The Contribution of Bank and Surface Sediments to Fluvial Sediment Transport of the Pra River

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Abstract

Sediment source studies involving a simple mixing model was undertaken in the Pra River Basin in Ghana using a single tracer ^{210}Pb to determine the relative contribution of surface and bank sediments to the fluvial sediment transport. Sediment source tracing was performed on the basis of sub-basins by comparing the concentration of ^{210}Pb in fluvial sediments to the bank sediments and potential surface sediment sources. The potential sediment source types sampled for analysis included surface sediments from arable top soils, illegal mining sites, path/untarred roads leading to rivers, gullies and gutters from settlements and farms. For bank erosion, river channel bank materials were sampled. Lead-210 fallout was determined by alpha spectrometry using the low background Gas-less Automatic Alpha counting system (Canberra iMatic™). Results showed that bank material was the dominant sediments and accounted for over 60% of suspended sediment loads in all tributaries. Measures should be put in place to control the entrainment of bank materials since bank sediments constitute a larger proportion of the fluvial sediments. High fluvial sediment load is known to have geomorphological, hydrological, water resource management and ecological implications.

Introduction

High fluvial sediment transport has been recognised as a major setback to the sustainability of reservoirs/dams for hydro-power generation, potable water supply, and irrigation (e.g. Alam *et al.,* 2007; Hazarika and Honda, 2001; Peng *et al.,* 2008; Schwartz & Greenbaum, 2009). Also, watershed sediment transport can lead to a number of environmental problems, including decreases in ecological diversity, and decreases in aesthetic properties of rivers and streams, impeding navigation and river channel morphology and stability (Davis & Fox, 2009).

These sediments are derived from bank and surface erosion processes. Eroding channel banks are thought to be a major source of sediment in some regions of the USA, and several attempts have been made to quantify this source (Collins *et al.* 1997; Collins *et al.*, 2001; Nagle *et al.,* 2007; Gellis, 2010). In response to the problems associated with traditional monitoring and measurement techniques, the fingerprinting approach has been increasingly employed as a means of establishing the relative importance of potential catchment sediment sources (Caitcheon *et al.* 2012; Collins *et al.,* 2001; Collins *et al*., 2013a; Collins *et al.,* 2013b; Walling & Collins, 2000; Wilkinson *et al*., 2013).

The most commonly used tracers include; radionuclides (^{137}Cs, ^{210}Pb) (Nagle *et al.* 2007; Walling, 2004), and cosmogenic isotopes (^{7}Be) (Schuller *et al.* 2006; Walling, 2004). ^{137}Cs has a core depth profile not greater than 20 cm and is

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anthropogenically introduced into the environment through fallouts of nuclear activities of bombs of 1950s and 1960s and reactors such as the 1986 Chernobyl disaster. Lead-210 ($t_{1/2}$ = 22years, with core depth of about 10 cm) and beryllium-7 ($t_{1/2}$ = 53days and depth profile not exceeding 3 cm) are natural fallouts from the atmosphere (Blake *et al.,* 2002; Matisoff and Whiting, 2011), hence are ubiquitous on the earth's surface and thus are suitable as environmental radionuclides tracers everywhere. Lead-210 is a product of atmospheric decay of ^{222}Rn gas (fallout ^{210}Pb) and *in situ* decay of ^{226}Ra. In most soils ^{210}Pb formed by *in situ* decay of ^{226}Ra will be in approximate equilibrium with ^{226}Ra, and usually is defined as 'supported ^{210}Pb'. Fallout ^{210}Pb in a soil or sediment sample is the excess of ^{210}Pb activity over the ^{226}Ra supported component. This is known as 'unsupported' or 'excess' ^{210}Pb (^{210}Pbex) (Wallbrink and Murray, 1996; Motha et al. 2002; Wallbring *et al*., 1998; Walling, 2004).

^{137}Cs, ^{7}Be, and ^{210}Pb are each suitable as particle tracers because they have a global distribution, adsorb efficiently to soil particles and thus move with soil, and are relatively easily measured (Matisoff & Whiting, 2011). Also these environmental radionuclide tracers are effective for distinguishing between surface-derived sediments from sheet and shallow rill erosion and sediments from gullies and stream channel walls, because channel and gully walls deeper than their profile depths of between 3 and 30 cm usually contain little or no traces of the radionuclides (Nagle *et al.,* 2007; Matisoff & Whiting, 2011). However, ^{137}Cs fallout from the atmosphere is currently near zero or near non-detectable limits (Matisoff & Whiting, 2011) in most parts of the world except northern Europe where release from the Chernobyl explosion was higher. Also due to the short half life of ^{7}Be, it is only suitable for simulating erosion of small catchments.

The fingerprinting technique could either be a simple mixing model using only one diagnostic tracer or a composite mixing model involving a combination of two or more tracers. Some researchers (Walling *et al.,* 1993, Yu & Oldfield, 1989; Molinaroli *et al.,* 1991) have, however, argued that no single diagnostic property of sediment can reliably distinguish different sources, because individual tracers may be subject to physical and chemical changes, which limit their use, e.g. particle size sorting, organic matter selectivity, and geochemical transformation during fluvial erosion and transportation (Collins *et al.,* 1997). Also, individual properties may be unreliable because of spurious source-sediment matches (Yu & Oldfield, 1989; Molinaroli *et al.,* 1991; Walling *et al.,* 1993). However, Nagle *et al.* (2007) have effectively used a simple mixing model of ^{137}Cs to distinguish between sediment from surface sources and gullies. Lead-210 (Brigham *et al.,* 2001; Motha *et al.,* 2002) and Berryllium-7 (Schuller *et al.,* 2006) have also been used singularly in sediment source tracing. Sediment source tracing has also been performed successfully in a subset of intermittent streams using amorphous to crystalline ratios of iron to estimate the fraction of sediment coming from in-stream vs. landscape sources (Schoonover *et al.,* 2007).

There are three basic approaches to the measurement of ^{210}Pb activity: (i) by gamma spectrometry, measuring the gamma radiation from ^{210}Pb directly; (ii) by beta spectrometry either counting the ^{210}Pb activity directly or after in-growth of its daughter ^{210}Bi; and (iii) by alpha spectrometry of the granddaughter ^{210}Po, assuming radioactive equilibrium exists between the two nuclides (Johansson, 2008). In sediments, ^{210}Pb and ^{210}P are often found in equilibrium and the activity of ^{210}Pb can be estimated from that of ^{210}Po. The ^{210}Po is typically analysed by alpha spectrometry following pre-concentration and spontaneous deposition onto silver discs (Johansson, 2008).

The Pra River Basin in Ghana has been engulfed by certain anthropogenic activities such as illicit logging, farming, urbanization and illegal small scale mining (Mensah, 2012). Serious concerns have been raised by stakeholders such as Water Resources Commission of Ghana, NGOs, District and Municipal Assemblies and chiefs of the level of pollution due to the release of chemicals and sediments into water bodies by these human activities. The high concentration levels of fine sediments are causing the breakdown of filters in treatment plants of Ghana Water Company Limited (GWCL) in most urban water supply systems within the basin.

In order to solve this problem, there is the need to identify the sources of these sediments because elevated sediment volumes have an array of detrimental impacts which threaten sustainable ecosystem functioning, increasing water treatment costs, flood risk problems etc (Copper *et al.,* 2015). Such information is required to design effective sediment and non-point pollution control strategies. Sediment source tracing studies will provide an improved understanding of erosion and suspended sediment transport within a basin which is an essential precursor to establish sediment budgets, develop distributed sediment yield models, and interpret sediment yields in terms of landscape evolution (Walling *et al.,* 1993). However, sediment provenance data are lacking for many areas of the world, including Africa, because of the spatial and temporal sampling constraints and the operational difficulties associated with most traditional measurement techniques (Peart & Walling, 1988). Consequently, very little studies of this kind have been undertaken in Ghana. Most studies have been centred on fluvial sediment transport (Akrasi, 2005; Akrasi and Ansa-Asare, 2008; Akrasi, 2011; Amisigo and Akrasi, 1998; Boateng et al. 2012; Kusimi, 2008).

In view of the necessity for accurate and reliable sediment source data in developing countries and the success of the fingerprinting approach in providing such data in other environments (Collins *et al.,* 2001), this paper reports the application of sediment mixing fingerprinting technique to identify sediment sources in the Pra Basin for effective river basin management. The paper is just an aspect of a study that investigated the sediment yield, bank erosion and sediment sources of the basin in order to ascertain sediment provenance in the basin. When the major sources of sediments in the basin are known, it will facilitate the development and implementation of appropriate control measures towards protecting water resources. This paper presents only findings on the sediment source tracking aspect of the study; the sediment yield component has been published by Kusimi *et al.,* 2014.

Materials and methods

Physical setting of the study area

The Pra River Basin is located between latitudes 5º00 'N and 7º15 'N and longitudes 0º03 'W and 2º80 'W (Fig.1) in south central Ghana. The major tributaries of the basin include the Ofin, Oda, Anum and Birim Rivers which drain from the Mampong-Kwahu and Atewa Mountain Ranges. The drainage basin area is 23,188 km^2 with a mean annual discharge of 214 m^3s^{-1} (Akrasi and Ansa-Asare, 2008). The basin is generally of low relief characterised by undulating topography with an average elevation of about 450 m above sea level. The Pra River drains into the Gulf of Guinea.

The main soil type of the catchment is forest ochrosols which are alkaline. The soils are weathered from the Tarkwaian geological formations composing of sandstones and granitoids and metamorphosed rocks such as phyllites and schists. The soils are clayey and not well leached; hence have the capacity to retain more moisture and are very cohesive (Dickson & Benneh, 1995).

The climate of the basin is the wet semi-equitorial and is characterized by two rainfall maxima. The first rainy season occurs between May–June with the heaviest rainfall falling in June and the second season is from September–October. The rains are brought by the south-west monsoons and the annual rainfall amount is between 125 and 200cm. The dry season spans from November to March and the dominant winds during this period are the dry harmattan winds. Temperatures are high throughout the year with the highest mean monthly temperature being 30 °C occurring between March and April and the lowest is about 26 °C which occurs in August (Dickson & Benneh, 1995).

The vegetative cover is that of the moist semi-deciduous forest which is heavily logged. Trees grow to heights of about 35–45 m or more. The forest consists of trees, lianas, climbers and shrubs/bushes. Due to the rapid expansion of cocoa plantations and the shifting cultivation system of farming in this zone, very little of the original forest remains and most of what is left is secondary growth. The size of trees in this belt therefore depends on how long the forest has been allowed to regenerate (Dickson & Benneh, 1995). However there are still a number of protected Forest Reserves within the basin which give good protection to the landscape.

The Pra Basin transcends 4 administrative regions of Ghana namely; the Ashanti, Eastern, Central and Western Regions. Consequently, it serves as the source of water supply for both commercial and domestic activities for most urban centres and other settlements within it. For instance, the Ofin sub-basin is the main source of water supply to Kumasi, the administrative capital of the Ashanti Region and its environs from two reservoirs, Barekese and Owabi Dams (Fig.1). Also the Birim River supplies water to towns such as Kibi, Kade, Akim

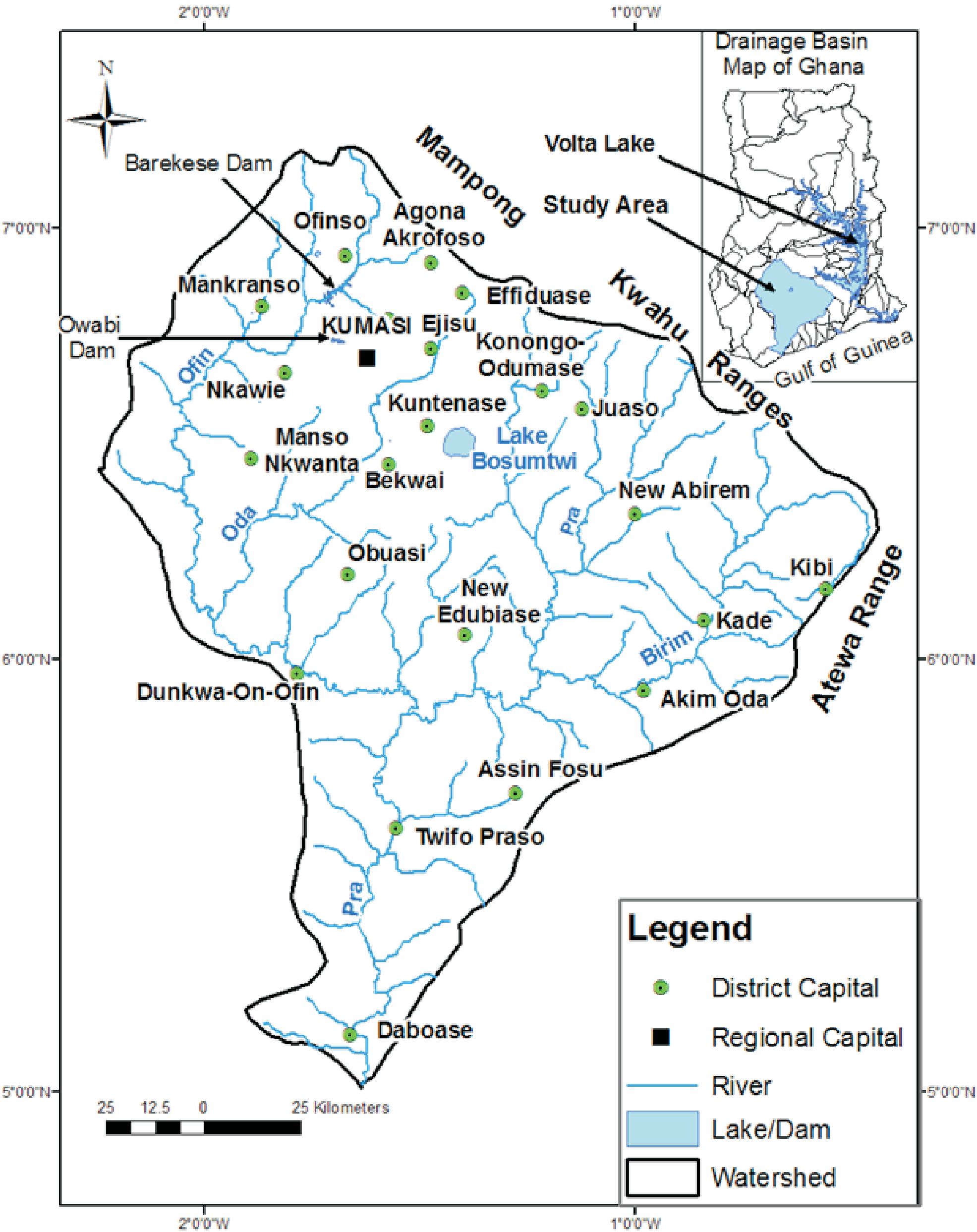

Fig.1. Map of the Pra River Basin

Oda among others. However, human activities such as small scale mining and illicit logging are degrading the surface water resources of the basin (Water Resources Commission, 2011).

The primary land uses within the Pra Basin are settlement development, farming, logging and mining. The basin contains the highest density of settlements both rural and urban in the country. It also contains most of the largest cocoa growing areas in south central Ghana. Agricultural practices include cash crop such as cocoa, oil palm and food crops. It has a high concentration of mining activities mainly concerned with gold exploitation. Mining is undertaken by multinational corporations and small scale miners most of them being illegal miners. Some of the large scale mining companies are AngloGold Ashanti and Perseus Mining Ltd (Water Resources Commission, 2011). The activities of illegal miners are of primary concern as their activities lead to the discharge of mine wastes or sediments into the rivers.

Data collection andaAnalysis

Sediment source tracing was performed on the basis of sub-basins using the finger print method (Gruszowski *et al.,* 2003). The following potential sediment source types were sampled for analysis; for surface erosion (arable top soils, illegal mining sites, paths/untarred roads leading to rivers, sidewalls of gullies and gutters/ditches that drain into streams; recently eroded sediments at the end of gullies and gutters/ditches) and for bank erosion channel banks were scrapped. Sampling sites (Fig.2) of these potential sediment sources were identified through field investigations and interviews with the local communities to identify areas of active sediment erosion (Davis & Fox, 2009).

To accommodate local spatial variability in ^{210}Pb in arable top soils and illegal mining sites, core samples of depth 10 cm within plot sizes of 15×15 m^2 at grid intervals of 3× 3 m were taken at each site with a 5 cm diameter pvc pipe as a corer. Recently eroded patches from paths/untarred roads, sidewalls of gullies and gutters not beyond 10 cm deep (*since Lead-210 depth profile does not exceeding 10 cm*) were randomly collected using the scapper. Same samples at each site were composited and one sample taken for analysis (Nagle *et al.,* 2007; Walling, 2004). Bank sediments were also collected by scrapping channel wall sediments not below 10 cm (Davis & Fox, 2009). Suspended sediments were sampled at the catchment outlets of sub-basins (Fig.2) using the depth integrated sampler based on the equal-width-incremental approach across each channel transect (Davis & Fox, 2009; Edwards & Glysson, 1999; Matisoff & Whiting, 2011) and composited for analysis to account for the spatial variability in ^{210}Pb concentration across the section. Collected surface sediments were placed in labelled polyethene bags whiles those of suspended were poured into plastic bottles and preserved in iced chests (Ohio EPA, 2001) to minimize biological and chemical changes from the time of collection to the time of analysis. Samples were collected in September at the peak of the rainy season when flows were high because ^{210}Pb environmental radionuclides

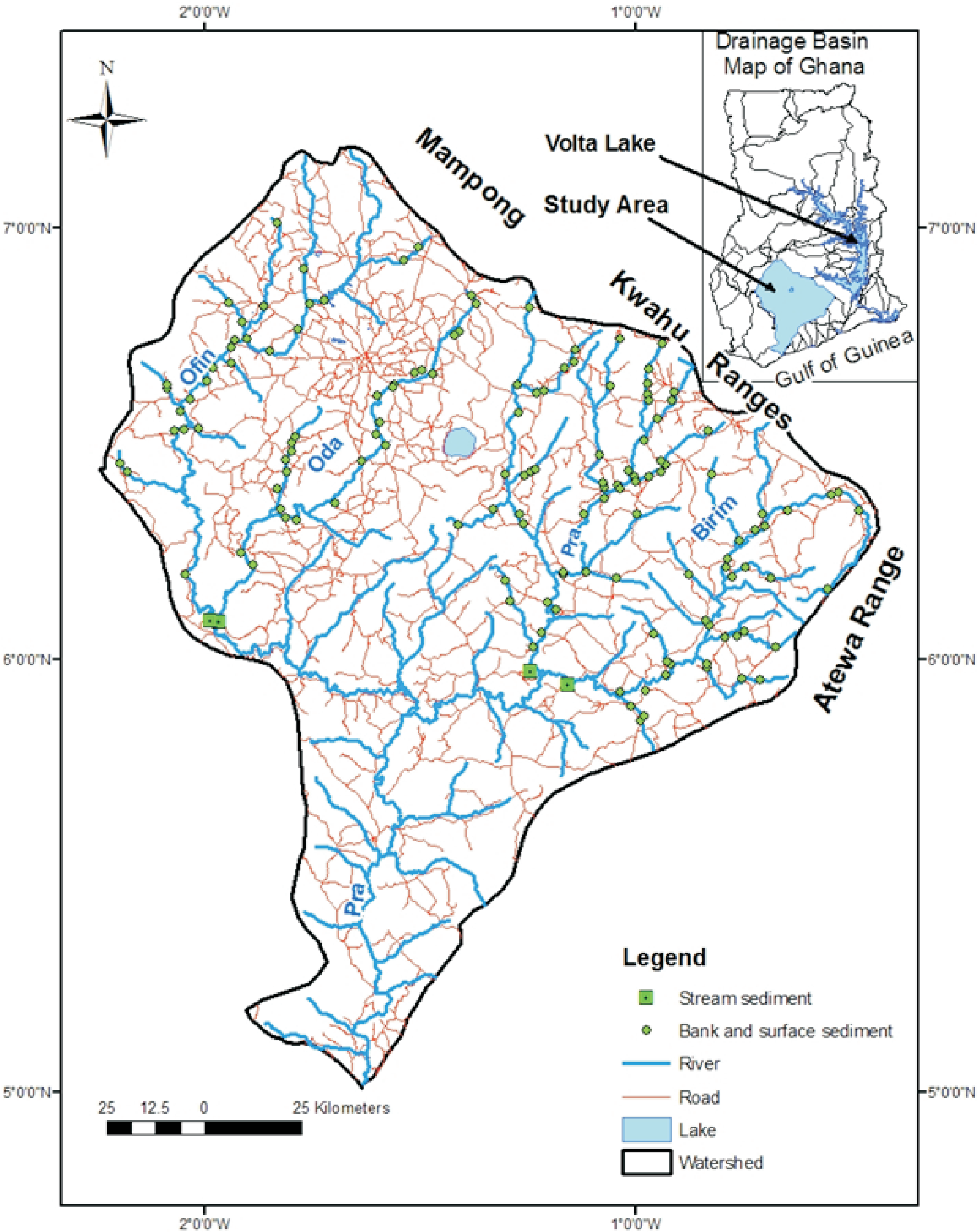

Fig. 2. Sampling sites

are known to fallout highest with high precipitation (Matisoff & Whiting, 2011).

Samples were prepared for analysis through the following processes. All source material samples were air-dried, ground in a mortar and dry-sieved to 63µm because radionuclides tend to have higher sorption to finer soils (Collins *et al.,* 2013a; Matisoff & Whiting, 2011) and also to facilitate direct comparison of suspended sediment and source samples (Collins *et al.,* 2001). Suspended sediments were centrifuged and the supernatant discarded, recovered solids were oven dried. Both suspended and surface sediment samples were weighed transferred into planchets and set aside for analysis. ^{210}Pb determination was by alpha spectrometry following similar procedures of Ogundare & Adekoya (2015) at the Ghana Atomic Energy Commission, Accra. Samples were counted for 200 min to determine alpha activity concentration using the low background Gas-less Automatic Alpha counting system (Canberra iMatic™) calibrated with alpha (241Am) standards. The system uses a solid state silicon (Passivated implanted Planar Silicon, PIPS) detector. Two measurements of central tendency, mean and median were extracted from results of the analysis.

To quantify the relative contributions of bank and surface sources, values of ^{210}Pb concentration were analysed using a simple mixing model (equation 1) based on mean ^{210}Pb values of samples measured. Equation (1) has been used effectively by Mukunda et al. (2009), Nagle and Ritchie, (2004) and Nagle *et al.* (2007);

$$Cs = \frac{Pr - Pb}{Ps - Pb} \times 100 \quad \ldots\ldots\ldots\ldots\ldots (1),$$

Where *Cs (%)* is the percentage contribution from surface sources; *Pr* is the value of ^{210}Pb for stream sediments, *Ps* the concentration value of ^{210}Pb in surface sediment sources and *Pb* the value of ^{210}Pb for bank materials. The use of the simplistic mixing model is acceptable when smaller samples and or two sources are involved. The procedure follows previously published works (Nagle & Richie, 2004; Nagle *et al.,* 2007). Where more sources are being discriminated, more complex mixing model approaches will be required (Caitcheon *et al.,* 2012; Collins *et al.,* 2001; Collins *et al.,* 2013a; Collins *et al.,* 2013b; Wilkinson *et al.,* 2013). The level of significance of surface and bank material contributions to the fluvial sediment transport was statistical tested by performing the *F*-test using the R programme.

Results and discussion

Tables 1–4 illustrate the mean concentration of unsupported ^{210}Pb for each of the surface samples as well as the mean and median concentration of all the samples in all sub-basins. The mean concentration levels of bank sediments and stream sediments are also provided for each sub-catchment. Except within the Ofin catchment, the median values were generally lower than the means (Table 4: Mean = 1.54; Median = 1.69 Bq/kg). Both the mean and median values were higher than bank samples in the Oda Basin (Table 1–4). The lowest mean concentration of unsupported ^{210}Pb for bank materials was 0.89 Bq/kg and was recorded in the Birim Basin and the highest value of 3.09 Bq/kg occurred in the Pra Sub-basin (Tables 1 and

TABLE 1

Mean and Median ^{210}Pb concentration levels for stream sediment and potential source materials in Birim Sub-basin

Tracer	*Galamsey (n = 7)*	*Road & Bridge (n = 7)*	*Farm (n = 8)*	*Settlement (n = 8)*	*Gully (n = 3)*	*Gutter (n= 2)*	*Mean sur-face soil (n = 47)*	*Bank Sediment (n = 12)*	*Stream Sediment*
Mean	1.45	1.79	1.43	1.65	1.06	0.74	1.34	0.89	1.10
							Median of surface soils		
Median	0.4	1.47	0.68	0.94	1.29	0.74	0.84	0.8	1.10

Units ((Bq/kg)

TABLE 2

Mean and Mean ^{210}Pb concentration levels for stream sediment and potential source materials in the Pra Sub-basin

Tracer	*Galamsey (n = 9)*	*Road & Bridge (n = 21)*	*Farm n = 7)*	*Settlement (n = 9)*	*Gully ((n = 1)*	*Gutter (n=10)*	*Mean sur-face soil (n = 72)*	*Bank Sediment (n = 15)*	*Stream Sediment*
Mean	2.32	4.02	2.88	3.31	0.68	4.25	3.40	3.09	3.18
							Median of surface soils		
Median	2.42	1.40	2.74	3.73	0.68	3.83	2.58	2.28	3.18

Units ((Bq/kg)

TABLE 3

Mean and Median ^{210}Pb concentration levels for stream sediment and potential source materials in Oda Sub-basin

Tracer	*Galamsey (n = 5)*	*Road & Bridge (n= 4)*	*Settlement (n = 4)*	*Gully (n = 2)*	*Gutter (n = 2)*	*Mean sur-face soil*	*Bank Sediment (n=29)*	*Stream Sediment (n=12)*
Mean	0.44	0.55	1.01	2.34	2.96	1.77	2.12	2.24
						Median of surface soils		
Median	0.01	0.55	0.54	2.34	2.97	0.55	1.84	2.24

Units ((Bq/kg)

TABLE 4

Mean ^{210}Pb concentration levels for stream sediment and potential source materials in Ofin Sub-basin

Tracer	*Galamsey (n = 2)*	*Road & Bridge (n = 8)*	*Farm (n = 2)*	*Settlement (n= 2)*	*Gully (n= 2)*	*Gutter (n= 3)*	*Mean surface soil (n=27)*	*Bank Sediment (n = 8)*	*Stream Sediment*
Mean	2.25	2.22	1.13	2.84	0.85	0.52	1.54	1.01	1.16
							Median of surface soils		
Median	2.25	2.47	1.13	2.84	0.85	0.01	1.69	0.84	1.16

Units ((Bq/kg)

TABLE 5

Contribution of bank material and surface soil sources to suspended sediment load in the various sub-catchments

River Basin Source Type	*Birim Surface soil*	*Bank sediment*	*Pra Surface soil*	*Bank sediment*	*Oda Surface soil*	*Bank sediment*	*Ofin Surface soil*	*Bank sediment*
^{210}Pb (%)	47	53	29	71	34	66	28	72

2). However the lowest mean and median surface soil values were recorded in Birim Basin (1.34 Bq/kg – Table 1) whiles higher levels were in the Pra Sub-basin (3.40 Bq/kg) (Table 2).

Roads that are not tarred (Plate 1a) and exposed urban landscapes (Plate 1b) were found to have the highest mean values of unsupported ^{210}Pb in surface samples as compared to other surface samples. The rationale for this high concentration of unsupported ^{210}Pb in these samples is due to the well exposed and less disturbed state of these landscapes as compared to soils of farms, galamsey, and gullies which are frequently being mixed/tilled and or eroded. Generally lower levels of ^{210}Pb in surface samples were found in disturbed sites. The exposed road and urban soils promote the accumulation of unsupported ^{210}Pb radionuclide fallouts. Samples from gutters/ditches were also high in ^{210}Pb concentration levels with a minimum value of 0.52 Bq/kg in the Ofin Basin (Table 4) and a maximum of 4.25 Bq/kg in the Pra Sub-basin (Table 2). This is so because, recent eroded sediments at the ends of ditches are residuals of sediments of radionuclide fallout being transported. In all the basins, unsupported ^{210}Pb mean levels in bank sediments were found to be lower than mean unsupported ^{210}Pb samples of most surface sites. Lower values were recorded in sites of intense surface and bank erosion (Tables 6; 8 and 9). Areas of active bank erosion do not promote the accumulation of ^{210}Pb fallouts in the soils of river banks as they are constantly being washed away into the river. Nagle *et al.,* 2007 also attributed low

(1a) Untarred road leading to Ofin River

(1b) Urban erosion - Eroded plant root at Konongo in the Pra sub-basin

(1c) Evidence of cantilever bank failure along the bank of the Oda River at Asaago – Kumasi

(1d) Mine waste along the Birim River at Ekorso Brimso

levels of an environmental radionuclide ^{137}Cs in bank sediments to active bank erosion. Another reason for lower Pb^{210} levels on stream banks is that on a vertical bank, much of the rainfall will run off and not soaked into the bank face hence does not enhance radionuclide accumulation.

Similarly, recent illegal mine sites (galamsey – Plate 2a) also recorded lower values of unsupported ^{210}Pb (Tables 6–9). For instance at Kibi, an abandoned illegal mine site that is becoming vegetated (Plate 2b) had almost 3 Bq/kg ^{210}Pb concentration as compared to an adjacent site with a value of 1.2 Bq/kg where mining was ongoing (Table 6 and Plate 2a). Soils are dug from pits of 20 m or more by these miners where ^{210}Pb fallouts do not reach, because maximum concentrations of ^{210}Pb in soils are usually found at the surface decreasing exponentially with depth, and reaching undetectable levels at depths greater than 10 cm. The mixing of top soils rich in ^{210}Pb with underground mined soils or the burial of top soils due to the mining activities account for the low unsupported lead-210 values in recent mine sites. These observations are in line with literature. According to Walling *et al.,* (1993) in undisturbed soils, ^{210}Pb are concentrated in

TABLE 6

Results of bank sediments and surface soil analyses in the Birim Basin

Sample No.	*Bank Sediment*	*Galamsey*	*Road & Bridge*	*Farm*	*Settlement*	*Gully*	*Gutter*
1	0.79	2.99	3.29	3.28	4.43	1.89	0.01
2	0.01	1.20	0.89	4.21	0.84	0.01	1.47
3	2.59	4.95	3.43	0.17	2.48	1.29	
4	0.01	0.01	0.45	0.67	2.95		
5	0.93	0.20	1.47	0.69	1.03		
6	2.28	0.40	1.61	0.67	0.01		
7	0.81	0.40	1.40	0.21	0.85		
8	0.56			1.53	0.64		
9	0.47						
10	1.24						
11	0.16						
12	0.85						
Mean	0.89	1.45	1.79	1.43	1.65	1.06	0.74
Median	0.8	0.4	1.47	0.68	0.94	1.29	0.74

Units ((Bq/kg)

Table 7

Results of bank sediments and surface soil analyses in the Pra Basin

Sample No.	*Bank Sediment*	*Galamsey*	*Road & Bridge*	*Farm*	*Settlement*	*Gully*	*Gutter*
1	2.28	2.71	2.55	0.01	4.05	0.68	6.03
2	0.01	1.42	0.01	0.16	3.85		5.73
3	2.71	2.65	3.81	6.29	1.12		0.99
4	0.32	0.55	2.73	1.72	3.73		1.45
5	5.59	1.42	0.84	3.75	4.64		1.33
6	6.68	0.83	3.6	5.47	1.85		6.86
7	2.11	4.01	0.63	2.74	6.49		3.69
8	2.41	4.85	1.40		3.25		11.88
9	1.01	2.42	0.60		0.83		3.96
10	0.84		0.61				0.55
11	2.44		0.51				
12	5.03		1.0				
13	1.72		1.24				
14	11.03		1.52				
15	2.21		2.27				
16			0.73				
17			1.8				
18			22.55				

19			0.72				
20			30.83				
21			4.41				
Mean	3.09	2.32	4.02	2.88	3.31	0.68	4.25
Median	2.28	2.42	1.40	2.74	3.73	0.68	3.83

Units ((Bq/kg)

TABLE 8

Results of bank sediments and surface soil analyses in the Oda Basin

Sample No.	*Bank sediment*	*Galamsey*	*Road & Bridge*	*Settlement*	*Gully*	*Gutter*
1	0.01	0.01	0.05	0.01	1.36	5.7
2	1.24	0.01	3.05	0.01	3.32	0.2
3	1.35	0.01		1.07		3.67
4	1.99	0.91		2.95		2.26
5	2.68	1.25				
6	2.27					
7	8.27					
8	2.27					
9	1.10					
10	1.69					
11	2.54					
12	0.03					
Mean	2.12	0.44	0.55	1.01	2.34	2.96
Median	1.84	0.01	0.55	0.54	2.34	2.97

Units ((Bq/kg)

Table 9

Results of bank sediments and surface soil analyses in the Ofin Basin Basin

Sample No.	*Bank sediment*	*Galamsey*	*Road & bridge*	*Farm*	*Settlement*	*Gully*	*Gutter*
1	3.05	2.81	4.74	1.36	3.57	0.01	0.01
2	0.01	1.69	3.37	0.89	2.1	1.69	0.01
3	0.56		0.01				1.53
4	0.01		0.01				
5	1.64		4.08				
6	1.11		1.56				
7	0.58		0.48				
8	1.09		3.48				
Mean	1.01	2.25	2.22	1.13	2.84	0.85	0.52
Median	0.84	2.25	2.47	1.13	2.84	0.85	0.01

Units ((Bq/kg)

(2a) Illegal mining site where mining is on-going

(2b). Abandoned illegal mining site becoming vegetated

the upper 10 cm of the soil profile, whereas in cultivated soils this radionuclide will be mixed throughout the plough layer and surface concentrations will be much lower. Also subsoil horizons below 25 cm and exposed river banks (apart from the upper 10 cm) will contain zero or only very low levels of unsupported ^{210}Pb. Also lower levels of ^{137}Cs in certain plots relative to others were explained by soil mixing due to cultivation (Nagle & Ritchie, 1999).

The simple mixing model results of equation (1) using mean values show that a higher percentage contribution of sediments into the fluvial sediment transport is coming from bank sediments with a range of 53–72% within the sub-catchments (Table 5). The lowest estimated bank sediment contribution is in the Birim Basin (53%) whiles the highest is recorded in the Ofin Basin (72%). Conversely, the lowest surface soil sediment source (28%) is in the Ofin Basin whiles the highest surface sediment source is in the Birim Basin (47%) (Table 5). The model results are buttressed by a statistical test which showed that stream bank erosion is a significant source of sediment transport in the main Pra Basin and its sub-catchments with a p-value of 0.0003 and an R^2-value of 0.99. The p-value of surface soil is however 0.08 with a higher AIC value of -4.9 as compared to -27.3 for bank sediments.

Due to the good vegetative cover of the landscape, soils are well protected and coupled with low gradient of the catchment which is less than 20 degrees, surface erosion will be quiet low. Over 81% of the catchment is protected by vegetative cover composing of forest reserves, open/secondary growth, savannah and coastal scrub/grassland with only about 22% being covered by bushes/cropland and built-ups/barelands (Kusimi *et al.,* 2014; Kusimi *et al.,* 2015). Collins *et al.,* 1997 and Collins *et al.,* 2001 also observed that, surface erosion is restricted by higher density provided by natural vegetation and plant litter.

On the other hand, channel erosion at the middle section and activities of alluvial small scale mining activities within the rivers entrain much bank materials into the rivers and this accounts for higher bank

Plate 3: Illegal alluvial gold mining of the river bed and bank of the Ofin River.

material tracer sources. At the peak of the rainy season river banks were flooded to bank full stage making them susceptible to mass failure and slumping (Plate 1c and Plates 4ab) due to bank wetness and the removal of vegetative cover. Bank toe undercutting during the falling limb stage of flow hydrograph results in the removal of bank material and bank collapse into river channels. Bank erosion was observed to be very widespread in the middle course of the tributaries. Wasson *et al.* (2010) also found that in the mid to lower Daly River channel bank erosion is an important sediment source due to increases in annual rainfall and discharge.

Secondly, alluvial gold mining is being undertaken along channel banks and bed (Plates 1d and 3) and this entrains sediments directly into the river or it results in the remobilization of deposited sediments into the sediment transport system. These processes generate plumes of sediments in the rivers which discolours the water. There are hundreds of these miners strung along all the major tributaries and most streams within the basin.

As part of the same study, Kusimi *et al.*, 2014 found sediment yield to be increasing downstream in all sub-catchments. This is inconsistent with the inverse relationship model between sediment delivery ratio and basin area which shows that sediment yield per unit area generally declines with increasing catchment area. It is well known that for most large river systems, most of the sediment which enters the system does not get transported to the outlet of the river owing to decreasing slope and channel

(4a) Flooded channel of the Birim River in the middle section where illegal mining is occurring

(4b) Flooded channel of the Oda River at Bepotenten near an illegal mining site

(4c) Clear water in the upper course at a non-galamsey site at Ejisu on Oda River.

(4d) Colour of the Oda River at Bepotenten in the dry season – same section as *4b* which is near an illegal mining site

gradients with increasing basin size and this increases opportunities for either a temporary/ permanent deposition to be associated with river channels, floodplains, valleys or the base of slopes (Caitcheon *et al.,* 2012; Prosser *et al.,* 2001). Kusimi *et al.* (2015) observed that, in the upper sections of the rivers where illegal mining was not taking place, the water was clear (Plate 4c) as compared to the middle and lower sections were illegal mining was occurring. At the middle and lower sections, the water was very dirty and of low virtual clarity or transparency (Plates 4a, b and d), an indication of high turbidity and sediment load transport.

Conclusion

A sediment source study using a sediment mixing model involving ^{210}Pb environmental radionuclide fallout is employed to determine that much suspended fluvial sediments in transport in the Pra River are originating from bank materials. Surface sediments in transport were relatively low owing to less surface erosional processes. Combinations of illegal mining (galamsey) along the river and bank erosion are the plausible explanatory factors accounting for the entrainment of bank sediments into the sediment transport budget. The method used in this study did not allow the discrimination between the contributions of the two subsurface sources to the fluvial sediment in transport in view of the small number of samples collected for the study. The model results are however consistent with field observations and sediment load analysis (Kusimi *et al.,* 2014) which showed that much of the bank sediment injection is as a result of illegal mining activities. Hence, the activities of illegal mining in the Pra Basin and for that matter the whole country need to be controlled by enforcing established policies and legislations on small scale mining (Minerals and Mining Act, 2006 and National Mining Policy, 2010), Water Use (LI 1692) and land use (National Land use Policy, 1999) as their proper implementation will ensure the sustainable exploitation of the natural resources of the Pra Basin without compromising its water quality.

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