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Probabilistic Assessment of Incidental Ingestion and External Doses in the Industrially Impacted Nun River, Niger Delta

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ABSTRACT

Dredging and oil and gas activities have a significant effect on the Niger Delta's Nun River, but the region has never had a radiological risk assessment based on drinking-water ingestion models that misrepresent local exposure scenarios. This study measures the activity concentrations of potassium-40 (^{40}K), uranium-238 (^{238}U) and thorium-232 (^{232}Th) in water samples collected from 10 sites along the Nun River and assesses a dual-pathway radiological risks. Gamma spectrometry revealed mean activity concentrations of 42.71 ± 26.69 Bq/L for ^{40}K, 5.36 ± 4.26 Bq/L for ^{238}U, and 2.10 ± 1.29 Bq/L for ^{232}Th, with ^{238}U and ^{232}Th exceeding WHO guidance levels at several sites. Annual effective doses due to external water immersion and incidental ingestion were estimated by Monte Carlo simulation, and the internal dose due to ^{40}K was not calculated because of strict homeostatic regulation. Results show that the external irradiation is about one order of magnitude lower than incidental ingestion at all locations. The total annual effective dose (mean 7.25 × 10^{-3} mSv/y) and Excess Lifetime Cancer Risks (ELCR) were statistically significant for Swali, Belelebiri and Opokuma, but were well below the WHO criterion of 0.1 mSv/y and US EPA acceptable range of 1.0 × 10^{-6} to 1.0 × 10^{-4}. The findings of the study show that the traditional approach to drinking-water guidelines fundamentally misunderstands the concept of risk in non-consumption scenarios, highlighting the need for a more targeted approach to public health risk reduction in industrially affected riverine systems.

Keywords: Radiological risk assessment; Incidental ingestion; NORM; Monte Carlo simulation; Nun River

1.0 INTRODUCTION

The Niger Delta region of Nigeria is one of the most studied but under-monitored environments in sub-Saharan Africa with respect to naturally occurring radioactive material (NORM) contamination, (Babatunde et al, 2019; Agbalagba & Onoja, 2011). This ecologically sensitive area has been exposed to technologically enhanced naturally occurring radioactive materials (TENORM) from decades of petroleum exploration and production in surface water systems (Joledo et al., 2025). The major distributary of the Niger River, the Nun River, cuts through the Bayelsa State, where a high density of oil and gas facilities, both active and abandoned dredging sites, and communities with complex relationships with the riverine environment are found (Nkajoe et al. 2026). The radiological impacts of oil and gas operations in the Niger Delta have been given intermittent consideration, but the potential for multi-

pathway and cumulative exposure from radionuclides in rivers with both geogenic and anthropogenic sources is under-characterized.

In this context the radionuclides of concern are potassium-40 (^{40}K), uranium-238 (^{238}U) and thorium-232 (^{232}Th). ^{40}K is a primordial radionuclide, an essential nutrient analog, and a significant contributor to the total beta activity in natural waters, but it is not a major concern for radiological health because potassium is homeostatically regulated in the human body (Ali et al., 2025). Nevertheless, radionuclides in the 238U and ^{232}Th series are more hazardous, particularly when they are discharged from the geological formations as a consequence of industrial activities (Uzorka et al., 2025). The reason is that it is quite obvious that oil and gas production operations may bring formation waters containing high concentrations of radium-226 and radium-228 (the daughters of ^{238}U and ^{232}Th, correspondingly), to the surface, thus contaminating produced water, scales, and sludge (Nobel & Hunter, 2024; Agbalagba et al., 2013). The activity of dredging, being widespread at the Nun River, may cause resuspension of polluted sediments and subsequent transport of particle-bound radionuclides into the water column (Nkajoe et al., 2026).

Most of the existing radiological assessments of water bodies in Nigeria have been based on the drinking water pathway, using the guidance level of 0.1 mSv y^{-1} for an adult drinking 2 litres of water per day (WHO, 2006). But this regulatory regime essentially misdescribes the exposure situation in communities located along the Nun River. Local populations are not using the river as a main source of drinking water as recorded in the sampling framework of the present study. Rather, the river is a source of incidental and indirect exposure pathways for occupational and domestic activities such as swimming, fishing, clothes washing and dredging. All of these activities have different levels of water contact, aerosol generation and sediment disturbance, which provide opportunities for radionuclide ingestion, inhalation of resuspended particulates, and dermal absorption. These pathways present lower individual doses than direct drinking water intake (Osiga-Aibangbee et al., 2025), but can add up to a significant cumulative radiological burden on vulnerable sub-populations such as children and adolescents, and on chronic timescales (Alnajjar & Hawwari, 2026).

There is limited scientific evidence regarding multi-pathway radiological exposure in recreational and occupational water environments, especially in riverine environments in oil-producing areas of the Global South. The WHO guidelines explicitly state the conservatism of their drinking water derived guidance levels and the need for site-specific assessments when exposure scenarios are not in line with the assumed residential consumption model. But there are not well-developed operational frameworks to translate this recognition into quantitative risk estimates for non-drinking water use scenarios. This knowledge gap is especially critical in the Niger Delta region where the combination of high natural background radiation, the high intensity of petroleum industrial activity and the high vulnerability of the population, with limited access to alternative water sources, can lead to potentially high radiological exposures that are not quantified.

This study aims to fill this important gap by performing a multi-pathway radiological risk assessment of the Nun River. The first step is to measure the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in water samples taken from ten strategically selected locations along the river from Kaiama to Belelebiri. Secondly, we describe the spatial pattern of these radionuclides and assess for potential relationships with the distance to dredging sites and oil and gas facilities. Third, we estimate annual effective doses by two pathways of exposure: incidental ingestion during water contact activities and external whole body irradiation from nearness to water and immersion. Fourth, we estimate the excess lifetime cancer risks (ELCR) from the local population and compare the cumulative doses with reference doses to see if current WHO guidance is sufficient to protect this non-drinking-water-using population.

This work creates and implements a multi-pathway exposure model for a scenario involving recreational and domestic water use in a contaminated riverine environment. The methods offer a template that can be applied to other scenarios in similar settings around the world, such as oil-producing areas in the Middle East and Central Asia, or mining-impacted watersheds in Latin America and Africa. In addition, our results have implications for radiological protection policy in Nigeria and other jurisdictions that have similar monitoring systems, which may be systematically underestimating population exposures by

ignoring non-ingestion pathways. If, as our analysis indicates, the combined doses from all pathways are above the 0.1 mSv/y individual dose criterion (WHO, 2022), regulatory agencies might need to re-evaluate the need for current guidance for populations that are not only consuming water but also using it for other purposes.

2.0 MATERIALS AND METHOD

2.1 Study Area

The Nun River is a large distributary of the Niger River in Bayelsa State, Nigeria, which runs for about 160 km from its source at Agbere Town to the Gulf of Guinea at Akassa (Akana & Adeigbe, 2019). It provides people living in riparian areas with water for domestic consumption, artisanal fisheries, transport and agriculture. The river, however, is under a lot of anthropogenic pressures such as dredging of sediments, oil prospecting by Shell Petroleum Development Company, discharge of industrial wastes and oil-refining activities (Gijo et al., 2016; Oyesanya, 2023). Hydrocarbon and heavy metal contamination has been reported (Izuchukwu et al., 2026), and the dredging has affected the hydrology of the river (Ilaboya et al., 2024). The study covered 10 locations in ten towns along the river corridor located in Yenagoa and Kolokuma/Opokuma LGAs. The anthropogenic activities are different in these areas and naturally occurring radionuclides (Oyanyan, 2023) may be present in the sedimentary formations of the region.

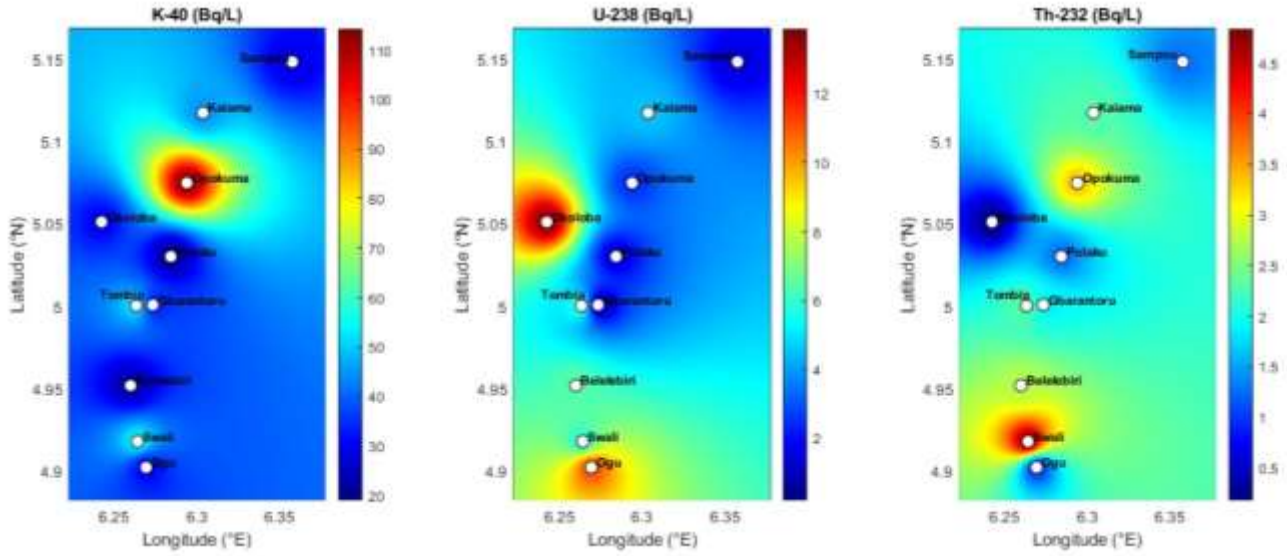


Figure 1. Location and distribution of the activity of radionuclides in samples collected from the Nun River

2.2 Sample collection and preparation

Water samples were taken at ten strategically located sites throughout the Nun River, from communities throughout the river as described in Table 1. The sampling sites were selected to reflect the spatial distribution of radionuclide activity concentrations throughout the river, including near dredging sites, oil and gas facilities, and residential communities in which local residents swim, wash, fish and participate in other household activities. Water samples were taken at each site from the surface layer (0–30 cm depth) in acid-washed high density polyethylene containers. Prior to collection, containers were rinsed three times with river water to minimize cross-contamination. As per standard procedure for radionuclide preservation in water samples, samples were immediately acidified to pH < 2 with ultrapure nitric acid (65%, Suprapur, Merck) to inhibit microbial activity and to prevent adsorption of radionuclides on the walls of the containers.

Water samples were received at the laboratory and were homogenized by shaking vigorously for 2 minutes. A 300 mL aliquot of each acidified sample was placed in a pre-cleaned Marinelli beaker for radionuclide activity concentration determination. The Marinelli beaker geometry was chosen to provide maximum counting efficiency, as is the norm for gamma spectrometric analysis of water samples. The transfer was done quantitatively and the beaker was capped and left undisturbed for at least 4 weeks to achieve secular equilibrium. Acidified ultrapure water in the same geometry was prepared and counted under the same conditions to correct for background interference.

2.3 Gamma Spectrometric Analysis

A thallium-activated sodium iodide [NaI(Tl)] detector was used to measure the activity concentrations of ^{40}K, ^{238}U and ^{232}Th. Standard point sources (^{22}Na, ^{57}Co, ^{60}Co, ^{137}Cs, ^{152}Eu) were used for energy calibration, and a mixed radionuclide standard solution in the same Marinelli geometry as the samples was used for efficiency calibration.

The peak centroid energies were used for radionuclide identification and the activity concentration (A, in Bq L^{-1}) for each radionuclide was calculated as follows:

$$A = \frac{N}{P_\gamma \cdot V \cdot T_c \cdot \varepsilon} \quad (1)$$

where N is the net counts per second (cps) obtained by subtracting background counts from sample counts, P_γ is the gamma emission probability (gammas per disintegration), V is the sample volume in liters (for liquid samples) or dried mass in kilograms (for solid samples), Tc is the counting time in seconds, and ε is the detector efficiency at the specific photopeak energy . For water samples, V corresponds to the volume in liters, and the equation yields activity concentration in Bq L^{-1} (Chowdhury et al., 2024; Althoyaib & El-Taher, 2015)

2.4 Radiological Health Indices from Activity Concentration in River water

Water from the Nun River is rarely used by locals for domestic purposes like drinking and cooking. This reduces the ingestion by a significant quantity. However, over the course of times, substantial amount of the water is accidentally ingested during activities like swimming, washing, fishing, dredging and other activities. Even though the amount is likely negligible, but when combined with external irradiation, the amount delivered builds up overtime which can result in stochastic effects.

1. External Effective Dose (AED_{ext}) from Water Immersion

The external gamma radiation dose received by individuals immersed in the Nun River was calculated using the dose rate coefficients specifically derived for the water immersion pathway, as provided in the U.S. Environmental Protection Agency's Federal Guidance Report No. 15 (EPA, 2025). Unlike soil-based conversion factors, which assume a semi-infinite terrestrial source geometry and are inapplicable to aquatic environments, the FGR 15 water immersion coefficients are derived from a Monte Carlo radiation transport model (MCNP6) using age-specific computational phantoms. These coefficients account for the specific geometry of a human body submerged in an infinite, uniformly contaminated water medium and incorporate the ICRP Publication 103 tissue weighting factors for effective dose (ICRP, 2007).

The external Annual Effective Dose (AED_{ext}) was estimated using the following equation:

$$AED_{ext} = \sum_i (C_i \times DCF_{imm,i}) \times T \times U \quad (2)$$

where:

C_i is the activity concentration of radionuclide (^{40}K, ^{238}U, ^{232}Th) in the water sample, converted from Bq L^{-1} to Bq m^{-3} (multiplied by 1000).

$DCF_{imm,i}$ is the FGR 15 adult reference person effective dose rate coefficient for water immersion for radionuclide, expressed in Sv Bq^{-1} s^{-1} m^3.

T is the annual exposure duration in seconds.

U is the unit conversion factor (10^3 to convert from Sv to mSv).

The radionuclide-specific water immersion dose rate coefficients for the adult reference person applied in this study were: $^{40}K = 1.65\times10^{-17}$ Sv Bq^{-1} s^{-1} m^3, $^{238}U = 6.51\times10^{-21}$ Sv Bq^{-1} s^{-1} m^3, and $^{232}Th = 1.50\times10^{-20}$ Sv Bq^{-1} s^{-1} m^3 (Bellamy et al., 2025).

To determine the annual exposure duration (T), a time-activity assessment specific to the local population was applied. Although the river water is not ingested for drinking, locals frequently engage in swimming, washing, fishing, and dredging. Assuming an average of 2 hours of daily immersion or close contact with the river water for occupational and domestic activities (which is a conservative estimate for active dredgers), the annual immersion time was calculated as:

$$T = 2\ h/day \times 365\ days/year \times 3600\ s/h = 2.628 \times 10^6\ s/year \quad (3)$$

The total external AED was calculated by summing the contributions from ^{40}K, ^{238}U, and ^{232}Th. Because ^{40}K possesses high gamma emission probability and energy, it is expected to dominate the external immersion dose, whereas the low activity concentrations and specific decay energies of ^{238}U and ^{232}Th series will contribute minimally to external exposure. This methodology corrects the fundamental geometric limitations of applying terrestrial dose coefficients to a water body, providing a highly accurate assessment of the external radiological hazard for the local population.

2.5 Committed Effective Dose due to incidental Ingestion (E_{ing})

The Committed Effective Dose (CED) resulting from the incidental ingestion of water contaminated with radionuclides is estimated using the radionuclide activity concentration in water, the annual water ingestion rate, and the ingestion dose conversion coefficient (DCC) recommended by ICRP and WHO (WHO, 2017; ICRP, 2012). Incidental ingestion of radionuclides from water during activities such as swimming or washing was estimated as:

$$E_{ing} = \sum_i (C_i \times DCF_{ing,i})\ IR \quad (4)$$

where:

DCF_U, DCF_{Th} is the ingestion dose conversion factors (Sv/Bq), ($DCF_U = 4.5\text{x}10^{-8}$ and $DCF_{Th} = 2.3\text{x}10^{-7}$) (ICRP, 2012). IR = 10 L/year = incidental ingestion rate which was assumed by the authors.

This represents internal exposure via incidental ingestion for the adult population, even though the water is not used for drinking (Bellamy et al., 2025; Eckerman et al., 2012).

3. Total Annual Effective Dose (E_{total})

The combined radiological burden from all pathways is:

$$E_{total} = AED_{ext} + E_{ing} + E_{inh} \quad (5)$$

This provides a comprehensive estimate of annual exposure.

4. Excess Lifetime Cancer Risk (ELCR)

The probability of developing cancer over a lifetime due to radiation exposure was computed as (ICRP, 2007):

$$ELCR = E_{total} \cdot DL \cdot RF \quad (6)$$

where:

DL=55 years = average lifespan,

RF=0.055 Sv^{-1} = fatal cancer risk factor.

ELCR quantifies the long-term stochastic health risk associated with cumulative exposure.

^{40}K was excluded from incidental ingestion calculations due to homeostatic regulation. Although ^{40}K is a beta and gamma emitter present in the water column, environmental potassium compounds are classified as Type F (fast absorption), and upon absorption into the bloodstream, ^{40}K is subject to strict homeostatic regulation by the human body. Because the kidneys maintain a constant total potassium inventory regardless of intake, the additional intake of ^{40}K via ingestion does not result in a net increase in internal radiation dose, as the excess is rapidly excreted. Consistent with WHO guidance, which explicitly states that ^{40}K does not need to be considered in health risk assessments of drinking water, the radiological contribution of internally incorporated ^{40}K to the total effective dose was therefore deemed negligible.

3.0 RESULTS AND DISCUSSION

Table 1 shows the activity concentration of radionuclides taken in samples from the 10 sampled location along the river. Table 2 presents the estimated external and ingestion contributions together with the associated Excess Lifetime Cancer Risk (ELCR) for river water samples collected across the study locations. These parameters provide important insight into the potential radiological health implications associated with the use and consumption of river water within the study area. Figure 2 illustrate the probability density functions (PDFs), cumulative density functions (CDFs), total dose distributions, ELCR trends, and box plot summaries of external and ingestion dose pathways for each sampling location. The PDF and CDF plots reveal the statistical distribution, variability, and cumulative occurrence of the radiological doses, while the box plots highlight differences in dispersion, median values, and potential outliers among the locations. Furthermore, Figures 3 provides a summary box plots for ELCR values, enabling clearer visualization of spatial variations and overall radiological risk patterns in the river water samples.

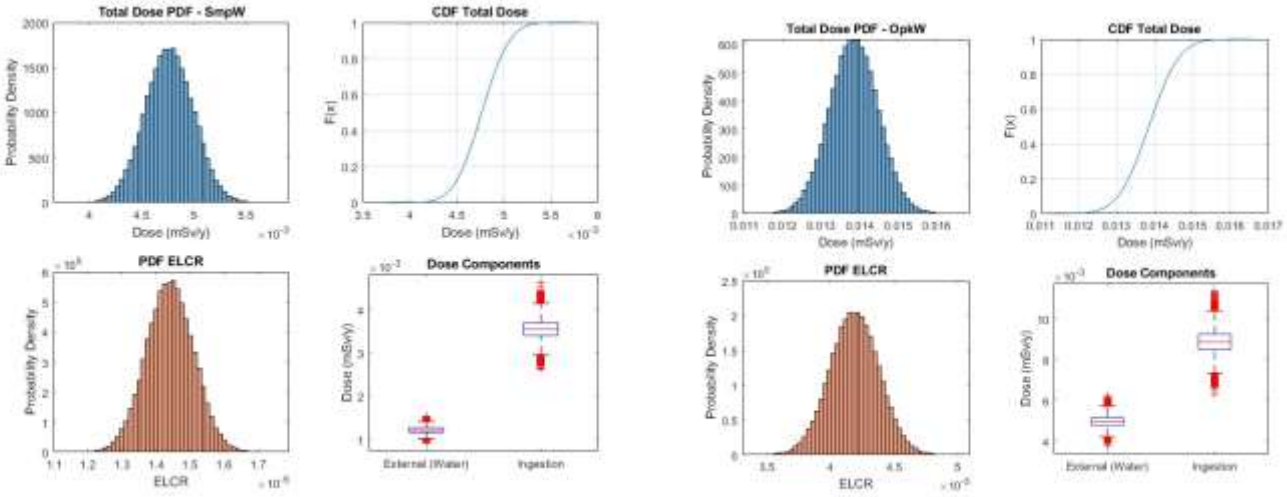
Table 1. Activity concentration of radionuclides in water samples taken from ten study locations in the Nun River.

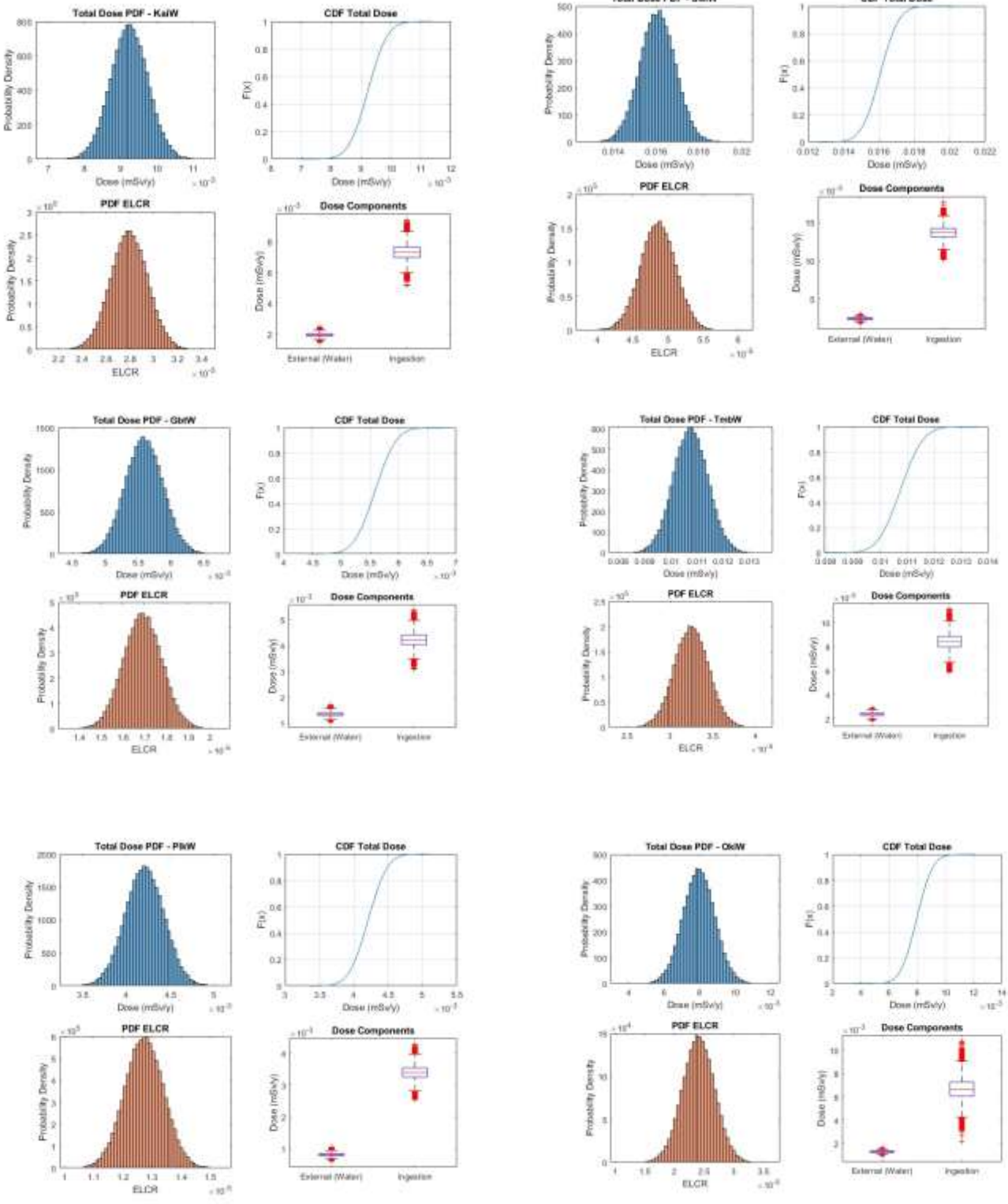
Town	Coordinate	SAMPLE CODE	^{40}K (Bq/l)	^{238}U (Bq/l)	^{232}Th (Bq/l)
Kaiama	E006.303883 N05.116939	KaiW	44.41 ± 2.74	4.54 ± 0.8	2.29 ± 0.15
Opokuma	E006.294129 N05.074453	OpkW	114.37 ± 6.49	2.41 ± 0.48	3.39 ± 0.23
Okoloba	E006.242516 N05.050800	OklW	29.67 ± 1.81	13.9 ± 1.99	0.18 ± 0.01
Polaku	E006.284448 N05.029851	PlkW	18.96 ± 1.14	1.24 ± 0.24	1.23 ± 0.08
Tombia	E006.263464 N05.000028	TmbW	54.07 ± 3.18	6.31 ± 1.17	2.42 ± 0.16
Gbarantoru	E006.273558 N05.000488	GbtW	31.23 ± 1.87	0.16 ± 0.03	1.81 ± 0.12
Swali	E006.264253 N04.917721	SwlW	55.22 ± 3.23	5.62 ± 0.9	4.84 ± 0.31
Ogu	E006.269500 N04.901989	OguW	29.37 ± 1.69	11.48 ± 1.81	0.81 ± 0.05
Sampou	E006.357945 N05.147935	SmpW	27.96 ± 1.68	1.4 ± 0.26	1.27 ± 0.08
Belelebiri	E006.260032 N04.951633	BlbW	21.83 ± 1.3	6.5 ± 1.14	2.76 ± 0.18
	Mean		42.71 ± 26.69	5.36 ± 4.26	2.10 ± 1.29
	WHO Guidance level			1	0.5

Table 2. External and Accidental Ingestion Dose Contributions with Associated Excess Lifetime Cancer Risk for Water Samples

SAMPLE CODE	AED_{ext} x10^{-6} (mSv/y)	E_{ing} x10^{-3} (mSv/y)	E_{total} x10^{-3} (mSv/y)	ELCR x10^{-3}
KaiW	1.9259	7.3100	7.3168	0.0221
OpkW	4.9595	8.8815	8.8936	0.0269
OklW	1.2868	6.6690	6.6707	0.0202
PlkW	0.8222	3.3870	3.3904	0.0103
TmbW	2.3448	8.4055	8.4130	0.0253
GbtW	1.3543	4.2350	4.2402	0.0128
SwlW	2.3947	13.661	13.6736	0.0413

OguW	1.2738	7.0290	7.0320	0.0213
SmpW	1.2125	3.5510	3.5549	0.0107
BlbW	0.9468	9.2730	9.2798	0.0281
Mean	1.8521	7.2402	7.2465	0.0219




Total Dose PDF - KaiW
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ELCR
External (Water)
Ingestion

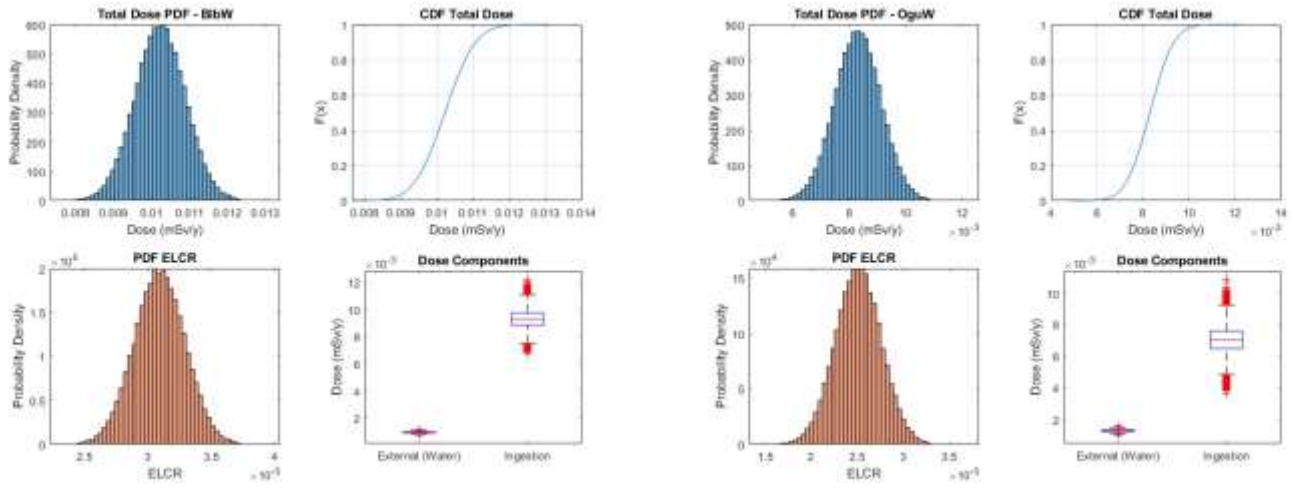
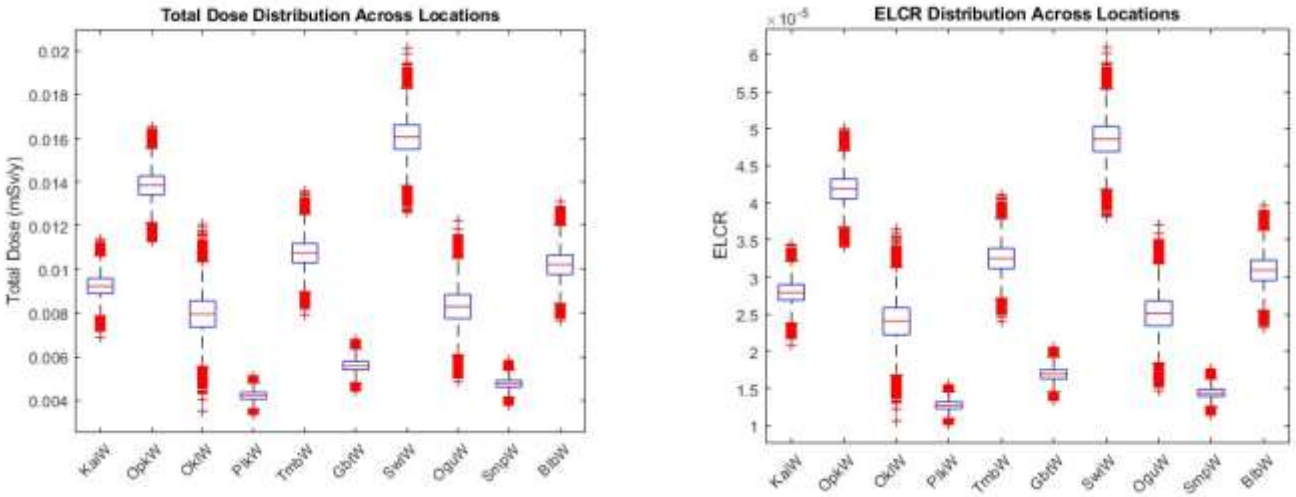


Figure 2: Plot of probability density function, cumulative density function Total dose and ELCR, and boxplot summary external and ingestion dose for river water samples.



(a) (c)

Figure 3 (a, b). Summary box plot of AED (external), Total dose and ELCR for river water Samples across locations

The probabilistic risk assessment performed for the Nun River represents a paradigm shift on the issue of radiological hazards in multi-use, industrially affected riverine systems. The Monte Carlo simulations (100,000 iterations) show that the most likely exposure route for the local population is incidental ingestion, not external water immersion, and with very high statistical certainty. The ingestion doses

(3.39×10^{-3} to 13.66×10^{-3} mSv/y) are roughly 10 times higher than the external water immersion doses (8.22×10^{-4} to 4.96×10^{-3} mSv/y) as seen in the summary table and the component box plots (Figure 2 and 3). This is a finding that is in line with the environment of the Nun River, where residents do not drink the water, but there are many opportunities for accidental ingestion due to swimming, washing and fishing. Immersion, on the other hand, is a very inefficient exposure pathway since water gives good protection against the low-energy gamma emissions of the ^{238}U and ^{232}Th decay series, and the physical geometry of immersion leads to a lower effective dose rate than direct internal intake.

Spatially, the results suggest that the distribution of risk is heterogeneous at a statistically significant level. The highest total doses (13.67×10^{-3}, 9.28×10^{-3}, and 8.89×10^{-3} mSv/y, respectively) are found in Swali (SwlW), Belelebiri (BlbW), and Opokuma (OpkW). The interquartile ranges of the summary box plots (Figures 3a, 3b and 3c) are very narrow and do not overlap with the interquartile ranges of the low-risk zones such as Polaku (PlkW) and Sampou (SmpW) to confirm that these locations are statistically different from the low-risk zones. In addition, the tight probability density functions (PDFs) and steep cumulative density functions (CDFs) validate the low parameter uncertainty, and indicate high confidence that the spatial differences are due to localized geogenic anomalies and anthropogenic activities, and not due to stochastic variance. The spatial variability is similar to the activity concentrations of ^{238}U and ^{232}Th. For example, Swali had the highest concentration of ^{232}Th (4.84 Bq/L), which is almost 10 times the WHO guidance level (0.5 Bq/L) and is directly related to its designation as a high risk zone.

The total annual effective doses at all locations are still well below the individual dose criterion of 0.1 mSv/y set by WHO (2022; 2006). Likewise, the calculated Excess Lifetime Cancer Risk (ELCR) values (1.03×10^{-5} at PlkW to 4.13×10^{-5} at SwlW) are within the range of acceptable risk (1×10^{-6} to 1×10^{-4}) established by the US EPA (2020) and Demissie et al (2024). This means that the likelihood of cancer in the population is very low and there is no immediate radiological epidemic. In spite of this regulatory compliance, the statistical certainty of ingestion dominance is very relevant. The results suggest that the water is not a statistically significant radiological risk from external contact, but rather from inadvertent ingestion of water containing radionuclides during domestic and occupational use. For long-term stochastic health effects, environmental management should focus on public health education on the potential health risks of incidental ingestion in the identified hotspots, and on ongoing monitoring of ^{238}U and ^{232}Th concentrations.

5.0 CONCLUSION

The present study was able to address the critical need in radiological risk assessment of characterizing the spatial distribution of ^{40}K, ^{238}U and ^{232}Th in the Nun River and assessing exposure from water immersion and incidental ingestion. The results indicate that the primary route of exposure for the local population is not external exposure from radiation, but rather incidental ingestion of water contaminated with radionuclides while swimming, fishing and at home. The statistically significant predominance of ingestion highlights a basic problem with using normal drinking-water guidelines for a population that doesn't drink water but is often exposed to it.

Spatially, the risk was very unevenly distributed, with concentrations of ^{232}Th and ^{238}U being significantly higher in Swali, Belelebiri and Opokuma. The probabilistic Monte Carlo simulations showed that all annual effective doses were well below the WHO criterion of 0.1 mSv/y and that Excess Lifetime Cancer Risks (ELCR) were in the acceptable range of the US EPA, but the certainty of the ingestion hazard cannot be disregarded. This study thus serves as a methodological model for other non-drinking water applications around the world. Environmental management in the Niger Delta should shift from external water column contamination to activities that encourage accidental swallowing and more stringent safety measures in dredging areas to reduce the stochastic risks in the long term.

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