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Screening-Level Radiological Risk Assessment of Natural Radionuclides in Jabi Lake Sediments Using RESRAD-Onsite: A Conservative Scenario-Based Assessment

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Abstract

Naturally occurring radioactive materials (NORMs) in lake sediments may contribute to human radiation exposure through multiple environmental pathways, making periodic radiological assessment important for environmental protection. This study conducted a screening-level radiological risk assessment of Jabi Lake, Abuja, Nigeria, using activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K measured from a one-time sediment sampling campaign and the RESRAD-Onsite computer code. Gamma spectrometric analysis showed that the measured radionuclide concentrations and the corresponding radium equivalent activity were below the recommended UNSCEAR limits, indicating that the present radiological status of the lake sediments is unlikely to pose significant health concerns. Conservative RESRAD-Onsite simulations identified fish consumption as the dominant potential exposure pathway and indicated increased radiation dose and excess lifetime cancer risk under hypothetical long-term exposure scenarios assuming persistent radionuclide concentrations. These results represent conservative screening-level estimates rather than predictions of future environmental conditions. The study provides baseline radiological data for Jabi Lake and demonstrates the value of integrating environmental measurements with conservative modelling to support preliminary risk evaluation and future environmental monitoring.

Keywords: Jabi Lake; Lake Sediments; NORMs; RESRAD-Onsite; Radiological Risk Assessment; Environmental Monitoring.

I. Introduction

The preservation of the environment and public health is intrinsically linked to the quality of aquatic ecosystems. A significant, yet often overlooked, threat in these environments stems from elevated concentrations of naturally occurring radioactive materials (NORMs). Primordial radionuclides from the ^{238}U and ^{232}Th decay series, along with ^{40}K, are ubiquitous in the Earth's crust [1-2]. However, their concentrations can become elevated in water bodies through natural processes, such as the weathering of uranium- and thorium-bearing geological formations, or through anthropogenic activities, including mining, fertilizer runoff, and industrial discharges and municipal wastes [3-4]. These radionuclides are not readily soluble and tend to associate with particulate matter, leading to their accumulation in sediments, rocks, and soils at the bed and banks of a water body [4]. From this reservoir, they can enter the aquatic food web, posing a significant radiological risk to humans through the ingestion of water, fish, and other aquatic organisms [1], [5-6]. Given the critical importance of water and aquatic food sources to global populations, the continuous radiological assessment of these media is not just prudent but essential for proactive health protection [2].

Lakes represent a specific class of water bodies subject to extensive and multifaceted human use [3], [7]. Unlike rivers, the lentic (still-water) nature of lakes promotes the settling and accumulation of sediments and their associated contaminants [1], [6]. Globally, both natural and artificial lakes are heavily utilized for fishing, boating, recreation, and as sources for municipal water supply [8]. This high level of human interaction amplifies the potential pathways of exposure, including external irradiation from sediments, inhalation of resuspended soil particles, and ingestion of water and aquatic food, and makes the assessment of lake contaminants, especially radiological ones, a priority. The health consequences of prolonged exposure to ionizing radiation, even at low doses, are a subject of ongoing concern, with potential risks including an increased lifetime risk of cancer and genetic effects [2]. Therefore, establishing baseline data and monitoring trends is crucial for environmental management and public safety.

Nigeria is a country with a growing population and increasing socio-economic activities, which has made the monitoring of NORMs a significant concern. Hitherto, assessments have been conducted in various environmental media, including soils, food crops, building materials, and some groundwater sources [4-5], [9-10]. However, a significant data gap persists for surface water bodies, particularly the lake systems. This gap hampers the development of a comprehensive national environmental radioactivity monitoring framework and leaves a blind spot in understanding the cumulative radiological exposure of populations around the surface water bodies. Jabi Lake is an artificial lake strategically located at the heart of Abuja, and it epitomizes a water body with substantial human patronage [11]. The lake was created for water supply into the metropolis; however, it has since evolved into a premier hub for recreation, fishing, boating, and social activities, attracting hundreds of visitors daily [11]. This large and recurrent population is potentially exposed to ionizing radiation originating from the NORM present in the lake's environment.

Although preliminary screening may indicate that radiation levels in the Jabi Lake environment are within typical background ranges, the potential radiological implications of prolonged exposure to NORMs remain an important environmental and public health concern. In aquatic systems such as lakes, radionuclides tend to accumulate within bottom sediments, which can serve as long-term reservoirs and secondary sources of radiation exposure through pathways such as external irradiation, inhalation of resuspended particles, and ingestion of aquatic food products [6], [12].

Long-term environmental monitoring programmes are widely recognized as the most reliable approach for characterizing temporal variations in environmental radioactivity. However, such programmes are often constrained in developing countries by limited financial resources, inadequate monitoring infrastructure, and logistical challenges. Consequently, screening-level risk assessments based on representative environmental measurements coupled with validated radiological assessment models have become valuable tools for preliminary evaluation of potential exposure scenarios. Although these assessments cannot replace comprehensive monitoring programmes, they provide a scientifically defensible basis for identifying potential concerns, prioritizing sites for further investigation, and supporting risk-informed environmental management decisions.

Although RESRAD-Onsite is primarily designed for terrestrial contaminated environments [13-14], its application in this study provides a conservative estimation framework for assessing possible long-term exposure trends associated with sediment-bound radionuclides. Accordingly, this study aimed to conduct a screening-level radiological risk assessment of naturally occurring radionuclides in the sediments of Jabi Lake using measured activity concentrations from a single sampling campaign as input to the RESRAD-Onsite model. The objective was not to predict future environmental conditions, but rather to evaluate conservative hypothetical exposure scenarios that could assist in identifying potential radiological concerns, establishing baseline information, and guiding future environmental monitoring programmes.

II. MATERIALS AND METHODS

A. Description of the Study Area

Jabi Lake is located between Latitude 9°4'38"N and Longitude 7°25'18"E at an altitude of 480 meters above sea level [15-16]. Jabi Lake is bordered by several highly populated districts, namely Kado in the northern region, Utako to the east, Dakibiyu to the south, Life Camp to the west, and Gwarinpa toward the northwest, as illustrated in Fig. 1. The lake is situated close to a major shopping complex that attracts both residents and visitors for commercial, recreational, and social activities. The reservoir was formed through the damming of Jabi Stream, a tributary of the Kubwa River, and occupies an estimated area of about 1,300 hectares.

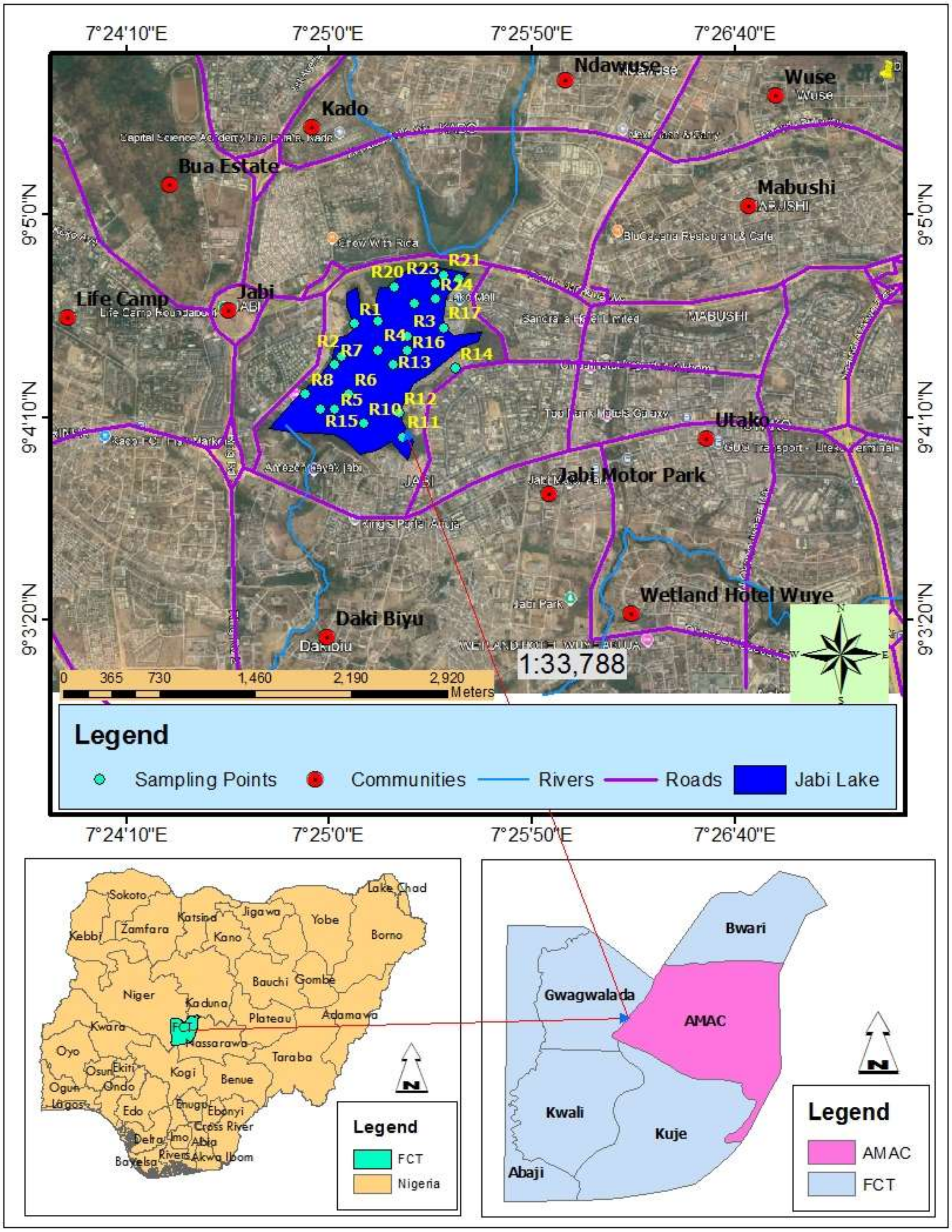

Fig. 1. Map of Nigeria (lower left), map of Abuja (lower right), and the Google Map of the study area showing the sampling locations within Jabi Lake.

B. Materials

The materials employed in this study included sample collection bottles, polythene bags, a sediment sampler, masking tape, indelible ink, a gamma spectrometer, the RESRAD-Onsite computer code, and a personal computer.

C. Methods

1) Sample collection

A purposive spatial sampling strategy was adopted to ensure that the major accessible regions of Jabi Lake were represented. The sediment collection was carried out using an Ekman grab sampler. At each sampling location, three sediment samples were taken from three different positions equidistant from each other and separated by approximately the same sectoral angle; all the samples were taken from an average depth of 18.5 m and combined to form a representative composite sample through homogenization. The samples were collected at the peak of the dry season (in the month of March) and at the early hours of the day (8 a.m.) when the water turbulence and sediment disturbance were low to ensure that the radionuclides released from the sediments were at an optimum low level.

The sampling strategy was designed to provide representative baseline information for a screening-level radiological assessment of Jabi Lake. The fifteen sampling locations were spatially distributed across the lake to capture the general variability in sediment characteristics while maintaining a practical balance between spatial coverage and analytical resources. Although this sampling design does not fully characterize all spatial variability within the lake, it provides an appropriate basis for preliminary radiological screening and identification of potential areas requiring more detailed investigation.

A total of 45 sediment samples homogenized into 15 samples, were taken, and at each location, coordinates were recorded with the aid of a global positioning system (GPS) as indicated in Fig. 1. The homogenised sediment samples were placed into plastic containers, securely sealed using stoppers and screw caps, and properly labelled with distinct identifications. These samples were moved to the Department of Biological Sciences' laboratory at the National Open University of Nigeria, Abuja, where they were spread in the laboratory under negative pressure conditions to prevent cross-contamination, allowed to dry under such laboratory conditions before subsequent elimination of visible impurities such as plastic fragments and plant residues, and repackaged in the sample bottles for the gamma spectrometry analysis at the Centre for Energy Research and Training (CERT) at Ahmadu Bello University (A.B.U.), Zaria.

2) Sample preparation

The sediment samples were processed for gamma spectrometric analysis to determine the activity concentrations of naturally occurring radionuclides present in the sediments. The preparation of the samples for gamma spectrometry was carried out at CERT, A.B.U., Zaria, based on the standard operating procedure of the laboratory [17]. The oven-dried sediment samples were pulverized into fine particles and sieved through a 2 mm mesh to obtain a uniform grain size. Thereafter, the processed samples were packed into cylindrical plastic containers measuring 6.5 cm in diameter and 6.0 cm in height. These container dimensions accommodate an optimal sample mass of approximately 300–350 g for bulk sediment gamma spectrometric measurements, as recommended in [18]. The prepared containers were hermetically sealed and kept for at least 28 days to establish secular equilibrium between radium and its radioactive decay products [5], [18-21]. The IAEA-certified gamma spectrometric standard reference materials (RGK-1, RGU-1, and RGTh-1) were packaged in identical sample containers, securely sealed, and maintained under the same storage conditions as the sediment samples.

3) Sample analysis

The sample analysis was also conducted at CERT, A.B.U., Zaria. The gamma spectrometric setup consists of a detector assembly with a 7.62 cm × 7.62 cm NaI(Tl) detector crystal (Model No. 727 series, Canberra Inc.) that is coupled via a pre-amplifier to a Canberra Series 10 computer-based plus Multichannel Analyzer (MCA) (Model No. 1104). To minimize interference from ambient background radiation, the detector crystal was housed within a 6 cm-thick lead shield lined internally with cadmium and copper sheets. For quality assurance and control, the system was calibrated for both energy and efficiency using the IAEA-certified reference materials RGK-1, RGU-1, and RGTh-1. References [10], [17-18], and [21-22] provide a detailed description of the procedure used for the calibration process.

Each sample was measured for a counting duration of 8 hours (28,800 s) to ensure adequate acquisition of gamma spectra and accurate determination of the specific activity concentrations.

4) Overview of the RESRAD-Onsite Computer Code

RESRAD (RESidual RADioactivity) is a pathway analysis computer code developed by the Argonne National Laboratory (ANL) for the United States Department of Energy (DOE) to evaluate radiological doses and risks associated with residual radioactive materials in the environment [23-24]. The code is widely applied in environmental radiological assessments to estimate radiation exposure to humans through multiple exposure pathways under site-specific conditions [9], [14], [25]. RESRAD-Onsite allows the user to model the transport of radionuclides from contaminated media such as soil or sediment into environmental compartments, including air, water, plants, animals, and aquatic organisms, and subsequently estimate the resulting radiation dose and excess lifetime cancer risk to a receptor [23-24].

The RESRAD-Onsite code performs dose calculations by combining radionuclide transport models with pathway-specific dose conversion factors. The total effective dose equivalent (TEDE) is computed as the sum of the doses received through all active exposure pathways and radionuclides considered in the scenario. The total annual dose is obtained from (1) [24].

$$TED(t) = \sum_{i=1}^{n} \sum_{p=1}^{m} C_i\,(t) \times DSR_{ip}(t) \qquad (1)$$

where, $TED(t)$ is the total effective dose equivalent at time t

(mSv·yr^{-1}), $C_i(t)$ is the activity concentration of radionuclide i at time t ($Bq.kg^{-1}$), $DSR_{ip}(t)$ is the dose-to-source ratio for radionuclide i through pathway p, n is the number of radionuclides, and m is the number of exposure pathways.

The code also estimates radionuclide decay and ingrowth using the Bateman equations, which describe the time-dependent behaviour of parent radionuclides and their progenies as presented in (2) [24].

$$N_i(t) = N_0 e^{-\lambda_i t} \quad (2)$$

where, $N_i(t)$ is the quantity at time t, N_0 is the initial quantity and λ_i is the decay constant of the radionuclide i.

For cancer risk estimation, RESRAD computes the excess lifetime cancer risk (ELCR) using (3).

$$ELCR = TED \times RF \quad (3)$$

where, $ELCR$ is the excess lifetime cancer risk, TED is the estimated total effective dose equivalent, and RF is the risk factor or cancer slope factor for the radionuclide.

The code incorporates several exposure pathways, including external gamma irradiation, inhalation of resuspended particles, ingestion of contaminated water, soil, plants, meat, milk, fish, and aquatic food products. In the present study, RESRAD-Onsite was adapted to evaluate potential radiological risks associated with sediment-bound naturally occurring radioactive materials (NORMs) in Jabi Lake under a conservative exposure scenario. Although the model is primarily intended for terrestrial contaminated sites, its application in this study provides a useful screening-level estimation of possible long-term radiological impacts from lake sediments. This approach does not explicitly simulate complex sediment transport processes, hydrodynamic mixing, or seasonal variations in radionuclide distribution; therefore, the results should be interpreted as screening-level estimates intended to identify potential radiological concerns and guide future site-specific investigations.

5) Radiological risk assessment using RESRAD Onsite

The radiological dose and risk estimation conducted with the RESRAD-Onsite computer code were implemented using RESRAD Onsite version 7.2. The code was installed on an HP personal computer powered by an Intel Core i5 processor, which was sufficient to perform the simulations. A representative exposure scenario (Fig. 2) was developed to mirror the prevailing environmental and human activity patterns at Jabi Lake, thereby providing a realistic basis for estimating potential radiological doses and health risks. The dose computations primarily accounted for water-dependent pathways, driven by radionuclide concentrations measured in the lake's sediments, following the established modelling procedures in [23]. This exposure scenario established a consistent and conservative basis for assessing the various pathways through which NORMs within the lake environment could contribute to human radiation exposure, notwithstanding the variability of the sediment's concentration.

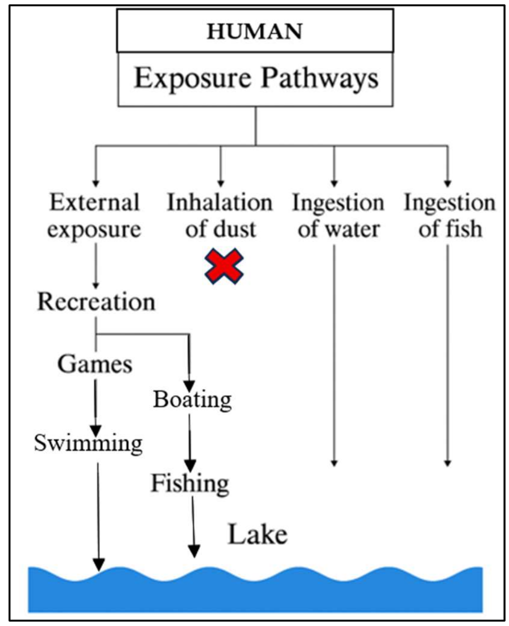

Fig. 2. Typical Radiation Exposure Pathways at Jabi Lake, Abuja.

To improve model fidelity, site-specific parameters such as the measured NORM activity concentrations, hydrological characteristics, and local lifestyle and dietary habits were used to customize the input dataset [9]. The modifications to RESRAD default parameters reflecting these site conditions are summarized in Table I, while unaltered parameters were retained at their default values. In line with the philosophy of radiation protection, only the parent and progeny radionuclides with half-lives greater than 30 days were included in this analysis. The dose estimations were computed at progressive time intervals of 0, 1, 30, 50, 70, 100, and 1000 years to evaluate both short-, medium-, and long-term exposure implications at Jabi Lake [10]. The dose conversion factors (DCFs), transfer coefficients, and bioaccumulation parameters were obtained from the DCFPAK 3.02 morbidity/mortality database, consistent with the recommendations of the International Commission on Radiological Protection (ICRP) Publication 107 [26]. An exposure period of 30 years was applied. The simulated doses were evaluated against a screening dose constraint of 0.25 mSv.y^{-1}, which is commonly adopted in the RESRAD methodology for environmental remediation and site release assessments to provide a conservative benchmark for radiological protection. This value is more restrictive than the 1 mSv y^{-1} annual effective dose limit recommended by the ICRP for members of the public and was selected to ensure a conservative screening-level assessment [10]. The risks associated with the site, based on the measured concentration, were estimated up to a maximum of 1000 years.

To maintain consistency across simulations, the ICRP reference adult (aged 20–30 years, 70 kg body weight, 170 cm height of Western European origin, residing in a temperate

10–20 °C climate) was used as the representative receptor [10]. This standardization minimized uncertainties associated with age- and gender-specific variability. The assessment incorporated all relevant exposure routes, such as external gamma irradiation, inhalation of resuspended materials, and ingestion of aquatic organisms, drinking water, and shoreline soil to derive a comprehensive estimate of the total effective dose from sediment-bound NORMs in Jabi Lake.

The modified input parameters were intentionally selected to provide a conservative screening-level assessment. Consequently, several assumptions, including uniform contamination, persistent radionuclide inventories, and continuous exposure, were adopted to ensure that the estimated doses represent upper-bound radiological exposure scenarios.

Table I. Modified RESRAD Onsite Input Parameters.

S/N	Parameter	Value	Description and/or Reference
1	Sediment activity concentration of ^{238}U (^{226}Ra), ^{232}Th, and ^{40}K (Bq/kg)	8.62 (^{238}U); 5.98 (^{232}Th); 202.64 (^{40}K)	Average activity concentrations in the sediment samples based on once-off sampling.
2	Cover depth (m)	19.00 m	Estimated average depth of Jabi Lake.
3	Area of contaminated zone (m^2)	13,000,000	The entire lake area was conservatively treated as a uniformly contaminated zone for screening purposes [15].
4	Thickness of contaminated zone (m)	0.30	Value is consistent with sediment layers used in similar lake/radiological risk assessments and represents a conservative scenario [4].
5	Density of contaminated zone (g/cm^3)	1.30	Typical for Jabi Lake, a shallow, man-made reservoir with fine, organic-enriched clayey silt.
6	Contaminated zone hydraulic conductivity (m/year)	0.4 x 10^3	Estimated saturated hydraulic conductivity of silty clayed sediment [27].
7	Precipitation rate (m/year)	1.50	Estimated average precipitation in Abuja [28].
8	Runoff coefficient	0.40	Based on littoral/urban/residential catchments typical for Abuja (with some impervious surfaces and moderate slopes)
9	Inhalation rate (m^3/year)	2.10	Average adult inhalation rate [27]
10	Depth of soil mixing layer (m)	18.50 m	Estimated based on the average depth of Jabi Lake
11	Average wind speed (m/s)	3.00	Average wind speed in Abuja [29].
12	Outdoor occupancy factor	0.20	Average outdoor occupancy factor around the lake, computed based on the social habits of the users of the lake and the shorelines around the lake.
13	Exposure duration (years)	30.00	As recommended in [23].
14	Soil ingestion rate (g/year)	36.50	Ingestion rate is a value recommended by the EPA for adults around residential areas [27].

III. Results and Discussion

A. Concentration of NORMs in Sediments

The concentrations of Naturally Occurring Radioactive Materials (NORMs) such as ^{226}Ra (^{238}U), ^{232}Th, and ^{40}K were determined from spectral analyses conducted using Canberra's *Genie2000* software. The results obtained for the analysed sediment samples are presented in Table II.

From the result presented in Table II, the average concentration (± Standard Deviation) of ^{226}Ra, ^{232}Th, and ^{40}K was determined to be 8.62 ± 3.63, 5.98 ± 1.11, and $202.64 \pm 60.42\ Bq/kg$, which is below the world's average values of $32, 45$, and $420\ Bq/kg$ for ^{226}Ra, ^{232}Th, and ^{40}K concentrations in soil as published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [22], [30]. These values indicate that, based on a one-time sampling, the concentrations of the natural radionuclides in the sediment of Jabi Lake are unlikely to pose any measurable biological effect on an individual exposed to the lake for an average lifetime of 70 years. The computed radium equivalent also followed a similar trend of values, with an average value of $32.77 \pm 8.72\ Bq/kg$ which is below the UNSCEAR recommended limit of $370\ Bq/kg$ by approximately 90%, indicating that the radiological hazard associated with the lake's sediment is extremely low.

The estimated radium equivalent activity was included to facilitate comparison with international standards and with previous environmental radioactivity studies. Although other conventional hazard indices, such as the external hazard index, internal hazard index, absorbed dose rate, annual effective dose, and gamma index, are commonly reported in environmental radioactivity investigations, the principal objective of this work was to perform a pathway-based screening-level radiological risk assessment using the RESRAD-Onsite model. Consequently, the subsequent dose and risk evaluations presented herein provide a more comprehensive characterization of potential human exposure under the defined conservative scenario.

Table II. The Concentration of NORMs in Sediments from Jabi Lake.

Sample ID	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Ra_{eq} (Bq/kg)
SD1	9.24	3.76	56.89	19.00
SD2	3.22	1.18	89.55	11.81
SD3	4.52	2.92	86.05	15.32
SD4	2.13	2.00	70.24	10.39
SD5	3.07	2.24	65.50	11.32
SD6	2.61	2.49	55.92	10.47
SD7	7.87	5.62	38.54	18.87
SD8	1.66	3.56	40.43	9.87
SD9	9.03	5.72	336.32	43.10
SD10	11.90	7.98	521.46	63.47
SD11	5.41	5.25	451.07	47.65
SD12	11.90	8.16	317.47	48.02
SD13	12.94	15.40	343.25	61.39
SD14	27.02	13.25	287.29	68.10
SD15	16.72	10.11	279.59	52.71
Average	8.62	5.98	202.64	32.77
Std Dev	3.63	1.11	60.42	8.72
UNSCEAR [30]	32	45	420	370

Despite the low risk observed from the estimated concentrations of NORMs in the sediment samples, it is imperative to evaluate the radiological hazards associated with the lake sediments over extended periods, owing to the progressive decay of natural radionuclides into various radioactive progenies with differing radiobiological characteristics and hazard potentials, which may consequently alter the overall radiological risk profile of the environment. Therefore, an additional pathway-based, screening-level radiological risk assessment was conducted using the RESRAD-Onsite computer code to evaluate the potential radiological implications of the measured sediment radionuclide concentrations under conservative exposure assumptions.

B. Radiological Risk Assessment with RESRAD Onsite

Multiple-pathway and water-dependent dose calculations, as well as risk assessments, were performed conservatively using the RESRAD-Onsite computer code. The total radiation dose and the corresponding excess lifetime cancer risk (ELCR) at progressive time intervals of 0, 1, 30, 50, 70, 100, and 1000 years, summed over all radionuclides and pathways defined by the scenario considered, are presented in Fig. 3a and 3b. Similarly, Figs 4a and 4b present the dose and cancer risk contributions from the individual exposure pathways.

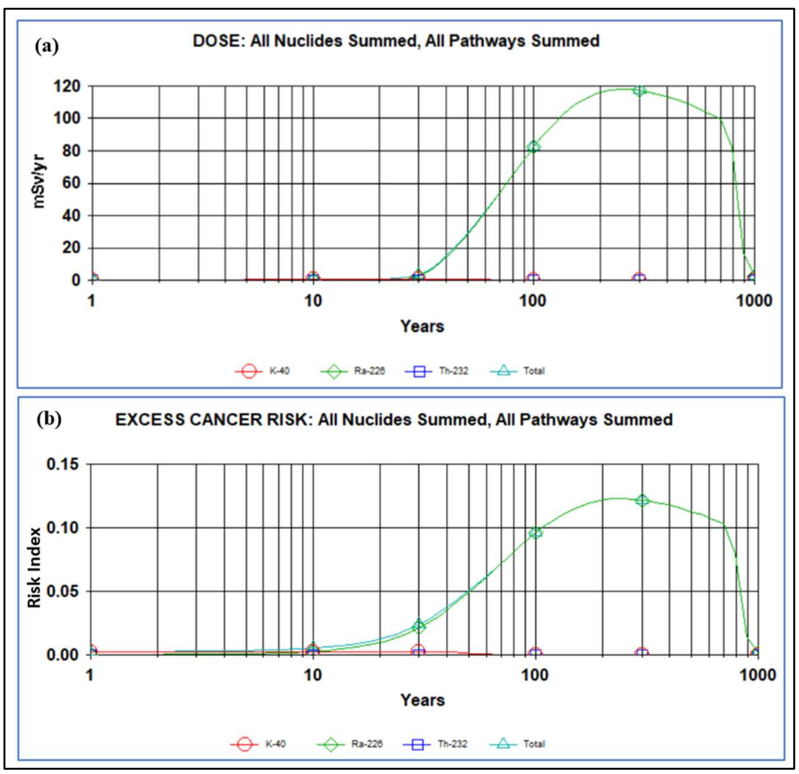

Fig. 3. (a) Radiation Dose from NORMs and (b) Excess Cancer Risk Summed for all the Radionuclides and Selected Pathways, Calculated with RESRAD Onsite.

From Fig. 3a, the radiation dose for exposure durations between 1 and 20 years remains well below the recommended public dose limit of 1 mSv·yr⁻¹. However, a slight increase in dose is observed after 30 years of exposure. This gradual rise becomes more pronounced, reaching approximately 60 mSv·yr⁻¹ after 70 years and peaking between 200 and 300 years before declining steadily thereafter, signifying that future exposures at 200 and 300 years may likely pose significant radiological risks to the users of Jabi Lake. A similar trend is observed in Fig. 3b, where the ELCR increases with the simulated radiation dose under the exposure scenarios considered. The simulated ELCR indicates a potential increase in theoretical radiological risk under highly conservative exposure assumptions, including continuous exposure, persistent radionuclide inventories, and uniform contamination throughout the assessment period, which might deviate significantly when a periodic sampling approach is adopted, and dynamic concentrations are incorporated into the simulation. This highlights one of the limitations of the present study.

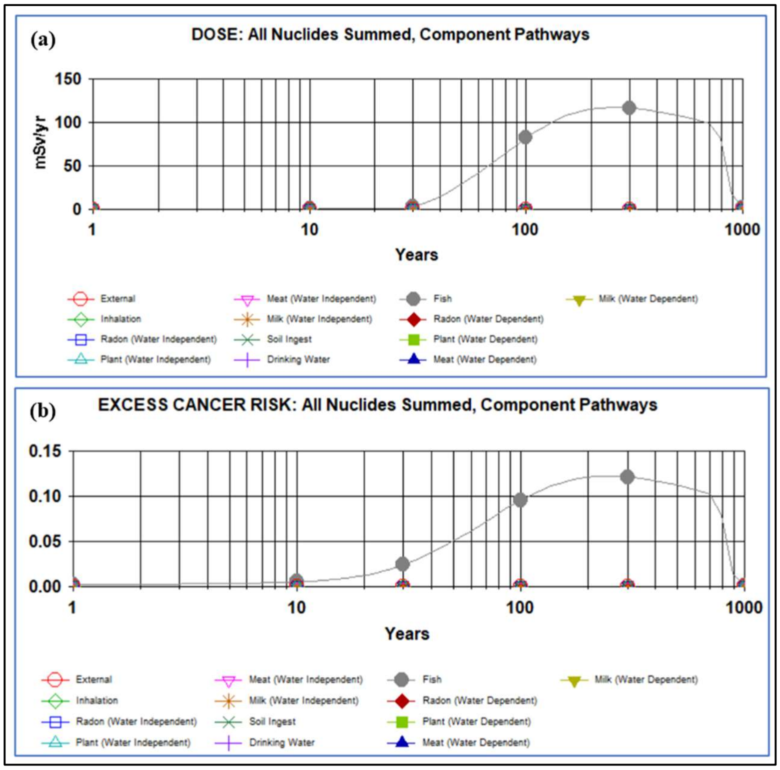

Fig. 4. (a) Radiation Dose, and (b) Excess Cancer Risk from Component Pathways, Calculated with RESRAD Onsite.

From Figs 4a and 4b, the simulations identified fish consumption as the dominant potential exposure pathway under the conservative exposure scenario adopted in this study, followed by external gamma irradiation. This result is derived from the model's radionuclide transfer and exposure assumptions rather than direct measurements of radionuclide concentrations in fish tissues. Consequently, an experimentally verified assessment of the radiological risk associated with fish consumption is still imperative, necessitating future investigations involving direct radionuclide measurements in fish and other aquatic organisms collected from the lake.

To identify the radionuclides with the highest contribution to the radiation dose, the dose-to-source ratio (DSR) was determined using RESRAD-Onsite. The DSR values for the individual radionuclides considered in this study, along with their decay progeny, are presented in Fig. 5a–5e. These figures show that during the early exposure period (up to 20 years), ^{40}K is the primary contributor to the radiation dose, reaching its peak around 20 years before declining sharply by 100 years. This behaviour can be attributed to the fact that potassium is a macronutrient with high biological mobility and turnover in the human body, and it is a non-series radionuclide in its decay, which results in a relatively short biological half-life. Beyond 20 years of exposure, ^{226}Ra and ^{232}Th, along with their decay products such as ^{210}Po and ^{228}Ra, become the main contributors to the radiation dose. These radionuclides are also the key drivers of the rise in the excess lifetime cancer risk observed in Fig. 3b. Consequently, a periodic assessment of the concentration of NORMs in Jabi Lake is imperative to provide more reliable data pertinent to regulatory decisions and public safety.

The findings of this study were compared with results from radioactivity assessments conducted on other lakes in Nigeria and across the world. For instance, [4] reported that the concentrations of NORMs in sediment samples collected from the Niger Delta floodplain lakes, as well as the associated radiation risks, were within the recommended safety limits, with the results indicating low radiological risk, which is consistent with the findings of the present study. However, unlike the current research, predictive analyses were not performed to evaluate the long-term exposure characteristics of the lakes.

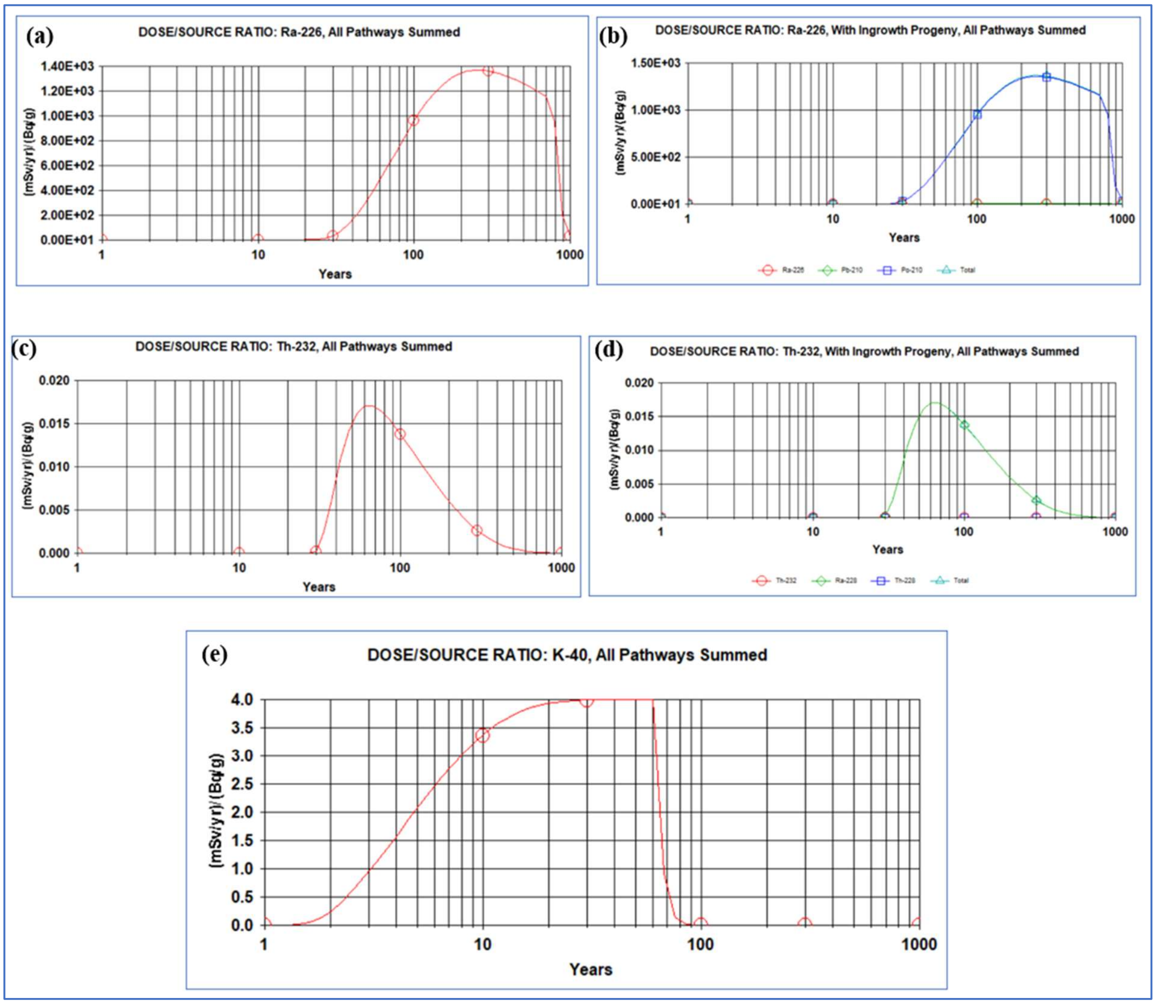

Fig. 5. Dose-to-source ratio with ingrowth progenies summed for the selected pathways, calculated with RESRAD Onsite.

Similarly, this study was compared with investigations conducted on Lake Qarun [8] and Lake Nasser in Egypt [13]. While [8] reported relatively higher concentrations of ^{40}K, [13] observed NORM concentrations that were within globally recommended limits. Both studies concluded that the radiological effects associated with NORMs in lake sediments were low, aligning with the findings of this research. Unlike previous investigations, which primarily reported measured radionuclide concentrations and conventional radiological indices, the present study integrates field measurements with a scenario-based RESRAD-Onsite assessment to examine the potential implications of conservative long-term exposure assumptions. Consequently, this study extends the existing body of knowledge by demonstrating how screening-level modelling can complement conventional environmental radioactivity assessments in situations where long-term monitoring data are unavailable.

Nonetheless, the radiological doses and excess lifetime cancer risks estimated by RESRAD-Onsite in this study should be interpreted within the context of the conservative assumptions adopted. The simulations assume that radionuclide concentrations remain spatially uniform and temporally persistent throughout the assessment period while also considering continuous exposure through all active pathways. Sediment deposition, erosion, hydrodynamic processes, seasonal fluctuations, and changes in land use are expected to modify radionuclide distributions over time. Consequently, the simulated doses do not represent forecasts of future environmental conditions but rather conservative screening scenarios designed to evaluate the potential upper bounds of radiological exposure under simplified assumptions. Such screening assessments are widely used in environmental radiological protection to support preliminary decision-making and identify situations where more detailed site-specific investigations may be warranted.

IV. Conclusion

This study provides baseline information on the occurrence of NORMs in the sediments of Jabi Lake based on a one-time sampling campaign and subsequently conducts a pathway-based, screening-level radiological risk assessment using the RESRAD-Onsite computer code. The measured activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, together with the corresponding radium equivalent activity, were all below the limits recommended by UNSCEAR, indicating that the current radiological status of the lake sediments is unlikely to pose significant health concerns under existing environmental conditions.

Conservative screening-level simulations performed with RESRAD-Onsite indicated that, under hypothetical long-term exposure scenarios assuming persistent radionuclide concentrations, uniform contamination, and continuous exposure, the simulated radiation doses and excess lifetime cancer risk increased over time, with the highest values occurring between approximately 200 and 300 years. Under the same conservative assumptions, fish consumption was identified as the dominant potential exposure pathway. Therefore, the study provides important baseline radiological information for Jabi Lake and demonstrates the usefulness of integrating environmental measurements with conservative pathway-based modelling where long-term monitoring data are unavailable.

Nevertheless, the assessment is constrained by the use of one-time sediment sampling and the simplifying assumptions inherent in the RESRAD-Onsite model. Consequently, periodic and multi-seasonal sampling, coupled with hydrodynamic characterization, sediment transport modelling, and direct measurements of radionuclides in water and aquatic organisms, is recommended to reduce uncertainty and provide a more comprehensive long-term radiological assessment of Jabi Lake. Such investigations would further strengthen the scientific basis for environmental monitoring and support evidence-based management and sustainable utilization of the lake.

Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Funding Declaration

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Authors' Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by all the authors. The first draft of the manuscript was written by the corresponding author, and the co-authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethical Approval

This is not applicable.

Consent to Participate

This is not applicable.

Consent to Publish

All the authors of this manuscript consent to its publication in this reputable journal.

Data Availability

The authors declare that the data supporting the findings of this study are available within the paper.

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