



## Assessment of Natural Radioactivity, Radiological Hazards and Spatial Variability of Coastal Sediments in Akwa Ibom State, Nigeria

<sup>1,2</sup>Abai, Idoroenyin Jacob; <sup>2</sup>George, Nyakno Jimmy; <sup>2</sup>Ekanem, Aniekan Martin

### Abstract

The present research work investigated the concentrations of natural radionuclides ( $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$ ) and their associated radiological hazards in sediment samples taken from Etiza (Eastern Obolo (EO)), Okorotak (Ibeno), and Enwang (Mbo) regions of Niger Delta coastline, Nigeria. Gamma-ray spectrometry was employed to determine the concentration levels of twenty-nine sediment samples, whereas radiological hazard parameters, namely radium equivalent activity ( $Ra(eq)$ ), absorbed dose rate (D), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR), were calculated based on international guidelines. Various statistical methods including descriptive statistics, Shapiro – Wilk test of normality, Levene's test, one-way ANOVA, Kruskal-Wallis's test, and Tukey's HSD test were applied to analyze the spatial variations. The mean activity concentrations varied between 180.04 – 463.83  $\text{Bq kg}^{-1}$  for  $^{40}\text{K}$ , 3.67 – 8.43  $\text{Bq kg}^{-1}$  for  $^{238}\text{U}$  and 48.57-74.81  $\text{Bq kg}^{-1}$  for  $^{232}\text{Th}$ . The  $^{238}\text{U}$  levels were still lower than the world average level but the  $^{232}\text{Th}$  levels were found to be higher than the world reference value, which indicated that there was an enrichment of thorium due to geological reasons in the area. Significant spatial variation occurred only for  $^{40}\text{K}$  ( $p < 0.05$ ), with Ibeno showing higher levels. All the mean  $Ra_{eq}$  values (86.99-151.13  $\text{Bq kg}^{-1}$ ), absorbed dose rate (38.54-68.42  $\text{nGy h}^{-1}$ ), AEDE (0.059-0.10  $\text{mSv y}^{-1}$ ) and ELCR ( $0.16-0.29 \times 10^{-3}$ ) fell within internationally accepted safety guidelines. These results suggest that there is no threat to human health and provide useful baseline data for the Niger Delta coast. The calculated radiological indices were below internationally recommended safety limits, indicating that the sediments presently pose insignificant radiological risks to residents and aquatic ecosystems.

✉ Abai, Idoroenyin Jacob: [j.idoroenyin@gmail.com](mailto:j.idoroenyin@gmail.com)

<sup>1</sup>Nigerian Nuclear Regulatory Authority (NNRA)

<sup>2</sup>Department of Physics, Akwa Ibom State University, Nigeria

**Keywords:** Natural radioactivity, Activity concentration, Sediments, Radiological hazard, Niger Delta, Gamma spectrometry

### Article history

Received: April 19, 2026

Received in revised form: June 24, 2026

Accepted for publication: June 30, 2026

Available online: July 4, 2026

## 1.0 Introduction

River sediments serve as both sinks and secondary sources of radioactive materials and are known to be environmental reservoirs of naturally occurring radionuclides. Radionuclides released from rocks and soils are released through weathering and erosion processes, surface runoff, and sediment transport and end up in the riverine sediments. The fine-grained sediments also have a high adsorption capacity, particularly due to the large surface area that is present and the number of clay minerals, which can adsorb a significant amount of uranium, thorium, potassium and other trace elements (Walling & Foster, 2016). Therefore, the radionuclide concentrations in the sediments can be used to gain insight into the geology of a drainage basin, the effect of natural weathering processes and the effects of human activities in the catchment. Sediments have been used as a good tool to assess long-term environmental radioactivity because the concentrations of radionuclides in surface water can vary seasonally (Coutelot et al., 2023).

The granites, phosphates, heavy minerals sand, micas and feldspars with potassium-rich composition typically have high concentrations of uranium and thorium, and potassium rich feldspars and micas are the most abundant source of  $^{40}\text{K}$  (Abdallah et al., 2025; Hassan et al., 2025). Human activities can also alter the natural distribution of radionuclides through geological material perturbation or technologically enhanced naturally occurring radioactive material (TENORM), such as mining, oil and gas exploration, industrial discharges, dredging, agriculture and urban development. The processes can result to the mobility, redistribution and accumulation of radionuclides in aquatic sediments, which can change the radiologic characteristics of the environment (Li et al., 2024). In addition to the radiological indices used traditionally, the use of statistical analysis has

become more and more important in the studies of environmental radioactivity, as it allows the identification of spatial patterns, the establishment of relationships between radionuclides and the identification of possible contamination sources. Descriptive statistics are used to learn about the variation and distribution properties, and normality tests are used to decide which statistical method to use in further analysis. The correlation analysis shows the strength of the relationship between the radionuclides and the radiological parameters and can help to determine if they are derived from similar geological sources or from different environmental processes (Obianwu et al., 2011). Moreover, multivariate statistical methods like principal component analysis (PCA), hierarchical cluster analysis (HCA) and factor analysis have been useful to separate the natural from anthropogenic sources of radionuclide distribution. With the use of spatial interpolation methods, these methods can provide a detailed picture of environmental radioactivity beyond the mere concentration of radioactivity. A number of studies have been reported worldwide that demonstrated a significant spatial variation in the concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in river sediments. It was hypothesized that activity concentrations and radiological hazards differ significantly among the three coastal communities because of differences in geological formations and anthropogenic influences.

In certain instances, however, the presence of radionuclides in excess has been attributed to specific geologic environments, to large scale mining, industries or even to exploration for oil (Esi et al., 2024; Chetty & Ilori, 2024). The studies conducted on the environment of radioactivity in Nigeria have been conducted on soil, water, construction materials, and sediments in oil and gas fields (Omeje et al., 2024; Adebayo et al., 2026; Omeje et al., 2023). The spatial extent of these studies is still limited, however, and many

river systems still lack a comprehensive radiological characterization, despite the growing anthropogenic pressures. In addition, some previous studies have been conducted on the concentration of the radionuclides without conducting a comprehensive statistical analysis, thus limiting the knowledge of the factors that influence the distribution of radionuclides and their potential environmental impacts.

These limitations have been overcome in this study by measuring activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in sediment samples from the study area and assessing the radiological hazards based on internationally accepted assessment indices. The study not only quantifies radionuclide concentrations, but also uses the appropriate statistical methods to analyse data variability, to look for relationships between radionuclides and to gain insights into the possible factors controlling their distribution (Ndoma et al., 2024). The results will be integrated in the existing database of natural radioactivity in aquatic environments, will be used as baseline radiological data for future environmental monitoring and will provide scientific information for the environmental protection, sustainable resource management and public health policies in the study area and in similar riverine environments. Radiological assessment and statistical evaluation give a more comprehensive view of the radioactivity of sediments, and the risk it poses to environmental quality and human safety.

Existing studies on coastal radioactivity in Nigeria have largely focused on radionuclide concentrations and radiological indices, with limited emphasis on rigorous statistical evaluation of spatial variability. Moreover, radiological baseline data for several coastal communities in Akwa Ibom State remain scarce. This study addresses these gaps by combining gamma spectrometric measurements with statistical

analyses to characterize radionuclide distributions and evaluate radiological risks.

Although several investigations have reported natural radionuclides in Nigerian coastal environments, few have integrated radiological hazard assessment with rigorous statistical analyses to evaluate spatial variability and identify geological controls in Akwa Ibom coastal sediments.

## 2. Materials and methods

### 2.1 Study area

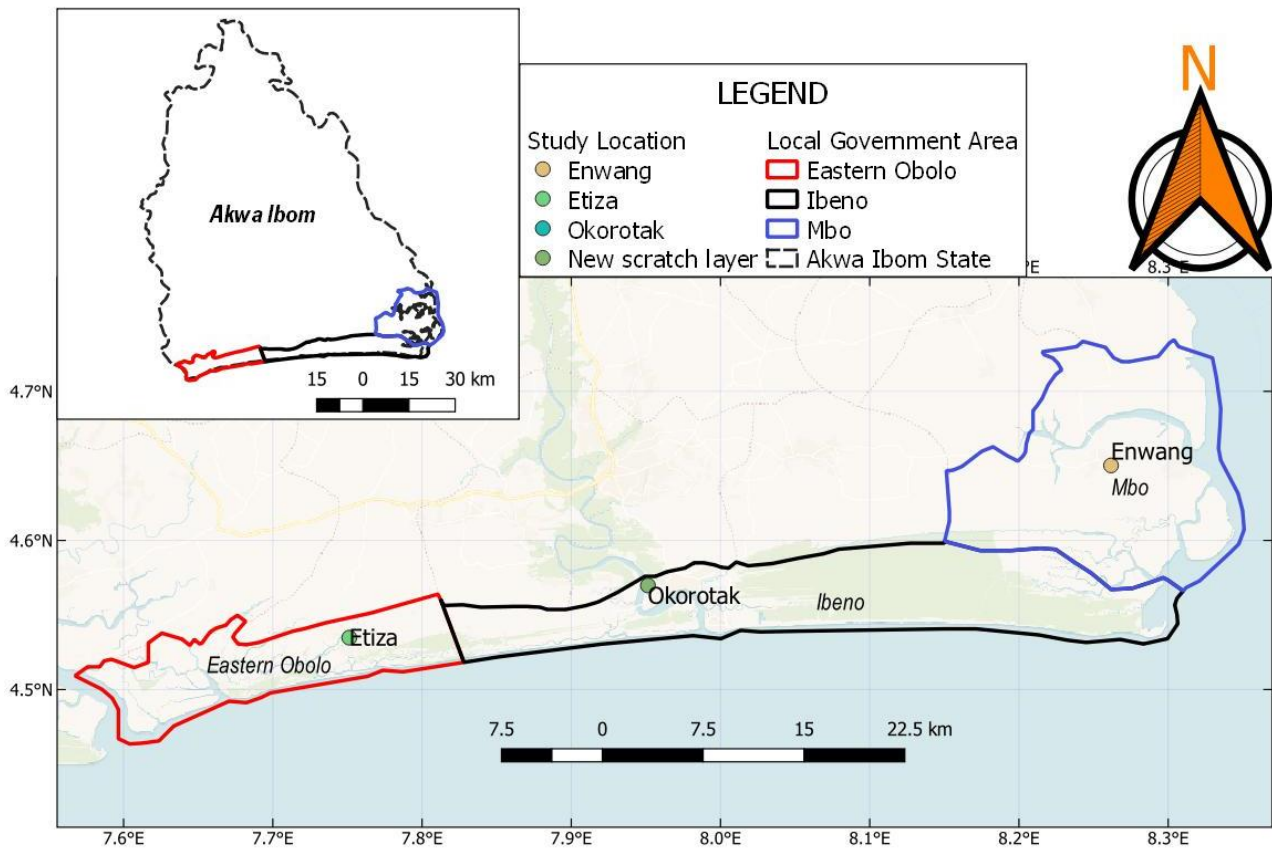
Three coastal settlements in the Nigerian state of Akwa Ibom were sampled. As shown in Figure 1, these settlements include Etiza in the Eastern Obolo Local Government Area (LGA) ( $4^{\circ}32'05.71\text{N}$ ,  $7^{\circ}45'04.26\text{E}$ ), Enwang in Mbo LGA ( $4^{\circ}39'01.44\text{N}$ ,  $8^{\circ}15'41.08\text{E}$ ), and Okorotak in Ibeno LGA ( $4^{\circ}34'37.45\text{N}$ ,  $7^{\circ}55'51.29\text{E}$ ). Because of their close vicinity to the Atlantic Ocean, all of the areas are part of the Niger Delta Coastal environment, which is made up of mangrove swamps, estuaries, and strong hydro-dynamism (Figure 1). From an ecological perspective, this specific ecosystem is vulnerable to the effects of environmental contamination brought on by prolonged petroleum exploration and production (UNSCEAR, 2000; Naser, 2013).

Furthermore, fishing communities along the mouth of the Imo River estuary are well-known in Eastern Obolo LGA. Fishing is the dominant economic activity, which provides for both commercial and subsistence operations. However, the area in Fig. 1 now faces some environmental risks as a result of offshore oil drilling, including as oil spills and radionuclide pollution from released produced water (IAEA, 2010). Enwang is another community that acts as Mbo LGA's administrative hub. Enwang is situated close to offshore oil installations, much as the preceding hamlet. With significant offshore oil installations situated here, Ibeno and Okorotak combined make

up one of Nigeria's biggest oil-producing coastal districts. This region has a sizable fishing population, and seafood is a vital source of sustenance.

The study area is located within the coastal sedimentary environment of Akwa Ibom State, southern Nigeria, a region that forms part of the eastern sector of the Niger Delta Basin (George et al., 2010). The Niger Delta is one of the world's

largest regressive deltaic systems, developed through prolonged sediment accumulation from the Niger and Benue River systems during the Tertiary to Recent periods (Uwa et al., 2019; Ekanem et al., 2021; Ekanem, 2022). The coastal zone is characterized by low-lying terrain, tidal flats, estuaries, beaches, mangrove swamps and extensive wetlands, all of which influence sediment deposition, redistribution and geochemical characteristics (George et al., 2025).



**Figure 1:** Map of the study area in Akwa Ibom State showing the study communities and their corresponding river

Geologically, the area is underlain predominantly by the Benin Formation (Coastal Plain Sands) of Miocene to Recent age (Udosen et al., 2024 a, b, c). The formation consists mainly of unconsolidated to poorly consolidated coarse- to medium-grained sands, gravelly sands, pebbles, clay lenses, silts and occasional lateritic horizons (George et al., 2020; Umoh et al., 2025). Toward

the coastline, these sediments grade into recent alluvial and marine deposits composed of beach sands, muds, silty clays and organic-rich sediments deposited under the influence of tidal currents, wave action and estuarine processes (George et al., 2022a, b; George & Thomas, 2024). The continuous interaction between marine and fluvial environments has resulted in complex

sedimentary facies with significant lateral and vertical variations in grain size, mineral composition and organic matter content.

The mineralogical composition of the coastal sediments is dominated by quartz, which constitutes the major framework mineral due to its resistance to weathering and transportation. However, accessory heavy minerals such as zircon, monazite, ilmenite, rutile, tourmaline, garnet and magnetite occur in varying proportions (Ndoma, et al., 2025a). These heavy minerals are particularly important because they serve as natural hosts for radioactive elements, especially uranium (U) and thorium (Th). Monazite is generally enriched in thorium and contains appreciable uranium, whereas zircon commonly incorporates uranium into its crystal lattice during crystallization. Potassium-bearing minerals, including feldspars, micas and clay minerals, contribute significantly to the occurrence of the naturally occurring radionuclide potassium-40 ( $^{40}\text{K}$ ) within the sediments.

The spatial distribution of  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  in the study area is therefore strongly controlled by the geological origin, mineralogical composition and depositional history of the sediments (Okon et al., 2025). Areas enriched with feldspathic materials and clay minerals generally exhibit elevated  $^{40}\text{K}$  concentrations because potassium readily substitutes within the crystal structures of feldspars and micas. Conversely, zones containing higher concentrations of heavy minerals such as monazite and zircon often show relatively increased activities of uranium and thorium. These minerals tend to accumulate in coastal environments through hydraulic sorting, where wave and current actions selectively concentrate dense mineral grains along beaches and nearshore sediments.

Weathering processes occurring within the drainage basin also influence radionuclide

distribution. The tropical climate of Akwa Ibom State promotes intense chemical weathering of crystalline rocks in the hinterland, releasing potassium, uranium and thorium-bearing minerals into river systems. These sediments are subsequently transported downstream and deposited within the coastal environment. During transport, hydraulic sorting, sediment reworking and grain-size segregation modify the concentration and distribution of radioactive minerals. Fine-grained sediments rich in clay and organic matter frequently adsorb dissolved uranium because uranium is relatively mobile under oxidizing conditions but becomes immobilized when reducing environments prevail (Ndoma, et al., 2025b). Thorium, on the other hand, is considerably less soluble and remains closely associated with resistant heavy mineral fractions throughout weathering and sediment transport.

The geological setting also reflects the influence of active coastal processes, including erosion, longshore drift, tidal flushing and periodic flooding (George et al., 2024). These processes continuously redistribute sediments, producing localized zones of radionuclide enrichment or depletion. Consequently, the measured radioactivity levels may exhibit considerable spatial variability even within relatively short distances. Such variations are often linked to differences in sediment texture, heavy mineral concentration, depositional environment and the relative contributions of terrestrial and marine sediment sources.

From a radiological perspective, the geology of the study area provides the fundamental basis for interpreting the occurrence of naturally occurring radioactive materials (NORM). The measured activity concentrations of  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  are primarily of geogenic origin, reflecting the abundance of potassium-bearing silicate minerals and uranium- and thorium-bearing accessory

minerals inherited from the parent geological materials (Inim et al., 2020). Therefore, understanding the geological evolution, sediment provenance and mineralogical composition of the coastal deposits is essential for accurately assessing natural radioactivity levels, evaluating radiological hazards and explaining the spatial variability observed across the coastal sediments of Akwa Ibom State.

In all, the coastal geology of Akwa Ibom State represents a dynamic sedimentary system in which fluvial deposition, marine reworking, mineral sorting and tropical weathering collectively govern the occurrence and distribution of naturally occurring radionuclides. This geological framework provides a sound scientific basis for interpreting variations in  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  activity concentrations and for assessing the associated radiological risks to both the environment and the coastal communities.

## 2.2 Sediment Sample Collection

Twenty-nine (29) sediment samples were collected from the sampling sites which were strategically located throughout the study area for good spatial coverage. The top 0-10cm of surface sediments was sampled using a stainless-steel grab sampler because this is the most recent layer of sediment and most likely to have been deposited and/or contain radionuclides. About 1–2 kg of sediment was collected from each site and placed in clean polyethylene bags with an individual identification number. All sampling was done without cross contamination. The samples were moved to the lab to prepare and radiometrically analyze.

## 2.3 Sample Preparation

Samples were air dried in the laboratory and then dried in an oven at approximately 105 °C until a constant weight was obtained, to remove moisture from the sediment. Coarse particles were removed by gently crushing the dried samples and sieving

them through a 2 mm mesh, to ensure homogeneous material for analysis. About 500 g of each homogenized sample was placed in a standard Marinelli beaker (or other calibrated counting container) and tightly covered to prevent the loss of radon gas. The sealed samples were kept for at least 28 days to ensure secular equilibrium between the parent elements,  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and their short-lived decay products prior to gamma spectrometric analysis.

## 2.4 Gamma Spectrometric Analysis

The activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  were measured using a calibrated gamma-ray spectrometry system with a sodium iodide activated with thallium [NaI (TI)] detector. The detector was housed in a lead shield to reduce the background radiation and to increase the counting accuracy. The detector was calibrated prior to measurement of the samples for energy and efficiency using certified standard reference materials of known radionuclide activity. Appropriate counting periods (usually 36,000 s or 10 hours) were used for each sample to obtain statistically reliable gamma spectra. The detector's spectral analysis software was used to identify and analyze the photopeaks of the radionuclides in the uranium and thorium decay series and the 1460.8 keV gamma emission of  $^{40}\text{K}$ . The activity concentration ( $A$ ) of each radionuclide was calculated using:

$$A = \frac{N}{\varepsilon P_{\gamma} t m} \quad (1)$$

where  $A$  = activity concentration ( $\text{Bq kg}^{-1}$ ),  $N$  = net count rate under the photopeak,  $\varepsilon$  = detector efficiency,  $P_{\gamma}$  = gamma emission probability,  $t$  = counting time (s) and  $m$  = sample mass (kg). Radiological hazard indices were computed from the measured activity concentrations of radionuclides using standard models recommended by international bodies (UNSCEAR, 2000; ICRP, 2007). These indices

provide quantitative measures of potential radiation exposure and associated health risks.

#### **Absorbed Dose Rate ( $D$ , $nGy/h^{-1}$ )**

The absorbed gamma dose rate in air at 1 m above ground level was calculated using (Darko et al., 2015):

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (2)$$

where  $A_{Ra}$ ,  $A_{Th}$ , and  $A_K$  represent the activity concentrations of  $^{226}Ra$ ,  $^{232}Th$ , and  $^{40}K$ , respectively.

#### **Annual Effective Dose Equivalent (AEDE, $mSv y^{-1}$ )**

The annual effective dose equivalent was estimated using occupancy factors and a dose conversion coefficient (AL-abrdi, 2023; Ahmadu, 2025):

$$AEDE = D \times 8760 \times OF \times 0.7 \times 10^{-6} \quad (3)$$

where  $OF$  represents the occupancy factor (0.25 for outdoor exposure and 0.75 for indoor exposure). The 0.25 (outdoor) and 0.75 (indoor) factors follow standard recommendations by the UNSCEAR for global comparability and capture villagers who spend more time indoors unlike fishermen. However, they may underestimate exposure for fishermen, who spend more time outdoors.

#### **Excess Lifetime Cancer Risk (ELCR $\times 10^{-3}$ )**

The excess lifetime cancer risk was determined as:

$$ELCR = AEDE \times 55 \times 0.05 \quad (4)$$

where 55 years represents the average lifespan and  $0.05 Sv^{-1}$  is the risk factor (ICRP, 2007).

#### **Radium Equivalent Activity ( $Raeq$ , $Bq/kg^{-1}$ )**

The radium equivalent activity was calculated as:

$$Raeq = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (5)$$

This index provides a single parameter for comparing the radiological hazard of different samples (Beretka & Mathew, 1985).

## **2.5 Statistical Analysis**

The statistical analyses were conducted in MATLAB R2024b (MathWorks Inc., Natick, MA, USA), assuming the level of significance as  $p < 0.05$ . The descriptive statistics like the mean, median, minimum, maximum, standard deviation, variance, coefficient of variation, skewness, and kurtosis were calculated in order to describe the distribution and dispersion of the activity concentrations of  $^{238}U$ ,  $^{232}Th$ , and  $^{40}K$ . The normality of data was tested using the Shapiro-Wilk test whereas Levene's test was used to check the equality of variances. In case both the assumptions of normality and equal variance were met, the difference in the means was analyzed using the one-way ANOVA, which was further followed by Tukey's HSD post hoc test. Otherwise, Kruskal-Wallis's test was conducted on the medians of activity concentration of different radionuclides. A quality assurance and quality control (QA/QC) process was established for the entire process. Calibration of the gamma spectrometer was done using standard reference material, and the background radiation was estimated and deducted from the sample spectrum. Repeat measurements and duplicate determinations were performed to confirm the precision of the analysis, and routine instrument performance checks were done to ensure the accuracy of the radionuclide activities.

## **3.0 Results and discussion**

Table 1 presents the activity concentrations of the naturally occurring radionuclides  $^{40}K$ ,  $^{238}U$  and  $^{232}Th$  together with the associated radiological hazard indices in sediment samples collected from Etiza, Eastern Obolo. The measured values demonstrate considerable spatial variability, reflecting differences in sediment composition, mineralogical characteristics and depositional processes across the sampling locations.

The activity concentration of  $^{40}K$  varied from 84.83 to 384.34  $Bq kg^{-1}$ , with a mean value of

180.04 Bq kg<sup>-1</sup>. This mean is substantially lower than the WHO (2023) global reference value of 400 Bq kg<sup>-1</sup>, suggesting that potassium-bearing minerals contribute only moderately to the natural radioactivity of the sediments. The relatively elevated concentration recorded at sample EO9 (384.34 Bq kg<sup>-1</sup>) approaches the global average and may reflect localized enrichment of feldspars, micas or clay minerals derived from weathered basement rocks transported into the coastal environment.

The activity concentration of <sup>238</sup>U ranged between 2.41 and 14.78 Bq kg<sup>-1</sup>, while three sampling points (EO5, EO6 and EO8) recorded concentrations below the detector's minimum detectable activity. Excluding these non-detectable values, the average uranium concentration was 3.67 Bq kg<sup>-1</sup>, which is nearly one order of magnitude lower than the world average of 35 Bq kg<sup>-1</sup>. This low uranium content indicates that uranium-bearing minerals are generally scarce within the study area and suggests minimal contribution from uranium-rich geological formations or anthropogenic contamination.

In contrast, <sup>232</sup>Th exhibited relatively higher concentrations, ranging from 12.55 to 110.26 Bq kg<sup>-1</sup>, with an average of 48.57 Bq kg<sup>-1</sup>. Unlike potassium and uranium, thorium exceeded the recommended global average (30 Bq kg<sup>-1</sup>) at several sampling locations, particularly EO3, EO5, EO6, EO8 and EO9. Thorium enrichment is often associated with heavy mineral assemblages such as monazite, zircon and ilmenite, which are commonly concentrated within coastal sediments through hydraulic sorting and long-term sedimentary reworking. This observation suggests that thorium is the dominant contributor to natural radioactivity within the Etiza sediments.

The calculated absorbed dose rate (D) ranged from 17.51 to 76.83 nGy h<sup>-1</sup>, with a mean value of 38.54

nGy h<sup>-1</sup>, which remains well below the global average value of 59 nGy h<sup>-1</sup>. Although EO6 produced a dose rate exceeding the world average, most sampling points recorded relatively low external gamma dose rates, indicating limited radiological exposure from natural sources (Ekong et., 2021).

Similarly, the Annual Effective Dose Equivalent (AEDE) varied between 0.03 and 0.12 mSv y<sup>-1</sup>, averaging 0.059 mSv y<sup>-1</sup>, far below the internationally accepted public exposure limit of 1.0 mSv y<sup>-1</sup>. These values indicate that the radiation dose received by individuals from sediment exposure is negligible and unlikely to constitute a significant health concern.

The Excess Lifetime Cancer Risk (ELCR) ranged from  $0.07 \times 10^{-3}$  to  $0.32 \times 10^{-3}$ , with an average value of  $0.16 \times 10^{-3}$ . This average is considerably lower than the reference value of  $0.29 \times 10^{-3}$ , implying that the probability of developing cancer due to prolonged exposure to radiation from these sediments remains very low.

The radium equivalent activity (Raeq), which integrates the radiological contributions of <sup>226</sup>Ra (represented by <sup>238</sup>U), <sup>232</sup>Th and <sup>40</sup>K into a single hazard parameter, ranged between 37.88 and 176.57 Bq kg<sup>-1</sup>, with an average of 86.99 Bq kg<sup>-1</sup>. This value is substantially lower than the internationally accepted safety limit of 370 Bq kg<sup>-1</sup>, confirming that the combined radionuclide content does not pose significant external radiation hazards.

In all, the results indicate that sediments from Etiza possess relatively low natural radioactivity. Although localized thorium enrichment occurs at several sampling points, all radiological hazard indices remain within internationally accepted safety limits, suggesting that the sediments present minimal radiological risk to the surrounding population and ecosystem.

**Table 1:** Activity concentration data of radionuclide and corresponding health risks in sediments from Etiza, Eastern Obolo

Sample Code	K-40 (Bq/Kg)	U-238 (Bq/Kg)	Th-232 (Bq/Kg)	D (nGy/h)	AEDE (mSv/y)	ELCR x 10 <sup>-3</sup>	Raeq Bq/Kg
EO1	199.97	9.53	12.55	20.32	0.03	0.09	42.87
EO2	149.31	3.53	15.98	17.51	0.03	0.07	37.88
EO3	84.83	3.66	63.51	43.59	0.07	0.18	101.01
EO4	263.54	2.41	38.88	35.59	0.05	0.15	78.30
EO5	120.56	NA	58.58	40.41	0.06	0.17	93.05
EO6	245.37	NA	110.26	76.83	0.12	0.32	176.57
EO7	141.11	2.80	34.91	28.26	0.04	0.12	63.59
EO8	211.35	NA	82.30	58.52	0.09	0.25	133.96
EO9	384.34	14.78	68.77	64.39	0.10	0.27	142.72
Mean	180.038	3.671	48.574	38.54	0.059	0.16	86.99
<b>World average WHO, 2023</b>	400	35	30	59.00	1.00	0.29	370.00

NA = bdl below detection limit and excluded from statistical analysis

Table 2 summarizes the radionuclide concentrations and radiological hazard parameters determined for sediment samples collected from Okorotak in Ibeno Local Government Area. Compared with Etiza, the results indicate slightly higher levels of natural radioactivity, particularly for thorium, resulting in correspondingly higher radiological hazard indices.

The measured <sup>40</sup>K concentrations ranged from 32.83 to 458.73 Bq kg<sup>-1</sup>, with a mean value of 248.96 Bq kg<sup>-1</sup>. Although sample MB3 exceeded the global average of 400 Bq kg<sup>-1</sup>, the overall mean remained substantially below the reference value. The exceptionally low concentration recorded at MB6 (32.83 Bq kg<sup>-1</sup>) suggests considerable heterogeneity in sediment mineral composition, reflecting differences in sediment source materials and depositional conditions.

The <sup>238</sup>U concentrations varied from 0.31 to 20.19 Bq kg<sup>-1</sup>, with an average of 4.82 Bq kg<sup>-1</sup>, remaining significantly below the global average

of 35 Bq kg<sup>-1</sup>. The consistently low uranium concentrations indicate that uranium contributes only minimally to the overall radiation budget of the sediments. Thorium again emerged as the dominant radionuclide. The activity concentration of <sup>232</sup>Th ranged from 13.36 to 129.12 Bq kg<sup>-1</sup>, averaging 57.78 Bq kg<sup>-1</sup>, nearly twice the recommended world average. Particularly high concentrations observed at MB4, MB6 and MB10 indicate localized accumulation of thorium-rich heavy minerals. Such enrichment is consistent with the geomorphological characteristics of coastal environments where wave action, tidal currents and longshore drift selectively concentrate dense resistant minerals. The absorbed dose rate varied between 18.42 and 94.42 nGy h<sup>-1</sup>, with a mean value of 47.50 nGy h<sup>-1</sup>, remaining below the global average of 59 nGy h<sup>-1</sup>. Nevertheless, individual locations such as MB3 and MB4 exceeded this benchmark, demonstrating that localized mineralogical enrichment significantly influences external gamma radiation.

**Table 2:** Activity concentration data of radionuclide and corresponding health risks in sediments from Okorotak, Ibeno

Sample Code	K-40 (Bq/Kg)	U-238 (Bq/Kg)	Th-232 (Bq/Kg)	D (nGy/h)	AEDE (mSv/y)	ELCR x 10 <sup>-3</sup>	Raeq Bq/Kg
MB1	243.17	7.43	47.45	42.23	0.06	0.18	94.01
MB2	278.63	1.30	40.82	36.87	0.06	0.16	81.13
MB3	458.73	7.24	72.88	66.49	0.10	0.28	146.78
MB4	170.46	20.19	129.12	94.42	0.14	0.40	217.96
MB5	226.97	1.91	13.36	18.42	0.03	0.08	38.49
MB6	32.83	1.48	72.53	45.86	0.07	0.19	107.73
MB7	329.45	2.53	52.59	46.67	0.07	0.20	103.10
MB8	200.10	2.93	39.58	33.60	0.05	0.14	74.94
MB9	285.26	2.83	34.14	33.82	0.05	0.14	73.62
MB10	264.03	0.31	75.28	56.62	0.09	0.24	128.29
Mean	248.963	4.815	57.775	47.50239	0.072821	0.20	106.60
<b>World average WHO, 2023</b>	400	35	30	59.00	1.00	0.29	370.00

NA = bdl below detection limit and excluded from statistical analysis

The calculated AEDE ranged from 0.03 to 0.14 mSv y<sup>-1</sup>, with an average of 0.073 mSv y<sup>-1</sup>, which remains far below the recommended public exposure limit of 1.0 mSv y<sup>-1</sup>. Consequently, routine exposure to these sediments is unlikely to produce adverse health effects.

The ELCR ranged from 0.08 × 10<sup>-3</sup> to 0.40 × 10<sup>-3</sup>, with a mean value of 0.20 × 10<sup>-3</sup>. Although MB4 recorded the highest cancer risk within this location, the overall average remains below the global reference value, indicating a low lifetime probability of radiation-induced cancer.

Similarly, the calculated Raeq values ranged between 38.49 and 217.96 Bq kg<sup>-1</sup>, with an average of 106.60 Bq kg<sup>-1</sup>, well below the permissible limit of 370 Bq kg<sup>-1</sup>. This confirms that the combined radioactivity from naturally occurring radionuclides does not constitute significant external radiation hazards. In totality, the sediments from Okorotak exhibit moderate natural radioactivity characterized by elevated

thorium concentrations but low uranium levels. Despite localized increases in dose rate and thorium activity, all calculated radiological hazard indices remain within internationally accepted safety limits, indicating that the sediments are radiologically safe for both environmental and human exposure. Table 3 presents the radionuclide distribution and associated radiological hazard indices for sediments collected from Enwang in Mbo Local Government Area. Among the three investigated coastal locations, Enwang exhibits the highest levels of natural radioactivity, reflecting pronounced geological and mineralogical enrichment.

The activity concentration of <sup>40</sup>K ranged from 275.75 to 793.42 Bq kg<sup>-1</sup>, with an average value of 463.83 Bq kg<sup>-1</sup>, exceeding the global average of 400 Bq kg<sup>-1</sup>. More than half of the sampling locations recorded concentrations above the recommended reference value, suggesting widespread abundance of potassium-rich silicate

minerals within the sediments. Such enrichment may be attributed to intense weathering of crystalline rocks and efficient transport of feldspar-rich sediments into the coastal depositional environment. The measured  $^{238}\text{U}$  concentrations varied between 1.92 and 18.32 Bq  $\text{kg}^{-1}$ , while one sample (IB1) was below the

detection limit. The average uranium concentration of 8.43 Bq  $\text{kg}^{-1}$  remained substantially below the global average of 35 Bq  $\text{kg}^{-1}$ , indicating that uranium continues to play a relatively minor role in the overall natural radioactivity despite the elevated potassium levels.

**Table 3:** Activity concentration data of radionuclide and corresponding health risks in sediments from Enwang, Mbo

Sample Code	K-40 (Bq/Kg)	U-238 (Bq/Kg)	Th-232 (Bq/Kg)	D (nGy/h)	AEDE (mSv/y)	ELCR $\times 10^{-3}$	Raeq Bq/Kg
IB1	793.42	NA	102.49	94.99	0.15	0.40	207.65
IB2	351.61	4.36	76.93	63.14	0.10	0.27	141.44
IB3	432.87	6.96	43.43	47.50	0.07	0.20	102.40
IB4	506.05	18.32	62.11	67.08	0.10	0.28	146.10
IB5	613.08	8.42	49.61	59.42	0.09	0.25	126.57
IB6	275.75	17.31	121.70	93.00	0.14	0.39	212.57
IB7	379.11	1.92	98.12	75.96	0.12	0.32	171.42
IB8	366.75	8.45	83.48	69.62	0.11	0.29	156.07
IB9	406.59	6.68	45.88	47.75	0.07	0.20	103.60
IB10	513.06	11.88	64.39	65.77	0.10	0.28	143.46
Mean	463.83	8.43	74.81	68.42	0.10	0.29	151.13
<b>World average WHO, 2023</b>	400	35	30	59.00	1.00	0.29	370.00

NA = bdl below detection limit and excluded from statistical analysis

Thorium concentrations ranged from 43.43 to 121.70 Bq  $\text{kg}^{-1}$ , with an average value of 74.81 Bq  $\text{kg}^{-1}$ , more than twice the global reference value. Every sampling location exceeded the recommended background level, demonstrating widespread thorium enrichment throughout the study area. The consistently elevated thorium concentrations strongly suggest the accumulation of thorium-bearing heavy minerals such as monazite and zircon, which commonly occur within coastal placer deposits.

The absorbed dose rate ranged from 47.50 to 94.99 nGy  $\text{h}^{-1}$ , averaging 68.42 nGy  $\text{h}^{-1}$ , which exceeds the global average of 59 nGy  $\text{h}^{-1}$ . This increase

directly reflects the elevated concentrations of potassium and thorium observed across the sampling sites. Nevertheless, the measured dose rates remain within ranges commonly reported for naturally mineralized coastal environments.

The corresponding AEDE varied from 0.07 to 0.15 mSv  $\text{y}^{-1}$ , with an average of 0.10 mSv  $\text{y}^{-1}$ , which is still considerably lower than the annual public dose limit of 1.0 mSv  $\text{y}^{-1}$ . Although exposure is higher than in Etiza and Okorotak, the effective dose remains within internationally accepted safety margins. The ELCR values ranged between  $0.20 \times 10^{-3}$  and  $0.40 \times 10^{-3}$ , with an

average of  $0.29 \times 10^{-3}$ . This mean value closely matches the recommended global reference value, indicating that Enwang represents the location with the greatest long-term radiological significance among the three study areas. While the estimated cancer risk remains within acceptable limits, continued environmental monitoring is advisable because prolonged accumulation of naturally occurring radioactive materials could gradually alter exposure conditions. The Raeq values ranged from 102.40 to 212.57 Bq kg<sup>-1</sup>, averaging 151.13 Bq kg<sup>-1</sup>. Despite being the highest among the three coastal locations, the mean value remains substantially below the recommended safety limit of 370 Bq kg<sup>-1</sup>, confirming that the combined radioactivity of the sediments does not present significant external gamma radiation hazards.

Generally, Enwang sediments display the greatest natural radioactivity within the study area, primarily due to widespread enrichment of <sup>40</sup>K and <sup>232</sup>Th. This spatial pattern likely reflects variations in sediment provenance, hydrodynamic sorting and heavy mineral accumulation associated with coastal depositional processes. Although the radiological parameters are consistently higher than those observed in Etiza and Okorotak, all hazard indices remain below internationally accepted intervention thresholds. Consequently, the sediments are considered radiologically safe for present environmental conditions, while the relatively elevated thorium and potassium contents justify periodic environmental surveillance to detect any future changes associated with coastal dynamics or anthropogenic activities.

A comparison of the three study locations reveals a clear spatial gradient in natural radioactivity. Etiza (Eastern Obolo) recorded the lowest radionuclide concentrations and hazard indices, Okorotak (Ibena) exhibited intermediate values, while Enwang (Mbo) consistently showed the

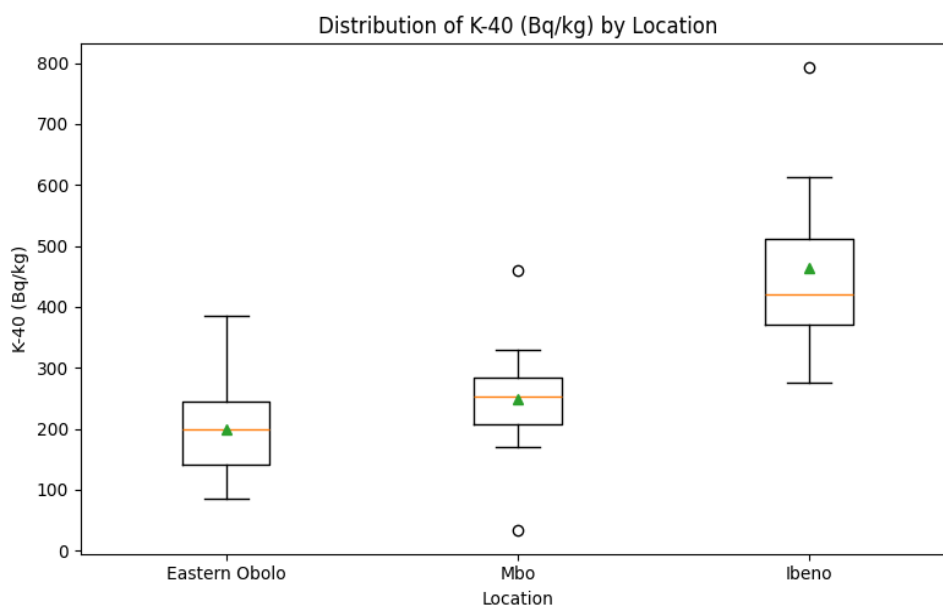
highest levels of radioactivity and radiological hazards. Across all three locations, <sup>232</sup>Th was the principal contributor to the external gamma dose and radiological hazard, whereas <sup>238</sup>U remained consistently low. The elevated thorium concentrations are characteristic of coastal environments where hydraulic sorting concentrates heavy minerals enriched in thorium.

Despite these spatial differences, the average values of Raeq, AEDE, and ELCR remained below internationally accepted safety limits in all locations. The only parameter that exceeded the global background average in Enwang was the absorbed dose rate, yet the corresponding annual effective dose remained well within permissible exposure limits. These findings demonstrate that the coastal sediments of Akwa Ibom State exhibit natural geological variability without posing significant radiological health risks. The observed spatial variability is therefore interpreted as a consequence of natural sediment provenance, mineralogical composition, coastal sediment transport and depositional processes rather than anthropogenic radioactive contamination.

Figure 2 illustrates the spatial distribution of potassium-40 (K-40) concentrations in sediment samples collected from Eastern Obolo, Mbo, and Ibena. The box plot reveals noticeable differences in the concentration levels among the three coastal environments. Ibena exhibits the highest median and mean K-40 concentrations, followed by Mbo and Eastern Obolo. The elevated K-40 values observed in Ibena suggest a greater abundance of potassium-bearing minerals within the sediment matrix, possibly resulting from differences in sediment provenance, mineralogical composition, and hydrodynamic sorting processes along the coastline. The relatively wider interquartile range observed in Ibena indicates greater heterogeneity in sediment composition and radionuclide accumulation. Mbo displays moderate variability

with the presence of both low and high outliers, suggesting localized enrichment and depletion processes. In contrast, Eastern Obolo exhibits

comparatively lower concentrations and a narrower spread, indicating a more uniform distribution of K-40 within the sediments.

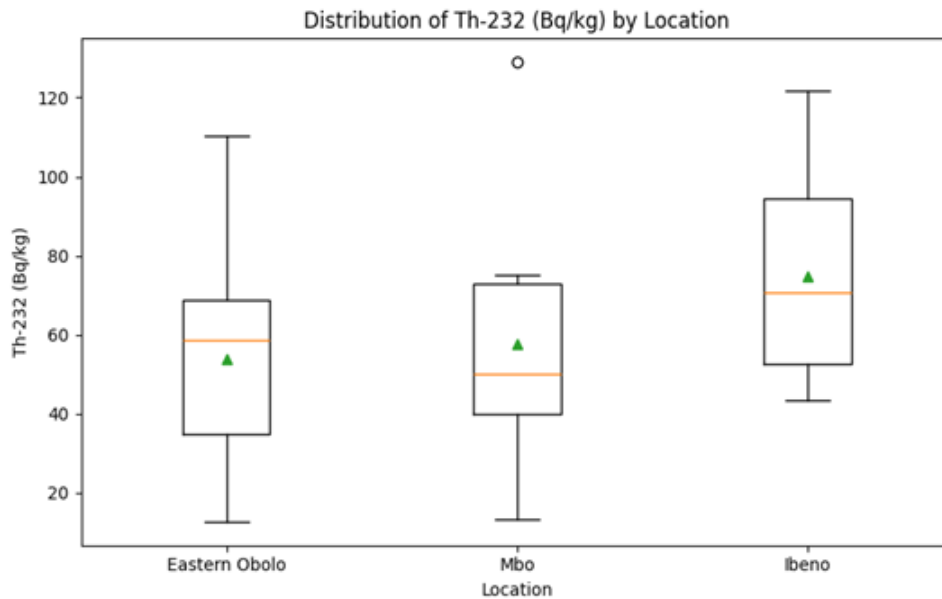


**Figure 2:** Box plot of the distribution of potassium-40 (K-40) concentrations in sediment samples across Eastern Obolo, Mbo, and Ibena

The occurrence of outliers in Mbo and Ibena may reflect localized geological inputs, anthropogenic influences, or variations in sediment transport and deposition mechanisms. Since K-40 is a naturally occurring radionuclide associated with feldspars, micas, and clay minerals, the higher concentrations observed in Ibena may be linked to increased weathering and deposition of potassium-rich sediments. Overall, the figure demonstrates significant spatial variability in K-40 distribution across the study area, emphasizing the influence of local geological and environmental factors on radionuclide accumulation. Figure 3 presents the distribution of thorium-232 (Th-232) concentrations across the three coastal locations. The results indicate that Ibena possesses the highest median concentration of Th-232, while Eastern Obolo and Mbo show comparatively lower values. Thorium is generally associated with resistant heavy minerals such as monazite, zircon, and thorite, which tend to accumulate in coastal environments through

sedimentary sorting and concentration processes. The box plot reveals substantial variability in Th-232 concentrations within each location. The wider distribution observed in Ibena suggests more pronounced fluctuations in thorium-bearing mineral content. Mbo displays a notable outlier with exceptionally high Th-232 concentration, indicating localized enrichment zones possibly associated with heavy mineral deposits or concentrated sediment inputs from adjacent drainage systems.

The relatively high thorium concentrations recorded in Ibena may reflect the preferential accumulation of heavy mineral sands within this coastal environment. Such enrichment is common in shoreline areas where wave action and longshore drift selectively concentrate dense mineral fractions. The observed variability further highlights the dynamic nature of sediment transport and depositional processes operating along the Akwa Ibom coastline.



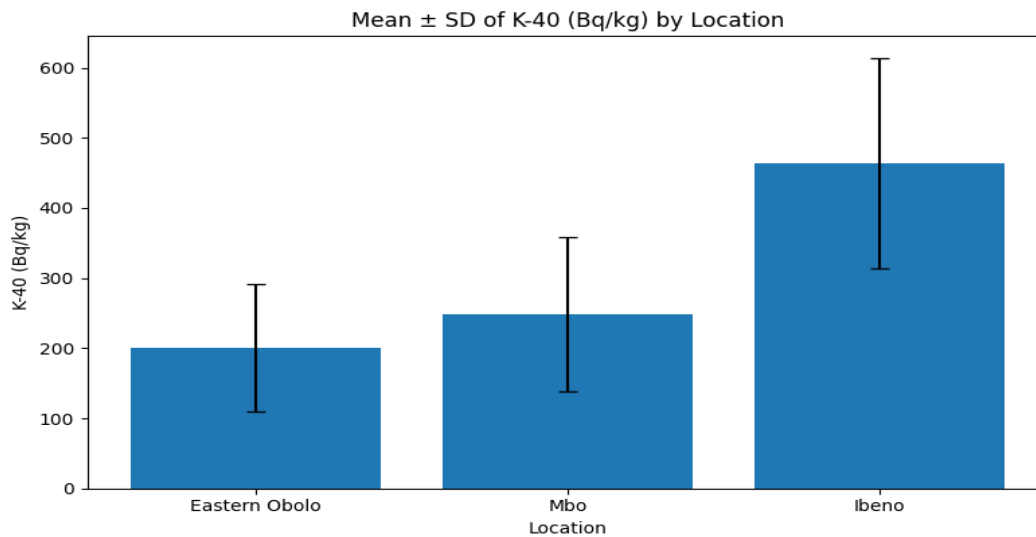
**Figure 3:** The box plot of the distribution of Th-232 (Bq/kg) by Location

The presence of elevated Th-232 concentrations in some locations is important from a radiological perspective because thorium contributes significantly to terrestrial gamma radiation. Nevertheless, the observed concentrations remain characteristic of naturally occurring radioactive materials commonly found in coastal sedimentary environments.

Figure 4 compares the mean K-40 concentrations among Eastern Obolo, Mbo, and Ibena, together with their corresponding standard deviation error bars. The results clearly show a progressive increase in mean K-40 concentration from Eastern Obolo through Mbo to Ibena. Ibena records the highest mean concentration, nearly twice that observed in Eastern Obolo. The standard deviation bars indicate considerable variability within each location, particularly in Ibena where the largest standard deviation was recorded. This suggests that sediment samples from Ibena exhibit substantial spatial heterogeneity, likely reflecting variations in mineral composition and depositional environments. The higher mean concentration may be attributed to greater

accumulation of potassium-rich minerals resulting from weathering, coastal sediment transport, and sediment sorting processes.

Eastern Obolo exhibits the lowest mean concentration and relatively lower variability, suggesting a more homogeneous sedimentary environment with limited potassium enrichment. Mbo occupies an intermediate position, reflecting moderate mineralogical diversity and radionuclide accumulation. The observed trend indicates that geological controls exert a strong influence on radionuclide distribution within the coastal sediments. The enrichment of K-40 in Ibena contributes significantly to the overall natural radioactivity of the area and may partly explain elevated radiological indices observed within the location. Figure 5 presents the mean uranium-238 (U-238) concentrations and associated standard deviations for the three coastal communities. Among the locations studied, Ibena exhibits the highest mean U-238 concentration, while Mbo records the lowest value. Eastern Obolo shows intermediate concentrations.



**Figure 4:** presents the mean concentration of K-40 across the three study locations with corresponding standard deviation error bars.

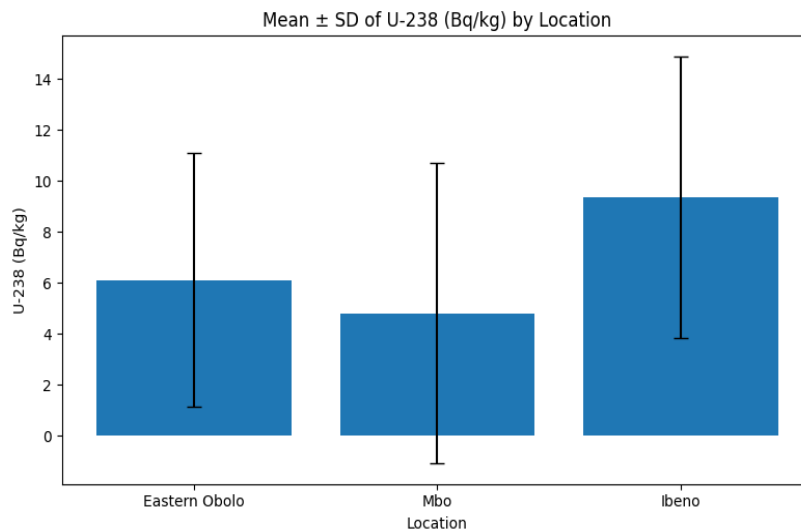
The higher uranium content in Ibeno suggests enhanced accumulation of uranium-bearing minerals within the coastal sediments. This may be linked to sediment provenance, groundwater interactions, and geochemical conditions favorable for uranium adsorption and retention. Coastal sediments rich in organic matter and fine-grained particles often exhibit greater uranium accumulation because these materials provide suitable sites for radionuclide adsorption.

The large standard deviation values observed, particularly in Ibeno and Mbo, indicate substantial spatial variability in uranium distribution. Such variability may arise from differences in sediment texture, mineralogy, depositional history, and local environmental conditions. The overlap of error bars among the locations suggests that although differences exist, some degree of similarity in uranium occurrence may also be present. From a radiological standpoint, U-238 is a key contributor to natural background radiation and serves as a precursor to several radionuclides within the uranium decay series. The elevated mean concentration recorded in Ibeno implies a greater potential contribution to external gamma radiation and associated radiological hazard indices relative to the other locations.

Figure 6 illustrates the mean Th-232 concentrations with corresponding standard deviations across Eastern Obolo, Mbo, and Ibeno. The figure shows that Ibeno has the highest average thorium concentration, followed by Mbo and Eastern Obolo. This trend is consistent with the distribution patterns observed in the box plot and further confirms the spatial enrichment of thorium-bearing minerals in Ibeno sediments. The relatively high standard deviation values indicate considerable variability in thorium concentrations within each location. Such variability is characteristic of coastal environments where sediment transport, wave action, and depositional dynamics continuously redistribute heavy mineral fractions. The larger variability observed in Ibeno suggests a heterogeneous distribution of thorium-rich minerals, possibly due to localized concentration of heavy mineral sands. The elevated mean thorium concentration recorded in Ibeno may be attributed to the preferential accumulation of resistant heavy minerals transported and deposited along the shoreline (George, 2021). Similar enrichment patterns have been reported in coastal regions where monazite and zircon-bearing sands contribute significantly to natural radioactivity levels. The results

highlight the importance of geological and sedimentological controls in determining radionuclide distribution. Since Th-232 contributes substantially to terrestrial gamma radiation, the higher concentrations observed in

Ibena indicate a relatively greater radiological significance compared to Eastern Obolo and Mbo. However, the measured values appear consistent with natural geological processes rather than anthropogenic contamination.



**Figure 5:** mean concentration of U-238 across the three locations with their respective standard deviations

Figures 2 - 6 collectively demonstrate a clear spatial pattern in radionuclide distribution across the coastal sediments of Akwa Ibom State. For all three radionuclides (K-40, U-238, and Th-232), Ibena consistently records the highest concentrations, suggesting stronger mineral enrichment and greater natural radioactivity relative to Eastern Obolo and Mbo. The substantial variability observed within locations reflects the influence of coastal sediment dynamics, mineralogical heterogeneity, weathering processes, and sediment provenance. These findings indicate that natural geological factors are the primary controls on radionuclide occurrence and provide important baseline information for evaluating radiological hazards and environmental safety in the coastal ecosystems of Akwa Ibom State.

### 3.1 Radiological Implications of Sediment Activity Concentrations

Systematic radiological evaluation of the sediment samples collected from the three sites (Etiza, Eastern Obolo; Okorotak, Ibena; and Enwang,

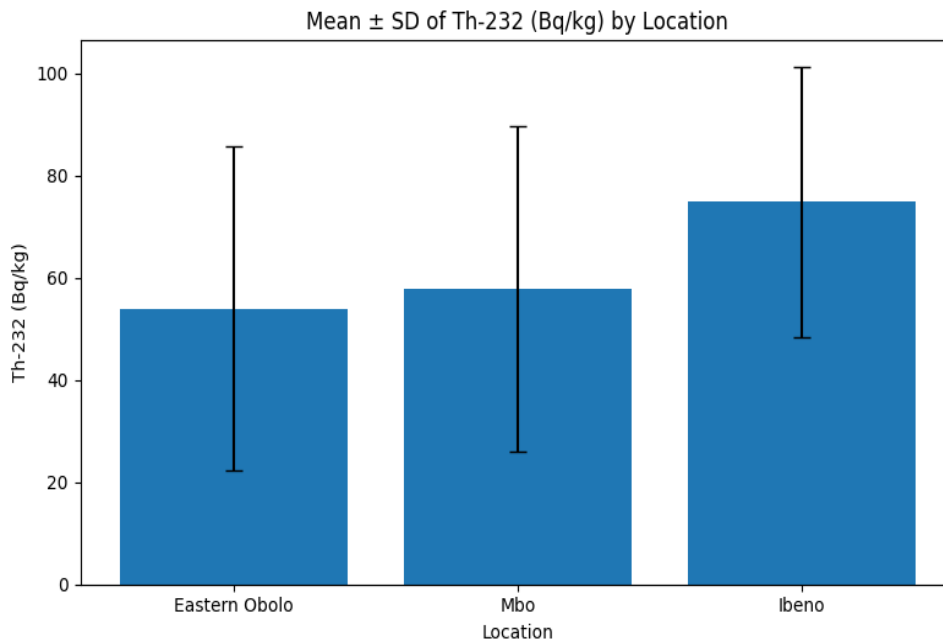
Mbo) provides a very interesting geochemical fractionation, sediment provenance and negligible health risk story. The primordial radionuclides (Potassium-40 (K-40), Uranium-238 (U-238) and Thorium-232 (Th-232)) measured show marked spatial variations with significant physical and geological implications to the Niger Delta coastline.

#### *Geochemical Fractionation and Weathering Signatures*

The most interesting physical implication is the inverse relationship between Uranium and Thorium for all three locations. However, the mean activities of the U-238 are significantly lower than the world average of 35 Bq/kg (48.57 Bq/kg at Etiza, 57.78 Bq/kg at Okorotak and 74.81 Bq/kg at Enwang), while the mean activities of the Th-232 are significantly higher than the world average of 30 Bq/kg (48.57 Bq/kg at Etiza, 57.78 Bq/kg at Okorotak and 74.81 Bq/kg at Enwang). This dichotomy is a typical feature of differential solubility under oxidizing estuarine conditions.

The uranium is mostly present as the highly soluble uranyl ion ( $\text{UO}_2^{2+}$ ) and is therefore easily leached and carried away from the depositional basin. Thorium, on the other hand, is strictly tetravalent ( $\text{Th}^{4+}$ ) and hydrolyzes easily to insoluble oxides and hydroxides that are resistant to chemical weathering and will remain in the residual heavy minerals. This is similar to what was observed by Ankapong et al. (2024) in the Ghanaian mining districts where thorium retention was higher than the mobility of uranium, but with

the absorbed dose rates (198–224 nGy/h) being much higher than the maximum of 68.42 nGy/h found in this study at Enwang, indicating a more intense mineralization in the mining districts. Likewise, Omeje et al. (2023) found higher concentrations of thorium (136.12 Bq/kg) and uranium (96.49 Bq/kg) in the sediments of the Unumherin community which is located along the Niger Delta coastline, but the values are much higher than the ones found in this study.



**Figure 6:** Mean concentrations of Th-232 with associated standard deviations across the study locations

### ***Provenance and Spatial Heterogeneity***

Physical differences between the three sites indicate different sediment sources. Enwang has the highest mean K-40 (463.83 Bq/kg) and Th-232 (74.81 Bq/kg) content among the three locations. This enrichment is a physical phenomenon that represents a source terrain of felsic igneous or metamorphic bedrocks (such as granites or gneisses), which are naturally enriched in potassium feldspar and accessory minerals containing thorium. The observation is in agreement with Oni et al. (2025) who reported potassium levels up to 1323.5 Bq/kg in the Nupe basin, north-central Nigeria, while the mean

thorium and uranium concentrations (48.88 Bq/kg and 35.3 Bq/kg, respectively) were close to the global averages. On the other hand, Etiza has the lowest mean K-40 (180.04 Bq/kg) which could be attributed to dilution due to quartz rich sands or catchment with lower radiogenic content, whereas Okorotak has intermediate mean K-40 (248.96 Bq/kg). Notably, the highest localised measurements in the entire data set are found in Okorotak, with U-238 at 20.19 Bq/kg and Th-232 at 129.12 Bq/kg, indicating heavy mineral placers in the area, possibly affected by variable current patterns along the Ibeno coastline. This spatial variability highlights the dynamic sediment

transport processes and settling velocities of radiogenic particulates in these adjacent estuarine environments. However, the mean values reported by Esi et al. (2024) for coastal sediments of Delta State (K-40: 3361.48 Bq/kg, U-238: 40.11 Bq/kg, Th-232: 45.73 Bq/kg) were significantly higher than the mean values obtained from the present study areas, indicating greater radiogenic enrichment in the Delta State coastal sediments than in the present study areas.

#### ***Radiological Hazard and Dosimetric Implications***

Although the thorium is systematically enriched, the calculated Radium Equivalent activities ( $Ra_{eq}$ ) which normalize the total gamma-ray production from the three radionuclides are 86.99 Bq/kg (Etiza), 106.60 Bq/kg (Okorotak) and 151.13 Bq/kg (Enwang). All these values are well below the international safety standard of 370 Bq/kg, which is radiologically equivalent to the external gamma exposure from these sediments being negligible. This is similar to Ghazal et al. (2024) who reported  $Ra_{eq}$  values between 48.20 and 105.49 Bq/kg in soil samples from Iraq, which are all lower than the limit of 370 Bq/kg, but the absorbed dose rates (22.91–49.76 nGy/h) were similar to those reported by Etiza and Okorotak. The mean absorbed dose rates (D) increase with the increase in the distance from Etiza (38.54 nGy/h) to Okorotak (47.50 nGy/h) and Enwang (68.42 nGy/h). Etiza and Okorotak are below the world average of 59 nGy/h, but Enwang is slightly above. This is consistent with the results of Darko et al. (2015) on the absorbed dose rate in farm lands of Ghana where the range was 23.63–50.51 nGy/h, which is within the global range of 18–93 nGy/h, and the results of Ba et al. (2019) in Ho Chi Minh City where the absorbed dose rate was found to be within the UNSCEAR safety limits. As a result, the Annual Effective Dose Equivalent (AEDE) averages are 0.059 mSv/y, 0.073 mSv/y, and 0.10 mSv/y for EO, MB, and IB, respectively. Most importantly, the highest value at Enwang is

only 1/10 of the 1.0 mSv/y public exposure limit recommended by the ICRP, which means that the sediments are radiologically safe for handling and ecological habitation. This is consistent with the findings of Oni et al. (2025) who reported AEDE value of 0.065 mSv/y in north-central Nigeria, which is much lower than the limit of 1 mSv/y.

#### ***Excess Lifetime Cancer Risk (ELCR)***

The ELCR values derived directly from the AEDE are  $0.16 \times 10^{-3}$  (Etiza),  $0.20 \times 10^{-3}$  (Okorotak), and  $0.29 \times 10^{-3}$  (Enwang). Only Enwang achieves the WHO reference level of  $0.29 \times 10^{-3}$ , or 0.029% above the natural rate, a level that is not statistically significant. The present study areas have significantly lower radiological risk as compared to Niger Delta coastal environments (ELCR  $> 7.54 \times 10^{-3}$  in some cases) reported by Omeje et al. (2024). Physically, it means that although the enrichment of thorium increases the local background radiation field at Enwang, the absolute energy deposition in biological tissue is still too low to cause deterministic effects or to increase the stochastic risk beyond the natural fluctuations.

#### **4.1 Statistical Analysis of Radionuclide Concentrations in Sediment Samples**

The descriptive statistics of the activity concentrations of  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  in sediment samples from Eastern Obolo, Mbo and Ibeno are shown in Table 4. Generally, Ibeno had the highest mean concentration for all three radionuclides, especially for  $^{40}\text{K}$  and  $^{232}\text{Th}$ , and Eastern Obolo generally had the lowest concentration. Mbo exhibited intermediate concentrations and higher variability particularly for  $^{238}\text{U}$ . The relatively large ranges, standard deviations and interquartile ranges between the three locations suggest that there is some spatial variation in the distribution of radionuclides. Such variations may be explained by the differences in lithology, sedimentology and anthropogenic activities like oil prospecting and other land uses. The Shapiro–

Wilk normality test indicated that the activity concentrations of  $^{40}\text{K}$  and  $^{232}\text{Th}$  were normally distributed at all the sampling points and were appropriate for parametric analysis. Unlike the case in Eastern Obolo and Mbo,  $^{238}\text{U}$  was not normally distributed in both of these areas, but it was normally distributed in Ibeno. Therefore, one-way ANOVA was used to compare the concentration of  $^{40}\text{K}$  and  $^{232}\text{Th}$ , and Kruskal–Wallis's test was used for  $^{238}\text{U}$ , which is a non-parametric test. The results of Levene's test showed that there was no significant difference between the variances of the three radionuclides at

the different study locations ( $p > 0.05$ ). Therefore, the assumption of equal variances in ANOVA was fulfilled. The results of the comparative analysis indicate that there exists a significant difference between the three locations in relation to the concentration of  $^{40}\text{K}$ , implying that the presence of this isotope is highly influenced by the environmental or geological nature of the locations. There are no significant differences in relation to  $^{238}\text{U}$  and  $^{232}\text{Th}$ , implying that the concentrations of these isotopes are relatively uniform within the study location and mainly depend on the natural geologic environment.

**Table 4:** Mean activity concentration of sediments collected from rivers within the study communities

Location	Radiation content for sediments ( $\text{Bq/kg}^{-1}$ )		
	$^{40}\text{K}$	$^{238}\text{U}$	$^{232}\text{Th}$
Eastern Obolo	200.04 ± 90.70	6.12 ± 4.98	53.97 ± 31.73
Mbo	248.96 ± 109.89	4.815 ± 5.907	57.78 ± 31.84
Ibeno	463.83 ± 150.52	9.367 ± 5.532	74.81 ± 26.49
Overall mean	304.278 ± 140.32	6.767 ± 2.345	62.187 ± 11.10
World Average (UNSCEAR, 2000)	400.00	35.00	30.00

Tukey's HSD post hoc analysis was conducted to establish which locations influenced the differences established during ANOVA in relation to  $^{40}\text{K}$ . It was observed that the concentration of  $^{40}\text{K}$  in Ibeno was significantly higher than the concentration of  $^{40}\text{K}$  in Eastern Obolo and Mbo, but there was no significant difference in the concentration of  $^{40}\text{K}$  in Eastern Obolo and Mbo. This suggests that the spatial variation in  $^{40}\text{K}$  is due to a local geological enrichment or to anthropogenic activity, with Ibeno being the primary source. These statistical results are confirmed by the boxplots and the error-bar plots (Figures 1-4.5). The concentrations of  $^{40}\text{K}$  are clearly higher at Eastern Obolo than at Ibeno, whereas the distributions of  $^{238}\text{U}$  and  $^{232}\text{Th}$  are quite similar between the three locations. In general, the results show that the spatial variation

of  $^{40}\text{K}$  is larger than that of  $^{238}\text{U}$  and  $^{232}\text{Th}$ , indicating that the environmental processes that lead to the presence of these elements in the sediment are different.

#### 4.0 Conclusion

This study provides a comprehensive assessment of the distribution of naturally occurring radionuclides ( $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$ ) and their associated radiological hazards in coastal sediments from Etiza (Eastern Obolo), Okorotak (Ibeno), and Enwang (Mbo) in Akwa Ibom State, Nigeria. The results demonstrate that natural radioactivity varies spatially across the study area, reflecting differences in geological origin, sediment composition, and coastal depositional processes rather than anthropogenic radioactive contamination.

A major finding of the study is that  $^{232}\text{Th}$  constitutes the dominant contributor to the natural radioactivity of the sediments, whereas  $^{238}\text{U}$  consistently occurs at relatively low concentrations in all three locations. Although  $^{40}\text{K}$  exceeded the global average in Enwang, and thorium concentrations were above the recommended world average at several sampling locations, the calculated radiological hazard indices, including absorbed dose rate (except for localized elevations in Enwang), annual effective dose equivalent (AEDE), excess lifetime cancer risk (ELCR), and radium equivalent activity (Raeq), remained below internationally accepted safety limits. Among the three locations, Etiza exhibited the lowest radioactivity levels, Okorotak showed intermediate characteristics, while Enwang recorded the highest radionuclide concentrations and radiological hazard indices, establishing a clear spatial gradient in natural radioactivity along the Akwa Ibom coastline.

From a scientific perspective, the study improves the understanding of the geochemical and sedimentological controls governing radionuclide distribution in tropical coastal environments. The observed enrichment of thorium, together with the spatial variability of potassium, demonstrates the significant influence of sediment provenance, heavy mineral concentration, hydraulic sorting, and long-term coastal reworking on the occurrence of naturally occurring radioactive materials. These findings contribute valuable baseline radiological data for the Gulf of Guinea coastal region and provide an important reference for future studies on coastal sediment evolution, environmental radioactivity, and geological processes.

The environmental implications of the findings are encouraging. Despite localized enrichment of thorium-bearing heavy minerals, the sediments do not currently present significant radiological risks to aquatic ecosystems, coastal communities, or

individuals who depend on these environments for fishing, recreation, or other socioeconomic activities. The measured radiation levels indicate that the coastal ecosystems remain environmentally safe under present conditions. Nevertheless, the relatively elevated thorium and potassium concentrations observed in some locations highlight the need for continued environmental surveillance, particularly in areas experiencing active shoreline modification, erosion, or sediment redistribution.

The findings also have important policy implications. The baseline radiological information generated by this study can support environmental impact assessments, coastal zone management programmes, mineral exploration activities, and public health risk assessments within Akwa Ibom State. Environmental regulatory agencies can utilize these data to establish long-term monitoring frameworks for naturally occurring radioactive materials in coastal environments. Such monitoring is particularly important in regions where increasing industrialization, offshore petroleum activities, dredging operations, and coastal development may alter sediment characteristics and influence radionuclide distribution over time.

Although the present study provides valuable insights into natural radioactivity within the investigated coastal sediments, certain limitations should be acknowledged. The investigation was based on sediment samples collected during a single sampling campaign and therefore does not capture possible seasonal variations associated with rainfall, tidal dynamics, river discharge, and sediment transport. In addition, only naturally occurring radionuclides ( $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$ ) were considered, while artificial radionuclides and radionuclide speciation were beyond the scope of the study. Furthermore, direct mineralogical analyses capable of identifying the specific heavy

minerals responsible for thorium enrichment were not undertaken.

Future research should therefore incorporate seasonal and multi-year monitoring programmes to evaluate temporal changes in radionuclide distribution under varying environmental conditions. Integrating high-resolution mineralogical techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), X-ray fluorescence (XRF), and heavy mineral analysis would provide a clearer understanding of the geological sources of radionuclide enrichment. Additional investigations involving sediment geochemistry, grain-size distribution, radionuclide mobility, ecological risk assessment, and Geographic Information System (GIS)-based spatial modelling would further strengthen knowledge of radionuclide behaviour within the coastal ecosystems of Akwa Ibom State. Comparative studies involving other coastal regions of the Niger Delta and the Gulf of Guinea would also help establish regional radiological baseline datasets for environmental management and sustainable coastal development (Esi et al., 2024; Omeje et al., 2023, 2024).

In all, the study demonstrates that the coastal sediments of Akwa Ibom State are characterized by natural geological variability in radionuclide distribution, with thorium-bearing minerals representing the principal source of radioactivity. Despite observable spatial differences among the three study locations, the measured radiological hazard indices indicate that the sediments are presently safe and do not pose significant health or environmental risks. These findings provide a robust scientific baseline for future environmental monitoring, radiological assessment, and evidence-based management of Nigeria's coastal environments.

Finally, these results physically reflect a sedimentary system dominated by thorium

retention and uranium depletion in the case of high chemical weathering, and by quartz-dilution in the case of Enwang and Etiza. The dose metrics show that the dose received at Enwang is the highest of the three sites while all the radiological indices clearly show that the dose received by the public from these naturally occurring radionuclides is not a public health concern, in contrast with the more radiogenically enriched coastal sites (Esi et al., 2024; Omeje et al., 2023, 2024). The data are useful as a fingerprint of geological provenance and sediment dynamics and not as a warning of radiological contamination, thus underlining the need for local baseline data for proper environmental monitoring and risk assessment in the Niger Delta region.

## References

- Abdallah, M., El-Mezayen, A. M., Adel, E. A. H., El-Shabasy, A. M., Draz, O., & Taalab, S. A. (2025). Radionuclides Migration Related to Alteration and Mineralogical Investigations of El Sela Uraniferous Two Mica Granites. *Egyptian Journal of Chemistry*, 68(9), 437 – 452. DOI: [10.21608/ejchem.2025.352763.1-1161](https://doi.org/10.21608/ejchem.2025.352763.1-1161)
- Adebayo, A. S., Olufemi, A. P., Njinga, R. L., Olowookere, C. J., Ogundele, L. T., & Ovie, O. (2026). Transfer of natural radionuclides from soil to plant crops in parts of southwestern Nigeria. *Environmental Monitoring and Assessment*, 198(3), 234.
- Ahmadu, I. (2025). Estimation of gross Alpha and Beta and to calculate AEDE, AGDE and ELCR in Mubi North metropolis. *London Journal of Physics*, 2(1).
- AL-abrdi, A. M. (2023). Estimation of annual gonadal dose equivalent and cancer risk for the barley samples in Libya markets. *Sirte University Scientific Journal*, 13(1), 66-70.

- Ankapong, E., Gyamfi, O., Agyei, V., Dodd, M., Akoto, O., & Darko, G. (2024). Soil-to-plant transfer factors of uranium and thorium in mining and non-mining districts of Ghana. *Journal of Environmental Radioactivity*, 280, 107566
- Ba, V. N., Van Thang, N., Dao, N. Q., Thu, H. N. P., & Loan, T. T. H. (2019). Study on the characteristics of natural radionuclides in surface soil in Ho Chi Minh City, Vietnam and radiological health hazard. *Environmental earth sciences*, 78(1), 28.
- Beretka, J., & Mathew, P. J. (1985). Natural radioactivity of building materials. *Health Physics*, 48(1), 87–95.
- Chetty, N., & Ilori, A. O. (2024). Activity concentration and transfer of <sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K from soil-to-crops in Irele Local Government Area of Ondo State, Southwestern Nigeria. *Scientific African*, 23, e02098.
- Coutelot, F., Wheeler, J., Merino, N., Kaplan, D. I., Owings, S., Taillefert, M., ... & Powell, B. A. (2023). Temporal evolution of Pu and Cs sediment contamination in a seasonally stratified pond. *Science of The Total Environment*, 857, 159320.
- Darko, G., Faanu, A., Akoto, O., Acheampong, A., Goode, E. J., & Gyamfi, O. (2015). Distribution of natural and artificial radioactivity in soils, water and tuber crops. *Environmental Monitoring and Assessment*, 187(6), 339.
- Ekanem, A. M. (2022). AVI- and GOD-based vulnerability assessment of aquifer units: a case study of parts of Akwa Ibom State, Southern Niger Delta, Nigeria. *Sustain. Water Resour. Manag.* **8**, 29 (2022). <https://doi.org/10.1007/s40899-022-00628-x>
- Ekanem, A. M., Akpan, A. E., George, N. J. Thomas J. E. (2021) Appraisal of protectivity and corrosivity of surficial hydrogeological units via geo-sounding measurements. *Environmental Monitoring Assess.*, **193**, 718. <https://doi.org/10.1007/s10661-021-09518-9>
- Ekong, G. B., Akpa, T. C., Umaru, I., Akpaowo, M. A., Yusuf, S. D., & Benson, N. U. (2021). Baseline radioactivity and associated radiological hazards in soils around a proposed nuclear power plant facility, South-South Nigeria. *Journal of African Earth Sciences*, 182, 104289. <https://doi.org/10.1016/j.jafrearsci.2021.104289>.
- Esi, O. E., Avwiri, G. O., Sylvanus, O. A., & Onwudiwe, D. C. (2024). Radiometric survey of sediments and health risk assessments from the southern coastal area of Delta State, Nigeria. *Heliyon*, 10(5).
- George, N. J. & Thomas, J. E. (2024). Typification of coastal depositional lithofacies with isophysical and isochemical hydro-sand beds via stratigraphic modified Lorenz plots (SMLP): geohydrodynamical implications and valorization of hydrogeological units. *Acta Geophys.* **72**, 1275 – 1291. <https://doi.org/10.1007/s11600-023-01160-y>
- George, N. J. (2021) Integrating hydrogeological and second-order geo-electric indices in groundwater vulnerability mapping: A case study of alluvial environments. *Appl Water Sci* **11**, 123. <https://doi.org/10.1007/s13201-021-01437-x>
- George, N. J., Agbasi, Umoh, A. J. Ekanem, A. M., Udosen, N. I., Thomas, J. E. M. U., Aka, M. U., Ejepu, J. S. (2025). Enhanced contamination risk assessment for aquifer

- management using the geo-resistivity and DRASTIC model in alluvial settings. *Cleaner Water*, 3, 100060, <https://doi.org/10.1016/j.clwat.2024.100060>
- George, N. J., Basse, N. E., Ekanem, A. M. & Thomas, J. E. (2020). Effects of anisotropic changes on the conductivity of sedimentary aquifers, southeastern Niger Delta, Nigeria. *Acta Geophys.* 68, 1833–1843 (2020). <https://doi.org/10.1007/s11600-020-00502-4>
- George, N. J., Ekanem, A. M., Thomas, J. E. & Harry, T. A. (2022a). Modelling the effect of geo-matrix conduction on the bulk and pore water resistivity in hydrogeological sedimentary bed-dings. *Model. Earth Syst. Environ.* 8, 1335 – 1349. <https://doi.org/10.1007/s40808-021-01161-0>
- George, N. J., Umoh, J. A., Ekanem, A. M., Agbasi, O. E., Jamal, A. & Thomas, J. E. (2022b). Geophysical-laboratory data integration for estimation of groundwater volumetric reserve of a coastal hinterland through optimized interpolation of interconnected geo-pore architecture. *J Coast Conservation*, 26, 56. <https://doi.org/10.1007/s11852-022-00902-2>
- George, N. J., Obianwu, V. I., Akpabio, G. T. & Obot, I. B. (2010). Comparison of thermal insulation efficiency of some select materials used as ceiling in building design, *Archives of Applied Science Research*, 2 (3): 253-259.
- Ghazal, A. I., Jasim, S. A., Al-Muhee, N. A. M. A., Wais, T. Y., Najam, L. A., Namq, B. F., & Mansour, H. (2024). Assessment of natural radionuclides and radiological health hazards of the soil of the general company for Sulphur Al-Mishraq in Ninevah Governorate, Iraq. *International Journal of Nuclear Energy Science and Technology*, 17(2-3), 197-216.
- Hassan, A., Saad, A., Draz, O., Aziz, M. A., Elshabasy, A., & Sakr, M. (2025). Subsoil Suitability Evaluation for Deep Foundation Using Geotechnical and Environmental Radioactivity Investigations: Case Study at Cairo, Egypt. *The Iraqi Geological Journal*, 1-23.
- ICRP (International Commission on Radiological Protection). (2007). The 2007 recommendations of the international commission on radiological protection. ICRP publication 103. *Ann ICRP*, 37(2–4), 1-332.
- Inim I. J., Udosen N. I., Tijani M. N., Afia, U. E., George, N. J. (2020). Time-lapse electrical resistivity investigation of seawater intrusion in coastal aquifer of Ibeno, Southeastern Nigeria, *Applied Water Science*, 10, 232 , <https://doi.org/10.1007/s13201-020-01316-x>
- Li, H., Wang, Q., Zhang, C., Su, W., Ma, Y., Zhong, Q., ... & Xiao, T. (2024). Geochemical distribution and environmental risks of radionuclides in soils and sediments runoff of a uranium mining area in South China. *Toxics*, 12(1), 95.
- Naser, H. A. (2013). Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. *Marine pollution bulletin*, 72(1), 6-13.
- Ndoma, E., George, N., Ekanem, A., Orosun, M., Ushie, P., Agbo, E., Eze, B., Mbonu, C., Adesina, K., Yahweh, B., & Okon, F. (2025a). Evaluating the health risks of radionuclides in welding and fabrication

- workshops in Akwa Ibom State, Southern Nigeria. *Journal of the Nigerian Society of Physical Sciences*, 2550. <https://doi.org/1-0.46481/jnsps.-2025.2550>
- Ndoma, E., George, N., Nathaniel, E., Orosun, M., Agbo, E., & Offorson, G. (2024). Technological Civilization and Health Impact Assessment of Non-Ionizing Radiation in Nigeria: Review. *Polytechnica*, 7(1), 3. <https://doi.org/10.1007/s41050-023-00045-9>
- Ndoma, E. G., George, N. J., Ekanem, A. M., Orosun, M.M., Ahamad, T., Adesina, K.E., Kaur, S., Bello, S., Akinyemi, A., Agbo, E. & Essiett, A. (2025b). Assessment of radioactivity levels and health hazards in welding electrodes using spectrometric and statistical methods, *Journal of Environmental Radioactivity*, 290, 107809, <https://doi.org/10.1016/j.jenvrad.2025.107809>.
- Obianwu, V. I., George, N. J., & Okiwelu, A.A. (2011). Preliminary geophysical deduction of lithological and hydrological conditions of the North-Eastern sector of Akwa Ibom State, Southern Nigeria, *Maxwell Science Publishing*, 8(3), 806-811.
- Okon, F. E., George, N. J., Ekanem, A. M., & Ndoma, E. G. (2025). Radiological Risk Assessment of Naturally Occurring Radionuclides in Commonly Consumed Stimulants in Akwa Ibom State, Southern Nigeria. *Researchers Journal of Science and Technology*, 5(4), 60 – 72. <https://doi.org/10.83080/rejost.vol5no4.192>
- Omeje, M., Orosun, M. M., Aimua, G. U., Adewoyin, O. O., Sabri, S., Louis, H., ... & Targema, T. V. (2024). Radioactivity distributions and biohazard assessment of coastal marine environments of niger-delta, Nigeria. *All Earth*, 36(1), 1-19.
- Omeje, M., Usiaka Aimua, G., Oladotun Adewoyin, O., Michael Orosun, M., Sunday Joel, E., Usikalu, M. R., ... Anne, O. U. (2023). Dispersion of gamma dose rates and natural radionuclides in the coastal environments of the Unumherin community in Niger Delta. *Cogent Engineering*, 10(1). <https://doi.org/10.1080/23311916.2023.2204546>
- Oni, E. A., Olajide, T. A., Oladejo, O. P., Suleman, K. O., Salaudeen, S. A., Adewumi, H. I., ... & Egbeyale, G. B. (2025). Spatial distribution of natural radionuclides and its radiological impact in a fractured sedimentary zone, Nupe basin north-central Nigeria. *Discover Geoscience*, 3(1), 157.
- Udosen, N. I., Ekanem, A. M. & George, N.J. (2024a) Modeling of aquifer geohydraulic characteristics with geoelectrical methods at a major coastal aquifer system in Uyo, southern Nigeria, *Water Practice & Technology*, 19 (2), 611-628
- Udosen, N. I., Ekanem, A. M. & George, N. J. (2024b). Geophysical exploration to assess leachate percolation and aquifer protectivity within hydrogeological units at a major open dump in Eket, Nigeria, *Results in Earth Sciences*, 2, 100022, ISSN 2211-7148, <https://doi.org/10.1016/j.rines.2024.100022>.
- Udosen, N. I., Ekanem, A. M., & Thomas, J. E. (2024c). Geo-hydraulic characterization of a coastal aquifer system in South-eastern Nigeria with the inverse slope method. *Researchers Journal of Science*

- and Technology*, 4(1), 1–20. <https://doi.org/10.83080/rejost.vol4no1.82>
- Umoh, J.A., George, N.J., Ekanem, A.M. Emah, J.B. (2025). Characterization of hydro-sand beds and their hydraulic flow units by integrating surface measurements and ground truth data in parts of the shorefront of Akwa Ibom State, Southern Nigeria. *Int J Energy Water Res* **9**, 13–29 <https://doi.org/10.1007/s42108-022-002-15-y>
- UNSCEAR (2000). *Sources and effects of ionizing radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation.
- Uwa, U. E., Akpabio, G. T. & George, N. J. (2019). Geohydrodynamic Parameters and their Implications on the Coastal Conservation: A Case Study of Abak Local Government Area (LGA), Akwa Ibom State, Southern Nigeria. *Nat Resour. Res.*, 28, 349–367.
- Walling, D., & Foster, I. (2016). Using environmental radionuclides, mineral magnetism and sediment geochemistry for tracing and dating fine fluvial sediments. *Tools in fluvial geomorphology*, 181-209.