

Assessment of Natural Radioactivity Levels and Radiological Health Risks in Coastal Sediments of the Niger Delta, Nigeria: Environmental and Human Health Implications

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ABSTRACT

Unregulated discharge of hydrocarbon-related wastes into Niger Delta coastal waters raises concerns over radionuclide contamination of sediments used in construction within the coastal region. Hence sediment samples were analyzed radiologically by means of Sodium iodide detector NaI (TI). The mean concentration of ⁴⁰K, ²³⁸U and ²³²Th that were analyzed are 1586.80, 27.25 and 46.90 Bq/kg respectively. The obtained values exceeded the world standard values of 400 and 30 Bq/kg for ⁴⁰K and ²³²Th respectively while ²³⁸U is below standard value of 35 Bq/kg. The computed radiological indices with the view of ascertaining the sediment contamination level are radium equivalent activity, representative gamma index, the internal and external hazard index, absorbed gamma dose rate, annual effective dose equivalent and excess lifetime cancer risk with overall mean values of 216.50 Bqkg⁻¹, 1.70, 0.60, 0.65, 107.80 nGyh⁻¹, 0.13 mSvyr⁻¹ and $\sim 4.6 \times 10^{-3}$ respectively. These radiological indices exceeded respective recommended permissible limits. The research work concludes that unprofessional discharge of radiological contamination waste can lead to contamination of the coastal sediment being use for construction, and can further affect health of the residents in the region. However, these results can be use in the future as baseline for further radiological research.

Keywords:

Contamination,
Sediment,
NORM,
Radiological indices,
Radioactive elements,
Gamma spectrometry.

INTRODUCTION

Natural Occurring Radioactive Materials (NORM) of primordial origin, uranium, thorium isotopes and potassium are the primary terrestrial sources of radiation that humans are constantly exposed to daily (WHO, 2011; Saat et al., 2011). Human exposure to radiation may occur externally, through gamma-emitting radioisotopes present in sediments or internally due to the ingestion or inhalation of radon gas (Lu & Zhang, 2008; Isinkaye, 2013). The strength of radiation is dependent upon the concentration of NORM as contain in the soil, water, sediment and air, with regard to the location ecological structure (Tari et al., 2013; George et al., 2018). However, human activities may lead to increase in naturally existing radionuclides in sediment within the locality. Some of these anthropogenic activities that can lead to increase in concentration of radionuclides in sediment are oil and gas exploration, coal extraction, phosphate fertilizer manufacture, medical waste and steel

production (Abbady, 2004; Esi et al., 2024; Agbalagba et al., 2012). The release of radioactivity waste from these anthropogenic activities into water bodies may lead to increase in radioactive elements in sediment, which is majorly used as raw materials in construction of road and buildings. Humans living in such building may be consistently subjected to radioactive elements released from the building (Suresh et al., 2014; Adewoyin et al., 2022). These released radioactive elements if inhaled or ingested may cause significantly impact on human health (El-Arabi, 2018; Xinwei & Xiaolon, 2008). The Delta State coastal area has been playing host to oil and gas explorations activities for decades. Hence the operational waste released by these oil and gas may have contaminated the water bed sediment of the area (environment) radiologically. It is a known fact that the dredged sediment is one of the major raw materials use for constructions in the area and it call for concern. Researcher at different occasions in similar environment

has evaluated radioactive element and the radiological health risk of sediment used as raw materials for the purpose of construction round the world in other to ascertain its concentrations and human health impact (Baafi et al., 2025; Adedokun et al., 2025; Serdar et al., 2024; Sivakumara et al., 2014; Onjefu et al., 2022; Tyongiga et al., 2024; Isinkaye & Emelue, 2015). But to a large extent, few radiological research works have been carried out in the study region. This has left radioactivity concentration knowledge gap within the region. It is thus necessary estimating environmental and health implications of radioactive elements in sediments used as construction materials in the region. The result of this research will make available in sequence the radioactive elements contain in the sediment are normal or high and also, serve as baseline of the region.

MATERIALS AND METHODS

Study Area

Hydrocarbon exploration activities are the major industrial activities in Nigeria (Niger Delta region), traceable to over decades. The region is vested with oil and gas deposits with a total area of 112,106 km². The region is located in the southernmost division of the Nigeria, which lies between latitudes 5°19'20.40" North and longitudes 6°28'8.99" East, with tectonically stable and height between 2.05 and 45 m over sea level. The region is surrounded with creek and rivers that discharge into the Atlantic Ocean.

Sample Preparation

Water bed sediments were sampled along the coastal area of the Niger Delta. Thirty (30) sediments samples were randomly collected across the study region with the aid of speed boat and hand tug and labeled. The samples were taken to the laboratory for radioactive analysis. In order to remove humidity, sediment samples were dried with atmospherically for several days and oven dried at 60 °C before milled with a machine. Samples were homogenized, sieved and further transferred into synthetic containers. The containers were completely sealed for thirty days to avoid escape of radionuclides (gaseous radon) from samples, which is fundamental for secular symmetry. The quantities of radionuclides

present in sediments was analyzed by means of 802 (3''x 3'') NaI (TI) detector, with features of serial 13000742 bases and Multichannel Analyzer (MCA) via a pre-amplifier Model 2007P. In order to reduce interferences of background radiation by a factor of roughly 95%, the detector has shielded with 10 cm thickness of lead. The detector undergoes energy calibration which translated the channel numbers to γ -rays energy in MeV with three-point standard sources of ²⁴¹Am, ¹³⁷Cs, and ⁶⁰Co that were acquired in 2010. This calibration was completed prior to sample measurement and continuously confirmed the peaks positions to ensure accurate results. Also, annual efficiency calibration was carried out on the detector by means of a mixed gamma source IAEA-Sediment-315 standard purchased from International Atomic Energy Agency (IAEA) in 2013. This is to enable area photopeak translate to radionuclides concentration in Bq/kg. The environment band was composed for 36000s at 600 V to yield heavy gamma peaks of 1764.5keV on ²¹⁴Bi on behalf of ²³⁸U, 2614 keV on ²⁰⁸Tl on behalf of ²³²Th and 1460.8 keV on behalf of ⁴⁰K. The energy resolution of the detector standards of ⁶⁰Co is 6.5% at 1332 keV peaks and ¹³⁷Cs is 7.5% at 662 keV peaks. The results of ²³⁸U, ²³²Th, and ⁴⁰K were achieved by connecting the detector to GENIE 2000 software. Equation (1) was use for the computation of the specific activity of the nuclides.

$$SA = \frac{HPC}{TI = I (CLD) \times \varepsilon (E) \times M} \quad (1)$$

Where SA = specific activity, HPC = highest point counts, $\varepsilon (E)$ = energy presentation, I (CLD) = counting life duration and M = mass.

Radiological Health Risk Parameters (RHRP)

The RHRP computed from the evaluated sediment samples of the Niger Delta were done in accordance with world scientific mathematical formulas as presented in Table 1. These computations were done to make certain the risk implications of radiological health that may come up from sediment usage as raw materials for construction. (UNSCEAR, 2000; Dieb et al., 2008; Jibiri et al., 2014; Jibiri & Okeyode, 2012; Ravisankar et al., 2015; Chandrasekaran et al., 2014)

Table 1: Showing Formulas Used for Computations of Radiological Health Implications

S/No	Hazard Index	Formulas
1	Radium Equivalent Index	$R_{eq} = AC_{Ra} + 1.43AC_{Th} + 0.077AC_k$
2	Representation Level Index	$I_{yr} = \frac{AC_{Ra}}{150} + \frac{AC_{Th}}{100} + \frac{AC_k}{1500}$
3	External Hazard Index	$H_{ex} = \frac{AC_{Ra}}{370} + \frac{AC_{Th}}{259} + \frac{AC_k}{4810}$
4	Internal Hazard Index	$H_{in} = \frac{AC_{Ra}}{185} + \frac{AC_{Th}}{259} + \frac{AC_k}{4810}$
5	Absorbed Does Rate (D)	$D = 0.461AC_{Ra} + 0.623AC_{Th} + 0.04144AC_k$
6	Annual Effective Dose Rate (Outdoor)	$AEDR = D (nGrh^{-1}) \times 8760 \text{ h} \text{ yr}^{-1} \times 0.7 \times (10^3 \text{ mSv} / 10^9) \text{ nGy} \times 0.2$
8	Excess Lifetime cancer risk	$ELCR = AEDE \times LD \times RF$

* All radiological symbols maintain their scientific connotation and values (Qureshi et al., 2014; Raghu et al., 2015; Taskin et al., 2009).

RESULTS AND DISCUSSION

Table 2: Mean Activity Concentration Results Of Sediment Samples (Bq/Kg)

	Sample code	Activity		
		⁴⁰ K	²³⁸ U	²³² Th
1	SSPC1	283.99	0.65	48.37
2	SSPC 2	1779.17	48.22	8.88
3	SSPC 3	0	87.72	68.3
4	SSPC 4	1070.6	10.02	52.89
5	SSPC 5	2132.34	67.29	35.71
6	SSPC 6	2243.37	41.55	28.94
7	SSPC 7	901.85	16.62	15.7
8	SSPC 8	1954.5	73.57	61.79
9	SSPC 9	4825.43	15.1	78.88
10	SSPC 10	6306.93	46.76	95.56
11	SSPC 11	654.06	0	22.42
12	SSPC 12	563.56	0	3.38
13	SSPC 13	1100	5.7	27.76
14	SSPC 14	1090.11	0	9.76
15	SSPC 15	878.52	8.31	14.72
16	SSPC 16	662.51	64.68	7.7
17	SSPC 17	1138.78	0	10.65
18	SSPC 18	1264.68	0.16	1.18
19	SSPC 19	3020.3	8.22	181.14
20	SSPC 20	5491.16	0	18.05
21	SSPC 21	0	6.03	1.72
22	SSPC 22	81.39	0	29.92
23	SSPC 23	301.29	43.5	38.26
24	SSPC 24	1507.11	59.58	45.01
25	SSPC 25	573.61	50.83	55.77
26	SSPC 26	358.41	44.35	69.56
27	SSPC 27	6190.57	34.05	307.84
28	SSPC 28	1078.04	50.02	57.29
29	SSPC 29	107.8	34.7	9.76
30	SSPC 30	44.25	0	0
	MEAN	1586.811	27.250	46.897

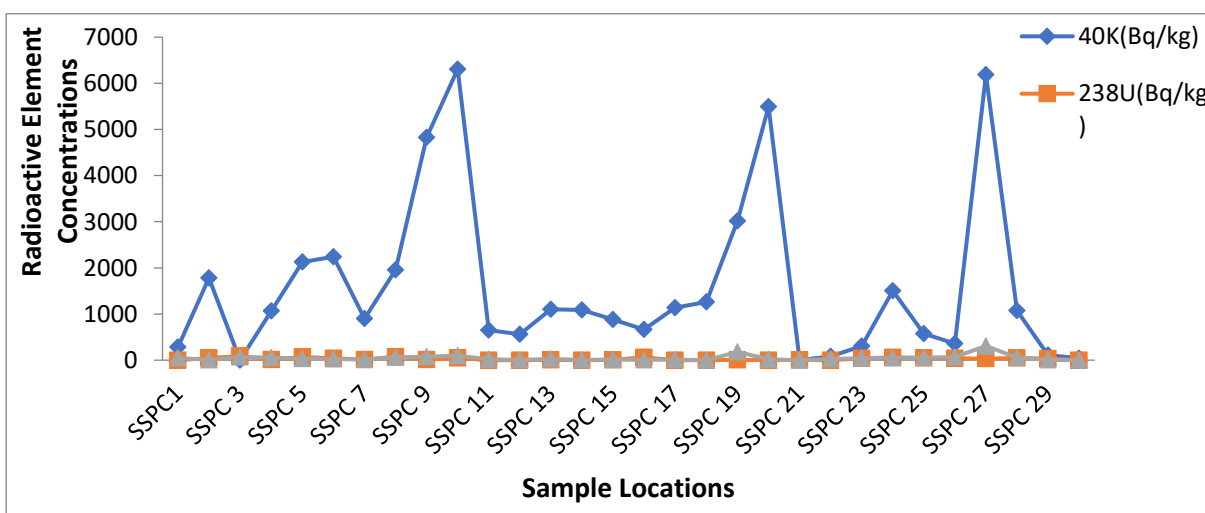


Figure 1: Deviation in Measured Radioactive Element Concentrations in Studied Sediments

Table 3: Showing Computed Results of Radiological Hazard Risk In Sediment Samples

Sample Code	R _{aeq}	I _{yr}	H _{ex}	H _{in}	D	AEDE Outdoor	ELCR×10 ⁻³
SSPC1	91.70	0.70	0.25	0.25	42.10	0.050	0.180
SSPC 2	197.90	1.60	0.50	0.65	101.10	0.120	0.440
SSPC 3	185.40	1.30	0.50	0.70	82.90	0.100	0.355
SSPC 4	168.10	1.30	0.45	0.50	82.10	0.100	0.350
SSPC 5	282.50	2.20	0.75	0.90	142.15	0.170	0.610
SSPC 6	255.70	2.10	0.70	0.80	130.70	0.160	0.560
SSPC 7	108.50	0.90	0.30	0.30	55.00	0.065	0.240
SSPC 8	312.40	2.40	0.80	1.00	153.80	0.190	0.660
SSPC 9	499.50	4.10	1.35	1.40	257.10	0.315	1.100
SSPC 10	669.00	5.50	1.80	1.90	343.80	0.420	1.475
SSPC 11	82.40	0.70	0.20	0.20	41.17	0.050	0.175
SSPC 12	48.20	0.40	0.13	0.13	25.60	0.030	0.109
SSPC 13	130.10	1.00	0.35	0.35	65.70	0.080	0.280
SSPC 14	97.90	0.80	0.26	0.25	51.50	0.063	0.220
SSPC 15	97.00	0.80	0.25	0.30	49.60	0.060	0.212
SSPC 16	126.70	0.95	0.30	0.50	62.30	0.076	0.265
SSPC 17	102.90	0.90	0.27	0.25	54.10	0.066	0.232
SSPC 18	99.20	0.85	0.25	0.25	53.50	0.065	0.229
SSPC 19	499.80	3.90	1.35	1.40	242.05	0.230	1.040
SSPC 20	448.60	3.80	1.20	1.20	240.17	0.295	1.030
SSPC 21	8.50	0.05	0.02	0.04	3.85	0.004	0.016
SSPC 22	49.10	0.35	0.13	0.10	21.90	0.025	0.094
SSPC 23	121.40	0.90	0.30	0.40	56.38	0.069	0.242
SSPC 24	239.10	1.85	0.65	0.80	118.25	0.145	0.510
SSPC 25	174.75	1.30	0.50	0.60	81.90	0.100	0.350
SSPC 26	171.40	1.20	0.50	0.50	78.50	0.095	0.335
SSPC 27	950.90	7.40	2.55	2.60	464.75	0.570	1.995
SSPC 28	214.95	1.60	0.60	0.70	103.60	0.127	0.445
SSPC 29	56.95	0.40	0.15	0.25	26.60	0.030	0.110
SSPC 30	3.40	0.03	0.10	0.10	1.85	0.002	0.008
MEAN	216.50	1.70	0.60	0.65	107.80	0.130	0.460

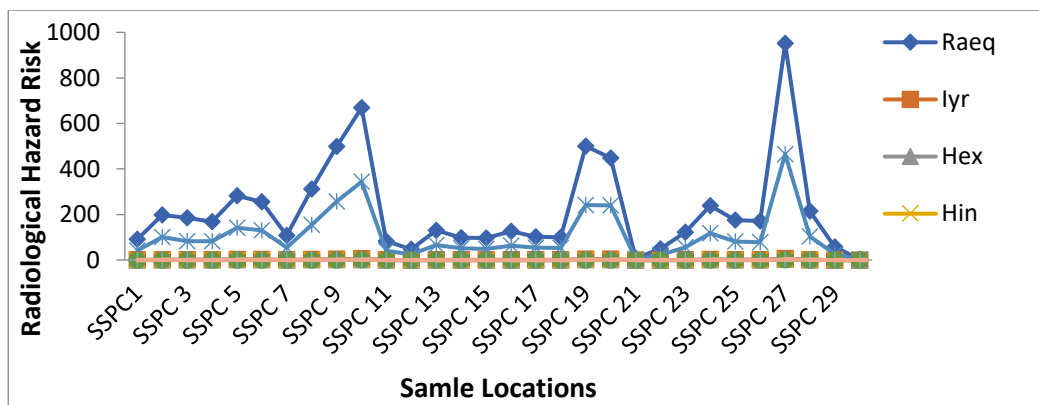


Figure 2: Deviation in Computed Radiological Hazards Risk in Studied Sediments

The measured activity concentration of radionuclides in sampled sediments and the potential health hazard implications of the Niger Delta region are as shown in Table 2 and Table 3, while Figs. 1 and 2 demonstrate the variations in radioactive elements concentrations and its radiological health implications in sediment samples collected from the region. The activity concentration of

⁴⁰K has a range of 44.25 Bq/kg at SP 30 to 6306.90 Bq/kg at SP 11 with a mean value of 1586.80 Bq/kg which exceeded 400 Bq/kg world average (UNSCEAR, 2012). The ²³⁸U activity concentration ranged from 0.16 Bq/kg at SP18 to 87.72 Bq/kg at SP 3 with a mean value of 27.25 Bq/kg which is within 35 Bq/kg world average (UNSCEAR, 2012), while the activity concentration of

²³²Th ranged from 1.18 Bq/kg at SP 18 to 307.84 Bq/kg at SP 27 and a mean value of 46.90 Bq/kg which exceeded 30 Bq/kg world average (UNSCEAR, 2012). These values at various locations exceeded the world average of the radionuclides. This increase may be attributed to the hydrocarbon exploration activities in the region, due to release of radiological polluted substances such as discharged produced, spillage, contaminated soil, and contaminated effluents in to the water bodies. The obtained values also exceeded reported values of scientists in similar region Virk, 2016, Ononugbo et al., 2016, Irunkwor et al., 2022, but are within the values reported by Sowole et al., 2019, Akinloye & Olomo 1995. The R_{aeq} of three natural radionuclides varies from 3.40 Bq/kg to 669.00 Bq/kg with a mean value of 216.50 Bq/kg, these values are below the threshold value of 370 Bq/kg (UNSCEAR, 2000). The I_{yr} values ranged from 0.03 Bq/kg to 7.40Bq/kg with a mean value of 1.70 Bq/kg, the H_{in} and H_{ex} ranged from 0.02Bq/kg to 2.55 Bq/kg, 0.04 Bq/kg to 2.60 Bq/kg with a mean value of 0.65 Bq/kg and 0.60 Bq/kg respectively, the D ranged from 1.85 ηGy/h to 464.75ηGy/h with a mean value of 107.80 ηGy/h, the annual effective outdoor dose rate ranged from 0.002 to 0.570 mSv/y with a mean value of 0.13 mSv/y, the indoor AEDR ranged 0.010 to 2.605 mSv/y with a mean value of 0.605 mSv/y while the ELCR ranged from 0.0079 to 1.99 with a mean value of 0.460. However, the computed mean hazard indices have important consequences for both the environment and human health. Elevated radiation levels in certain areas might harm local ecosystems. For example, plants and

animals in these places may be exposed to more radiation, affecting development, reproductive habits, and other ecological activities.

Although most sediment samples fell under the prescribed radiological limits, the increased dosage rates recorded in some locations are alarming. Long-term exposure to excessive radiation levels may offer major health concerns to people, including an increased risk of cancer.

Statistical Analysis

Statistical software SPSS 25.0 was used to analyze the measured activity concentration and a bell-shaped pattern frequency distribution of corresponding histograms are presented in Figures 3 – 5. These histogram distributions illustrate the uniform spread of radionuclides across the studied area. Additionally, the histograms reveal that ⁴⁰K, ²³⁸U and ²³²Th (Bq/kg) exhibit a certain level of multimodality in their distribution, suggesting the presence of diverse mineral compositions within the sediment samples. To further identify the type distribution, a quantile-quantile plot (Q-Q plot) was examined for measured radionuclides as presented in figures 3- 5. The plots shows that the data point along the position line suggesting that the activity concentration data follow a normal distribution. Figure 6 display box plots illustrating the distribution of activity concentration. The median values for ²³⁸U and ²³²Th (Bq/kg) are positioned near the center of their respective boxes; whereas the median for ⁴⁰K is positioned closer to the lower boundary, indicating a skewed distribution.

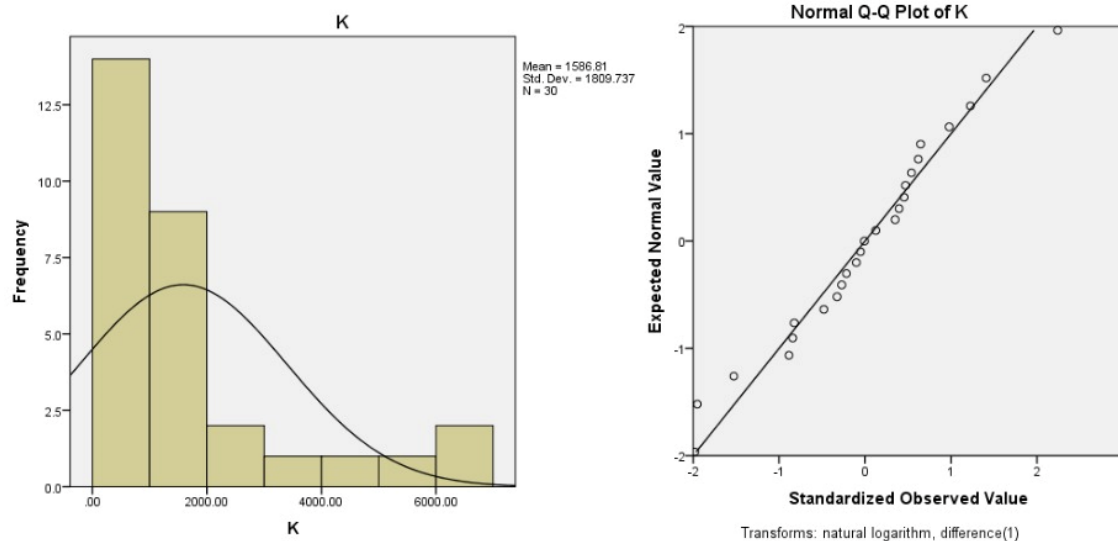


Figure 3: Showing Pie Chart Statistical Diagram and Q-Q plots of ⁴⁰K in Sediment

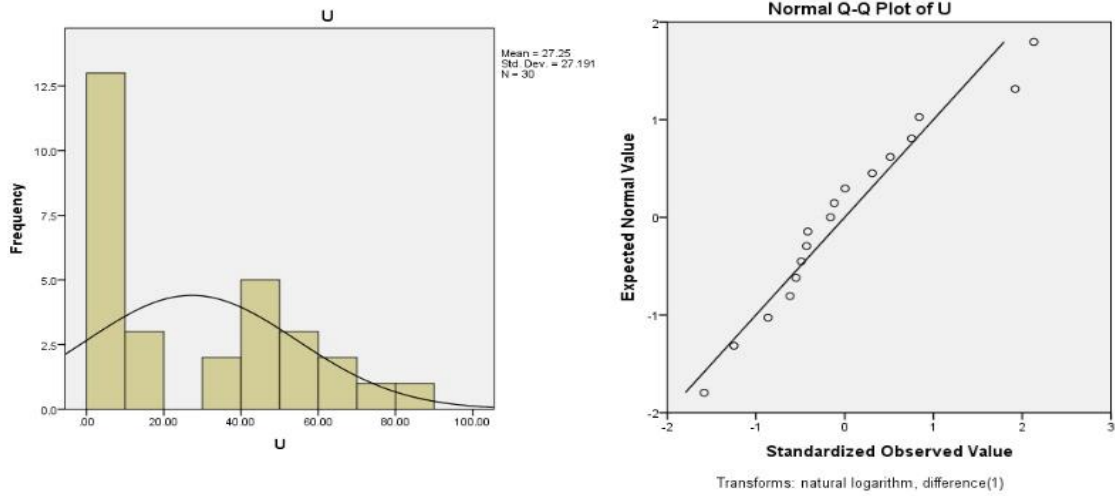


Figure 4: Showing Pie Chart Statistical Diagram and Q-Q plots of ^{238}U in Sediment

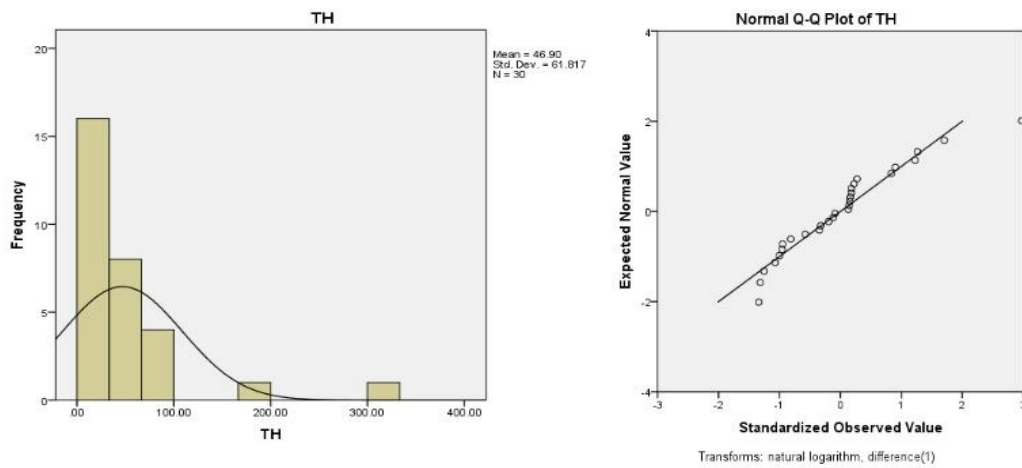


Figure 5: Showing Pie Chart Statistical Diagram and Q-Q plots of ^{232}Th in Sediments

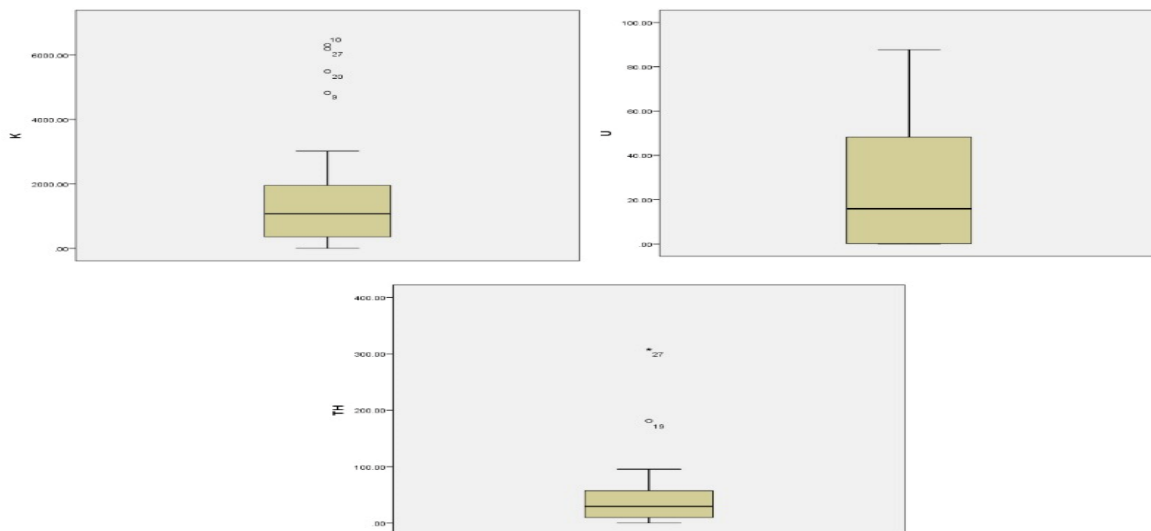


Figure 6: Showing Radioactive Elements Activity Concentrations of Sediments Box Plots

CONCLUSION

The specific activity of the thirty (30) natural radionuclides in sediment samples collected were analyzed using NaI (TI) detector. The activity concentrations of these radionuclides in the sediment exceeded the world standards permissible limit. These sediments therefore may not be too safe for constructions since it contain high level of radiation. However, sediments should be properly monitor and remediated before it can be used for construction, to avoid radiological health concern and environmental hazards. Nevertheless, the findings can be used as a reference point for other research activities to be conducted in the future in relation to the study area.

REFERENCES

- Abbadly, A. G. E. (2004), Estimation of radiation hazard indices from sedimentary rocks in Upper Egypt. *Appl. Radiat. Isot.* 60, 111–114
- Adedokun B. Margaret, Ibitoye Z. Ayo, Victor Saghana & Olasunkanmi I. Olusola (2025) Assessment of radiological risks in using coastal sediments as building materials in Lagos, Nigeria. *Discover Environment*. | <https://doi.org/10.1007/s44274-025-00265-z>
- Adewoyin, O. O, Maxwell, O, Akinwumi, S. A, Adagunodo, T. A, Embong, Z. & Saeed, M. A, (2022). Estimation of activity concentrations of radionuclides and their hazard indices in coastal plain sand region of Ogun state, *Scientific Reports* 12 (1). <https://doi.org/10.1038/s41598-022-06064-3>.
- Agbalagba, E O, Avwiri, G O, & Chad-Umoreh, Y E (2012) ; γ - Spectroscopy measurement of natural radioactivity and assessment of radiation hazard indices in soil samples from oil fields environment of Delta State, Nigeria. *Journal of Environmental Radioactivity*. 109: 64-70
- Baafi E. Nyarko, Kpeglo D. Okoh, Philip Deatanyah, Augustine Faanu (2025) Assessment of natural radioactivity levels in beach sand and their associated radiation hazards in the Southwestern coastline of Ghana. *Journal of Radiation Research and Applied Sciences* 18 (2025) 101521 <https://doi.org/10.1016/j.jrras.2025.101521>
- Diab, H. M., S.A. Nouh, A. Hamdy & S.A. El- Fiki (2008). Evaluation of natural radioactivity in a cultivated area around a fertilizer factory. *J. Nucl. And Rad. Phys.* 3(1): 53- 62.
- El-Arabi, A. M. (2006), ^{226}Ra , ^{232}Th and ^{40}K concentrations in igneous rocks from eastern desert, Egypt and its radiological implications. *Radiat. Meas.* 42, 94–100.
- Esi E. Oghenevovwero, Akpoyibo Ogheneovo, Nwankwo Rufus Chigozie & Vwawware Oruaode Jude (2023) [Estimation of the variability of sand deposits in chosen communities in parts of Niger delta, Southern-Nigeria using geophysical techniques](#), *Solid Earth Sciences* 8 (4), 267-282
- Esi EO & Akpoyibo O. (2023) [Estimation Of Aquifer Transmissivity For Typical Oil Producing Communities of Western Niger Delta Using Electrical Resistivity Survey](#), *Coast Journal of the School of Science OAUSTECH Okitipupa* 5 (2), 893-908
- Esi Oghenevovwero E., Avwiri Gregory O., Sylvanus Onjefu A., & Onwudiwe Damian C. (2024) Radiometric survey of sediments and health risk assessments from the southern coastal area of Delta State, Nigeria. *Heliyon* 10: 1 – 15, e26805
- George, A I, Adagunodo, T A, Ojesanmi, K, Ojoawo, I A & Ravisankar, R (2018), Radioactivity and radiological hazards from a kaolin mining field in Ifonyintedo, Nigeria. *MethodsX* 5, 362-374
- Irunkwor, T C, Abanjo, N & Ogboi, K. C, (2022) Assessment of Natural Radionuclides and Radiological Health indices in Soil of Oil Producing Communities, Rivers State, Nigeria, *International Journal of Advances in Engineering and Management*. 4(9), 1327-1338.
- Isinkaye M.O. & Emelue H.U. (2015) Natural radioactivity measurements and evaluation of radiological hazards in sediments of Oguta Lake, South East, Nigeria *J. Radiat. Res. Appl. Sci* 8: 459, <https://doi.org/10.1016/j.jrras.2015.05.001>.
- Isinkaye, M.O. (2013), Natural radioactivity levels and the radiological health implications of tailing enriched soil and sediment samples around two mining sites in Southwest Nigeria. *Radiat Prot Environ*. 36:122-127.
- Jibiri ,N.N, Isinkaye M.O & Momoh H.A. (2014), Assessment of radiation exposure levels at Alaba e-waste dumpsite in comparison with municipal waste dumpsites in southwest Nigeria *J of Rad Research and App Sci.*, 7(5) 36 -541.
- Jibiri N N. & Okeyode, I C. (2012), Evaluation of radiological hazards in the sediments of Ogun River, South-Western Nigeria, *Radiat. Phys. Chem.* 81: 103–112.

- Ononugbo, C.P, Avwiri, G.O. & Ogan, C.A. (2016), Natural radioactivity measurement and evaluation of radiological hazards in sediment of Imo River, in rivers state, Nigeria by gamma ray spectrometry, *IOSR J. Appl. Phys.* 8 (3), 75–83.
- Qureshi A A, Tariq S, Din K U, Manzoor S, Calligaris C. & Waheed W, (2014) Evaluation of excessive lifetime cancer risk due to natural radioactivity in the rivers sediments of Northern Pakistan, *J. Radiat. Res. Appl. Sci.* 7(4) 438–447.
- Serdar Dizman, Tolga Akdemir, Cafer Mert Mes, ilkanat, Vagif Nevruzoglu Esra Bal & Recep Keser, (2024) Investigation and mapping of natural and artificial radioactivity in sediment samples from borçka black lake, artvin-Turkey, *Int. J. Environ. Anal. Chem.* 104 (9): 2165–2179, <https://doi.org/10.1080/03067319.2022.2060084>
- Sivakumara, A. Chandrasekaran, R. Ravisankar, S.M. Ravikumar, J. Prince Prakash Jebakumar, P. Vijayagopal, I. Vijayalakshmi, M.T. & Jose R.M (2014) Measurement of natural radioactivity and evaluation of radiation hazards in coastal sediments of east coast of Tamilnadu using statistical approach, *J. Taibah Univ. Sci.* 8: 375–384.
- Suresh, G M., Ravisankar, R., Rajalakshmi, A., Sivakumar, S., Chandrasekaran, A., and Anand, D.P., (2014) Measurements of natural gamma radiation in beach sediments of north east coast of Tamilnadu, India by gamma ray spectrometry with multivariate statistical approach. *J. Radiat. Res. Appl. Sci.* 7 (1), 7–17.
- Sylvanus Ameh Onjefu, Aina Nancy Iyaloo Kauluma, Munyaradzi Zivuku, Emmanuel Ejembi, Roswita Hambeleleni Hamunyela & Bismark Mzubanzi Tyobek (2022) Assessment of radioactivity levels in shore sediments along the coastline of the Orange River, Oranjemund, Namibia, *Heliyon* 8: e10579.
- Taskin, H, Karavus, M, Ay, P, Touzogh A, Hindiroglu S. & Karaham G (2009); Radionuclide concentration in soil and lifetime cancer risk due to gamma radioactivity in Kirklareli, Turkey. *J Environ Radioact* .100 (1): 49-53. <https://doi.org/10.1016/j.jenvrad.2008.10.012> PMID:19038480
- Tyongiga S., Atsue, T. & Joseph E. (2024). Assessment of Natural Radioactivity in Sediments and Groundwater from Selected Areas in Funtua Town, Katsina State, Nigeria. *J. Appl. Sci. Environ. Manage.* 28 (6) 1799-1806
- UNSCEAR, (2012). “Effects and Risk of ionizing Radiation; United Nations Scientific Commission on the Effects of Atomic Radiation. Report to the General Assembly, with Scientific Annexes. United Nations, New York
- UNSCEAR (2000). Sources and Effects of Ionizing Radiation. United Nations Scientific Commission on the Effects of Atomic Radiation. Report to the General Assembly, with Scientific Annexes Volume 1. United Nations, New York
- Virk HS (2016). Measurement of the concentration of natural Uranium in ground waters of Bathinda District (S. Punjab) for the assessment of annual effective dose. *Glob. J. hum. Soc. Sci.* 16 (5) 24-30.
- WHO (2011). Guidelines for drinking water quality 4th Ed; World Health Organization, Geneva
- Xinwei, L. & Xiaolon, Z, (2008) Natural radioactivity measurements in Rock samples of Chihua Mountain National Geological Park, China. *Radiat. Prot.Dosi.*128, 77-82.