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Estimating Recent Sedimentation Rates Using Lead-210 in Tropical Estuarine Systems: Case Study of Volta and Pra Estuaries in Ghana, West Africa

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Abstract

The Volta River and its basin form about one-third of Ghana's total land area and contributes significantly to the hydrological network of the country's river system while the River Pra basin is noted for large and small scale mining activities within it. Both river systems are important for sediment delivery for beach nourishment along Ghana's coast. This work presents the first ever estimates of the sedimentation rates at the estuaries of these rivers using 40 cm long sediment cores. Sediment accumulation rates were estimated using the ^{210}Pb sediment dating technique which is based on alpha and gamma emitting radionuclides. The total ^{210}Pb concentration in the sediment was measured with an alpha spectrometer while the activities of supported ^{210}Pb and ^{137}Cs were measured with a gamma spectrometer with high germanium n-type detector. The unsupported ^{210}Pb was determined by subtraction of the supported from the total at each core sediment level. Irregularities in the ^{210}Pb activity versus depth profile, indicated variation in the net sedimentation accumulation rate during the past 96 and 182 years at the Volta and Pra estuaries, respectively. From the CRS model calculations, sedimentation rates varied markedly before (1.08 $gcm^{-2}y^{-1}$) and after (0.50 $gcm^{-2}y^{-1}$) construction of the Akosombo dam resulting in about 50% drop in sedimentation rate at the Volta estuary. Sediment accumulation rates were relatively low at the Pra estuary compared to the Volta estuary. Depositional fluxes of ^{210}Pb were 190.05 ± 15.85 $Bqcm^{-2}y^{-1}$ and 217.78 ± 11.76 $Bqcm^{-2}y^{-1}$ in Pra and Volta estuaries respectively. ^{137}Cs profile did not show defined peaks. However, the ages and sedimentation rates were better explained using historical events and anthropogenic activities that occurred within the catchment areas, providing a better understanding of deficit in sediment budget caused by hydric erosion processes prevailing in the Ada and Keta beaches in Ghana, due to reduction of sediment input from the Volta estuary.

Keywords: Lead-210 dating; CRS; Keta; Sedimentation rate; Coastal erosion

Introduction

Coastal zones are important but are also sensitive areas due to their vulnerability to global or man-induced changes which are of direct socio-economic importance to coastal zone management policies [1]. The zones are built through the supply of sediment mostly by fluvial origins into the coastal waters and are then transported by longshore drift along the coastline. Sediment mobilization into coastal waters is therefore an important process in the development and maintenance of coastal zones including wetlands, lagoons, estuaries and dunes. Any interference with the natural supply of sediment such as channeling of river water for irrigation, creation of reservoir, damming of rivers and deforestation along the banks of rivers often leads to modification in their flow and the amount of sediment they carry. The cumulative effect could result in changes in geomorphology and hydrology leading to either accretion or erosion of the shorelines. Appeaning Addo et al. [2] have reported that over 70% of the world's shorelines are experiencing coastal erosion as a result of multiple stressors on the beaches. Coastal erosion is as a result of activities impeding supply of sediment into the coastal zone for maintaining beach front equilibrium. Generally, shoreline changes have been attributed to damming of major rivers. In Africa for instance, the damming of Moulouya and Sebou rivers in Morocco was pinpointed as the principal cause of coastal erosion in North West Africa. Rivers Senegal, Niger and Volta are deemed as the prime cause of erosion in West Africa. In East Africa, coastal erosion is attributed to damming of Tana and Sabaki rivers and erosion of Central African coast has been solely attributed to the damming of River Zambezi and Incomati [1,3]. In Nigeria, Victoria Beach has eroded 2 km inland since the construction of breakwaters during the extension of the port of Lagos [1] suggesting that port construction in coastal areas could also lead to coastal erosion. Shoreline stability is achieved through the continuous supply of sediment into coastal zones via estuaries and contiguous coasts. Hence, coastal marine and lacustrine sediment can serve as excellent archives of environmental changes [4,5]. The evaluation of sedimentation rate is a tool that can be used to check sediment delivery and sedimentation patterns as well as helping to explain changes in shoreline due to interference with the sediment supply budget [6]. The application of specific activity profiles of ^{210}Pb in bottom sediment cores allows tracing of the history of pollutants and quantification of sedimentation rates in coastal and lacustrine systems [4,7]. ^{210}Pb activity in sediment chronology has two components, supported and unsupported.

The supported fraction is produced within the sediment through ^{226}Ra disintegration and unsupported ^{210}Pb is incorporated into the sediment through dry or wet deposition. Once ^{210}Pb is adsorbed onto the particles, it is deposited in the sediment and its activity decays with time. There is, however, a continuous addition of supported ^{210}Pb by its

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long-lived precursor ^{226}Ra inside the sediment matrix. The activity of the unsupported fraction of ^{210}Pb in the sediment can be calculated as the difference between the supported and the total ^{210}Pb activities [8]. In principle, the age of sediment deposition can be estimated by applying conventional dating models. Practically, there are two standard models connecting the unsupported ^{210}Pb specific activity profile of sediment cores with sedimentation deposition rates; the constant initial concentration (CIC) and the constant rate of supply (CRS) models [8]. The latter is the most widely used either for lakes; coastal zones or estuaries where sedimentation processes are significantly influenced by anthropogenic activities [9].

In Ghana, the Volta and Pra rivers are important sources of water for the country and are major sources of sediment supply to the coast. The impact of human intervention upstream of these two river systems leading to shoreline changes along the coastal zone of Ghana is not fully understood due to paucity of data. Therefore, the aim of this research was to use the CRS model to determine the age and sedimentation accumulation rates in the Volta and Pra estuaries and to ascertain whether the sediment supply from these estuaries into Ghana's coastal zone has varied significantly over the years.

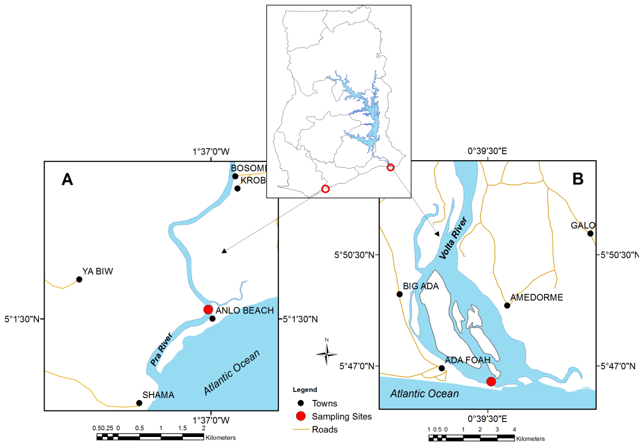

Figure 1: Map of Ghana showing the sampling sites. Pra estuary (A) in the western zone and the Volta estuary (B) in the eastern zone.

Materials and Methods

Site description

The coastline of Ghana is about 550 km and it is divided into three zones; the western, central and eastern. The study was conducted in the Pra and Volta estuaries which are located at the western and eastern coastal areas of Ghana respectively (Figure 1)

The Pra estuary is located in the Shama District of Ghana's Western Region (Figure 1A) and forms the lower section of the Pra river system that originates from Birim and Offin sub-basins in the Eastern and Ashanti Regions of Ghana respectively [10]. This basin (the Pra basin) is a site for gold mining for close to a century and has the largest concentration of mines in a single area of the African continent [11]. The drainage area is about 23,188 km^2 with an estimated suspended sediment yield of 50.8 km^2 [12]. The annual mean water discharge into the Atlantic Ocean is estimated at 214 m^{3}s^{-1} loaded with about 1,139,171 tonnes of suspended sediment [12,13]. The Volta estuary on the other hand is located in the lower basin of the Volta River at Ada in the Greater Accra Region of Ghana (Figure 1B). River Volta is a transboundary system and the largest river in Ghana (total drainage area of 379,000 km^2) [14]. Its' sources are the White Volta, Black Volta, Red Volta and the Oti River all of which originate from the Burkina Faso [15].

The Volta River was dammed at Akosombo and Kpong in 1965 and 1982 respectively for hydro-electric power production. The construction of these dams have resulted in reducing the annual mean water flow from 1160 to 1100 m^{3}s^{-1} to the Volta estuary [14,16].

Sampling and radionuclides analyses

Two sediment cores were sampled from the Pra and Volta estuaries (Figure 1A-B) using Uwitec corer of length 60 cm and inner diameter 8.7 cm. The cores were taken at low tide by manually inserting the whole corer into the sediment and retrieved and corked at both ends. The corer and its content were stacked in a vertical position in corer rack and transported to the laboratory.

Each core was sectioned (using a core slicer in the laboratory) into layers of 2 cm thickness. About 0.5 cm of the outer layer of the sliced cores was discarded to minimize cross contamination among layers [17]. Wet and dry masses were determined before and after drying the samples at a constant temperature of 80°C for 48 hours in a drying oven. Bulk density of each sample was calculated using the dry weight fraction approach and equating particle density of mineral solid as 2.65 g/cm^3 [18]. The samples were grounded to fine powder using an electronic grinder and then homogenized.

The total ^{210}Pb concentrations in the sediment were inferred indirectly by measurement of the daughter product ^{210}Po using alpha spectrometry as described by Laissaoui et al. [19]. About 0.5 g of the homogenized sediment was weighed into a pre-acid cleaned Teflon® beaker and spiked with 50 µl of ^{209}Po yield tracer (the certified specific activity was 0.357 ± 0.011 Bqg^{-1}). The samples were digested using a mixture of concentrated hydrochloric, nitric and hydrofluoric acid (HCl-HNO3-HF) solutions. Hydrogen peroxide solution was added for complete digestion of organic matter while heating the mixture at 80°C. The solution was further treated by repeated evaporation with HCl-boric acid solution to neutralize HF acid before it was filtered into a 100 ml cleaned beaker and the volume was adjusted to 80 ml with 0.5M HCl solution. Reduction of Fe^{3+} to Fe^{2+} was achieved by the addition of ascorbic acid to the solution to prevent oxidized iron from interfering with the target nuclide during auto-deposition. Self-deposition of polonium isotopes were carried out for four and half hours by introduction of silver discs into the 0.5M HCl acid solution and warmed at 80°C while stirring. Activities of the polonium isotopes were measured by an ORTEC alpha-spectrometer which was interfaced with Maestro$^{\text{TM}}$ data acquisition software after calibration and adjustment of the energy levels to 4887 KeV (^{209}Po) and 5305 MeV (^{210}Po). The gross counts and counting time were recorded for the computation of the activity of ^{210}Po and determination of the chemical recovery.

The supported ^{210}Pb activities, in secular equilibrium with ^{226}Ra in each and all sections of the cores were inferred indirectly by averaging ^{214}Bi and ^{214}Pb activities obtained by an n-type high-purity germanium detector (HPGe). The activity of ^{214}Bi was scanned at 352.9 KeV and ^{214}Pb at 609.3 KeV photopeaks while ^{137}Cs was scanned at 662 KeV photopeaks. For ingrowth of ^{222}Rn to attain a secular equilibrium with ^{226}Ra, the homogenized samples were weighed and sealed in a pre-defined geometry and incubated for three weeks along with an IAEA reference material (IAEA-137). Efficiency calibration and quality control of the HPGe detector were carried out using a prepared multi-standard solution and the reference material. All the samples were counted for 24 hours and the spectra obtained were analyzed using Genie 2000 VDM software. The experimentally derived and calculated efficiency of each gamma emitting radionuclide were in close proximity with a variance between 1.8 and 3.7%. The derived polynomial equation was then employed in calculating the specific activities of ^{214}Bi and ^{214}Pb, both in secular equilibrium with ^{226}Ra. The activity of unsupported ^{210}Pb was established by subtracting supported ^{210}Pb from the total ^{210}Pb activities on level by level basis.

The age of each core and the sedimentation rate of the samples from the two estuarine systems were estimated by applying the CRS model to the obtained unsupported ^{210}Pb profiles [19].

Results and Discussion

The concentration of ^{210}Pb (total, supported and unsupported) from each estuary is shown in (Figure 2). In the Pra estuary, the concentrations of total ^{210} Pb varies between 58.79 ± 5.47 and 16.28 ± 1.76 while supported ^{210} Pb was between 34.22 ± 4.07 and 10.21 ± 3.00 and the unsupported ^{210} Pb between 32.51 ± 6.5 and 0.63 ± 0.04 Bq/Kg (Figure 2A). The levels of alpha and gamma activities within the first 10 cm depth were fairly constant presumably due to post-depositional mixing affecting the upper layers. This could be attributed to the re-suspension and demineralization through the activity of both epifauna and infauna organisms [6]. Fishing activities within the estuary could also be possible causes of perturbation of the first 10 cm of the sediment layer. On the other hand, the concentrations of ^{210}Pb decrease with increase in depth in the Volta estuary (Figure 2B). The total ^{210}Pb depth profile varies between 87.01 ± 6.25 and 19.91 ± 1.61 while supported was between 25.51 ± 2.72 and 11.93 ± 1.78 and unsupported ranged between 68.75 ± 7.01 and 3.96 ± 2.94 Bq/kg (Figure 2B). Generally, the concentrations in the Volta estuary are higher than those recorded in the Pra estuary.

The CRS model could be applied to the unsupported ^{210}Pb of the Pra estuary starting from the depth where the activity begins to decay. In this case, the highest activity of unsupported ^{210}Pb of the Pra estuary was observed at 11 cm depth and followed by a decline in activities with depth reflecting no post-depositional perturbation or mixing of the sediment layers. This follows the general assumptions for ^{210}Pb applications of homogeneity and steady-state conditions [9]. The CRS model also assumes that there is no diffusion and unsupported ^{210}Pb activities decline to zero in the deepest layer.

In this way, the first 10 cm core activities were excluded from dating and only the rest of the profile was taken into consideration (Figure 2A right graph).Concentrations of^{137}Cs were mostly below the limit of detection in the Pra and Volta estuaries and could not be used as a good time marker for the validation of the CRS dating results [20]. The history of mining within the Pra basin and the construction of dams on the Volta River were used in explaining the variation in sedimentation rates [4].

The dates of the sediment cores in the Pra estuary span between 1829.18 ± 5.10 and 2010.14 ± 0.63 years while the Volta estuary covered between 1915.66 ± 23.75 and 2009.88 ± 0.49 years (Figure 3A-B).

The surface layer of the Pra core was about two years and the bottom (37 cm depth) was about 180 years. For the Volta, the surface layer was about three years and the bottom layer (39-40 cm depth) about 94 ± 23 years old at the time of coring. The age intervals between the bottom layer and the next layer above it (35 cm depth) was about 95 years and subsequent intervals were relatively uniform in the Pra estuary (Figure 3A) compared to a uniform age interval between the sediment layers in the Volta estuary (Figure 3B). The error margins between the ages of the cores from Pra estuary were much smaller and consistent while that of the Volta estuary increased from the surface towards the bottom layers (Figure 3B). The gross overlapping of ages in sediment layers in the Volta estuary could be attributed to the reworking of the sediment after deposition as well as possible dredging at the entrance of the estuary into the sea.

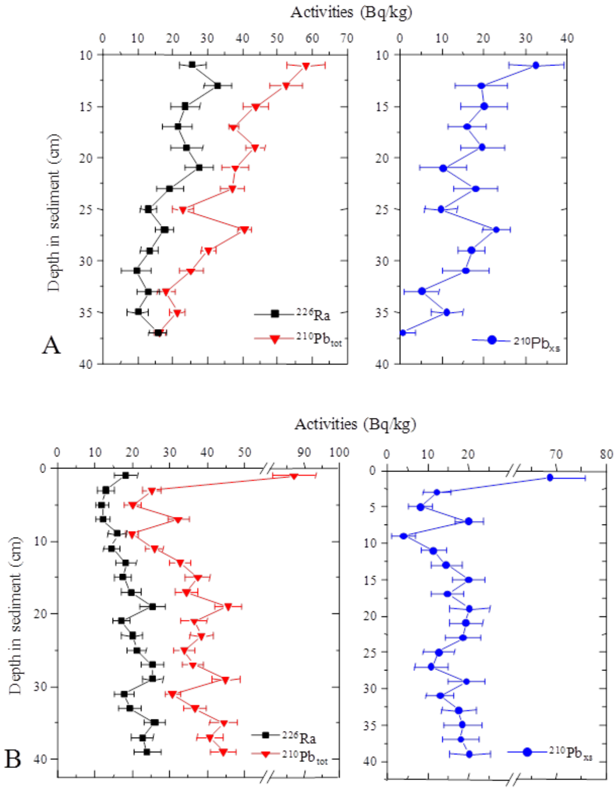

Figure 2: Vertical distribution of total, supported and unsupported ^{210}Pb in the cores collected from Pra estuary (A) and Volta estuary (B).

The computed depositional flux of ^{210}Pb into the sediment was 190.05 ± 15.85 Bqcm^{-2}y^{-1} for Pra estuary and 217.78 ± 11.76 Bqcm^{-2}y^{-1} for the Volta estuary. The average flux of radionuclides into the sediment was 203.92 ± 20.26 Bqcm^{-2}y^{-1}.

The sedimentation rate in the Pra estuary (mean value of 0.51 ± 0.31 gcm^{-2}y^{-1}) was lower than the Volta estuary (mean value of 1.04 ± 0.81 gcm^{-2}y^{-1}) (Figure 4A and Figure 4B). This was due to differences in volume of water and sediment from the two rivers as the Volta River is bigger than the Pra River. Although data on sedimentation rates in estuaries in the West African sub-region were not available for comparison, the findings in this study were however, similar to the

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sedimentation rates within the Bang Pakong River estuary, eastern coast of Thailand (0.69, 0.74, 0.57, 0.48 and 0.46 cm/yr) [4].

The sedimentation rate in the Pra estuary increased from 0.03 $gcm^{-2}y^{-1}$ to about 0.29 $gcm^{-2}y^{-1}$ within 95years (bottom layer of the sediment core), It then declined and remained constant ((0.22 $gcm^{-2}y^{-1}$) from 1935 to 1969). In 1981, the sedimentation rate increased gradually and yielded the highest (1.07 $gcm^{-2}y^{-1}$) in 2009 and dropped suddenly in 2010 (surface core). In contrast, a stable sedimentation rate in the Volta estuary (mean 1.08 $gcm^{-2}y^{-1}$) occurred between 1915 and 1967 (bottom layer of the sediment core). This was followed by a sharp drop in sedimentation rate (mean of 0.47 $gcm^{-2}y^{-1}$) between 1971 and 1984.

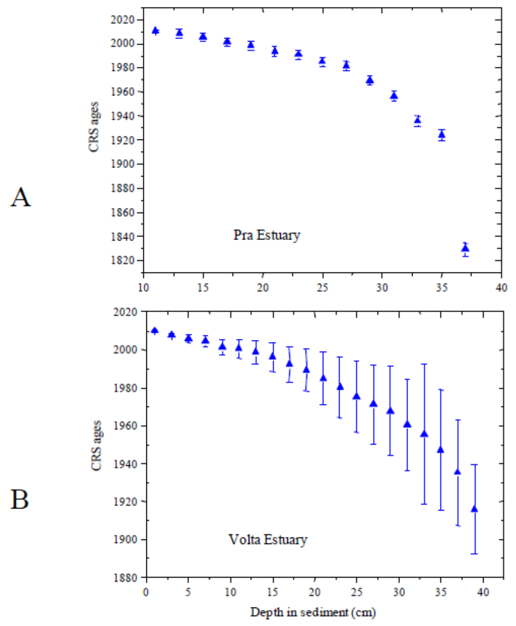

Figure 3: The chronologies provided by the dating model for the cores collected from Pra (A) and Volta (B) estuaries.

The sedimentation rate from 1989 to 1998 increased gradually and yielded an exceptional high rate of 3.90 $gcm^{-2}y^{-1}$ in 2000 (Figure 4B). This was then followed by a decline in sedimentation rate between 2001 and 2009 to the lowest of 0.02 $gcm^{-2}y^{-1}$ (surface sediment core). The sedimentation rate verses time depicts patterns of variations and stabilities which provides a reasonable interpretation of the data in both estuaries. This also confirms that the activities and corresponding inventories of transuransic elements in sediments strongly depend on the sedimentation rate, which is itself a function of local hydrodynamic conditions [19].

The variability of sedimentation rates within the Pra estuary is largely due to excess sediment input as a result of gold mining activities in the catchment area since the 15th century [21]. The decline in sedimentation rates from 1935 to 1967 indicates paucity of sediment supply which coincided with the introduction and enforcement of the Mercury Law in 1933 [21].

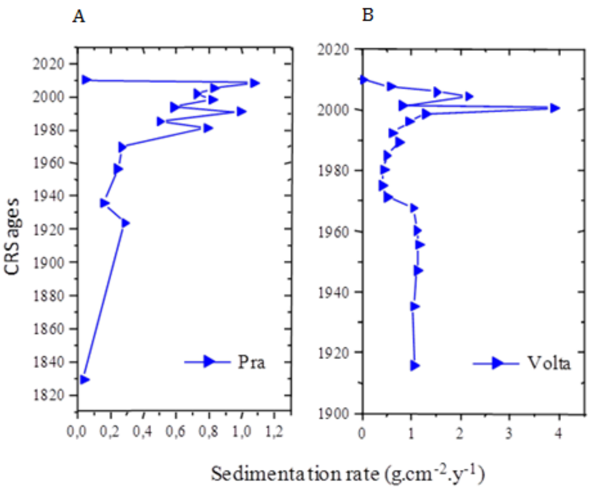

Figure 4: The sedimentation rate ($gcm^{-2}y^{-1}$) versus age (yrs) for the sediment cores collected from Pra (A) and Volta (B) estuaries.

The Mercury Law prevented the local (native) people from unauthorized digging for gold but allowed British and other foreign investors to acquire large concessions for commercial gold mining operation in the late 19th century [21]. Hence the commercial gold mining could have led to an increase in sediment supply into the river system leading to an increase in sedimentation rates between 1956 and 1981 of the Pra estuary. The fall in sedimentation rates in 1984 was caused by low water inflow due to drought in 1983 in Ghana which caused most rivers to dry up. On the other hand, the sudden increase in sedimentation rates after 1984, especially from 1990 to 2008 could be due to improved rainfall patterns and the proliferation of small scale mining (locally referred to as galamsey) activities as a result of enactment of artisanal mining law in 1989 [21]. Finally, the fall in sedimentation rate in 2010 could be due to the lack of sediment inflow as a result of siltation of streams and rivers that supplied the Pra River with sediment.

The sedimentation pattern in the Volta estuary depicts the anthropogenic activities before and after the construction of the Akosombo dam on the Volta River (Figure 4B). Before the construction of the dam, sedimentation rate was fairly constant (1.03-1.14 $gcm^{-2}y^{-1}$ between 1915 and 1967). After the commissioning of the dam in 1965, the sedimentation rate reduced remarkably (about 50% reduction) and remained almost uniform (0.40-0.51 $gcm^{-2}y^{-1}$ between 1971 and 1984). After 1984, there was a rise in sedimentation rate till 2000 where the highest peak was observed (Figure 4B) inspite of the commissioning of the Kpong dam, also on the Volta River. This was due to increase in sediment flow as a result of improved rainfall in the mid-80s and 90s after the 1983 drought which led to the opening of the spillways of both the Akosombo and Kpong dams to expel excess water in 1991.

The fall in sedimentation rate after 2000 until 2009 again was due to lack of sediment inflow because of the closure of the spillways of the dams and adverse rainfall patterns within the catchment area of the Volta basin (for most part of the period from (2000-2009)). However, a

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slight increase in sedimentation rate was observed in 2004, due to improved rainfall in the area in that particular year, that led to the second opening of the spillways to save the dams from collapsing.

Conclusion

The average activity of total ^{210}Pb in Pra and Volta estuaries were 33.30 ± 2.95 Bq/kg and 37.43 ± 3.13 Bq/kg, respectively. However, the Volta samples showed consistency in the profile values as compared to the Pra profile which needed modification of data to fit the CRS dating model. The age of the Pra core was between 2010 and 1829 as compared to the Volta core which was between 2009 and 1915 indicating that the Pra core was relatively older than the Volta core. The gross margin of error between the ages of the cores suggested possible dredging activities in the Volta estuary that could have resulted in re-deposition of sediment over the years. The mean sedimentation rate in the Pra and the Volta were 0.52 $gcm^{-2}y^{-1}$ and 1.05 $gcm^{-2}y^{-1}$, respectively. This confirms that, the Pra core was older than the Volta core. The mean flux of radionuclides into the sediment for the two estuarine systems is 203.92 ± 20.26 $Bqcm^{-2}y^{-1}$. Though the ^{137}Cs profiles were insufficient in validating the dating records of the sediments, historical events such as mining activities and construction of dams as well as rainfall patterns were important in the interpretation of the ages and sedimentation rates. The damming of the Volta River has caused about 50% reduction in the sedimentation rate at the Volta estuary. This will further decline due to damming of the Bagre River (White Volta) in Burkna Faso, a major source of inflow into the River Volta.

Proliferation of small scale-mining is enhancing sedimentation rates and may lead to siltation of rivers and streams with resulting impacts of flooding of riparian vegetation and adjoining communities.

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