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RESEARCH

A baseline monitoring of radiological sediment quality and associated risk assessment in coastal ecosystems of the Republic of Congo

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Abstract This study presents the first data on levels of natural radioactive elements in sediments from coastal ecosystems of the Republic of Congo. Sediment samples from five coastal sites were collected and analyzed by high-resolution gamma spectrometry for determination of activities of long-lived gamma-emitting radionuclides (^{234}Th, ^{238}U, ^{226}Ra, ^{210}Pb, ^{228}Th, ^{228}Ra, and ^{40} K). The specific activities were of the same order of magnitude as those measured in sediments of most countries neighboring the Republic of Congo. However, variations in activities were observed from one site to another and also from one sampling point to another within the same site without exceeding the global average reference values. It can be assumed, therefore, that no significant anthropogenic impact is perceptible in the study area. The most commonly used radiological hazard parameters, based mainly on ^{238}U, ^{232}Th, and ^{40} K activities, were assessed and the ERICA tool was applied to quantify the radiation exposure burden to human and biota resulting from radionuclides in sediments. Besides being useful for future monitoring efforts, the data produced in this work could be important for the worldwide database on radioactivity in the oceans and seas (MARIS) since no data are available in the Congolese marine environment.

Highlights

- Levels of radionuclides were assessed for the first time in coastal sediments in the Republic of Congo.
- Large variabilities of radionuclide activities within some sites despite the short distance between the sampling points.
- No significant radiological impact was perceptible in the study area.

Keywords Radionuclide · Coastal sediment · Radiological risk · ERICA tool · Republic of Congo

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Introduction

Coastal zones, the natural interface between terrestrial basins and the marine environment, are natural resources of great environmental and economic value that are subject to increasing human pressure. The exploitation of coastal resources has often led to the degradation of marine ecosystems or adverse effects on their environmental quality.

The contamination of marine sediments with radioactive elements can expose organisms, such as plants and animals, to harmful ionizing radiation and make ecosystems vulnerable.

The exploration and exploitation of mining resources, such as oil, gas, and ore, have undoubtedly been primary drivers of development for human society. However, they also pose a significant source of environmental degradation and radioactive pollution (Babatunde et al., 2015; Menet-Dressayre, 1992; Oni et al., 2011; Thi Hong Hanh Le, 2020). The Republic of Congo's economy is based on oil exploitation in its coastal sedimentary basin, as well as some mining activities (such as the phosphate mines of Hinda and Potash of Sintou-Nkola), port operations, fishing, agriculture, and livestock farming. These anthropogenic activities have led to environmental radioactive contamination, as many studies have shown that mining activities can result in the mobilization and distribution of radionuclides from the earth's crust, causing pollution in the environment in general and in marine and coastal environments in particular (Thi Hong Hanh Le, 2020; Oni et al., 2011; IAEA (International Atomic Energy Agency), 2004; IRSN, 2002; Menet-Dressayre, 1992). Unfortunately, there are no studies on radioactive pollution in marine and coastal environments in the Republic of Congo. This study is the first of its kind and was conducted on the natural radioactivity and estimation of effective doses for the marine-coastal environment of Congo, which aims to determine the concentrations of natural radioactive contaminants, such as $^{234}Th(^{238}U)$, $^{214}Bi(^{226}Ra)$, ^{210}Pb, $^{212}Bi(^{228}Th)$, $^{228}Ac(^{228}Ra)$, and ^{40} K, to identify, characterize, and assess their radiological and toxicological risks in these ecosystems (Babatunde et al., 2015; Hashim et al., 2004; Oni et al., 2011). The objective of this work is to produce baseline data on radionuclide activities in the Congolese coastal sediments to be used in future radioactive assessment efforts and, on the other hand, to contribute to the global database by providing data from a region where none is available. Another objective is the use of ERICA tool and common radiological parameters to assess the potential radiation dose received by biota and to assess the potential risk to human health resulting from exposure to ionizing radiation.

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Materials and methods

Description of the study area

The Congolese coastal sedimentary basin is located in the Republic of Congo's Pointe-Noire and Kouilou departments, part of the Gulf of Guinea in the South Atlantic. The basin extends over an area of approximately 17,000 km^2, running parallel to the Mayombe chain, from southwest Gabon (Mayumba) to northeast Angola (Cabinda) (Desthieux et al., 1993; Kebi-Tsoumou, 2018). The study area consists of five coastal waterbodies distributes along the coastline:

- The Tchilassi River (Loango Village) discharges into the ocean, at Loango Beach and features a dock for small traditional fishing boats. The river originates from the village at the foot of the Graben known as the Diosso Gorges, with small fields of cassava, maize, vegetables, and fruit plantations surrounding it. The study site is situated in a grassy savannah region predominantly consisting of Loudetia hypparhenia (Miyouna et al., 2019).

- The Loukondzi lagoon site consists of two branches—one parallel and one perpendicular to the coastline. It is located near a construction project area upstream. Among other things, there is a sand quarry, an area for raising cattle, and some small metallurgical industrial complexes of the Kounda Special Economic Zone.

- The Red River site originates in the Diosso grabens, is oriented perpendicular to the Atlantic coast, and empties into the ocean via a predominantly tidal estuary on the Loango bay. The Red River flows through the village of Lémba, where upstream and downstream of the village, ponds and cattle breeding areas are observed. Also observed is the metallurgical industrial complex of the Kounda Special Economic Zone towards the collection points, vast fields of vegetables belonging to several cultivators and, above all, underground and surface oil pipelines. It should also be noted that in the area there are discharge pipes for petroleum effluents in the marshes of the area, which are tributaries of the Red River. The distance between the Red River site and the Loukondzi lagoon is approximately 500 to 800 m along the shoreline.

- At its mouth in Pointe-Noire Bay, the Songolo River is composed of a large mangrove swamp of Rhizophora mangle and Avicennia mangroves. The Songolo River runs through the city and serves as the largest repository for household waste in the city, as well as the main collector for small streams in the area. Near its mouth, there is a complex of industrial facilities such as the autonomous port, onshore bases of different oil companies and others. Located in the center of an area of loading and unloading of fishing boats, there is also a fish market and homes of fishermen nearby.

- The Mvassa Lagoon is located to the south of the city and opens into the ocean through a tidal-dominated channel. A tourist beach can be found here. The lagoon is composed of a disappearing mangrove of Rhizophora mangle and Avicennia mangroves due to the presence of human constructions and sand mining. Upstream from the lagoon, there is an industrial complex specialized in the treatment of petroleum.

Sampling and description of marine sediments

The sampling campaign was performed over a period of 17 days in the low tide, between the end of the rainy season and the start of the dry season (May 15), from May 3 to May 21, 2022. Five hundred grams of surface sediment samples were obtained, using a scalpel and an auger, from a point at five sites (rivers and lagoons), Fig. 1 in depths between 0 and 5 cm. The distance between sampling points is approximately between 50 and 80 m at each site. Information regarding the sampling sites, their corresponding GPS readings and sample descriptions, are listed in Table 1.

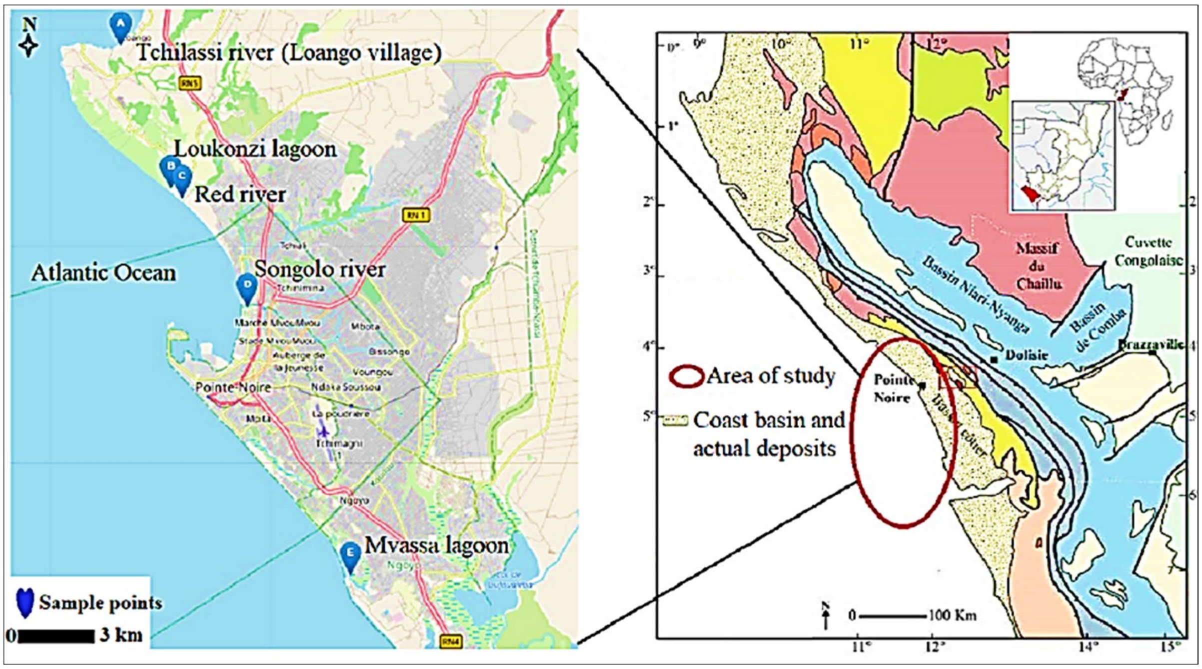

Fig. 1 Sampling points and location of study area

Table 1 GPS location of sampling points and description of marine sediment samples

Site	Code	GPS coordinates	Color	Comment
Tchilassi River (Loango village)	LTCH	S04°39.570' E011°48.300'	Dark gray	Fine-grained silty clay, presence of fine roots and plants
Loukonzi Lagoon	RLK02	S04°43.042' E011°49.506'	Gray to red	Plastic clay, presence of dead leaf on surface, fine roots, and plant
	RLK05	S04°43.052' E011°49.488'	Gray to red	
	RLK07	S04°43.022' E011°49.517'	Gray to red	
Red River	RR01	S04°43.287' E011°49.773'	Blood red	Very plastic clay, covered by a layer of sand at the top (0–2 cm about)
	RR02	S04°43.277' E011°49.781'	Blood red	
	RR03	S04°43.274' E011°49.782'	Blood red	
Songolo River	RS01	S04°45.918' E011°51.340'	Dark	Organic matter rich-mud, plant debris, rest of fractured and unbroken of biological organisms, presence of human materials
	RS05	S04°45.879' E011°51.333'	Dark	
	RS06	S04°45.874' E011°51.301'	Dark	
Mvassa Lagoon	MV01	S04°52.426' E011°53.807'	Dark	Fine-grained silty clay, presence of fine roots, plants' debris, shells, and over rest of broken and unbroken biological organisms
	MV03	S04°52.439' E011°53.813'	Dark	
	MV04	S04°52.446' E011°53.820'	Dark	

Sample preparation and measurement

The sediment samples were first cleaned of biological materials and debris before drying to a constant weight and crushing and then conditioned in polyethylene containers which were closed and hermetically sealed for more than three weeks to allow radioactive equilibrium between ^{226}Ra and its short-lived decay products before being analyzed by gamma-ray spectrometry. Gamma-ray spectrometry involves measuring the energy and counting the number of γ photons emitted from a sample for a period of time; this allows for the identification of different radioelements through qualitative analysis and the determination of their concentration through quantitative analysis (Pirard, 2006). At CNESTEN in Morocco, gamma-emitting radionuclides were measured through the use of an ORTEC broad energy germanium detector, surrounded by a copper layer and housed in a 10-cm-thick, high-purity lead shield. The Maestro software was used for data acquisition and spectra analysis. The relative efficiency and resolution were, respectively, 50% and 1.8 keV for the 1332 keV ^{60}Co gamma peak. A multi-gamma-certified solution, provided by Amersham conditioned in the same geometry as that of samples (50 ml), was used for energy and efficiency calibration of the gamma spectrometer. The activity concentration (Bq kg^{-1}) for each radionuclide in each sample was determined from the net count rate under the photopeak of interest, detector efficiency, gamma intensity, and sample mass. ^{210}Pb activities were corrected for self-absorption using a disk source of ^{210}Pb counted in an empty sample vial, on a sample vial filled with tap water, and on the sample vial filled with sediment. This procedure allowed obtaining the self-absorption factor used in the activities correction). K = 1 is the coverage factor of measurements. Quality control of the procedure was carried out using a reference material (IAEA-326 and IAEA-327) (IAEA, 2001). There was good agreement between measured and certified values, reaching more than 96% in all cases. The activity concentrations of ^{234}Th(^{238}U), ^{214}Bi(^{226}Ra), ^{212}Bi(^{228}Th), ^{228}Ac(^{228}Ra), and ^{40} K in the samples were determined through measuring the gamma emissions of their progeny nuclides while assuming secular equilibrium, while ^{210}Pb and ^{40} K were directly determined using gamma peaks 46.54 keV and 1460.8 keV, respectively.

Radiological parameters assessment

Sediments in general are utilized by humans for various purposes and can act as storage reservoirs for both radioactive and non-radioactive materials such as heavy metals and hydrocarbons. In order to understand the potential radioactive hazards presented by the marine sediments found in the Congolese coastal basin and the risks they pose to people who rely on them for various uses, five radiological parameters were evaluated. These parameters include the total absorbed dose rate in air (D_{air}), radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), annual gonadal dose equivalent (AGDE), and annual effective dose equivalent (AEDE). These radiological parameters are calculated from the activity concentrations of three natural radionuclides ^{226}Ra, ^{228}Ra(^{232}Th), and ^{40} K expressed in Bq kg^{-1} (Ait Bouh et al., 2021b; Kritsananuwat et al., 2014; Tripathi et al., 2013).

In addition to the above parameters, the Environmental Risk from Ionizing Contaminants Assessment (ERICA) tool has been used to evaluate the potential radiation dose received by biota. The software implements three-tiered approaches, beginning with generic screening, followed by more detailed screening assessments and probabilistic assessment capability processes to suggest potential risks. More details about the potential of ERICA tool can be found in Ait Bouh et al. (2021a) and Botwe et al. (2016).

Results and discussion

Activity concentrations

The activity concentrations of radionuclides ^{234}Th(^{238}U), ^{214}Bi(^{226}Ra), ^{210}Pb, ^{212}Bi(^{228}Th), ^{228}Ac(^{228}Ra), and ^{40} K in marine sediments of the coastal sedimentary basin of Congo are presented in Table 2. The highest concentrations were observed for ^{40} K (72.21 Bq kg^{-1} dw), followed by ^{210}Pb, ^{228}Ra(^{232}Th), and ^{212}Bi(^{228}Th) with average activities of 39.02 Bq kg^{-1} dw, 29.12 Bq kg^{-1} dw, and 23.43 Bq kg^{-1} dw, respectively, while the lowest activity is observed for ^{234}Th(^{238}U) and ^{226}Ra with values of 19.57 Bq kg^{-1} dw and 9.86 Bq kg^{-1} dw respectively. The Loukonzi lagoon seems to exhibit the highest activity concentrations for most measured radionuclides.

Several factors influence the concentration of radionuclides in sediments and their transport in sedimentation media, such as geology (petro-mineralogical parameters), hydrology, external geodynamic parameters, and the physico-chemical parameters (e.g., pH, salinity), organic matter content of the environment (Botwe et al., 2016; IRSN, 2010; Onjefu et al., 2017; Szarlowicz et al., 2019). The low radionuclide contents of ^{234}Th(^{238}U) and ^{226}Ra could be linked to one

Table 2 Activity concentrations (in Bq kg^{-1} dw) of radionuclides in marine sediment samples taken from the Congolese coastal sedimentary basin

Location	Ref	A[^{234}Th (^{238}U)]	A(^{226}Ra)	A(^{210}Pb)	A(^{228}Th)	A(^{228}Ra)	A(^{40} K)
Tchilassi River	LTCH	10.0 ± 3.1	5.2 ± 0.7	8.4 ± 3.9	4.8 ± 0.3	6.5 ± 0.9	40.8 ± 3.9
Loukonzi Lagoon	RLK02	29.3 ± 2.0	17.6 ± 1.0	38.4 ± 2.0	76.0 ± 3.9	80.5 ± 4.9	107.2 ± 6.8
	RLK05	26.5 ± 1.9	14.1 ± 1.2	66.3 ± 3.1	62.3 ± 3.4	87.5 ± 5.9	122.7 ± 9.6
	RLK07	28.9 ± 5.7	14.9 ± 1.6	34.5 ± 7.3	56.4 ± 3.0	66.7 ± 4.4	96.9 ± 8.0
Red River	RR01	31.9 ± 4.7	15.2 ± 1.4	28.7 ± 6.0	29.2 ± 1.6	34.8 ± 2.5	46.4 ± 4.9
	RR02	19.5 ± 1.5	14.0 ± 0.9	27.9 ± 2.9	20.9 ± 1.1	25.2 ± 2.0	34.5 ± 2.1
	RR03	9.0 ± 1.4	9.0 ± 0.6	17.5 ± 2.2	10.0 ± 0.6	17.1 ± 1.6	26.8 ± 2.0
Songolo River	RS01	33.7 ± 1.8	4.9 ± 0.5	9.6 ± 1.8	5.5 ± 0.4	9.3 ± 1.1	63.8 ± 4.0
	RS05	12.9 ± 1.9	6.7 ± 0.6	35.1 ± 2.4	10.0 ± 0.5	11.8 ± 1.0	133.3 ± 7.7
	RS06	15.4 ± 1.1	7.2 ± 0.5	30.1 ± 1.7	12.0 ± 0.6	14.5 ± 1.1	71.6 ± 4.5
Mvassa Lagoon	MV01	15.0 ± 3.3	7.9 ± 0.8	79.6 ± 6.4	7.2 ± 0.4	8.5 ± 1.0	93.6 ± 6.8
	MV03	8.7 ± 1.2	6.2 ± 0.5	53.5 ± 2.4	5.3 ± 0.3	9.3 ± 1.0	38.3 ± 2.9
	MV04	13.7 ± 2.7	5.4 ± 0.6	77.8 ± 6.0	5.1 ± 0.3	6.9 ± 0.9	62.9 ± 4.8
Minimum		8.7	4.9	8.4	4.8	6.5	26.8
Maximum		33.7	17.6	79.6	76.0	87.5	133.3
Mean		19.6	9.9	39.0	23.4	29.1	72.2

of the abovementioned parameters, such as the content of these radionuclides in the bedrock, as well as sediment transport processes and deposition into the marine environment, as highlighted in previous work (Botwe et al., 2016; IRSN, 2010; Szarlowicz et al., 2019).

Overall, the average activity values for the three radionuclides ^{226}Ra, ^{228}Ra, and ^{40} K in the samples were below the average reference values of 35 Bq kg^{-1}, 30 Bq kg^{-1}, and 400 Bq kg^{-1} respectively, as recommended by UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (2000). It can be assumed, therefore, that no significant anthropogenic impact is perceptible in the study area.

Radionuclide activities were of the same order of magnitude, with few exceptions, from one site to another but with large variabilities within some sites despite the short distance (~50 m) between the sampling points in each site. In the Red River, activities decreased substantially from the river mouth (location RR01) to the other locations in the inner part, while in Songolo River, the inverse effect was observed; the lowest activity was registered in the river mouth. On the other hand, activities were fairly uniform in the lagoons (Loukonzi and Mvassa). Large fluctuations of ^{40} K activity concentrations were registered among and/or within the studied sites. This radionuclide is known to be strongly associated with clay minerals (Love et al., 2003), i.e., at high clay content, high ^{40} K activity. Differences in mineralogical compositions of sediments could be behind the variabilities observed in radionuclide activities. In order to account for mineralogy variations among samples, the activities in Table 2 were normalized to ^{40} K mean activity according to the equation bellow:

$$C_{(Ri)_n} = C_{Ri} \times \left(C_m\left(^{40}k\right)/C\left(^{40}k\right)\right) \quad (1)$$

$C_{(Ri)n}$ the activity of radionuclide i to normalized;

C_{Ri} the initial activity of radionuclide i;

$C_{(m(^{40}k))}$ mean activity concentration of 40 k;

$C_{(^{40}K)}$ initial activity concentration of 40 k.

The results are plotted in Fig. 2. As can be seen in the plots, variabilities in most radionuclide activities are persistent but less intense. At the exception of ^{210}Pb activities, the plots showed two regions: the first covering the sites of the north of the basin (Loukonzi Lagoon and Red River) and those of the south (Songolo River and Mvassa Lagoon) with almost uniform activities in each region, but a notable difference in the activities between the two regions can be observed. From Table 2, it can be seen that ^{210}Pb and ^{226}Ra are not in equilibrium (the ^{210}Pb/^{226}Ra ratios are ranging from 3.2 to 72.4), which suggest that part of ^{210}Pb present in all sediments is of atmospheric origin, being this fraction the so-called excess ^{210}Pb derived from ^{222}Rn decay in the air and the subsequent dry and wet deposition (Laissaoui et al., 2018). The wide range of ratios indicates different delivery of ^{210}Pb to sediments among the studied sites, most likely due to differences in the amount of precipitations. Furthermore, all the studied sites are areas of sediment accumulation since the ^{226}Ra/^{228}Ra were below the unity, ranging from 0.16 to 0.93, in all the sampling points. Indeed, Arriola-Velásquez et al. (2021) suggested that ratios below 1 are indicative of accumulation and values above 1 would imply erosion.

The activity concentration results obtained from the Congolese coastal basin are consistent with previous studies conducted in coastal areas of the African marine environment (Table 3).

Bonny Estuary in Nigeria has the highest activity concentrations of all radionuclides. With the exception of ^{210}Pb, the results of the other radionuclides are similar to those of Botwe et al. (2016) in Ghana. Regarding ^{238}U, except for Orangea and Ramena in Madagascar, Bonny Estuary in Nigeria and Henties Bay Beach in Namibia, where activity concentrations are high, results from the Congolese coastal basin are quite consistent with those of other studies. Similar results were also obtained for ^{226}Ra, ^{232}Th, and ^{228}Th. However, for ^{40} K, results indicate lower activity concentrations compared to other studies. This difference could be attributed to the mineralogical and geochemical characteristics of the deposited sediment, which may have undergone natural and/or anthropogenic reworking (IRSN, 2010; Szarlowicz et al., 2019).

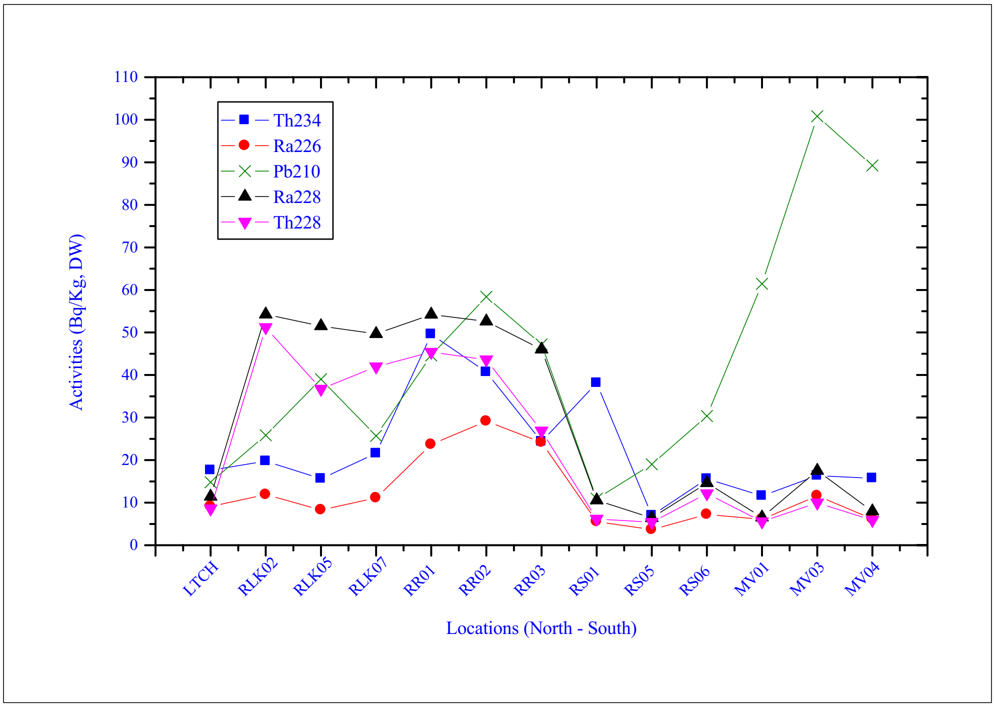

Fig. 2 Radionuclide Activities, in Bq kg^{-1} dw, in sediment samples of the Congolese coastal basin

Assessment of radiological health parameters

The calculated radiological parameters are given in Table 4. The absorbed dose rate (D_{air}) ranges from 7.97 nGy h^{-1} in Tchilassi River (Loango village) to 64.48 nGy h^{-1} in RLK05 located in Loukonzi Lagoon with an average value of D_{air} is 25.16 nGy h^{-1}. In Loukonzi Lagoon, D_{air} exceeds the radiological quality standard in 51 nGy h^{-1} (the world reference value) (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000) and has exceeded this limit twice.

For radium equivalent activity (Ra_{eq}), all sites except Loukonzi Lagoon have relatively low values. However, in Loukonzi Lagoon, Ra_{eq} exceeds the value of 100 Bq kg^{-1}, but it still under the recommended value of 370 Bq kg^{-1} (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000).

The mean value of external hazard index (H_{ex}) is lower than the recommended limit of 1 (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000), as the maximum value is 0.40.

Concerning the annual gonadal dose equivalent values (AGDE), this parameter was found in the range of 55.66–447.83 μSv y^{-1} with a mean value of 174.88 μSv y^{-1}, which is smaller than the recommended admissible limit of 300 μSv y^{-1} (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000).

Finally, the annual effective dose equivalent (AEDE) ranges from 9.78 to 79.08 μSv y^{-1} with a mean value of 30.85 μSv y^{-1}. The AEDE values, except for those in Loukonzi Lagoon, are considered normal and are low when compared to the background radiation value of 70 μSv y^{-1} (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000).

It should be noted that all calculated radiological parameters exhibit the same profile. Those estimated in Loukonzi Lagoon showed relatively high values, with absorbed dose rate (D), annual gonadal dose equivalent (AGDE), and annual effective dose equivalent (AEDE) values exceeding reference standards. Furthermore, these high values of the radiological parameters may have serious consequences on human health, particularly the AGDE value, which indicates

Table 3 Mean activity concentrations of radionuclides in sediment samples in (Bq kg^{-1} dw) reported for African marine environments

Country	Location	^{238}U series			^{232}Th series		^{40} K	Reference
		^{238}U	^{210}Pb	^{226}Ra	^{232}Th	^{228}Th		
Kenya	Mombassa Coast	23	-	-	26	-	480	(Hashim et al., 2004)
	Malindi Coast	21	-	-	19	-	519	
	Gazi	12	-	-	11	-	206	
	Sabaki River SBK2	27.7	39.8	21.7	40.8	42.9	485	(Wanjeri et al., 2021)
	Sabaki River SBK3	35	35.9	21	40.3	42.7	473	
Madagascar	Orangea and Ramena	109	-	-	77	-	198	(Kall et al., 2014)
Egypt	Nile Delta coastal	-	-	24	24	-	281	(El Gamal et al., 2007)
	Alexandria-Port Said	-	-	8	2	-	46	(Ramadan et al., 2017)
	coast shore sediment	-	26	25	31	-	428	(El Mamoney & Khater, 2004)
	Safaga Coast	-	-	25	21	-	618	(El-Arabi, 2005)
	Hurgada Coast	-	-	21	22	-	548	(El-Arabi, 2005)
Sudan	Flamingo bay	-	9	3	-	-	-	(Sirelkhatim et al., 2008)
Morocco	Oualidia Lagoon	-	-	29	41	-	265	(Ait Bouh et al., 2021b)
	Sidi Moussa Lagoon	-	-	63	65	-	449	(Ait Bouh et al., 2021b)
	Sebou Estuary	-	-	18	19	-	319	(Laissaoui et al., 2013)
Ghana	Tema Harbor	34	210	14	30	31	320	(Botwe et al., 2016)
	Coast of Greater Accra	-	-	22	109	-	30	(Amekudzie et al., 2011)
	Pra estuary	44	25.1	24.4	36.2	-	218	(Klubi et al., 2017)
	Volta estuary	69	87	18.3	30.5	-	319	
	Tonno Irigation, Navrongo	7	-	-	7	-	380	(Agalga et al., 2013)
Nigeria	Bonny Estuary	550	-	282	578	-	3626	(Babatunde et al., 2015)
	Ondo State, Igbokoda River	-	-	11	11	-	64	(Ademola and Ehiedu, 2010)
	Coastal area (oil producing)	19	-	-	29	-	122	(Oni et al., 2011)
	Coastal area (no oil producing)	15	-	-	28	-	89	(Oni et al., 2011)
	Delta of Niger	9	-	-	12	-	302	(Iwetan et al., 2015)
Namibia	Henties Bay Beach	176	-	-	40	-	350	(Onjefu et al., 2017)
	Orange River	63.5	-	-	54.9	-	417.0	(Onjefu et al., 2022)
Republic of Congo	Coastal Sedimentary Basin	20	39	10	29	23	72	Present Study

that the gonadal values may pose a serious threat to the bone marrow and bone surface cells of people in the study area (Abba et al., 2017). This is especially worrying in case these sediments are used as a construction material (Krieger, 1981), while other areas are considered safer for human health.

The variability in radiological parameters values could be explained by changes from one site to another in several factors such as mineralogical, petrographic, geochemical, hydrochemical, hydrophysical, and anthropological factors in the study areas (Szarlowicz et al., 2019; Onjefu et al., 2017; Botwe et al., 2016; IAEA (International Atomic Energy Agency), 2010; IRSN, 2010). The obtained results suggest undertaking further studies to understand the origin of the high indices in these study areas especially in Loukonzi Lagoon.

Application of ERICA tool

In this study, the ERICA tool (version 1.2) was used to assess the radiological risk to biota in surface marine sediment samples collected from the Congolese coastal basin. For all radionuclides: ^{234}Th(^{238}U), ^{226}Ra, ^{210}Pb, ^{212}Bi(^{228}Th), and ^{228}Ra(^{232}Th), maximum concentrations in Bq kg^{-1} dw corresponding to the worst-case scenarios in sediment samples were inputted into the tool. It is worth noting that ^{40} K

Table 4 Radiological risk parameters in marine sediment samples from the Congolese coastal basin

Sample references	D_{air} (nGy h^{-1})	H_{ex}	Ra_{eq} (Bq kg^{-1})	AGDE (μSv y^{-1})	AEDE (μSv y^{-1})
LTCH	8.0	0.1	17.5	55.7	9. 8
RLK02	61.3	0.4	141.0	424.7	75.1
RLK05	64.5	0.4	148. 7	447.8	79.1
RLK07	51.2	0.3	117.8	355.3	62.8
RR01	30.0	0.2	68.6	207.2	36.8
RR02	23.1	0.1	52.6	159.2	28.3
RR03	15.6	0.1	35.5	107.6	19.1
RS01	10. 6	0.1	23.2	74.2	13.0
RS05	15.8	0.1	33. 9	112.1	19.4
RS06	15.1	0.1	33.4	105.2	18.5
MV01	12. 7	0.1	27.2	89.2	15.5
MV03	10.1	0.1	22.4	69.9	12.3
MV04	9.3	0.1	20.2	65.4	11.4
Minimum	8.0	0.1	17.5	55.7	9. 8
Maximum	64.5	0.4	148. 7	447.8	79.1
Mean	25.2	0.2	57.1	174.9	30.9
The world reference values (UNESCAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000)	51	< 1	370	300	70

was not included by default in the ERICA database. In the first tier, the risk quotient (RQ) was calculated (Table 5). Phytoplankton and polychaete worms were selected as good bioindicators of marine ecosystem pollution because they accumulate higher concentrations of radionuclides (^{210}Pb, ^{228}Th, and ^{228}Ra). The work of Botwe et al. (2016), Klubi et al. (2017), and Wanjeri et al. (2021) also supports this assertion, where ^{210}Pb is the most concentrated radionuclide in biota in general and in phytoplankton in particular. The results of the risk quotients calculated in this tier exceeded unity for ^{228}Th, as shown in Table 5.

This result led to the assessment of the second tier, in which thirteen reference organisms specified by ERICA were considered by default, including benthic fish, birds, crustaceans, macroalgae, mammals, mollusks-bivalves, pelagic fish, phytoplankton, polychaete worms, reptiles, sea anemones and true corals, vascular plants, and zooplankton. The risk quotients for all organisms obtained were less than 1 (Fig. 3), suggesting that these organisms are not exposed to contamination by the radionuclides analyzed in our samples.

Additionally, radionuclide activity concentrations in Bq kg^{-1} f.w. (fresh weight) were determined for the thirteen reference organisms (Fig. 4). Among the studied organisms, phytoplankton was found to have the highest concentration of ^{210}Pb, followed by

Table 5 Risk quotients and limiting reference organisms at Congolese coastal basin using Tier 1 of the ERICA tool

Isotope	Maximum measured activity in sediment [Bq kg^{-1} dw]	Risk quotient (RQ) [unitless]	Limiting reference organism
Th-234	33.7	0.0	Phytoplankton
Ra-226	17.6	1.0	Phytoplankton
Pb-210	79.6	0.0	Phytoplankton
Th-228	76.0	3.6	Phytoplankton
Ra-228	87.5	0.0	Polychaete worm
Sum of risk quotients		4.7	

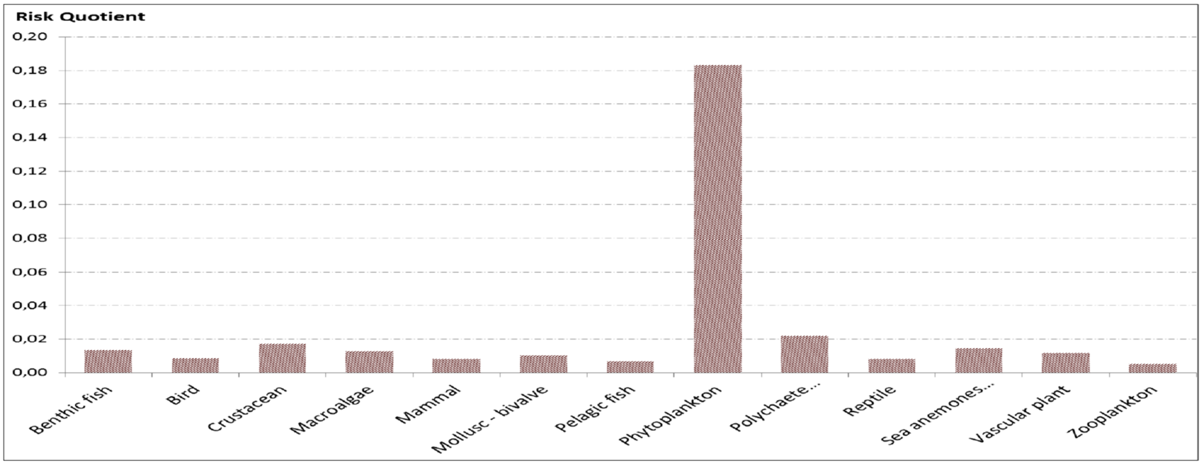

Fig. 3 Risk quotient calculated for reference organisms given by the ERICA tool

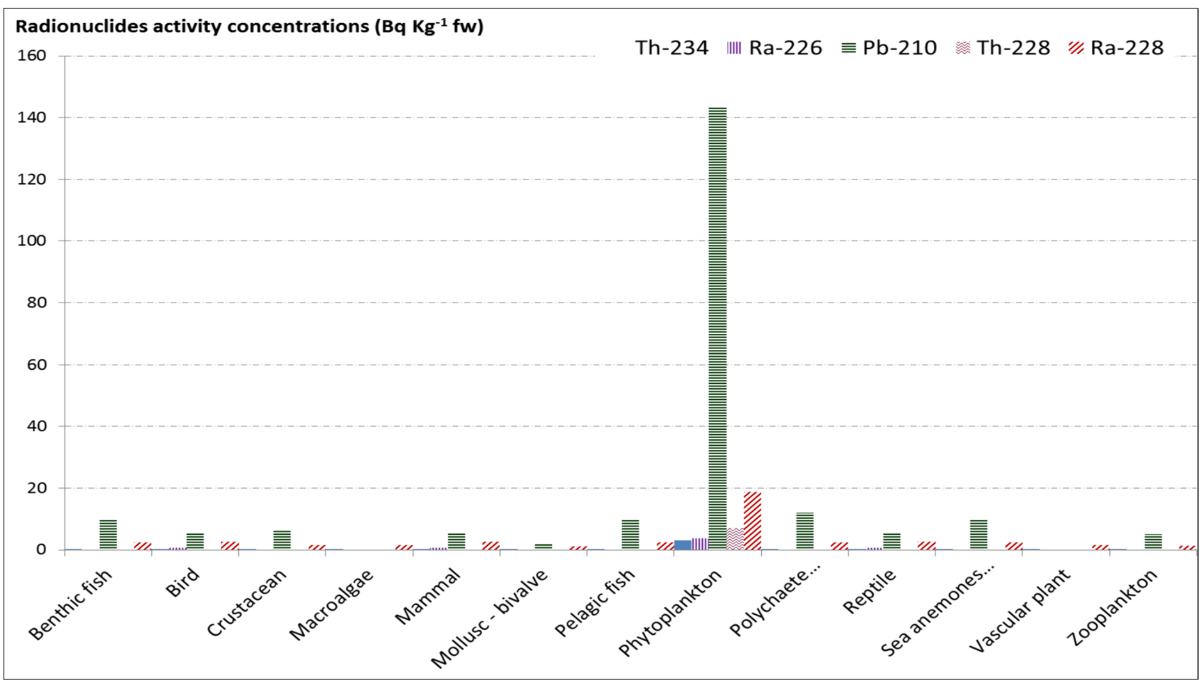

Fig. 4 Activity concentrations calculated by ERICA tool for all reference organisms

^{228}Ra and ^{228}Th. This suggests that phytoplankton is the most susceptible organism to contamination from radionuclides. Previous studies conducted by Botwe et al. (2016), Klubi et al. (2017), Wanjeri et al. (2021), and Ait bouh et al. (2021a) have also reported high concentrations of ^{226}Ra in phytoplankton, indicating that it may serve as a useful bioindicator for monitoring radioactive pollution.

To estimate potential dose rates, external, internal, and total dose rates were calculated and presented in Fig. 5. The screening dose rate recommended in the ERICA tool was set at 10 μGy h^{-1} per organism.

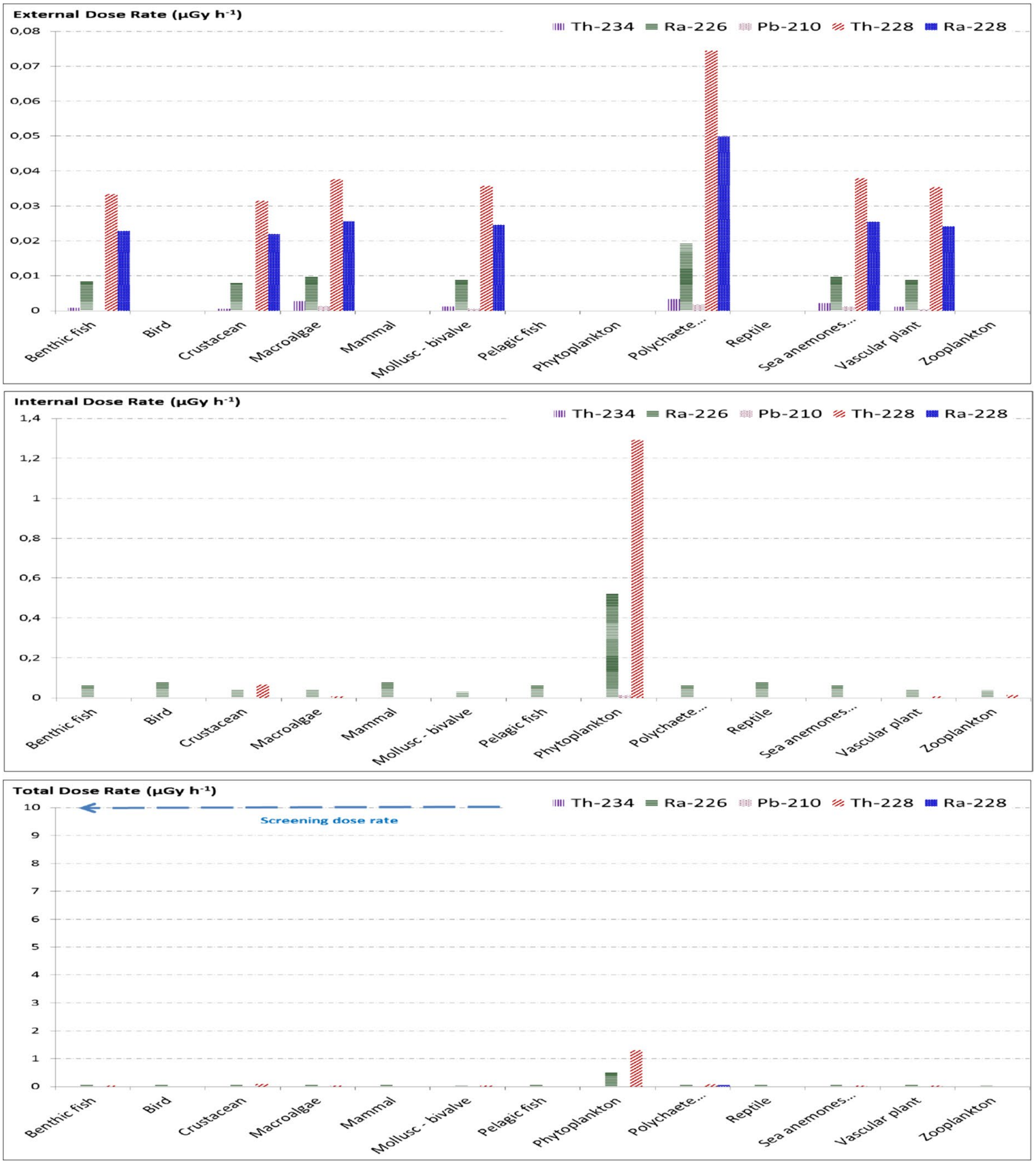

Fig. 5 External, internal, and total dose rates (µGy h^{-1}) for all reference organisms in Congolese coastal basin

The contribution of external dose rates, expressed in µGy h^{-1}, was found to be negligible. However, internal dose rates in µGy h^{-1}, especially those resulting from ^{228}Th, were found to contribute the most to the overall dose rates for phytoplankton. The total dose rates in µGy h^{-1} indicate that phytoplankton receive the highest doses, but still remain below the screening dose rate of 10 µGy h^{-1}, which corresponds to a risk quotient of 1. This suggests a very low probability of radioecological risk in our study area.

Notably, ^{228}Th was found to be the main contributor to the dose rates, particularly for the phytoplankton.

Conclusion

The levels of radioactivity of ^{234}Th(^{238}U), ^{214}Bi(^{226}Ra), ^{210}Pb, ^{212}Bi(^{228}Th), ^{228}Ac(^{228}Ra), and ^{40} K in surface sediments of the Congolese coastal sedimentary basin, using gamma-ray spectrometry, were assessed for the first time in the Republic of Congo. The results obtained for radionuclide activity concentrations show that the highest concentration is observed for ^{40} K, followed by ^{210}Pb, ^{228}Ra(^{232}Th), and ^{212}Bi(^{228}Th), while the lowest activity is observed for ^{234}Th(^{238}U) and ^{226}Ra. The highest activity concentrations were registered in the Loukonzi lagoon.

The radiological health risk parameters showed some variabilities from one sampling point to another, in particular, the Loukonzi lagoon has significant values of radiological parameters exceeding the reference standards.

The application of the ERICA tool made it possible to assess the total dose rates, which were mostly due to internal exposure, with a large contribution from ^{228}Th, mainly for phytoplankton. The total dose rates were well below the screening dose rate of 10 μGy h^{-1} and therefore unlikely to cause harmful effects on organisms.

The set of data produced would be, in addition to be most useful for future monitoring efforts, a valuable contribution to the worldwide database of the International Atomic Energy Agency (Marine Radioactivity Information System, MARIS) to cover the Congolese marine environment where no data are available.

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Declarations

Ethics approval and consent to participate Not applicable.

Competing interest The authors declare no competing interests.

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