$$

where C_W is the annual intake of water of (150, 350, and 500) (l.y^{-1}) for infants, children, and adults, C_{RnW} is the concentration of radon-222 in water, and $D_{F\text{-}Ing}$ is the ingested dose conversion factor that equals (7×10^{-8}, 2×10^{-8}, and 1×10^{-8}) (Sv.Bq^{-1}) ICRP, 1996.

Using the UNSCEAR parameters, the annual effective doses for inhalation of radon in water were calculated:

$$E_{Inh}(\mu Sv{\cdot}y^{-1}) = C_{RnW} \times O \times E_f \times R \times D, \quad (4)$$

where O is the average indoor occupancy time per individual (7000 h.y^{-1}). The ingestion dose calculated by multiplying inhalation and ingestion dose tissue weighting factors, with a tissue weighting factor of 0.12 ICRP, 1996; UNSCEAR, 2000.

The total annual mean exposure doses for people may be determined by adding the annual effective doses for ingestion and inhalation.

3 Results and discussion

This study examines radon concentration levels, annual effective dose rates, ingestion and inhalation dose rates, and effective dose rates for adults, children, and infants in water samples from 26 locations in Gezira State, Sudan, as shown in Tables 1 and 2 and Figures 1–9.

Table 1 and Figure 3 show how the levels of radon concentration vary from 1.55 ± 0.13Bq.l^{-1} to 18.38 ± 3.05Bq.l^{-1} with an average of 7.68 ± 1.07Bq.l^{-1}. The study examined water radon concentrations in various locations, revealing variations may be due to geological conditions, proximity to uranium-rich rocks, underground water, local water sources, and human activities and industrial processes. However, all measured radon concentrations were well below the recommended limits, maintaining safe domestic water standards. 23.1% of samples exceeded the USEPA's maximum contamination level, while 76.9% were below the maximum contaminant level (USEPA, 2022). 100% of radon concentrations were below the UNSCEAR, WHO, and EU's

Table 1. Average radon concentration, annual effective doses released to air, total annual effective doses for inhalation and ingestion and the annual effective doses rates for (infants, children and adults) from the water samples.

No	Location	Longitude	Latitude	C ($Bq.l^{-1}$)	($E \pm \Delta E$) ($\mu Sv.y^{-1}$)	($E_{ing} \pm \Delta E_{ing}$) ($\mu Sv.y^{-1}$)	($E_{inh} \pm \Delta E_{inh}$) ($\mu Sv.y^{-1}$)	($E_{Tot} \pm \Delta E_{Tot}$) ($\mu Sv.y^{-1}$)	*Effective dose rate with respect to the age groups of the inhabitants*($\mu Sv.y^{-1}$)		
									E_{Infant}	$E_{Children}$	E_{Adults}
1	AlBagair	15.374	32.759	1.55 ± 0.13	3.87 ± 0.32	3.80 ± 0.32	3.91 ± 0.33	7.70 ± 0.65	16.28 ± 1.37	10.85 ± 0.91	7.75 ± 0.65
2	AlKamlin	15.086	33.173	1.57 ± 0.88	3.92 ± 2.20	3.85 ± 2.16	3.96 ± 2.22	7.80 ± 4.37	16.49 ± 9.24	10.99 ± 6.16	7.85 ± 4.40
3	Barakat	14.316	33.538	2.64 ± 0.15	6.59 ± 0.37	6.47 ± 0.37	6.65 ± 0.38	13.12 ± 0.75	27.72 ± 1.58	18.48 ± 1.05	13.20 ± 0.75
4	Tabat	14.666	33.094	2.64 ± 0.29	6.59 ± 0.72	6.47 ± 0.71	6.65 ± 0.73	13.12 ± 1.44	27.72 ± 3.05	18.48 ± 2.03	13.20 ± 1.45
5	AlShabarga	14.259	33.642	2.77 ± 0.37	6.92 ± 0.92	6.79 ± 0.91	6.98 ± 0.93	13.77 ± 1.84	29.09 ± 3.89	19.39 ± 2.59	13.85 ± 1.85
6	Almasudia	15.304	32.875	2.95 ± 0.94	7.37 ± 2.35	7.23 ± 2.30	7.43 ± 2.37	14.66 ± 4.67	30.98 ± 9.87	20.65 ± 6.58	14.75 ± 4.70
7	Abu Ushar	14.920	33.207	3.68 ± 0.89	9.19 ± 2.22	9.02 ± 2.18	9.27 ± 2.24	18.29 ± 4.42	38.64 ± 9.35	25.76 ± 6.23	18.40 ± 4.45
8	AlHaj AbdAllah	13.960	33.592	5.47 ± 0.56	13.66 ± 1.40	13.40 ± 1.37	13.78 ± 1.41	27.19 ± 2.78	57.44 ± 5.88	38.29 ± 3.92	27.35 ± 2.80
9	AlHasahisa	14.755	33.272	5.83 ± 0.69	14.56 ± 1.72	14.28 ± 1.69	14.69 ± 1.74	28.98 ± 3.43	61.22 ± 7.25	40.81 ± 4.83	29.15 ± 3.45
10	Wad ElHaddad	13.819	33.546	6.14 ± 0.73	15.33 ± 1.82	15.04 ± 1.79	15.47 ± 1.84	30.52 ± 3.63	64.47 ± 7.67	42.98 ± 5.11	30.70 ± 3.65
11	ElHosh	14.089	33.493	6.71 ± 0.96	16.75 ± 2.40	16.44 ± 2.35	16.91 ± 2.42	33.35 ± 4.77	70.46 ± 10.08	46.97 ± 6.72	33.55 ± 4.80
12	Al-Lauotah	15.193	32.957	6.76 ± 0.79	16.88 ± 1.97	16.56 ± 1.94	17.04 ± 1.99	33.60 ± 3.93	70.98 ± 8.30	47.32 ± 5.53	33.80 ± 3.95
13	Alaidaj	15.191	33.122	6.79 ± 0.87	16.95 ± 2.17	16.64 ± 2.13	17.11 ± 2.19	33.75 ± 4.32	71.30 ± 9.14	47.53 ± 6.09	33.95 ± 4.35
14	Hashaba	14.664	32.747	6.99 ± 0.78	17.45 ± 1.95	17.13 ± 1.91	17.61 ± 1.97	34.74 ± 3.88	73.40 ± 8.19	48.93 ± 5.46	34.95 ± 3.90
15	Wad Yasin	13.930	33.445	7.02 ± 0.91	17.53 ± 2.27	17.20 ± 2.23	17.69 ± 2.29	34.89 ± 4.52	73.71 ± 9.56	49.14 ± 6.37	35.10 ± 4.55
16	Wad Medani	14.398	33.527	7.12 ± 0.82	17.78 ± 2.05	17.44 ± 2.01	17.94 ± 2.07	35.39 ± 4.08	74.76 ± 8.61	49.84 ± 5.74	35.60 ± 4.10
17	Wad AlHindi	14.204	33.527	7.34 ± 0.89	18.33 ± 2.22	17.98 ± 2.18	18.50 ± 2.24	36.48 ± 4.42	77.07 ± 9.35	51.38 ± 6.23	36.70 ± 4.45
18	AlMuhayriba	14.841	33.027	8.51 ± 0.98	21.25 ± 2.45	20.85 ± 2.40	21.45 ± 2.47	42.29 ± 4.87	89.36 ± 10.29	59.57 ± 6.86	42.55 ± 4.90
19	Rufaa	14.768	33.361	9.01 ± 1.07	22.50 ± 2.67	22.07 ± 2.62	22.71 ± 2.70	44.78 ± 5.32	94.61 ± 11.24	63.07 ± 7.49	45.05 ± 5.35
20	Tamboul	14.928	33.421	9.54 ± 1.23	23.82 ± 3.07	23.37 ± 3.01	24.04 ± 3.10	47.41 ± 6.11	100.17 ± 12.92	66.78 ± 8.61	47.70 ± 6.15
21	AlHilalyia	14.946	33.252	12.18 ± 1.87	30.41 ± 4.67	29.84 ± 4.58	30.69 ± 4.71	60.53 ± 9.29	127.89 ± 19.64	85.26 ± 13.09	60.90 ± 9.35
22	UmDagarsi	14.998	33.230	13.12 ± 1.46	32.76 ± 3.65	32.14 ± 3.58	33.06 ± 3.68	65.21 ± 7.26	137.76 ± 15.33	91.84 ± 10.22	65.60 ± 7.30
23	Almanagil	14.263	33.005	14.30 ± 2.78	35.71 ± 6.94	35.04 ± 6.81	36.04 ± 7.01	71.07 ± 13.82	150.15 ± 29.19	100.10 ± 19.46	71.50 ± 13.90
24	AlAzzazi	14.472	32.746	14.34 ± 1.93	35.81 ± 4.82	35.13 ± 4.73	36.14 ± 4.86	71.27 ± 9.59	150.57 ± 20.27	100.38 ± 13.51	71.70 ± 9.65
25	AlMadina Arab	14.360	33.314	16.23 ± 1.89	40.53 ± 4.72	39.76 ± 4.63	40.90 ± 4.76	80.66 ± 9.39	170.42 ± 19.85	113.61 ± 13.23	81.15 ± 9.45
26	AlAmarah	14.299	32.648	18.38 ± 3.05	45.89 ± 7.62	45.03 ± 7.47	46.32 ± 7.69	91.35 ± 15.16	192.99 ± 32.03	128.66 ± 21.35	91.90 ± 15.25
Minimum				1.55 ± 0.13	3.87 ± 0.32	3.80 ± 0.32	3.91 ± 0.33	7.70 ± 0.65	16.28 ± 1.37	10.85 ± 0.91	7.75 ± 0.65
Maximum				18.38 ± 3.05	45.89 ± 7.62	45.03 ± 7.47	46.32 ± 7.69	91.35 ± 15.16	192.99 ± 32.03	128.66 ± 21.35	91.90 ± 15.25
Average				7.68 ± 1.07	19.17 ± 2.68	18.81 ± 2.63	19.34 ± 2.71	38.15 ± 5.34	80.60 ± 11.27	53.73 ± 7.51	38.38 ± 5.37

Table 2. A comparison of the study findings and global results.

No.	Location	C ($Bq.l^{-1}$)	E_{ing} ($\mu Sv.y^{-1}$)	E_{inh} ($\mu Sv.y^{-1}$)	E_{Tot} ($\mu Sv.y^{-1}$)	Effective dose rate with respect to the age groups of the inhabitants($\mu Sv.y^{-1}$)			References
						E_{Infant}	$E_{Children}$	E_{Adults}	
1	Ghana	0.026-0.093							Opoku-Ntim *et al.* (2019)
2	China	11.4-102							Piao *et al.* (2020)
3	Qassim area, Saudi Arabia	5.08 ± 1.08	12.80	18.50	31.30				Massoud *et al.* (2020)
4	Iwaraja-Ifewara faults Southwestern, Nigeria	45.8	3.30	115.40	59.40				Dosunmu *et al.* (2022)
5	India		4.20	0.05	4.25				Kandari *et al.* (2016)
6	Turkey		0.75	8.06	8.81				Tabar and Yakut (2014)
7	Venezuela		200.00	-	200.00				Horváth *et al.* (2000)
8	Oyun, Kwara State- Nigeria					548.64	483.10	352.20	Michael *et al.* (2022)
9	Northeastern, Saudi Arabia					6.14	2.26	2.96	Mamun and Alazmi (2022)
10	India					21.80	19.40	19.80	Sukanya *et al.* (2021)
11	Iraq					285.6	133.76	116.24	Ameen and Mansour (2022)
12	Pakistan	5.67 ± 1.34	0.11	–	0.11	30 ± 7.1	11 ± 2.6	14.5 ± 3.4	Ahmad *et al.* (2020)
13	Sudan –Gezira state	7.68 ± 1.07	18.81	19.34	38.15	80.60	53.73	38.38	Present study

recommended reference level of $100 Bq.l^{-1}$ (EUC, 2001; UNSCEAR, 2008; WHO, 2011). Table 2 presents a comparison of radon concentrations from various locations globally, including Ghana, the Qassim area of Saudi Arabia, Pakistan, and China. Higher concentrations were reported in China and the Iwaraja-Ifewara faults in Southwestern Nigeria, whereas lower values were observed in Ghana, Qassim area of Saudi Arabia, and Pakistan.

Table 1 and Figure 4 present the annual effective doses released into the air from water samples in the study area. The calculated effective dose rates reserved by radon released from water to indoor air ranged from $3.87 \pm 0.32\ \mu Sv.y^{-1}$ to $45.89 \pm 7.62\ \mu Sv.y^{-1}$ with a mean value of $19.17 \pm 2.68\ \mu Sv.y^{-1}$. The study has found that the amount of radon exposure in water can vary significantly due to different levels of concentration and leakage from normal usage. This variation leads to a wide range of effective dose rates in indoor air, which means it's crucial to consider these variations when assessing potential health risks in residential settings. It's important for individuals to be aware of these risks and take appropriate measures to mitigate radon exposure. The World Health Organization (WHO) has established a tolerable annual mean exposure dose level for safe water use, and if the dose exceeds this limit, remedial action must be taken. The cumulative annual mean exposure doses for all samples are within the permissible level range suggested by the WHO and EU Council (EUC, 2001; WHO, 2011).

Table 1 and Figures 5 and 7 display annual effective dose rates for ingestion, inhalation and total effective dose from water samples, with values ranging from 3.80 ± 0.32 to $45.03 \pm 7.47\ \mu Sv.y^{-1}$; 3.91 ± 0.33 to $46.32 \pm 7.69\ \mu Sv.y^{-1}$; and 7.70 ± 0.65 to $91.35 \pm 15.16\ \mu Sv.y^{-1}$, with mean values of $18.81 \pm 2.63\ \mu Sv.y^{-1}$ for ingestion, $19.34 \pm 2.71\ \mu Sv.y^{-1}$ for inhalation, and $38.15 \pm 5.34\ \mu Sv.y^{-1}$ for total annual effective dose rate, respectively. The study aimed to investigate the amount of radon exposure in household water samples and its effects on human health. When radon-contaminated water is consumed, it diffuses and irradiates the stomach wall, exposing it to radiation. The study found that both lung epithelial cells and stomach lining cells are affected, as the mean annual dose gained through inhalation is almost the same as that obtained through consumption, indicating that both lung epithelial cells and stomach lining cells are prone to risk (Sukanya *et al.*, 2021). The average ingestion dose per individual and the inhalation dose were both lower than the required limit of $10^3\ \mu Sv.y^{-1}$, as established by UNSCEAR in 2000 (UNSCEAR, 2000). Additionally, the combined mean effective dose was less than the recommended maximum value set by the WHO for 2011 (WHO, 2011). The study also revealed that the radon concentrations in the water sources and locations within the study area were within the stochastic range. This indicates that there are minimal health risks and a low probability of developing cancer due to the exposure to radon. The study compares the effective dose rates resulting from ingestion, inhalation, and total effective dose rates from water samples with previous studies worldwide, as shown in Table 2. The study found that lower effective dose rates for ingestion were reported in Pakistan, Turkey, the Iwaraja-Ifewara faults in southwestern Nigeria, India, and the Qassim area of Saudi Arabia, higher values were reported only in Venezuela. Additionally, lower inhalation values were reported in India and Turkey, at the same time, the Iwaraja-Ifewara faults in southwestern Nigeria showed a higher value, whereas the value in Qassim area in Saudi Arabia showed a nearly

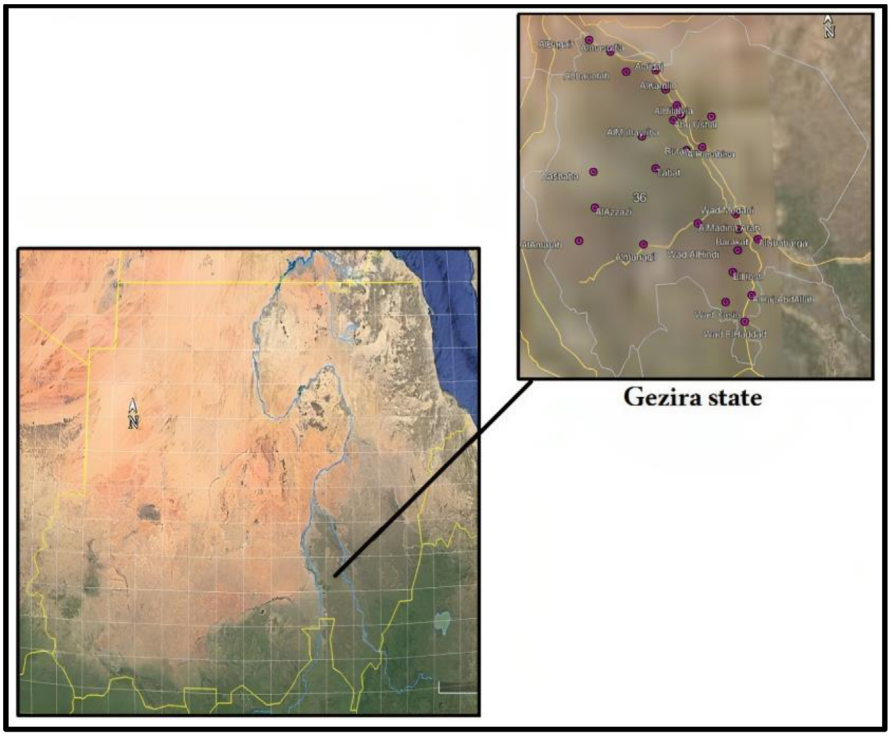

Fig. 1. The study area in Gezira State of Sudan.

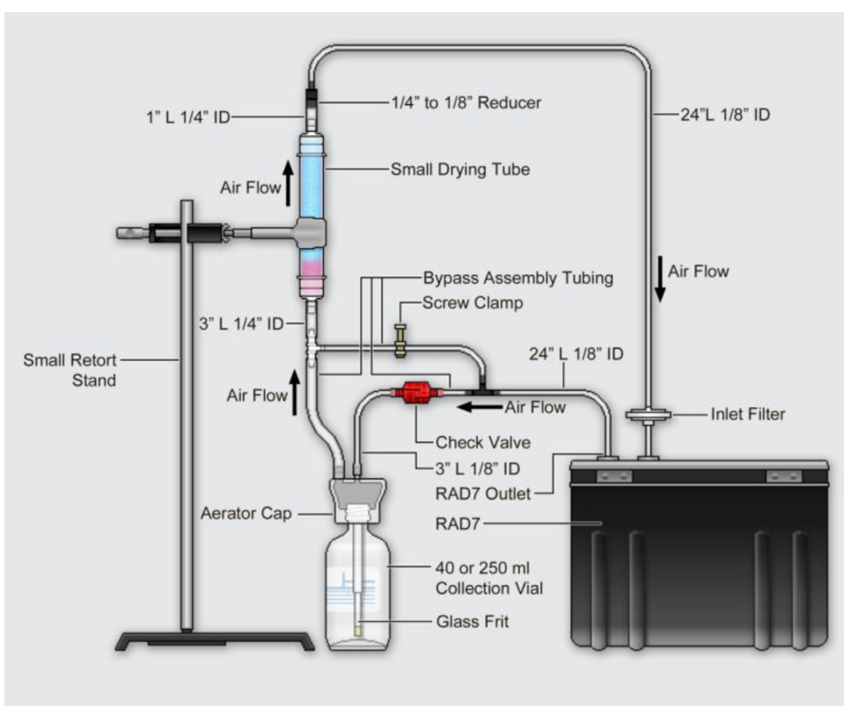

Fig. 2. The RAD7-H_2O configuration device's schematic illustration for measuring radon in water.

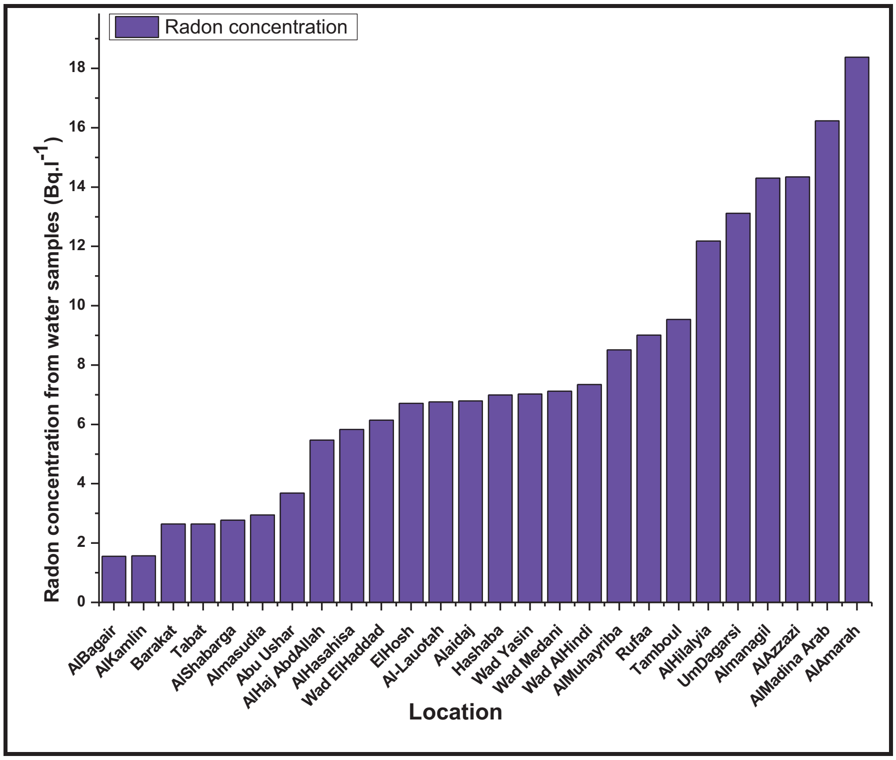

Fig. 3. Radon concentration from water samples ($Bq.l^{-1}$).

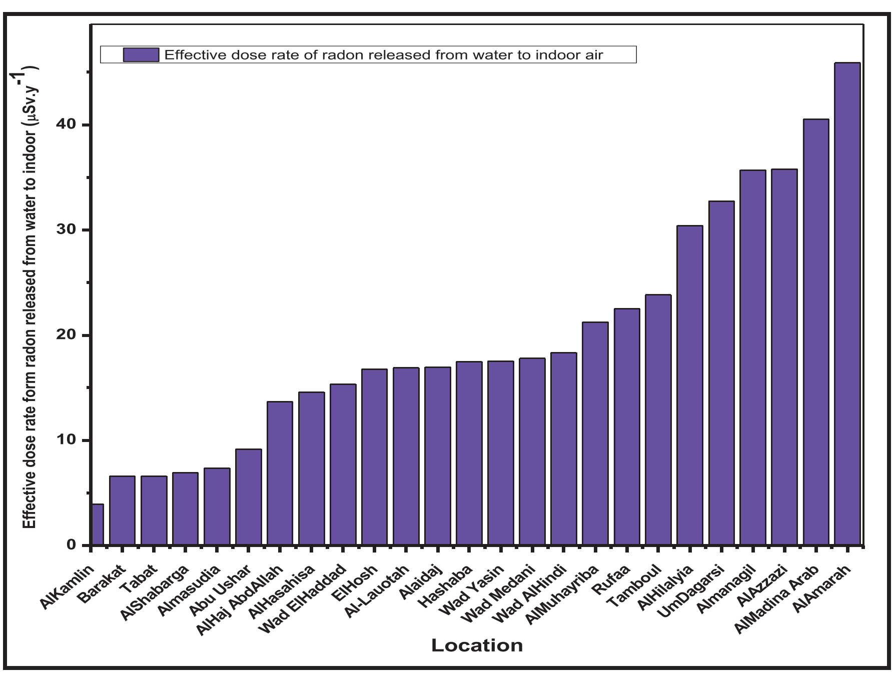

Fig. 4. Effective dose rate released from water to indoor air for various locations.

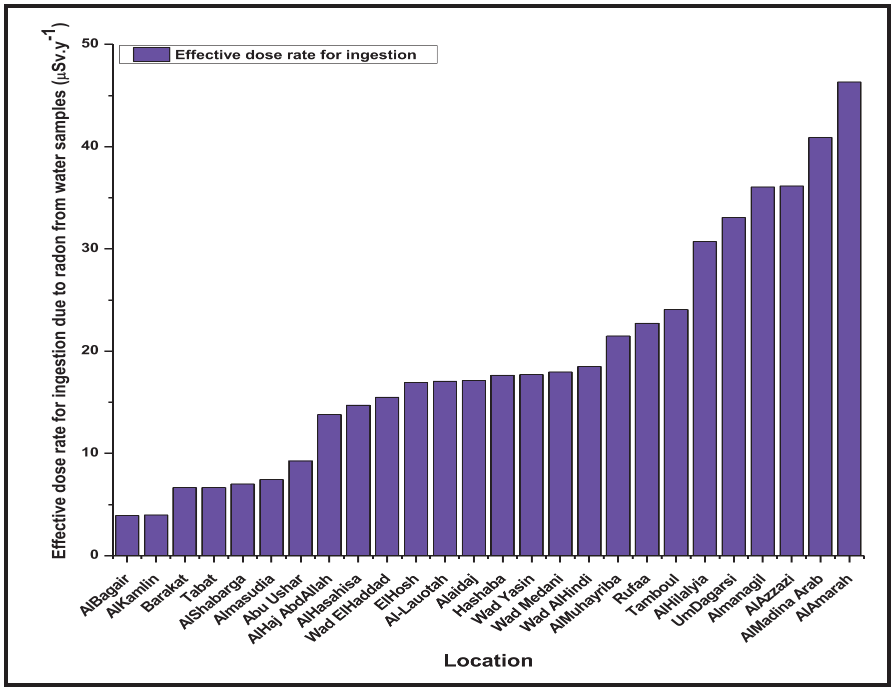

Fig. 5. Effective dose rate for ingestion due to radon concentration from water samples.

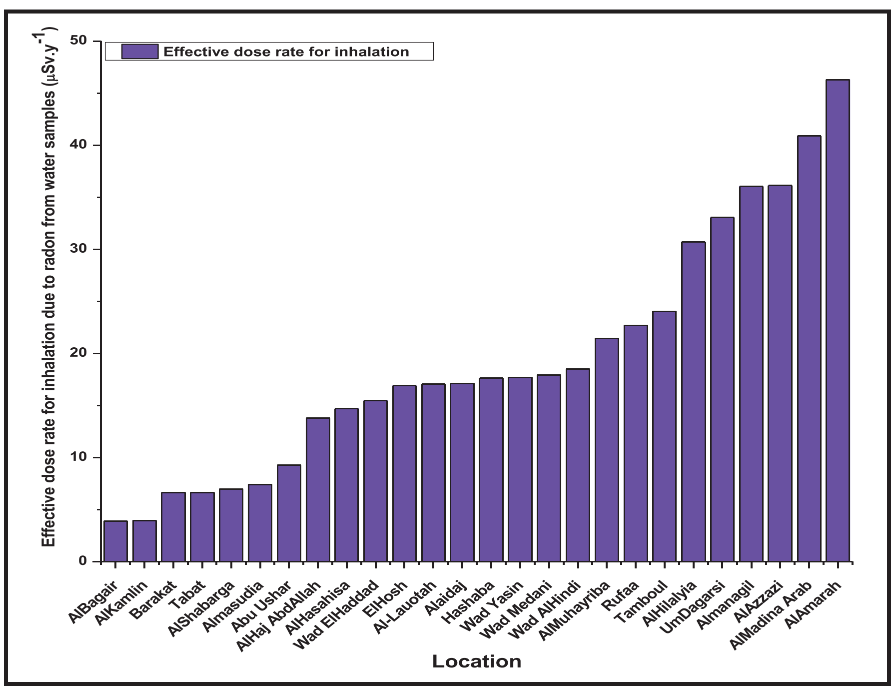

Fig. 6. Effective dose rate for inhalation due to radon concentration from water samples.

congruent value compared to the study results. In comparison, the total effective dose rates from Pakistan, India, Turkey, and the Qassim area of Saudi Arabia showed lower values concerning our results, on the other hand, higher values were reported for the Iwaraja-Ifewara faults in southwestern Nigeria and Venezuela.

Table 1 and Figures 8 and 9 show the estimated values of the effective dose rates for the aimed age groups, namely, infants, children, and adults, have ranged from 16.28 ± 1.37 to 192.99 ± 32.03 $\mu Sv.y^{-1}$; 10.85 ± 0.91 to 128.66 ± 21.35 $\mu Sv.y^{-1}$ and 7.75 ± 0.65 to 91.90 ± 15.25 $\mu Sv.y^{-1}$, with mean values of 80.60 ± 11.27 $\mu Sv.y^{-1}$; 53.73 ± 7.51 $\mu Sv.y^{-1}$

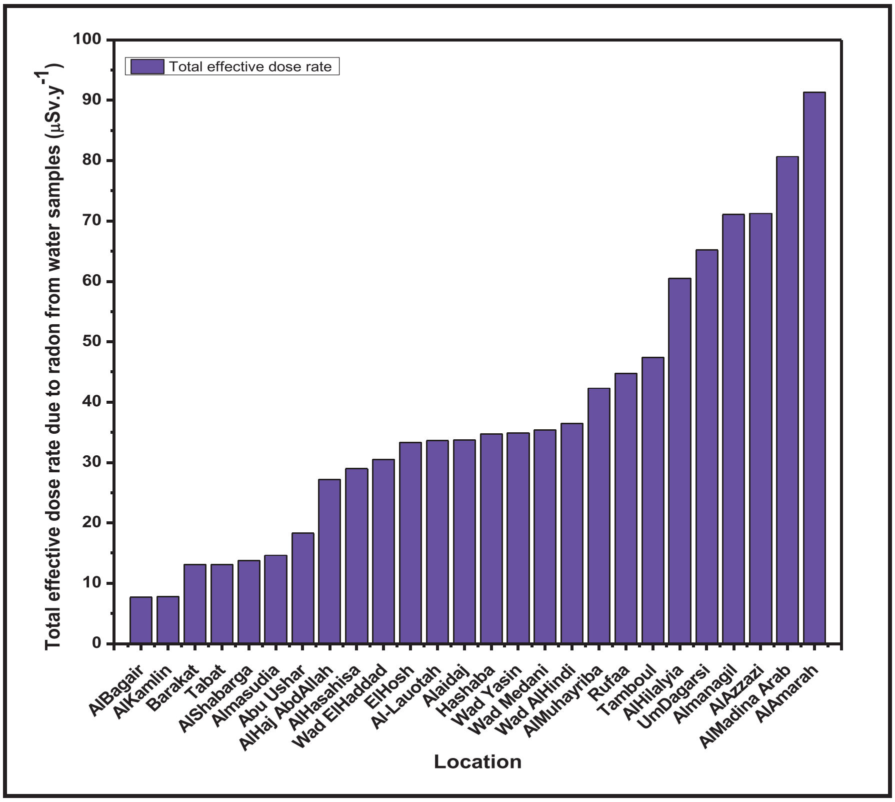

Fig. 7. Total effective dose rate at various locations in Gezira state.

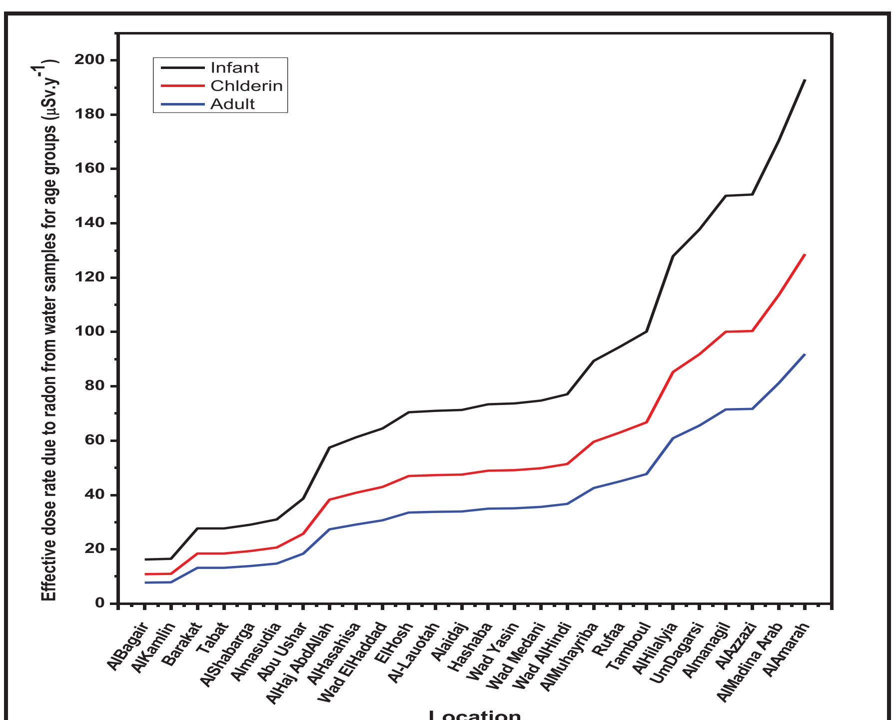

Fig. 8. Effective dose rate for ingestion due to age groups.

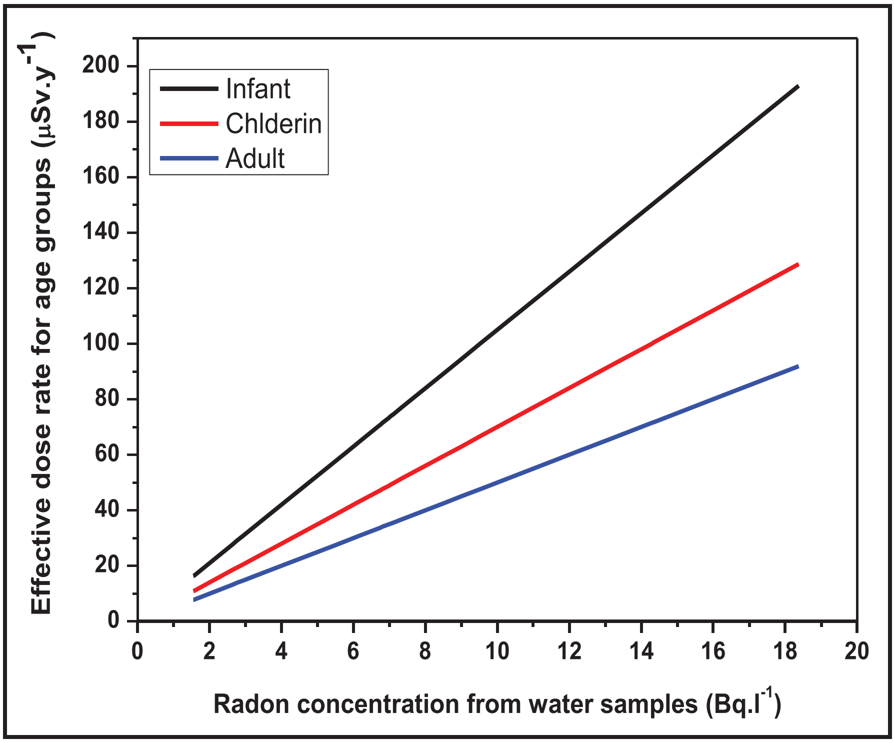

Fig. 9. Radon concentration from water vs effective dose rate for ingestion due to age groups.

and 38.38 ± 5.37 μSv.y^{-1} for these age groups, respectively. The study aims to investigate the health effects of exposure to radon in different age groups, particularly focusing on water consumption. It was found that infants are more vulnerable to radiation exposure due to their low organ mass and rapidly dividing cells (Alzen and Benz-Bohm, 2011). Adults are the second-most susceptible group due to their routine water intake. While the estimated dose of radiation does not pose a significant risk, the potential for radiation-induced damage varies depending on the dose and duration of exposure (Kesäniemi *et al.*, 2019). Therefore, it is crucial to prioritize minimizing exposure to radon by monitoring and regulating its levels and implementing safety measures. These results are within the UNSCEAR (2000) and WHO (2011) recommended limits, but far below the ICRP, 1993 recommended action level for radon in homes. According to Table 2, the study findings reveal the compared annual effective dose rates for infants, children, and adults in various age groups globally. The lowest values were observed in Northeastern Saudi Arabia, India, and Pakistan, while the highest values were reported in Iraq and Oyun, Kwara State, Nigeria, for all age ranges. Further research is necessary to understand these risks, develop mitigation strategies, and reduce infants' exposure to water sources and indoor air.

4 Conclusion

The study aimed to analyze the concentration levels of radon and effective dose rates concerning age groups in Gezira State, Sudan, by collecting 26 water samples using the RAD7 technique. Results showed that the radon concentration levels were below the recommended limits, indicating that there was no immediate health risk for people who consume domestic water. However, 23.1% of the samples exceeded the maximum contamination level recommended by the USEPA, while 76.9% were below it. The total radon concentration was also found to be below the recommended reference levels of UNSCEAR, WHO, and the EU. All age groups had annual effective and cumulative exposure doses within permissible levels, with infants having a higher risk but minimal radiation dose. Nonetheless, further research is needed to better understand these risks and develop strategies to mitigate them.

Acknowlegments

The authors are thankful to the inhabitants of these locations for their help in this work.

Funding

This research did not receive any specific funding.

Conflicts of interest

The authors declare no competing interests.

Data availability statement

The research data associated with this article are included within the article.

References

Abdelgalili EB, Ahmed M, Adam J, Hamid S, Afsatou T, Elshiekh I, Natasha P. 2019. Water source quality testing in Gezira State, Sudan, using the compartment bag test. *Appl Water Sci* 9(8): 193.

Ahmad N, Uddin Z, Rehman JU, Bakhsh M, Ullah H. 2020. Evaluation of radon concentration and heavy metals in drinking water and their health implications to the population of Quetta, Balochistan, Pakistan. *Int J Environ Anal Chem* 100 (1): 32–41.

Alzen G, Benz-Bohm G. 2011. *Radiation Protection in Pediatric Radiology. Deutsches Ärzteblatt International*.

Ameen AIM, Mansour HH. 2022. ^{222}Rn activity concentration measurement and its radiological risks in the environment of Barserin Village, Erbil-Iraq. *Zanco J Pure Appl Sci* 34 (2): 6–21.

Darby S, *et al.* 2006. Residential radon and lung cancer detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand J Work Environ Health* 32(suppl 1): 1–83.

Dosunmu GO, Ademola AK, Jidele PA, Ajayi KF, Olowofila IO. 2022. Measurements of radon and estimation of excess lifetime cancer risk in water-well samples along Iwaraja-Ifewara faults Southwestern, Nigeria. *Int Res J Public Environ Health* 9 (4): 120–124.

Duong VH, Vu HD, Nguyen D.T. *et al.* 2024. Seasonal 222Rn activity in spring water close to rare earth element and uranium mines in North Vietnam. *J Radioanal Nucl Chem* 333(5): 2537-2545.

Durridge. 2023. *RAD7 Electronic Radon Detector User Manual. Durridge Company Inc*.

EC. 2013. European Commission, Council Directive 2013/51/EURATOM of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption. Official Journal of the European Union L 296/12. Rome, Italy, 2013.

Elzain AEA. 2014. Measurement of Radon-222 concentration levels in water samples in Sudan. *Adv Appl Sci Res* 5 (2): 229–234.

Elzain AEA. 2015. Radon exhalation rates from some building materials used in Sudan. *Indoor Built Environ* 24 (6): 852–860.

Elzain AEA. 2016. Measurements of indoor radon levels and dose estimation and lung cancer risk determination for workers in health centres of some towns in the Sudan. *Am J Mod Phys* 5 (4): 51.

Elzain AEA. 2017. *Radon Monitoring in the Environment*. *Radon. InTech*.

Elzain AEA. 2023. Assessment of environmental health risks due to indoor radon levels inside workplaces in Sudan. *Int J Environ Anal Chem* 103 (6): 1394–1410.

Elzain AEA, *et al.* 2019. Assessment of radioactivity from selected soil samples from Halfa Aljadida area, Sudan. *Radiochim Acta* 107 (6): 489–502.

Elzain AEA, *et al.* 2019. Assessment of radioactivity from selected soil samples from Halfa Aljadida area, Sudan. *Radiochim Acta* 107 (6): 489–502.

EUC. 2001. (European Union Commission) Commission recommendation of 20th December 2001 on the protection of the public against exposure to radon in drinking water. 2001/982/Euratom, L344/ 85–8. *Official Journal of the European Commission*.

EUC. 2013. European Commission, Council Directive 2013/51/ EURATOM of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption. Official Journal of the European Union L 296/12.

Horváth, Bohus L, Urbani F, Marx G, Piróth A, Greaves E. 2000. Radon concentrations in hot spring waters in northern Venezuela. *J Environ Radioact* 47 (2): 127–133.

ICRP. 1993. International Commission on Radiological Protection). *Protection Against Radon-222 at Home and at Work. International Commission on Radiological Protection. (Annals of the ICRP)*; 23 (2), ICRP Publication; 65.

ICRP. 1996. International Commission on Radiological Protection-Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients. *ICRP Publication 72. Ann ICRP* 26 (1).

Idriss H, Salih I, Elzain AEA. 2020. Environmental radon mapping in Sudan, orderly review. *J Taibah Univ Sci* 14 (1): 1059–1066.

Isinkaye MO, Ajiboye Y. 2017. Assessment of annual effective dose due to radon concentrations in deep and shallow wells within Ekiti State, Nigeria. *Radioprotection* 52 (3): 167–170.

ISO. 2023. International Organization for Standardization (ISO), *Water Quality—Radon-222. Part 4: Test Method Using Two-Phase Liquid Scintillation Counting*. *Institution BS. BS EN ISO* 13164–4.

Kandari T, Aswal S, Prasad M, Bourai A, Ramola R. 2016. Estimation of annual effective dose from radon concentration along Main Boundary Thrust (MBT) in Garhwal Himalaya. *J Radiat Res Appl Sci* 9 (3): 228–233.

Kesäniemi J, *et al.* 2019. Exposure to environmental radionuclides associates with tissue-specific impacts on telomerase expression and telomere length. *Sci Rep* 9 (1).

Mamun A, Alazmi AS. 2022. Investigation of radon in groundwater and the corresponding human-health risk assessment in North-eastern Saudi Arabia. *Sustainability* 14 (21): 14515.

Massoud E, El-Taher A, Elzain AEA. 2020. Estimation of environmental radioactivity and radiation dose from exposure to radon in groundwater for inhabitants in Qassim Area, Saudi Arabia. *Desalin Water Treat* 205: 308–315.

Messier KP, Serre ML. 2016. Lung and stomach cancer associations with groundwater radon in North Carolina, USA. *Int J Epidemiol*, dyw 128.

Michael OM, *et al.* 2022. Annual effective dose assessment of radon in drinking water from Abandoned Tin and Cassiterite Mining site in Oyun, Kwara State, Nigeria. *Pollution* 8 (1): 181–192.

MOG. 1994. Meteorology Office-Gezira, Meteorology Office-Gezara (MOG). *Rainfall records 1922*–1994.

Nakano Y, *et al.* 2020. Measurement of the radon concentration in purified water in the Super-Kamiokande IV detector. *Nucl Instrum Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment* 977: 164297.

Nazaroff WW, Nero Jr., AV. (Eds.). 1988. Radon and Its Decay Products in Indoor Air. Pp. 65-69. Wiley, New York.

Niculita-Hirzel H, Goekce S, Jackson CE, Suarez G, Amgwerd L. 2021. Risk exposure during showering and water-saving showers. *Water* 13 (19): 2678.

Opoku-Ntim I, Gyampo O, Andam AB. 2019. Risk assessment of radon in some bottled water on the Ghanaian market. *Environ Res Commun* 1 (10): 105001.

Piao C, Tian M, Gao H, Gao Y, Ruan J, Wu L, Gao G, Yi L, Liu J. 2020. Effects of radon from hot springs on lymphocyte subsets in peripheral blood. *Dose-Response* 18 (1): 155932582090233.

Riudavets M, Garcia de Herreros M, Besse B, Mezquita L. 2022. Radon and lung cancer: current trends and future perspectives. *Cancers* 14 (13): 3142.

Sami OE, Mustafa YM, Shamseddin MA, Hilmi HS. 2014. Estimation and mapping of groundwater characteristics in Greater

Wad-Medani Locality, Gezira State, Sudan. *Int J Water Res Environ Eng* 6 (5): 164–169.

Sukanya S, Joseph S, Noble J. 2021. Evaluation of radiation dose from radon ingestion and inhalation in groundwater of a small tropical river basin, Kerala, India. *Isotopes Environ Health Stud* 57 (2): 204–215.

Traoré I, *et al.* 2013. Assessment of activity and effective dose rate of 222Rn in several dwellings in Bamako, Mali. *Radioprotection* 48 (2): 277–284.

Tabar E, Yakut H. 2014. Radon measurements in water samples from the thermal springs of Yalova basin, Turkey, Journal of Radioanaly and Nucl Chem 299: 311319.

UNDP. 2010. *Socio-Economic and Opportunity Mapping Assessment Report for Gazira State* 26th – 28th October 2010.

UNSCEAR. 2000. *Report to the General Assembly, with scientific Annex B: Exposure from Natural Radiations Sources*. *New York: UN Publication*.

UNSCEAR. 2008.*United Nations Scientific Committee on the Effect of Atomic Radiation*, *Sources and Effects of Ionizing Radiation*. Report to general assembly with scientific annexes. New York: UN Publications.

USEPA. 2022. Proposed radon in drinking water regulation. EPA. https://www.epa.gov/dwreginfo/radionuclides-rule. Accessed 15 Aug 2022.

WHO. 2004. *Guidelines for Drinking-Water Quality.* First Addendum to 3rd Edition. Geneva, Switzerland: World Health Organization, 2004; Vol. 1.

WHO. 2011. World Health Organization, Guidelines for Drinking-Water Quality. 4th Ed. WHO press.

Cite this article as: Elzain AEA, Shady R, Yagob AA. 2024. Assessment of environmental radioactivity concentration and effective dose rates from radon gas exposure from water samples in Gezira State, Sudan. *Radioprotection* 59(3): 235–245