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Assessment of Natural Radioactivity and Radiological Health Hazards in Core Sediments of the Sundarbans Using Gamma-Ray Spectrometry

Zarin Tasnim Nijhum[1] Dr. Mohammad Amirul Islam[2], Dr. Farzana Nahid[3]
[1]*(Physics Discipline, Khulna University, Bangladesh)*
[2]*(Institute of Nuclear Science &Technology, Atomic Energy Research Establishment, Bangladesh)*
[3]*(Physics Discipline, Khulna University, Bangladesh)*

Abstract
In this study, the activity concentrations of naturally occurring radionuclides (Ra-226, Th-232 and K-40) in core sediment samples from three different locations of the Sundarbans mangrove forest, Bangladesh were determined using gamma-ray spectrometry technique. The activity concentrations of the artificial radionuclides Cs-137 in the studied sediment samples are below the detection limit (<9.1 Bq/kg). The quality control of the analysis was studied by analyzing certified reference standard IAEA-Soil-6. The activity concentrations (Bq/kg) of the naturally occurring radionuclides ^{226}Ra, ^{232}Th and ^{40}K in sediment samples of the Sundarbans were found as 22.8±2.5 to 153.3±13.3, 50.8±2.2 to 128.5±8.7 and 868±50 to 17059±251, respectively. For the three cores, the mean activity concentrations of the natural radionuclides are of the order of K-40>Th-232>Ra-226. From this study, it is observed that activity concentrations of ^{232}Th and ^{40}K in sediments are relatively higher than those of the world average values. The depth-wise variations of the activity concentrations show that there is an increasing trend in activity concentrations in the surface sediments than the deeper layers. Different radiological hazard indices calculated in this study indicate that the sediments at some cores indicate some extent radiological risks to the biota of the Sundarbans. Finally, since there is no literature data available on activity concentration of the naturally occurring radionuclides in the Sundarbans, the results of this study will be used as baseline data for future study and also to assess radiological hazards in the sensitive Sundarbans mangrove forest.

Keywords: *Natural Radioactivity, Sediment, Activity Concentration, Radiological Hazard Gamma ray Spectrometry*

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I. Introduction

Radioactivity is a key component of our surroundings. All living creatures are exposed to a steady natural radiation stream on the surface of our friendly planet. Since the Big Bang and the birth of the universe, natural radiation has been with us. Radiation and radionuclides are natural components of the earth that play vital roles in natural processes (Saleh et al., 2012). Cosmic and telluric radiations are responsible for the majority of natural radiation in the environment and in humans (IAEA, 2007). Natural radiation comes from both extraterrestrial (cosmic) and terrestrial sources (radionuclides in the Earth's crust, building materials, and air, water, and foods). When radionuclides are inhaled or swallowed from these sources, they induce both exterior and internal exposures (ICRP, 1996). Sediments are a key source of radiation exposure for aquatic biota, and they also serve as a pathway for radionuclide migration in the aquatic environment (Baltas, 2017). It is the most fundamental sign of environmental radiation pollution. The sediments deposited at the river's bottom is mostly made up of sand and gravel of varied particle sizes from various geological formations. River sediments can be thought of as a temporary sink for various components that travel through the earth's surface's aquatic, chemical, and biological cycles. As a result, many of the waste products emitted by society or from natural sources such as weathering and recycling of terrestrial minerals and rocks, as well as anthropogenic activities, end up in sediments. The uranium and thorium series, as well as natural potassium, all contribute to natural radioactivity in the sediment. The study of primordial radionuclide distribution provides for a better understanding of the radiological implications of these elements as a result of gamma ray exposure of the body and radiation of lung tissue caused by inhalation of radon and its daughters.

Mangrove forests can be found in the intertidal zones of tropical and subtropical coastlines. Around 75% of the world's coastline is covered by these habitats (Giri et al., 2011). They are thought to cover an area of 156,220 square kilometers (Ghosh et al., 2015). The tropical and subtropical parts of the planet are home to 118 countries and territories with large populations of these animals.

Mangroves are vital for coastal environment and biodiversity protection, but the distribution of radionuclides in soils from these ecosystems has received little attention in the scientific literature. Mangrove ecosystems are regarded as one of the world's richest sources of biological and genetic diversity, providing a variety of goods and services like fisheries, forest products, and pollution remediation. Mangrove forests, in general, serve an important role in safeguarding and stabilizing coastal zones and in preventing the damaging consequences of natural disasters such as hurricanes and tsunamis (Alongi, 2002, 2008). Mangroves play a significant role in the global change scenario because of their significance as a source of nutrients and carbon. Mangrove forests in Bangladesh have undergone anthropogenic influences like deforestation for the Mari culture, human habitation and waste dumping since the Portuguese colonized the nation. Changes in soil composition have an impact on the environment's quality, necessitating increased monitoring, especially for radioactive chemicals. Mangrove soil radionuclide dispersion studies are rare, particularly in Bangladesh.

The Sundarbans is a deltaic mangrove forest produced by the deposition of sediments from the Himalayan foothills through the Gangas river system about 7000 years ago. It is fertile mangrove wetland ecosystems that provide several social, economic, and environmental benefits. Fishing, tourism, wood and non-wood products are all supported by the trees. Despite various laws, rules, and management plans, the forest is now clearly degrading (Didar-Ul Islam et al., 2018). They are the world's largest mangrove forests, located between India and Bangladesh. The Sundarbans are situated between 89°00′ and 89°55′E and 21°30′–22°30′N on the northern Bay of Bengal shoreline. It has one of the world's most productive and diverse ecosystems (Borrell et al. 2016).. They protect coastal residents from storms, tidal flooding, erosion, and other natural calamities, in addition to providing a distinct habitat (Das and Vincent 2009; Payo et al. 2016). So, for example, the Sundarbans protected coastal people from recent cyclones Sidr and Aila (Islam et al., 2013; Bhowmik and Cabral 2013).This forest consists of 200 islands, detached by 400 inter connected tidal rivers and canals. According to the recent estimation, the area of the Sundarbans in Bangladesh is 599,330 ha; which contains about 62% (Rahman et al., 1979) and the rest of the area (426,300 ha) is in West Bengal province of India (Sanyal et al., 1983).

Though Sundarbans acts as a natural shield for Bangladesh and a significant part of it is declared as UNESCO world heritage site but very few studies have been conducted on Bangladesh part of Sundarbans. Several studies have been conducted on metal pollution in the Indian side of the Sundarbans mangroves (Silva Filho et al., 2011; Banerjee et al., 2012; Bhattacharya et al., 2015; Akhand et al., 2016 etc.). Another study reported the distribution and enrichment of trace metals in surface sediments of the Pashur River in Bangladesh part of Sundarbans. (Islam et al., 2017, Kumar et al., 2016)

The determination of the concentration of Naturally Occurring Radioactive Materials (NORM) in the core sediments of the Sundarbans is important to study the historical variations of the concentrations of NORM and radiological risk assessments of the biota of the Sundarbans mangrove forest. There is no literature data available on NORM of the sediments of the Sundarbans. Therefore, it is very significant to assess the health risk associated with the concentration of NORM in sediments of Sundarbans.

II. Materials and Methods

Study Area

In this research, three core sediment samples were collected from three different places of the Sundarbans. The first core (C1) was collected from the Jongra (22º22´13´´ N to 89º36´37´´ E); the second core (C2) was collected from near the Mongla Port named Karomjol (22º25´45´´ N to 89º35´29´´E) and the third core (C3) was collected from Satkhira region (22º15´59´´ N to 89º11´51´´ E) of the Sundarbans.

Sample Collection and Preparation

The sample collection was done on a nice day. The three cores were taken from three distinct locations in the Sundarbans on two consecutive days in 2018. The cores were obtained from the Sundarbans riverbed using a hand-operated corer, which was a GPI pipe with a rubber stopper and a rubber sample remover (diameter 8 cm, height 2 m). A digital GPS (Global Positioning System) system was used to fix the sampling point at initially.

The sediment samples were obtained using a soil auger. The length of each core was approximately 48 cm. The core samples were then cut into 2 cm intervals with a clean knife and placed in a pre-cleaned zip-lock bag. The samples were collected in little polyethylene bags with distinct identification and retained in the lab for further testing. Hand gloves were worn while collecting the samples to avoid contamination. Samples were collected and dried in an electric oven at 45°C until they were uniform in weight. To eliminate organic elements, stones, and lumps, the dried sediment samples were sieved with a 0.25 mm mesh sieve. Each of the samples was pulverized with an agate mortar and pestle to get a small grain size and uniform mixture. Each dried powder sample was weighted and transferred to 350 cm^3 polyethylene vials, which were then sealed with tape. Each sample was sealed for four weeks in order to achieve secular equilibrium, in which the daughters' rate of decay equaled the parent's.

Sample Counting Using Gamma-Ray Spectrometry System

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the samples were determined through use of a hyper pure germanium (HPGe) gamma-ray spectrometry system. For data acquisition the HPGe detector was connected to a 8 k MCA and the γ-rays emitted from the samples was analyzed through use of Gamma Vision 5.0 software (EG&G ORTEC). Cylindrical Radium was mixed with Al_2O_3 matrix for gamma-ray source having homogeneously distributed activity was used for detector energy calibration and absolute photo-peak efficiency evaluation. The activity concentration of ^{226}Ra was measured using the characteristic gamma-lines of 351.93 keV (35.6%) from ^{214}Pb and 609.32 keV (45.49%) from ^{214}Bi; the gamma-ray lines of 238.632 keV (43.6%) from ^{212}Pb and 583.19 keV (85.0%) from ^{208}Tl, 911.204 keV (25.8%) from ^{228}Ac was used to determine the activity concentrations of ^{232}Th. The single gamma-ray line 1460.822 keV (10.66%) was used to determine the activity concentrations of ^{40}K.

III. Result and Discussion

In this study, core sediment samples from three different locations of the Sundarbans mangrove forest were collected and measured using high resolution gamma-ray spectrometry system to study activity concentrations and related radiological hazards in the Sundarbans. A typical gamma-ray spectrum of a sediment sample analyzed in this study is shown in Figure 1. The spectrum shows the gamma-ray peaks emitted from natural radioisotopes of Pb-212, Tl-208, Bi-214, Ac-228 and K-40 used to determine activity concentrations of Ra-226, Th-232 and K-40. There is no peak observed at 662 keV from artificial radioactive isotope Cs-137 in the spectrum.

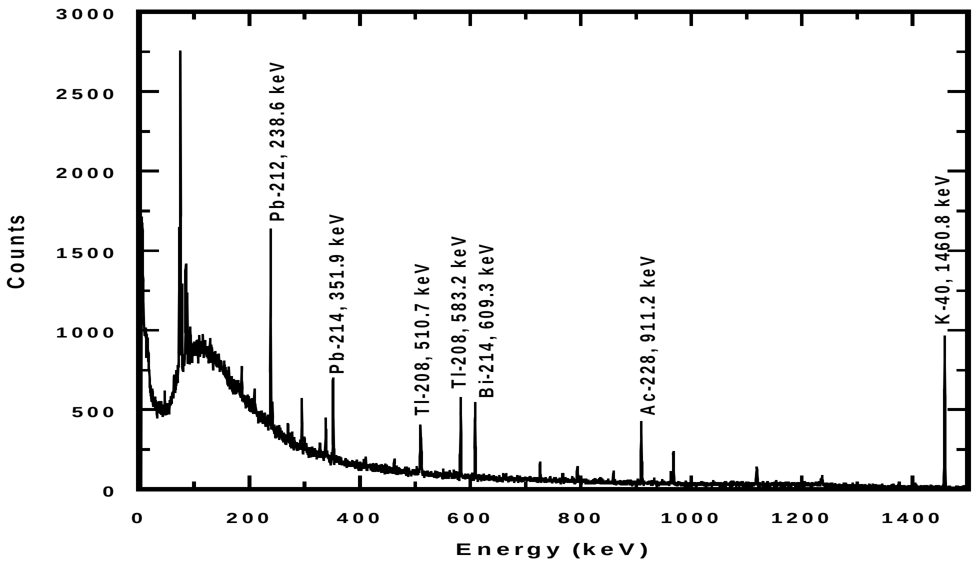

Fig. 1: A Typical Gamma-Ray Spectrum for Natural Radioactivity Concentration Determination of a Sediment Sample from the Sundarbans Mangrove Forest

Table 1: The Nuclear Data Used for Activity Concentrations Calculations (NUDAT, 2009)

Isotope	Energy (Isotope)	Gamma ray intensity, (I_γ)
Ra-226	351.93 keV (Pb-214)	35.6%
	609.32 keV (Bi-214)	45.49%
Th-232	238.63 keV (Pb-214)	35.6%
	583.19 keV (Tl-208)	85.0%
K-40	1460.82 keV	10.6%
Cs-137	662 keV	85.10%

Quality Control of the Analysis

In order to study quality of the analysis, the activity concentrations of the studied natural isotopes in a reference standard from International Atomic Energy commission (IAEA) Soil-6 were determined and compared with their certified values. Comparison of the mean (n=3) activity concentrations (Bq/kg) obtained in this study with their certified values of IAEA-Soil-6 are given in Table 2. It should be mentioned that certified values of the activity concentrations of Th-232 and K-40 in IAEA-Soil-6 is not published. Therefore, the determined values of activity concentrations of Th-232 and K-40 obtained in this study can be used as certified values for future analysis of this standard. When determined activity concentrations of Ra-226 in this study are compared with certified value, it is observed that measured value is within 6% deviation from the certified value that ensures accuracy of the analysis (Table 2).

Table 2: Comparison of Mean Activity Concentrations (Bq/Kg) Obtained in This Study with Certified Values of IAEA-Soil-6 to Study Quality Control of the Analysis

Standard	Ra-226			Th-232		K-40	
	This study (n=3)[a]	Certified value	Deviation	This study	Certified value	This study	Certified value
IAEA-Soil-6	74.8±2.08	79.9	-6.3%	23±1.3	-[b]	3400±35.5	-

[a]n=number of analysis.
[b]No certified values.

Activity Concentration of Ra-226, Th-232 and K-40 in the Sediments

The activity concentrations of Ra-226, Th-232 and K-40 in the core sediment samples are determined and given in Table 3 to 5. The activity concentrations of Cs-137 in the studied samples are below detection limit (<9.1 Bq/kg). The descriptive statistics, USCEAR values and World soil values and some other literature data are also give in the tables. The ranges of activity concentrations of Ra-226 in core-1, core-2 and core-3 are 22.8 - 54.4 with mean 32.9±9.4 Bq/kg, 36.8-123.8 with mean 72.2±28.2 Bq/kg and 50.8-153.3 with mean 82.0±24.2 Bq/kg, respectively (Table 3). The ranges of activity concentrations of Th-232 in core-1, core-2 and core-3 are 55.5±1.7 - 128.5±8.7 with mean 86.1 Bq/kg, 50.8±2.2 - 115.3±9.1 with mean 87.3 - Bq/kg and 58.0±2.0 – 101.3 ±9.2 with mean 83.1Bq/kg, respectively (Table 4) whereas for K-40 the ranges are 868.1±49.9 – 2961.3 ±219.0 with mean 1836.9 Bq/kg, 1484.8±61.7-16265.3±234.7 with mean 8241.3 Bq/kg and 4293.7±54.8 – 17059.1±2050.6 with mean 9880.9 Bq/kg, respectively (Table 5). The surface activity concentration of Ra-226, Th-232 and K-40 in different cores of sediments of the Sundarbans varies from site to site because different layers of mangrove sediments can exhibit large variation in chemical and mineralogical properties. For the three cores, the order of mean activity concentration of the natural radionuclide is of the order of K-40>Th-232>Ra-226. The activity concentrations of Ra-226 for all measured samples are within the world average value of 35.0 Bq/kg while the mean activity concentration of Th-232 and K-40 are higher than those of world average values of 30.0 Bq/kg and 400.0 Bq/kg (UNSEAR, 2000) respectively. Among the three cores, mean activity concentrations of Ra-226 and K-40 are higher at Burigoalini Range of the Sundarbans. It was mentioned in a previous study that natural radioactivity concentrations are high at North-West Bangladesh region (Hamid et al, 2000). The Sundarbans mangrove forest was formed by sediments deposited from the rivers originated from North-West region of Bangladesh (Himalayan ranges). Therefore, the high activity concentrations of natural radioisotopes at Sundarbans can be explained due to the formation of the Sundarbans by sediments of those rivers. The higher concentration of Th-232 and K-40 may be due to the presence of high content of monazite minerals in the sediments of the Sundarbans (Rasamy et al., 2009). The activity concentration data obtained from this study compared with those of the other mangrove and river sediments of the world in Table 6. The activity concentrations of the Sundarbans sediments are relatively higher than the mangrove sediments of Brazil. However, our mangrove activity concentrations data are lower than those of the world beach sands (Table 6).

Table 3: Activity Concentration (Bq/Kg) of Ra-226 in the Three Cores

Depth (cm)	Ra-226		
	Core 1	**Core 2**	**Core 3**
0-2	54.4±11	101.3±13.1	75.4±8.2
2-4	28.2±10.8	92.1±10.5	85.7±9.2
4-6	22.8±9.1	86.4±10.7	84.2±13.3
6-8	23.2±12.4	56.2±10.5	93.3±8.5
8-10	30.2±8.1	81.6±10.2	87.9±9.9
10-12	40.3±10.4	76.6±8.0	95.5±9.2
12-14	50.2±9.4	123.8±10.0	76.7±11.8
14-16	35.3±5.8	100.2±9.7	82.6±8.6
16-20	34.3±4.1	101.0±5.6	70.5±4.2
20-24	30.4±4.5	40.9±4.2	65.4±5.4
24-28	22.9±5.9	36.7±5.3	153.3±6.2
28-32	33.2±3.4	38.7±4.7	65.1±4.1
32-40	25.5±3.0	40.4±3.6	60.7±3.0
40-48	29.2±2.9	50.0±3.2	50.8±3.5
48-56	32.7±2.4	57.6±3.6	
Min	22.8±2.5	36.8±3.2	50.8±3.5
Max	54.4±12.4	123.8±13.1	153.3±13.3
Mean	32.9	72.2	82.0
SD	9.4	28.2	24.2
RSD (%)	28.5	39.0	29.5
UNSCEAR	35[a]		
World soil	30 (7-180)[b]		
South east Bangladesh	18[c]		
North west Bangladesh	91[d]		

[a]UNSCEAR (2000); [b]Calculated data from elemental abundances (Bowen, 1979)\
[c]South east Bangladesh (SEB): (Rashed-Nizam, 2015); [d] North west Bangladesh(NEB):(Hamid, 2002);

Table 4: Activity Concentration (Bq/Kg) Of Th-232 in the Three Cores

Depth (cm)	Th-232		
	Core 1	**Core 2**	**Core 3**
0-2	97.8±7.5	115.3±9.1	94.3±5.8
2-4	105.2±7.6	94.8±7.2	77.1±6.3
4-6	105.8±6.4	78.7±7.3	101.3±9.2
6-8	128.5±8.7	87.2±7.4	83.4±5.9
8-10	110.7±5.7	98.3±7.1	90.6±6.9
10-12	112.5±7.3	84.0±5.5	93.9±6.4
12-14	101.1±6.5	108.3±6.8	100.4±8.2
14-16	71.5±4.0	86.1±6.6	105.7±6.1
16-20	77.1±2.9	96.6±3.9	71.3±2.9
20-24	65.4±3.1	84.5±3.0	78.6±3.8
24-28	78.4±4.2	95.4±3.8	73.3±3.6
28-32	65.4±2.4	92.0±3.3	75.1±2.8
32-40	59.3±2.1	77.9±2.6	58.0±2.0
40-48	57.3±2.1	50.8±2.2	60.2±2.5
48-56	55.5±1.7	60.1±2.5	
Min	55.5±1.7	50.8±2.2	58.0±2.0
Max	128.5±8.7	115.3±9.1	101.3±9.2
Mean	86.1	87.3	83.1
SD	23.7	16.5	15.1
RSD (%)	27.5	18.9	18.1

UNSCEAR	30
World soil	37 (4-78)
South east Bangladesh	46
North west Bangladesh	151

[a]UNSCEAR (2000); [b]Calculated data from elemental abundances (Bowen, 1979)
[c] South east Bangladesh (SEB): (Rashed-Nizam, 2015);[d] North west Bangladesh(NEB):(Hamid, 2002);

Table 5: Activity Concentration (Bq/Kg) Of K-40 in the Three Cores.

Depth (cm)	K-40		
	Core 1	**Core 2**	**Core 3**
0-2	2549.8±193.3	16265.3±234.7	11093.4±156.5
2-4	2584.6±192.7	13291.8±190.9	11854.7±175.8
4-6	2961.3±178.2	14198.16±196.9	17059.1±250.7
6-8	2636.9±219.0	14090.3±196.8	11166.8±155.6
8-10	2550.5±142.7	13324.7±187.3	13087.9±187.1
10-12	1058.5±164.9	5166.0±112.1	11946.8±168.8
12-14	2456.6±164.9	12052.9±186.2	15324.5±218.4
14-16	1745.0±111.9	12101.5±184.1	11613.1±158.2
16-20	1726.4±74.7	7177.8±105.5	5322.1±85.2
20-24	1484.9±83.1	1517.3±74.1	7785.3±103.4
24-28	1517.3±108.8	1714.8±102.9	7117.3±100.6
28-32	1391.4±64.5	1652.9±82.3	5699.7±74.9
32-40	868.1±49.9	1484.8±65.3	4293.7±54.8
40-48	1060.5±51.4	4433.4±61.7	4967.9±65.8
48-56	962.1±42.7	5148.2±67.2	
Min	868.1±49.9	1484.8±61.7	4293.7±54.8
Max	2961.3±219.0	16265.3±234.7	17059.1±250.6
Mean	1836.9	8241.3	9880.9
SD	718.2	5518.0	4032.3
RSD(%)	39.0	66.9	40.8
UNSCEAR	400		
World soil	440 (0.2-1200)		
South east Bangladesh	321		
North west Bangladesh	1958		

[a]UNSCEAR (2000); [b]Calculated data from elemental abundances (Bowen, 1979)
[c] South east Bangladesh (SEB): (Rashed-Nizam, 2015);[d] North west Bangladesh(NEB)☹ Hamid, 2002);

Table 6: Comparison of Activity Concentration Of Present Work With Other Literature.

Country	Ra-226		Th-232		K-40		
Sundarbans mangrove (Bangladesh)	22.8-153.3		50.8-	128.5	868-	1760	This study
Chico science mangrove, Brazil	24		-		410		De Paiva et al.,2016 2015
Rio Formoso mangrove, Brazil	21		-		851		De Paiva et al.,2016 2015
Bangladesh (raw sand-Cox's Bazar)	2400- 2500[a]		3300	- 4300	80 -	260	Sasaki et al., 2015
Malaysia (black sand)	451.4 -2411.4		232.2-	1271.9	60.9-	135.6	Khandaker et al., 2018
Malaysia (Pasir hitam at Lankawi)	210 -	2430	150 -	1040	-		Omar and Hassan, 2002
Greece (Atticocycladic)	12 -	2292	16 -	10,143	191 -	1192	Papadopoulos et al., 2016
India (Kalpakkam beaches)	36 -	258[a]	352 -	3872	324 -	405	Kannan et al., 2002
India (Kerala)	99 -	3192	1288-	18,515	-		Pinto and Yerol, 2014
Brazil (Sao Paulo, Rio de Janeiro, Espirito Santo and Bahia)	5 – 4043		7- 55,537		27 – 8	88	Veiga et al., 2006
Srilanka (West Coast)	7 - 1243[a]		14 -	6257	170 -	647	Mahawatte and Fernando, 2013
China (Xiamen Island)	7.8 -	25.7	6.5 -	41.4	197.4	- 487.6	Huang et al., 2015
Turkey (Black sea coast)	4.41	- 14.04[a]	2.62-	16.55	11.60	- 513.32	Korkulu and Ozkan, 2013
Turkey (Mediterranean coast)	4.0 -	21.5	1.8 -	27.9	19.0-	590.3	Ozmen et al., 2014
Montenegro coast	2.09-	15.46	1.37-	16.58	7.13-	304.87	Antovic et al., 2013
Romania (Black sea shore)	2.9 -	14.0	1.2 -	8.5	9- 233		Margineanu et al., 2013
Iran (Ramsar)	14.6-	29.6	14.8-	21.7	179.5	- 464.5	Tari et al., 2013

[a]U-238.

Depth Wise Variation of Activity Concentration In Sediment Cores Of The Sundarbanss

The activity concentration variation with depth of the studied naturally occurring radionuclides are shown in Fig. 2. For the three core sediments, the overall activity concentrations are increased from deeper sediments to the surface. The higher activity concentrations at surface of the cores are likely to be due to the increased anthropogenic activities in the Sundarbans like marine transportation, cargo accidents etc. For Ra-226, the activity concentrations are abruptly increased at 25 cm of the core-3. The activity concentration variations of Ra-226 and K-40 for core-1 are relatively lower than the core-2 and core-3 (Fig. 2). The activity concentration variations of the studied radionuclides at core-2 is relatively higher at core-2.

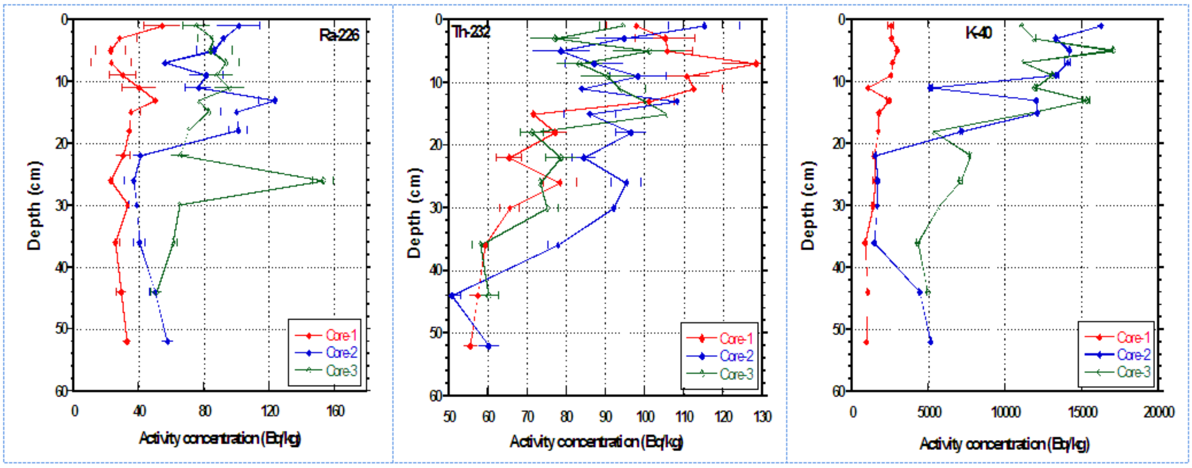

Fig. 2: The Activity Concentration Variation with Depth in Core Sediments of the Sundarbans.

Radiological Hazard Indices Assessment

The gamma ray radiation hazards due to the specified radionuclides in Sundarbans sediments are estimated by calculating different indices. Even though total activity concentration of radionuclides is determined, it does not provide the exact indication about the total radiation hazards. The calculated radiation hazard indices are given in Table 7 to 9.

Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity index (UNSCEAR, 2000) (Ra_{eq}) was calculated according to the following equation

$Ra_{eq} = 370(A_{Ra}/370+A_{Th}/259+A_K/4810)$ Bq/kg…………….(1)

Where A_{Ra}, A_{Th} and A_K are the activity concentrations of Ra-226, Th-232 and K-40 respectively, constituted of the weighted sum of the activities of the three particular radionuclides, is linked to the external and internal gamma doses.

From this study, the mean radium equivalent activity of core-1, core-2 and core-3 of sediment samples of the Sundarbans are 297.2 Bq/kg, 831.0 Bq/kg and 960.8 Bq/kg, respectively. The mean R_{eq} of Core-1 is below the recommended value 370 Bq/kg (Table 7), whereas the values are excess than the recommended values in core-2 and core-3. Therefore, The Ra_{eq} values at core-2 and core-3 are indicative of radiological risks (OECD, 1979).

Gamma Radiation Representative Level Index (Iγ)

Estimation of gamma radiation hazard associated with the natural radionuclide in specific investigated sample is called gamma representative level index which is given as:

$I\gamma = ((A_{Ra}/150) + (A_{Th}/100) + (A_K/1500))$Bq/kg ……..(2)

Where A_{Ra}, A_{Th} and A_K are the average activity concentration of Ra-226, Th-232 and K-40, respectively. The calculated I_γ values of core-1, core-2 and core-3 in the sediment samples of the Sundarbans are 2.3 Bq/kg, 6.8 Bq/kg and 7.9 Bq/kg, respectively (Table 7-9).

External Absorbed Gamma Dose Rate D_r ($nGyh^{-1}$)

The mean activity concentration of A_{Ra}, A_{Th} and A_K were converted to dose rate based on the conversion factor given by UNSCEAR (2000) by the following equation,

D_r ($nGyh^{-1}$) = $0.462\ A_R + 0.604\ A_{Th} + 0.04\ A_k$ ------------------ (3)

Where, D is the absorbed dose rate ($nGyh^{-1}$), A_{Ra}, A_{Th} and A_K are the activity concentrations (Bq/kg) of Ra, Th and K in sediments of the Sundarbans, respectively. From this study, the mean values of absorbed dose are 144.3, 432.3 and 503.1 $nGyh^{-1}$, respectively. It is observed that the absorbed dose rate for all the samples are higher than the world average value of 55 nGyh-1 (UNSCEAR, 2000) (Table 7-9).

Annual Effective Dose (E_{AED})

The annual effective dose was determined using the following equation

E_{AED} ($nGyh^{-1}$) = D_r ($nGyh^{-1}$) × 8760 hy^{-1} × 0.7 Sv/Gy × 0.2 ×10^{-6} -------- (4)

Here, the conversion factor of 0.7 Sv Gy^{-1} for absorbed dose-rate in air to the effective dose received by an adult and an outdoor occupancy factor of 0.2 (UNSCEAR, 2000) were used and also taking 8760 h as the number of hours per year and with 10^{-6} the nano to milli conversion. It is observed that E_{AED} values for the 3 cores are 0.17, 0.5 and 0.6 $nGyh^{-1}$, respectively. The mean values of E_{AED} are above & below the recommended values (UNSCEAR, 2008).

Radiation Hazard Indices (Hex, Hin)

The external and internal hazard index is used for the evaluation of external exposure to gamma radiation in the outdoor air. The external and internal hazard that allowed maximum value (equal to unity) correspond to the upper limit of Ra_{eq} (370 Bq kg -1). The external hazard index (H_{ex}) can be calculated from the equation and (UNSCEAR, 2000).

$H_{ex} = (A_{Ra}/370+A_{Th}/259+A_K/4810)$ Bq/kg……..(5) and

Internal hazard index (H_{in}) can be calculated from the equation (Senthilkumar et al., 2010): $(A_{Ra}/185+A_{Th}/259+A_K/4810)$ Bq/kg……….(6)

In this study, the mean H_{ex} values for the 3 cores are 0.80, 2.2 and 2.6, respectively, whereas the H_{in} are 0.89, 2.4 and 2.9, respectively (Table 7-9). It is observed that H_{ex} and H_{in} for core-1 is below the recommended value (UNSCEAR, 2000), however, the values are above the recommended values for core-2 and core-3.

Table 7: Calculated Radiological Parameters of Sediment Samples of Core 1 in The Sundarbanas

Depth (cm)	Radium equivalent activity Ra_{eq}(Bq/kg)	Gamma representative level index I_γ	Absorbed dose rate D_r(nGy/h)	Annual effective dose E_{aed}(mSv/y)	External hazard index H_{ex}	Internal hazard index H_{in}
0-2	390.2	3.0	191.3	0.23	1.0	1.2
2-4	377.3	2.9	185.1	0.22	1.0	1.0
4-6	401.7	3.2	198.8	0.24	1.1	1.1
6-8	409.6	3.2	199.0	0.24	1.1	1.2

8-10	384.6	3.0	187.9	0.23	1.0	1.1
10-12	282.5	2.1	131.0	0.16	0.7	0.8
12-14	383.6	2.9	187.4	0.22	1.0	1.1
14-16	271.7	2.1	132.8	0.16	0.7	0.8
16-20	277.3	2.1	134.9	0.16	0.7	0.8
20-24	238.1	1.8	115.9	0.14	0.6	0.7
24-28	251.6	1.9	121.6	0.14	0.6	0.7
28-32	233.8	1.8	113.3	0.13	0.6	0.7
32-40	177.0	1.3	84.07	0.10	0.4	0.5
40-48	192.8	1.5	92.71	0.11	0.5	0.6
48-56	186.1	1.4	89.10	0.10	0.5	0.5
Mean	297.2	2.3	144.3	0.17	0.8	0.8
Recommended value	370	1.0	55	0.46	<1.0	<1.0

Table 8: Calculated Radiological Parameters of Sediment Samples of Core 2 in Sundarbans.

Depth (cm)	Radium equivalent activity Ra_{eq} (Bq/kg)	Gamma representative level index I_γ	Absorbed dose rate D_r(nGy/h)	Annual effective dose E_{aed}(mSv/y)	External hazard index H_{ex}	Internal hazard index H_{in}
0-2	1517.2	12.6	799.6	0.9	4.1	4.3
2-4	1250.0	10.4	658.1	0.8	3.3	3.6
4-6	1291.0	10.8	683.8	0.8	3.4	3.7
6-8	1264.6	10.6	670.4	0.8	3.4	3.5
8-10	1247.1	10.4	656.8	0.8	3.3	3.6
10-12	594.10	4.79	303.1	0.3	1.6	1.8
12-14	1205.6	9.94	628.8	0.7	3.2	3.5
14-16	1154.0	9.59	606.5	0.7	3.1	3.3
16-20	791.27	6.42	406.5	0.4	2.1	2.4
20-24	278.42	2.12	133.7	0.1	0.7	0.8
24-28	304.96	2.34	146.6	0.1	0.8	0.9
28-32	297.40	2.28	142.9	0.1	0.8	0.9
32-40	265.97	2.03	128.1	0.1	0.7	0.8
40-48	463.76	3.79	240.0	0.2	1.2	1.3
48-56	539.80	4.41	279.3	0.3	1.4	1.6
Mean	831.0	6.849767	432.3349	0.530216	2.246053	2.441423
Recommended value	370	1.0	55	0.46	<1.0	<1.0

Table 9: Calculated Radiological Parameters of Sediment Samples of Core 3 in Sundarbans.

Depth (cm)	Radium equivalent activity Ra_{eq}(Bq/kg)	Gamma representative level index I_γ	Absorbed dose rate D_r(nGy/h)	Annual effective dose E_{aed}(mSv/y)	External hazard index H_{ex}	Internal hazard index H_{in}
0-2	1063.5	8.84	557.7	0.6	2.8	3.0
2-4	1107.8	9.24	584.1	0.7	2.9	3.2
4-6	1541.2	12.9	816.6	1.0	4.1	4.3
6-8	1071.4	8.90	562.5	0.6	2.8	3.1
8-10	1224.1	10.2	645.0	0.7	3.3	3.5
10-12	1149.1	9.54	602.8	0.7	3.1	3.3
12-14	1399.0	11.7	739.7	0.9	3.7	3.9
14-16	1127.0	9.35	589.8	0.7	3.0	3.2

16-20	581.80	4.73	299.2	0.3	1.5	1.7
20-24	776.72	6.41	404.7	0.4	2.0	2.2
24-28	805.58	6.50	414.0	0.5	2.1	2.5
28-32	610.87	4.98	314.8	0.3	1.6	1.8
32-40	473.97	3.84	243.4	0.2	1.2	1.4
40-48	519.08	4.25	268.5	0.3	1.4	1.5
Mean	960.8203	7.965186	503.124	0.617031	2.596812	2.818492
Recommended value	370	1.0	55	0.46	<1.0	<1.0

IV. Conclusion

The activity concentrations of the naturally occurring radionuclides Ra-226, Th-232 and K-40 in three core sediments from different locations of the Sundarbans mangrove forest, Bangladesh are determined using gamma-ray spectrometry technique. This study reveals that activity concentrations of Ra-226 for all measured samples are within the world average value of 35.0 Bq/kg, while the mean activity concentration of Th-232 and K-40 are higher than those of the world average values of 30.0 Bq/kg and 400.0 Bq/kg, respectively. Among the three cores, mean activity concentrations of Ra-226 and K-40 are higher at Burigoalini Range than those of the Chandpi Range of the Sundarbans. The overall higher concentration of Th-232 and K-40 in sediments of the Sundarbans may be due to the presence of high content of monazite minerals in the sediments of the Sundarbans. For the three core sediments, the overall activity concentrations are increased from deeper sediments to the surface which indicates the increased anthropogenic activities at present than the past. Different radiological hazard indices calculated in this study indicate that there is no radiological risk for the sediments at core-1, however, the sediments at core-2 and core-3 are indicative of some extent radiological risks to the biota of the Sundarbans . Finally, since there is no literature data available on activity concentration of the naturally occurring radionuclides in the Sundarbans, the results of this study will be used as baseline data for future study and also to assess radiological hazards in the sensitive Sundarbans Mangrove forest.

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