Radon Concentration Assessment and Potential Health Impact in Selected Wetlands of Warri, Delta State

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Abstract
This study establishes a baseline radiological profile of radon-222 (^{222}Rn) in surface water from eight wetlands-Ajamimogha, Esisi Road, Iyara, Market Road, McDermott Road, NPA Axis, Okere, and Okumagba, within Warri South Local Government Area, Delta State, Nigeria. Sixteen samples were collected during a single dry-season campaign in March 2026 and analyzed using a RAD7 electronic radon detector with closed-loop protocols. Decay-corrected concentrations were evaluated through descriptive statistics, Kruskal–Wallis testing, Spearman correlation, and exploratory GIS mapping, while annual effective dose and excess lifetime cancer risk were modeled using ingestion dose coefficients of 3.50×10^{-9} and 6.90×10^{-10} Sv/Bq. Of sixteen samples, fourteen yielded quantifiable concentrations of 3.87–53.70 pCi/L (≈0.143–1.987 Bq/L), with a mean of 20.10 pCi/L (≈0.743 Bq/L). The relatively highest readings occurred at Iyara and Esisi Road, though all values remained far below the 100 Bq/L WHO/Euratom parametric limit. The Kruskal–Wallis test showed no significant differences among locations ($p = 0.161$), reflecting limited sample size, while GIS contouring suggested localized clustering of comparatively higher values. Spearman correlation indicated a moderate negative association between radon and temperature ($\rho = –0.503$, $p = 0.067$) and a moderate positive association with relative humidity ($\rho = 0.458$, $p = 0.100$), with negligible spatial correlations. Radiological assessment confirmed that annual effective doses (≈0.49–4.92 µSv/y) were well below the 0.1 mSv/year reference, and excess lifetime cancer risks (≈2.02×10^{-6}–2.03×10^{-5}) were negligible compared to the UNSCEAR benchmark of 0.29×10^{-3}. These findings demonstrate that Warri wetlands exhibit low dissolved-radon concentrations and do not pose significant radiological hazards if consumed directly, while underscoring the importance of continued monitoring, seasonal sampling, and hydrogeological follow-up to strengthen long-term environmental risk evaluation.

Keywords: *Radon, Wetland, Radiological, Correlation, Concentration*

Introduction

While Freshwater ecosystems represent less than 3% of the global water resources, it establishes strong pillars for the biodiversity of the terrestrial environment, agricultural productivity and food security. Amongst the terrestrial aquatic environments, the wetlands are ecotone regions where soil surface is saturated by surface and groundwater with different permanencies. Their physio-chemical and biological features enable them to position among the most biogiochemically active environments in the globe (Mitsch, 2015; Cowardin et al., 1979) hydrophytic vegetation, hydric soil and anaerobic conditions are key in controlling water inputs and outputs, carbon acquisition and accumulation, the filtering of anthropocentric contaminants and support a high proportion of terrestrial biodiversities in relation to their relatively small size (Ramsar Convention Secretariat, 2013). Nevertheless, the water in the wetland is affected not only by direct input from man-made effluents but also by natural geogenic activities of radionuclides. Naturally occurring radionuclide (mostly isotopes from the uranium-238 and thorium-232 decay series) is mainly trapped in crustal rocks, and gradually migrates to water systems through processes such as dissolution of constituent minerals in host rock, leaching of soils as well as ascending of groundwater from beneath (Rajamannan et al., 2013; Avwiri et al., 2016). Radon-222 (^{222}Rn), radioactive noble gas with a half-life of 3.82days is an alpha emitting daughter product of radium-226, a decay product of the uranium decay chain is colorless, odorless, easily soluble in water, highly mobile through permeable sedimentary structures like the Benin Formation rocks in most parts of Delta State and easily accumulative within still water bodies such as lakes and wetlands with limited convection and turbulent release to air (Hassan et al., 2024; El-Taher and Al-Turki, 2016). However, wetland with high water table, poor surface drainage, high soil organic content and frequent groundwater to surface water interactions is expected to favor the retention of Radon and increased human radiation dose exposure (Cook et al., 2008). Ways in which one can get exposed to radon are; Exposure to radon-bearing water and so a direct delivery of doses to gastric parts. In-house activities like cooking, washing, bathing etc. These are associated with increased, supported exhalation of dissolved gas and therefore an inhalation risk inside the enclosed or semi enclosed living environments (Mehnati et al., 2022; Ijabor et al., 2022). Chronic exposure has an established epidemiologic correlation with the occurrence of stomach and lung cancers (Darby et al., 2005). To this end, regulatory authorities worldwide have prescribed guideline values of radon in drinking water. The U.S. Environmental Protection Agency has a guideline value of 148 Bq/L (4 pci/L) of maximum contaminant level (MCL) (USEPA, 1999), and the WHO has recommended a value of 100 Bq/L (WHO, 2011), same with Euratom (Council of European Union, 2013). However, systematic radiometric surveys of Nigeria surface waters especially wetland systems are far from extensive and many of the previous studies had focused on contained groundwater aquifer, boreholes and mining districts where they had reported radon levels ranging from < BD.L to significantly above internationally derived guideline values (Duggal et al., 2020; Isinkaye and Ajiboye, 2017; Ajiboye et al., 2018; Fatoki et al., 2021; Orosun et al., 2021; Michael et al., 2022). Given that wetlands are major source of water supply to both rural and semi-urban population in Niger Delta, the radiological characterization of these systems has not been adequately assessed. This is critical for Warri South Local Government Area (LGA), Delta State of Nigeria, where the existence of wetland ecosystems at Pessu, Okumagba, Market Road, NPA, Esisi Road, Iyara and Okere serve as domestic water source for numerous dwellers of these areas. The geology of the area predominantly comprised porous, permeable sands of the Benin Formation coupled with extensive petroleum industries' operations, presents factors both for geogenic entry and manmade alteration of the water's chemistry . Unfortunately, there are currently no published baseline data for assessing the radiometric hazard from radon emanating from these wetlands or informing preventive health and regulatory action. This study is spatially limited to eight selected wetlands in Warri South LGA which are Pessu, Okumagba, Market Road, NPA, Esisi Road, Iyara, McDermott and Okere, representing wetlands with varying degrees of anthropogenic influences and proximity to petroleum facilities. Analytically, the study is limited to surface

water samples and the determination of their radon activities concentrations as well as derived radiation protection indicators; namely the annual effective dose (AED) and excess lifetime cancer risk (ELCR). Methodologically, the investigation is constrained to a one-time (single-session), dry- season (March 2026) sample collection of sixteen (16) samples covering these selected wetlands with limited spatial coverage to reflect representative variation at each sampling location but not temporal, tidal or inter-annual variation of radon flux. This study utilizes the RAD7 electronic radon monitor (Durridge Inc., USA) according to manufacturer and accepted protocol. Although efficient and portable, use of a single detection system makes intercomparison with other measurement systems such as liquid scintillation an indirect method. Statistical analyses performed were solely descriptive (mean, std. Deviation, range), non-parametric comparison test (Kruskal-Wallis), and correlation between other relevant parameters (temperature, relative humidity, GPS) and radon concentrations. Two observations reported as below detection limit were excluded from quantitative statistical analysis in accordance with international recommendations for reporting censored environmental data. Due to small size N=16 samples, with N=14 quantified, this study was not conducted with adequate statistical power to support geostatistical analyses required to construct predictive models, therefore only exploratory spatial mapping is shown. There have been several radiological investigations that focused on assessing environmental radioactivity in Nigeria within the last two decades. Radon activities in groundwater, boreholes, wells and surface waters as well as soils from various parts of the country have been analyzed using different analytical techniques like the RAD7 and liquid scintillation methods. Comparatively few studies were carried out in the wetland ecosystems, but wetlands are usually receptor of pollutants and are considered to be prone to accumulation of naturally occurring radioactive materials. Studies that have been carried out over Nigeria include an investigation of radon gas concentration in Ogbomosho, Oyo State using RAD7 (Oni et al., 2019). Also liquid scintillation method was used to determine Radon concentration in water of Idah and environs (Gyuk et al., 2017) as well as well waters along the Iwaraja-Ifewara Faults, South-western Nigeria using a RAD7 radon detector (Dosunmu et al., 2022). While radon concentrations in well waters and boreholes was carried out at Dutse, Jigawa State (Dankawu et al., 2021) and in soils in Aramoko, Ekiti state (Ajiboye et al., 2016) by taking a look at their associated annual effective doses and excess lifetime cancer risks, the assessment was at various states and locations of the country. Therefore, measurement of radon concentration is very important in environmental surveillance of public exposures.
Therefore, in this work, the concentration of222Rn in some selected wetlands at Warri, Warri South Local Government area, Delta State was measured and evaluated by taking reading using a calibrated RAD7 radon detector alongside measuring the radon activity concentrations present; The Annual Effective Dose (AED) and Excess lifetime Cancer Risk (ELCR) are also determined. These data are expected to provide information on background radiation for the wetlands in Warri and environmental radiation monitoring at the area.

Materials and Method

Study Area

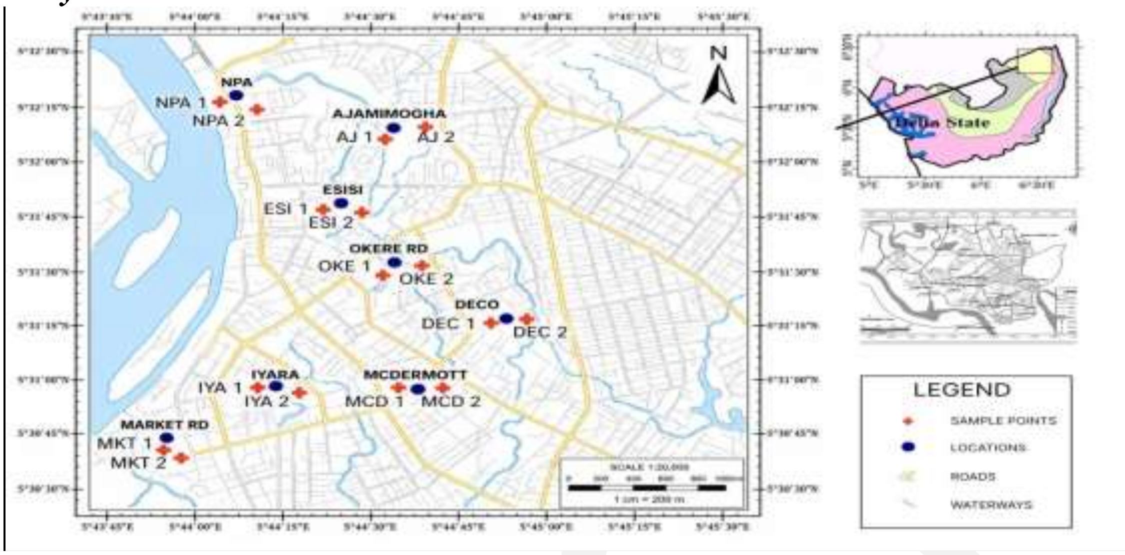


Figure 1. Geological map of the study area

The study region is a major urban and economic centre in the coastal zone of Delta State within the Nigeria's south – based Niger-Delta. The area lie geographically within Latitude 5.5442 N-5.7602 E, it is the seat of Warri South Local Government Area (LGA) (Delta State Ministry of Lands and survey, 2021). The LGA is bounded on the east by the Warri River, on the western side it is flanked by Warri South-West Local Government area and on the southern side, by the Atlantic Ocean. Covering about 460km2 of land area, spatial structure of the area is significantly shaped by the network of modified and natural rivers and streams present (National Bureau of Statistics [NBS], 2022) The major ecological characteristics of the study region is widespread network of wetlands such as mangrove wetlands, fresh water swamps, tidal creek, tidal mangrove and etcetera that hitherto protected the coastline against erosion and filtered water bodies.

Materials

The materials used are 75cl water containers containing samples of water, GPS equipment to map down coordinates and one Electronic radon detector (RAD7)

Methods

Sample collection and preparation

Sixteen samples were collected from the eight designated wetlands in Warri. The water samples were obtained with a 1.5-L plastic bottle and each had a volume of 1.5 L. Before sample collection, the bottle was rinsed 3 times with the wetland water in order to prevent contamination of samples by the sampling vessels themselves. To minimize gas leakage and radon loss from the sealed samples, each bottle was tightly sealed soon after sample collection. The sampling site was noted on each bottle label. Samples were drawn in two different locations from each wetland site and the GPS coordinates were taken at each sampling location. The samples were then taken to the Energy Laboratory at Afe Babalola University, Ado-Ekiti on the next day for analysis. Measurement of radium concentration was carried out using a RAD7 within 48 hours to minimize loss from radon decay.

Sample Analysis

The radon detector used in this investigation as demonstrated in Figure 2 was RAD7, an electronic radon detector produced by Durridge Company Inc., USA. This apparatus consists of a compact, stand-alone instrument that takes advantage of sampling water to analyze for radon concentration by means of detecting the short alpha particle emitting progeny of radon; mainly Po arising after decay from Radon, by measuring resultant alpha particles. The instrument's mechanism involves circulation of air via a semi-closed loop through the water sample, thereby equilibrating the radon concentration between both media (water and air). The short lived progeny's emitted alpha particles strike and energize the semiconductor detector, and these signals from the latter are then integrated so as to arrive at a measure of radon content. According to the manufacture's data sheet, the minimum detectable limit (MDL) in water of the RAD 7 detector is < 0.37 Bq L^{-1}(Durridge Company Inc., 2016). Methods applied for water analysis by RAD7 were in accordance with manufacturer guidelines and similar literature (Dosunmu et al., 2022 & Dankawu et al., 2021). RAD7 accuracy is affected by the sampling process, the sample size, the duration of counting, the temperature, the relative humidity and its background signals. High degree of relative humidity would lower the effectiveness with which atoms like Po are being captured inside the counting chamber. It, hence, became necessary that RAD7 detector had been carefully dried prior to any measurements and filled with desiccants as they remove excessive humidity from the air circulation loop before the detection process

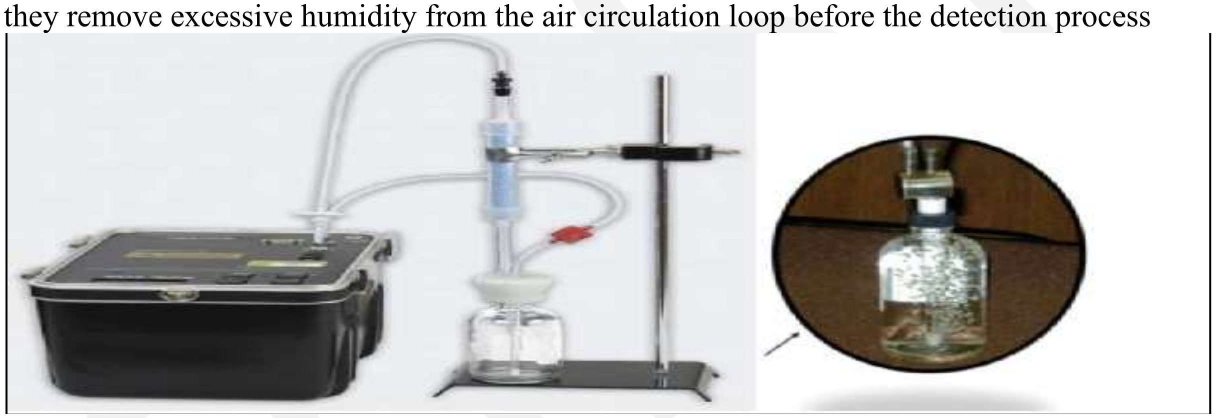


Figure 2 RAD7 and RAD7H_2O Set-up for detection

Radiological Hazard Parameters

Determination of Annual Effective Dose (AED)

The annual effective dose from ingestion of radon-containing water was estimated using a water-consumption model. The basic relationship for the ingestion dose is as given by Jidele et al. (2021):

$$\mathbf{E = C_{Rn} \times V \times DCF} \tag{1}$$

Where E is the annual effective dose in sieverts per year, C_{Rn} is the radon activity concentration in water in Bq/L, V is the annual volume of water consumed in litres per year and DCF is the ingestion dose coefficient in Sv/Bq. The resulting dose was converted to millisieverts per year according to (UNSCEAR, 2024).

Estimation of Excess Lifetime Cancer Risk

The excess lifetime cancer risk was estimated from the calculated annual effective dose to provide a quantitative indication of the potential radiological risk associated with long-term ingestion of the sampled water. The excess lifetime cancer risk was calculated according to equation 2 as used by Shuaibu et al. (2021):

$$\mathbf{ELCR} = E_{Sv/y} \times \mathbf{LE} \times \mathbf{RF} \quad (2)$$

where $E_{Sv/y}$ is the annual effective dose in sieverts per year, LE is the assumed lifetime exposure duration of 75 years and RF is the nominal lifetime risk coefficient of 0.055 Sv^{-1}. The risk coefficient corresponds to the nominal risk for stochastic effects recognized in international radiological protection frameworks (International Commission on Radiological Protection, 2007).

Results and Discussions

Sixteen (16) wetland water samples were collected from different wetlands in Warri, Delta State, Nigeria, and analyzed for radon gas activity concentration. The measured results of Radon concentration are tabulated in Table 1.

Table 1. Results of radon concentration of selected wetlands water samples in Warri South Local Government Area of Delta State, measured in pCi/L.

S/N	SAMPLE ID	LONGITUDE	LATITUDE	AVERAGE RnC (pCi/L)	CORRECTED RnC (pCi/L)
1	ESI 1	5.751095	5.13371	11.0	12.0
2	ESI 2	5.621526	5.12909	37.5	52.4
3	AJ 1	5.738300	5.524671	Bdl	Bdl
4	AJ2	5.534533	5.244334	5.0	5.2
5	NPA 1	5.732483	5.516582	21.3	21.9
6	NPA2	5.487329	5.466322	7.5	7.4
7	MKT 1	5.751095	5.507103	10.0	10.8
8	MKT 2	5. 723123	5.491238	5.0	5.2
9	IYA 1	5.763159	5.502989	40.0	52.4
10	IYA 2	5.612453	5.376727	37.5	52.4
11	MCD 1	5.765819	5.513371	8.0	8.4
12	MCD 2	5.676871	5.412662	3.75	4.1
13	OKE 1	5.746814	5.520175	7.5	7.9
14	OKE 2	5.687900	5.488719	5.0	5.2
15	DEC 1	5.759689	5.526532	20.0	26.0
16	DEC 2	5.568788	5.383877	30.25	37.6

**BDL—Below Detectable Limit

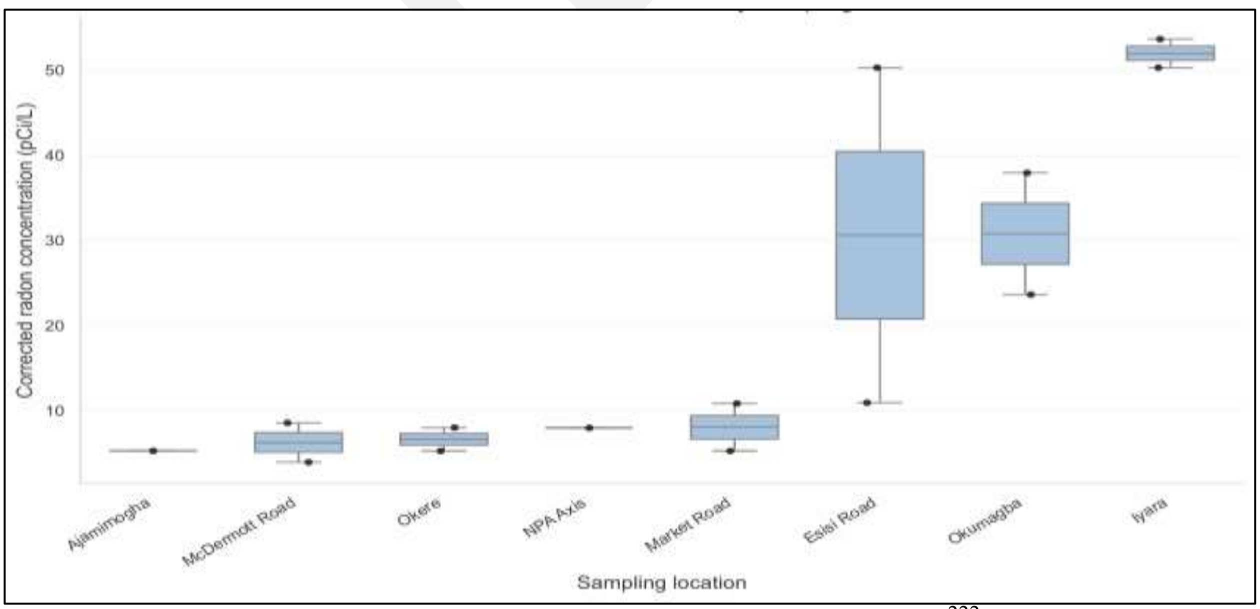
The corrected radon concentrations obtained from the Warri wetlands (Table 1) were converted from picocuries per litre (pCi/L) to becquerels per litre (Bq/L) using the standard conversion factor (1 pCi/L = 0.037 Bq/L) as presented in Table 2. This conversion facilitated comparison with international reference values, particularly the parametric value of 100 Bq/L established by the Council Directive 2013/51/Euratom for drinking water intended for human consumption.

Table 2 Corrected Radon Concentrations in Bq/L

Sampling Location	n	Mean (Bq/L)	SD (Bq/L)	Minimum (Bq/L)	Maximum (Bq/L)	CV (%)
Ajamimogha	1	0.1921	—	0.1921	0.1921	—
Esisi Road	2	1.1324	1.0329	0.4021	1.8628	91.21
Iyara	2	1.9249	0.0878	1.8628	1.9870	4.56
Market Road	2	0.2956	0.1463	0.1921	0.3990	49.50
McDermott Road	2	0.2287	0.1212	0.1430	0.3144	53.00
NPA Axis	1	0.2926	—	0.2926	0.2926	—
Okere	2	0.2429	0.0718	0.1921	0.2937	29.56
Okumagba	2	1.1388	0.3749	0.8738	1.4039	32.92

The overall range of corrected radon-222 (^{222}Rn) concentrations in the Warri wetlands was 0.143–1.987 Bq/L, corresponding to 3.8650–53.7015 pCi/L. The observed concentrations were therefore substantially below the 100 Bq/L parametric value recommended for drinking water under European guidance. The highest mean concentration was recorded at Iyara (1.925 Bq/L), followed by Okumagba (1.139 Bq/L) and Esisi Road (1.132 Bq/L), whereas comparatively lower mean concentrations were observed at McDermott Road (0.229 Bq/L) and Okere (0.243 Bq/L). Ajamimogha recorded a concentration of approximately 0.192 Bq/L, while the NPA Axis recorded approximately 0.293 Bq/L. Overall, the measured ^{222}Rn concentrations indicate relatively low levels of dissolved radon in the sampled wetland waters when compared with the 100 Bq/L reference value as shown in Fig 3

Fig. 3 Bar Chart showing the Radon concentration levels of the studied wetlands



The annual effective dose (AED) attributable to the ingestion of ^{222}Rn-containing water was estimated under two consumption scenarios. The first scenario employed the UNSCEAR-weighted direct-water assumption of 60 L/year, while the second represented a conservative adult water-consumption rate of 730 L/year (2 L/day). Using the traditional ingestion dose coefficient of 3.5 × 10^{-9} Sv/Bq, the resulting AEDs were correspondingly low under the 60 L/year scenario and increased under the 730 L/year scenario, reflecting the direct dependence of ingestion dose on water-consumption rate and ^{222}Rn concentration. Application of the updated ingestion dose coefficient of 6.9×10^{-10} Sv/Bq produced is still lower than the dose estimates. The calculated doses are presented in Figures 4 and 5 respectively, while the location-specific mean AEDs from ^{222}Rn ingestion are presented in Figure 6. Overall, the results suggest that ingestion of the sampled wetland water would contribute relatively low radiological doses under the assessed scenarios, although the estimates represent the hypothetical consumption of untreated wetland water and should therefore be interpreted within the context of actual water-use patterns and exposure pathways.

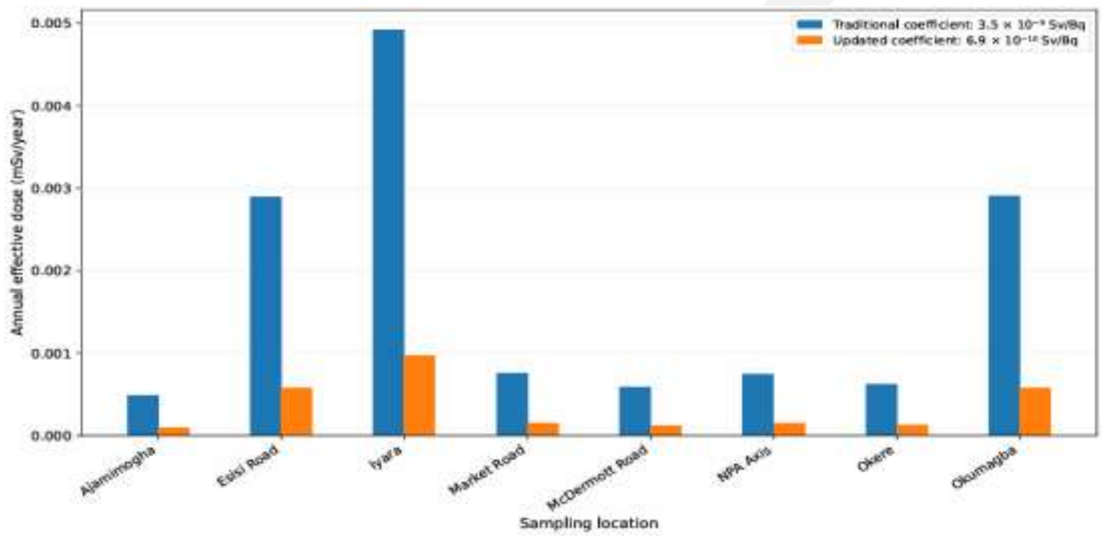


Figure 4 Sensitivity of ^{222}Rn Ingestion Dose to the Ingestion Dose Coefficient

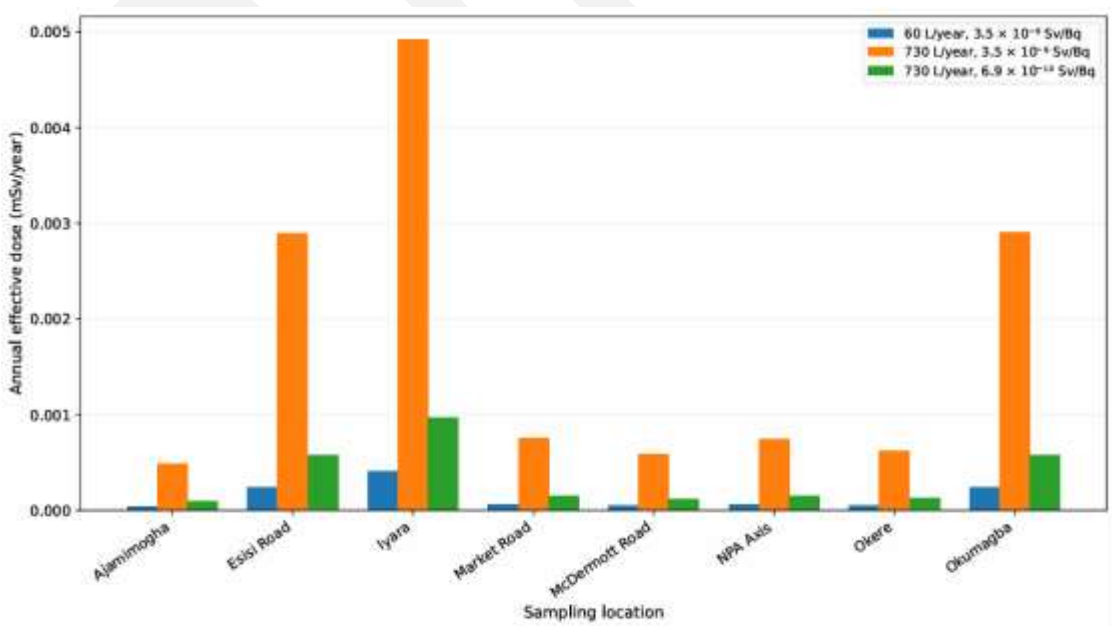


Figure 5 AED from ^{222}Rn Ingestion under the two water-consumption scenarios.

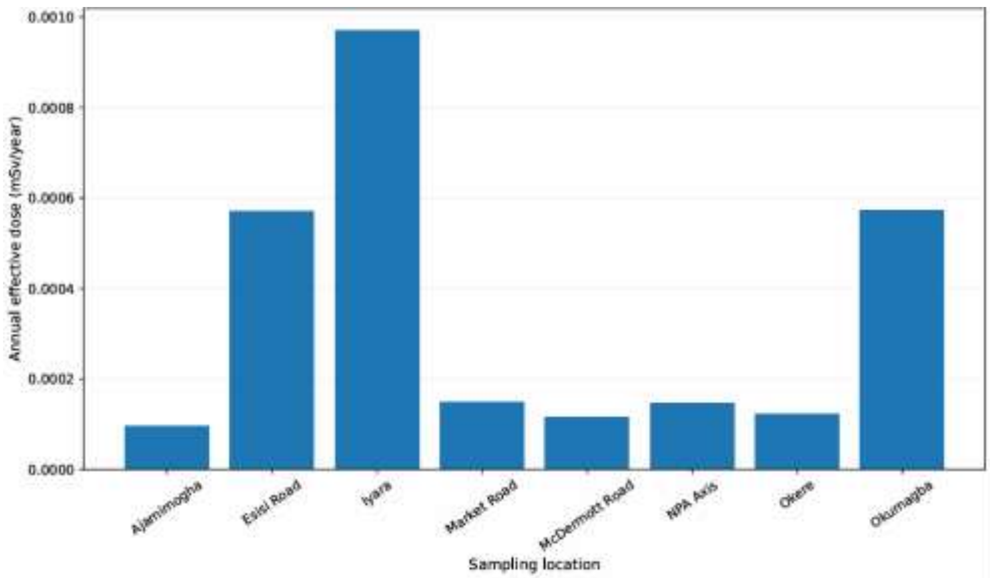


Figure 6. Location-Level Mean Dose from ^{222}Rn Ingestion

The excess lifetime cancer risk (ELCR) was estimated using the nominal risk coefficient of 0.055 Sv^{-1} and lifetime exposure duration of 75 years. Using the corrected ^{222}Rn concentrations and the 730 L/year water-consumption scenario with the conventional ingestion dose coefficient of 3.5×10^{-9} Sv/Bq, the estimated ELCR values ranged from approximately 2.02×10^{-6} to 2.03×10^{-5} across the sampled locations. The highest ELCR was obtained at Iyara (2.03×10^{-5})**,** followed by Okumagba (1.20×10^{-5}) and Esisi Road (1.19×10^{-5})**,** corresponding to the locations with relatively higher mean ^{222}Rn concentrations. The lowest estimated ELCR occurred at Ajamimogha (2.02×10^{-6})**,** while Market Road, McDermott Road, NPA Axis and Okere also recorded comparatively low values. Thus, although the ELCR estimates varied spatially in response to differences in ^{222}Rn concentration, none of the calculated values exceeded 0.29×10^{-3}**.** The results therefore indicate a relatively low incremental lifetime cancer risk from the hypothetical ingestion of the sampled wetland water under the assumed exposure scenario. The observed spatial variation nevertheless demonstrates the importance of location-specific monitoring and assessment of ^{222}Rn in wetland water resources.

To contextualize the findings from the Warri wetlands, Table 3 presents a comparative summary of ^{222}Rn concentrations and associated radiological risk indicators reported for selected water studies in Nigeria and internationally. The corrected ^{222}Rn concentrations measured in the Warri wetlands ranged from 0.143 to 1.987 Bq/L, with the location-specific mean concentrations generally below 2 Bq/L. These values are substantially below the 100 Bq/L reference value used for comparison in this study. Consequently, the present findings do not indicate elevated dissolved-radon concentrations relative to this reference value. Furthermore, the Warri wetland concentrations are also lower than those reported in several Nigerian studies.

Table 3 Comparative ^{222}Rn Concentrations and Radiological Risk Indicators in Drinking-Water Studies

Study Location & Authors	Radon Concentration Range (Bq/L)	Mean/Key Value (Bq/L)	Annual Effective Dose (μSv/y)	ELCR	Relative to 100 Bq/L Reference Value
Warri South LGA Wetlands (Present Study, 2026)	**0.143–1.987**	**≈0.743**	**≈0.49–4.92***	**2.02×10^{-6}–2.03×10^{-5}***	**Well below reference value at all sites**
Bosso, Nigeria (Kolo *et al.*, 2023)	2.8–39.2	14.3	74–104	0.10–0.13×10^{-3}	Below reference value
Edu, Kwara, Nigeria (Ajibola *et al.*, 2021)	16–28	24.2	237–370	$>0.29 \times 10^{-3}$†	Below reference value
Yerevan, Armenia (Petrosyan & Perikhanyan, 2022)	2–11	7.1	<100	Below 0.29×10^{-3}	Below reference value
Ubon Ratchathani, Thailand (Sittitanadol *et al.*, 2026)	≈0.4	≈0.4	0.78–2.13	Negligible	Well below reference value
Saudi Arabia Bottled Water (Khan *et al.*, 2026)	0.13–0.39	≈0.3	1.69–9.24	Negligible	Well below reference value

The concentrations obtained in the present study are therefore considerably lower than those reported for these Nigerian locations. International studies, including those conducted in Yerevan, Armenia, Thailand and Saudi Arabia, have likewise reported relatively low ^{222}Rn concentrations in water. The comparative results indicate that the Warri wetlands based on the sampled locations and corrected measurements, do not exhibit an unusually high dissolved-radon burden. Rather, the concentrations fall within the lower range of values reported in many published studies as shown in Figure 7.

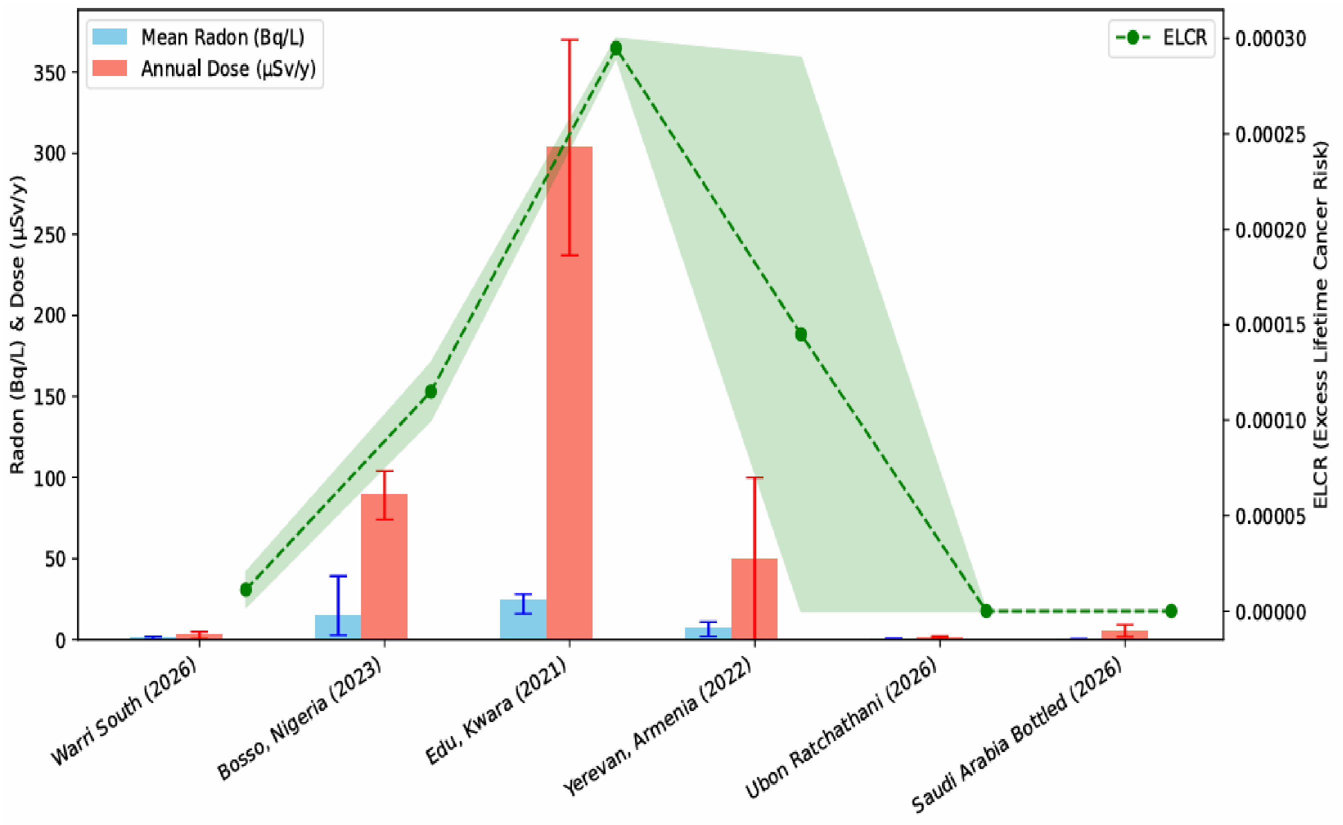


Figure 7 Comparative ^{222}Rn Concentrations, Dose, and ELCR in Drinking-Water Studies

Conclusion

The radiological interpretation of the Warri South LGA wetlands dataset indicates that radon concentrations are lower relatively to international reference values. From a radiological perspective, all wetlands produced concentrations well below the 100 Bq/L parametric value established by Euratom (2013) and WHO (2008)**.** The calculated annual effective doses (≈0.49–4.92 µSv/y) are far beneath the 0.1 mSv/year reference dose level, and the excess lifetime cancer risk estimates (≈2.02×10^{-6}–2.03×10^{-5}) remain negligible compared to the UNSCEAR benchmark of 0.29×10^{-3}. These findings indicate that wetland water in Warri South LGA does not pose a significant radiological hazard if consumed directly**.** This contrasts sharply with elevated risks reported in Nigerian mining regions (Ajibola *et al.,* 2021; Kolo *et al.,* 2023) and highlights the safer baseline observed in Warri, comparable to international studies in Armenia (Petrosyan & Perikhanyan, 2022), Thailand (Sittitanadol *et al.,* 2026), and Saudi Arabia (Khan *et al.,* 2026). The implications of the lower concentrations observed at Market Road, McDermott Road, and Okere are equally important. Although these values were the lowest in Warri, they still confirm the overall safe profile of the wetlands relative to international standards. This reinforces the conclusion that Warri South LGA wetlands are radiologically safe, while also emphasizing the need for continued monitoring and public awareness.

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