

**SEDIMENT YIELD AND BANK EROSION ASSESSMENT
OF PRA RIVER BASIN**

BY

**John Manyimadin Kusimi
(10096985)**



This thesis is submitted to the University of Ghana, Legon in partial fulfilment of the requirement for the award of PhD Geography & Resource Development degree.

June, 2014

Declaration

This thesis entitled “**Sediment yield and bank erosion assessment of Pra River Basin**” is entirely an original study that I conducted. With the exception of relevant literature and ideas of specific sources which have been duly referenced, the work has not been presented anywhere in part or whole for any award of a degree.

.....
John Manyimadin Kusimi
(Student)
(10096985)

Date.....



.....
Dr. Emmanuel Morgan Attua
Dept of Geography & Resource Dev't
University of Ghana, Legon
(Principal supervisor)

Date.....

.....
Prof Bruce Banoeng-Yakubo
Department of Earth Science
University of Ghana, Legon
(Supervisor)

Date.....

.....
Dr. Barnabas Amisigo
Water Research Institute
CSIR, Accra
(Supervisor)

Date.....

DEDICATION

This work is dedicated to my family for their immense support, prayers and contribution.



Acknowledgement

I am grateful to God for bringing me this far in life and academia; to my supervisors: Dr. Emmanuel Morgan Attua, Dr. Barnabas Amisigo and Prof Bruce Banoeng-Yakubo for their support, suggestions, patience and making time off their busy schedules to supervise my work.

The University of Ghana partially funded this thesis by awarding me a Faculty Development Grant which was very helpful in undertaking the field work and meeting the costs of field data analysis.

I will like to express my gratitude to my brother Jonathan Kusimi, wife Mrs. Bertha Kusimi and Mr. Gabriel Appiah of Water Research Institute, CSIR – Accra for assisting me in my field data collection.

I will wish to thank Water Research Institute, CSIR - Accra and Ecological Laboratory (ECOLAB) of the Dept of Geography & Resource Development, University of Ghana for providing field equipment and laboratory space to collect and analyze my field samples. The support of Mr. Prince Owusu of ECOLAB during my field data analyses is also acknowledged.

Lastly, I wish to thank Mr. Gerald B. Yiran of the Dept of Geography & Resource Development, University of Ghana for always responding to my call anytime I was in need of assistance with respect to data processing and analysis on the modelling aspect of the thesis.

List of Tables

Table	Page
Table 2.1: Examples of models for the derivation of R values.....	34
Table 3.1: Discharge Rating Curves.....	42
Table 3.2: Annual suspended sediment load and specific suspended sediment yield for the monitored stations in the Pra River Basin.....	56
Table 3.3: Parameters for suspended sediment rating curves.....	57
Table 4.1: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in Birim Basin.....	64
Table 4.2: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in Pra Basin.....	64
Table 4.3: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in Oda Basin.....	64
Table 4.4: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in Offin Basin.....	64
Table 4.5: Contribution of bank material and surface soil sources to suspended sediment load in the various sub-catchments.....	64
Table 5.1: Annual bank erosion or deposition rates at Anyinam.....	75
Table 5.2: Annual bank erosion or deposition rates at Amuanda Praso.....	75
Table 5.3: Annual bank erosion or deposition rates at Akim Oda.....	76
Table 5.4: Annual bank erosion or deposition rates at Brenase.....	76
Table 5.5: Annual bank erosion or deposition rates at Ejisu.....	76
Table 5.6: Annual bank erosion or deposition rates at Adiembra.....	77

Table 6.1A: K Factor Values of the Soil types.....	86
Table 6.1B: Soil erodibility classification.....	86
Table 6.2: Land Cover Types and Cover Management (C) factor values.....	88
Table 6.3: Attributes of Landsat ETM+ 2008.....	88
Table 6.4: Land cover co-efficient values.....	90
Table 6.5: Statistics of the different sediment yield model variables.....	100
Table 6.6: Estimates of sensitivity analysis of sediment yield for 12 mm event.....	101
Table 6.7: Estimates of sensitivity analysis of sediment yield for 12.5 mm event.....	101

List of Figures

Figure	Page
Fig.1.1: Map of the Pra River Basin.....	14
Fig.3.1: Sediment Yield Sampling Stations.....	40
Fig.3.2: Daily mean concentration of samples at Anwiankwanta.....	44
Fig.3.3: Daily mean concentration of samples at Brenase.....	44
Fig.3.4: Daily mean concentration of samples at Akim Oda.....	45
Fig.3.5: Daily mean concentration of samples at Adiembra.....	45
Fig.3.6: Daily mean concentration of samples at Twifo Praso.....	46
Fig.3.7: Daily mean concentration of samples at Assin Praso.....	46
Fig.3.8: Daily mean concentration of samples at Sekyere Heman.....	47
Fig.3.9: Mean monthly sediment load at Akim Oda.....	50
Fig.3.10: Mean monthly sediment load at Brenase.....	50
Fig.3.11: Mean monthly sediment load at Anwiankwanta.....	51

Fig.3.12: Mean monthly sediment load at Adiembra.....	51
Fig.3.13: Mean monthly sediment load at Twifo Praso.....	52
Fig.3.14: Mean monthly sediment load at Assin Praso.....	52
Fig.3.15: Mean monthly sediment load at Sekyere Heman.....	53
Fig.3.16: Annual sediment yield.	56
Fig.5.1: Particle size distribution curves of bank sediments.....	80
Fig.5.2: Eroded bank sediments.....	82
Fig.6.1: Schematic chart of GIS applications to soil erosion mapping and the derivation of Sediment Delivery Ratio, SDR.....	84
Fig.6.2: Effective total rainfall erosivity (Re) factor map of 2008 for 12 mm.....	92
Fig.6.3: Effective total rainfall erosivity (Re) factor map of 2008 for 12.5 mm.....	92
Fig.6.4: The soil erodibility (K) map of the basin.....	92
Fig.6.5: The length and slope (LS) map of the basin.....	92
Fig.6.6: Cover management factor (C) map derived from satellite image classification.....	93
Fig.6.7: Soil erosion potential map of the basin.....	93
Fig.6.8: Gross soil erosion map of 12 mm erosive event.....	95
Fig.6.9: Gross soil erosion map of 12.5 mm erosive event.....	95
Fig.6.10: Sediment delivery ratio map of the basin.....	95
Fig.6.11: Sediment yield map of 12 mm erosive event.....	95
Fig.6.12: Sediment yield map of 12.5 mm erosive event.....	96

List of Plates

Plate	Page
Plata1.1a: Illegal gold mining along the bank of the Birim River at Kyebi.....	8
Plata1.1b: Illegal alluvial gold mining of the river bed and bank of the Ofin River at Adwumain.....	8
Plate 3.1: A and B show colour of water in the upper courses before galamsey activities. C and D show colour of water at galamsey sites.....	48
Plate 3.2: Colour of water near galamsey sites at low flows.....	57
Plate 4.1: Evidence of direct sediment and mine waste water entrainment into the rivers.	67
Plate.5.1: Erosion Pin at the bank of the Birim River at Akim Oda.....	71
Plate.5.2: River bed channels in the upper course of the Pra River at Amuanda Praso – Evidence of bed incision and steep pools.....	77
Plate.5.3A: Evidence of cantilever bank failure along the bank of the Oda River at Asaago – Kumasi.	79
Plate.5.3B: Evidence of cantilever bank failure along the bank of the Birim River at Akim – Oda.	79
Plate.6.1: Erosion of a well and house foundations at Odumase.....	97
Plate.6.2: Eroded plant root at Konongo.....	97

Abstract

The Pra River Basin has been engulfed by certain anthropogenic activities particularly illegal small scale mining (popularly called *galamsey*) and serious concerns have been raised by stakeholders within the basin of the level of pollution due to the release of chemicals and sediments into the water bodies. Fluvial sediment yield data is an essential requirement for informed decision making on water resources development and management. However, information on the sediment load of most rivers is very rare due to the lack of financial resources to regularly undertake sediment yield studies. This study was undertaken to assess the sediment yield levels, sediment sources and bank erosion within the Pra Basin through field data collection and spatial modelling to ascertain stakeholder's perceptions and suggest remedial measures to the problem.

Suspended sediment concentration measurements were undertaken for 9 months in selected stream discharge measuring stations within the basin. Daily mean suspended sediment concentration was determined from which monthly and annual suspended sediment yields were derived. Sediment source tracking was done using a single tracer ^{210}Pb and the relative contribution of surface and bank sediments to the fluvial sediment transport was determined using the simple mixing model. Lead-210 was analysed using the Atomic Absorption Spectrophotometer (AAS). Bank erosion was assessed using erosion pins. The spatial patterns in soil erosion and sediment yield were modelled using the revised universal soil loss (RUSLE) equation integrating it into Geographic Information System (GIS).

Suspended sediment concentration and sediment yield of the Pra Basin were found to be very high resulting in a high annual specific suspended sediment yield. Bank erosion measurement revealed very active bank erosion and deposition within the river channel and bank erosion was

observed to increase downstream. Sediment source analyses showed that bank material was the dominant sediments which accounted for over 60% of suspended sediment loads. However, predicted sediment yields using the RUSLE were very low as compared to observed data.

To promote coordinated development and sustainable management of the resources of the basin, there is the need to resource agencies in charge of regulating natural resource utilization in the basin to control land use activities particularly galamsey to ensure the sustainability of vital ecosystems. The Government also needs to resource financially and improve upon staff strength of the Hydrological Services Departments and the Sediment Unit of the Water Research Institute of CSIR to enable them maintain and monitor critical stations for flow and sediment discharge measurements. Also future research works in sediment yield modelling should consider deploying a model that is capable of modelling both surface and concentrated sediment discharges as this will give a better perspective to a comparative assessment between observed and simulated sediment yield within the Pra Basin.

Table of Contents

Contents	Page
Declaration.....	i
Dedication.....	ii
Acknowledgement.....	iii
List of Tables.....	iv
List of Figures.....	v
List of Plates.....	vii
Abstract.....	viii
Table of content.....	x
Chapter One: Background to the Study	1
1.0 Introduction.....	1
1.1 Statement of the Research Problem.....	6
<i>1.1.1 Research Questions</i>	12
1.2 Objectives of the Study.....	12
1.3 Hypotheses.....	13
1.4 Background Information on the Study Area.....	13
1.5 Structure of the thesis.....	17
Chapter Two: Literature Review	19
2.0 Introduction.....	19
2.1 Stream Bank Erosion Processes and Measurement.....	19
2.2 Sediment Source Analytical Techniques.....	21
2.3 Sediment Yield Measurements.....	26
<i>2.3.1 Field Measurements of Sediment Yield</i>	27

2.3.2 <i>Sediment Yield Modelling</i>	29
2.4 Soil Erosion and Sediment Yield Modelling.....	31
2.4.1 <i>The Revised Universal Soil Loss Equation (RUSLE)</i>	31
2.5 Justification for Research Methodologies.....	37
Chapter Three: Sediment Concentration and Yield Measurement in the Pra Basin	39
3.0 Introduction.....	39
3.1 Research Materials and Methods.....	39
3.2 Results and Discussion.....	43
3.3 Conclusion.....	59
Chapter Four: Sediment Source Analysis	60
4.0 Introduction.....	60
4.1 Research Materials and Methods.....	61
4.2 Results and Discussion.....	63
4.3 Conclusion.....	69
Chapter Five: Changes in River Channel	70
5.0 Introduction.....	70
5.1 Research Materials and Methods.....	71
5.2 Results and Discussion.....	73
5.3 Conclusion.....	82
Chapter Six: Catchment Scale Soil Loss and Sediment Yield Modelling	83
6.0 Introduction.....	83
6.1 Research Materials and Methods.....	83
6.2 Results and Discussion.....	91

6.3 Sediment Yield Sensitivity Analysis.....	99
6.3.1 <i>Sensitivity of sediment yield to overestimation and underestimation of model variables</i>	100
6.4 Conclusion.....	102
Chapter Seven: A Synthesis of Results, Conclusion and Recommendations	103
7.0: Introduction.....	103
7.1 The Nexus between Field Measurements and Modelling of Soil Loss and Sediment Delivery.....	103
7.2 Limitations of the study.....	108
7.3 Conclusion.....	110
7.4 Recommendations.....	112
References	115
Appendices	132
Appendix A	132
Appendix B	137
Appendix C	141

Chapter One

Background to the Study

1.0 Introduction

Rivers are natural systems that sculpture and modify the landscape (Nagle, 2000). Increasingly, they are subject to pressure from human activities, and many are so altered or managed that they bear little resemblance to ‘natural rivers’ (Nagle, 2000). Land disturbance has been widely recognized as the main cause of accelerated erosion rates, but there is very little information on past or current sediment delivery rates to the marine environment (UNEP, 1994; cited in Ramos-Scharro´n and MacDonald, 2007). Historically there have been few efforts to remedy this problem (Lugo et al. 1981; in Ramos-Scharro´n and MacDonald, 2007) and this situation can be partly attributed to the lack of data and spatially explicit models to quantify sediment delivery rates and identify sources which will help establish priorities for remediation of accelerated erosion in river basins (Ramos-Scharro´n and MacDonald, 2007). Watershed sediment transport is one of the primary sources of nonpoint source (NPS) pollution for surface waters (Davis and Fox, 2009). Of the nearly 1.1 billion km of impaired rivers and streams in the United States assessed by the Environmental Protection Agency, transport of fine sediments is the most common NPS pollutant (Davis and Fox, 2009).

According to Akraasi (2005, 2011) and Akraasi and Ansa-Asare (2008), estimates of suspended sediment yield of most rivers in Ghana including the Pra are low by world standards and this low values are attributed to the forest reserves, secondary forest, cocoa, coffee and oil palm plantations covers of the drainage areas. These types of vegetation protect the soil from the erosive activity of rainfall that is very high in the basin. However, since Ghana’s independence, encroachment of human activities on forest reserves and river

corridors has become an acute problem in the country. An estimate of the forest cover as of 2007 is about 16,000 km² with an annual rate of depletion of almost 2% (220 to 650km² of forest loss per annum) (UNDP Ghana 2004; Dogbevi 2008). Clearing of forests for farming and logging has had serious consequences on surface water hydrology and accelerated the processes of soil erosion, particularly on steeply sloping lands. Not only has the encroachment accounted for biodiversity loss, but also soil erosion and soil fertility depletion, resulting in the sedimentation and pollution of most rivers and reservoirs/dams. In recent times, the activities of illegal small scale miners have compounded the problem of river sedimentation and pollution. Almost all rivers in Ghana that have alluvial gold deposits have been besieged by these illegal mining activities which are entraining thick plumes of sediments and other pollutants into the rivers making the water unwholesome for consumption by local communities. In 2005, the then Minister for Works and Housing Mr. Hackman Owusu-Agyemang stated in Kumasi that, the Owabi Dam was to be desilted at a cost of about 2 million US dollars to save it from collapsing (Ghana News Agency, 2005).

Sediments are eroded by two main processes, sheet erosion and channel erosion (Roehl, 1962). Sheet erosion is an upland source of sediments while channel erosion results from gully erosion, valley trenching, stream bed and stream bank erosion (Roehl, 1962). The importance of each source of sediments varies widely in different areas and may vary markedly at different points within a given watershed (Roehl, 1962). Several studies in the field of sedimentation have resulted in the development of relationships involving measurable watershed factors in order to predict sediment yield. Among them are Wischmeier and Smith (1978), Chakraborti (1991), Peng et al., (2008), and Yüksel et al., (2008).

Erosion and deposition processes lie at the centre of geomorphological explanation, but progress in understanding these processes has been limited by a lack of appropriate high-resolution monitoring methodologies which permit detection of erosion and deposition

dynamics (Lawler, 2005b). Soil erosion leads to surface soil decomposition and sedimentation in dams and channels, so river capacities will be reduced (Solaimani et al. 2008). Thus, the measurement of turbidity and suspended sediment concentration in rivers, estuaries, reservoirs, nearshore zones, etc is attracting increasing attention from hydrologists, limnologists, geomorphologists, freshwater ecologists, engineers, oceanographers, glaciologists, water resource managers and policy makers (Lawler, 2006a). Such measurement programmes can allow inferences to be made about upstream hydro-geomorphological processes, catchment erosion rates, downstream fluvial processes and sedimentation impacts, pollutant and contaminant transfer, and aquatic habitat quality (Lawler, 2006a).

For the purposes of studying sediment dynamics, tracers are introduced into a river, estuary, or coastal system, to obtain general information on the characteristics of sediment movement within such environments (Hassan, 2003). Tracers provide a relatively simple means of overcoming technical and sampling problems without the need for a detailed kinematic study of the sedimentary regime (Crickmore et al., 1990; cited by Hassan, 2003). The type of tracer to be used will largely depend on the objectives, environment characteristics, and intended observation period of the experiments (Hassan, 2003). The aim of sediment transport studies at the watershed scale is often to understand the source, fate, and transport of sediment mobilized within a watershed (Davis and Fox, 2009). However, many complex watershed and climatic factors such as rainfall, vegetation, topography, soil type, and human disturbances can affect source, fate, and transport processes of sediment (Davis and Fox, 2009). Due to the large variability of environmental variables over spatial and temporal scales, the source, fate, and transport processes are difficult to predict and model precisely. However researchers and engineers within the environmental field are developing new data-

based methods to study these complex, interdependent processes with greater certainty (Davis and Fox, 2009).

Accelerated erosion and increased sediment yields resulting from changes in land use are critical environmental problems (Ramos-Scharro´n and MacDonald, 2007). Resource managers and decision makers need spatially explicit tools to help them predict the changes in sediment production and delivery due to unpaved roads and other types of land disturbance (Ramos-Scharro´n and MacDonald, 2007). Land use changes that disturb the natural vegetative cover can greatly increase erosion rates and watershed scale sediment yields, and these increases are critical environmental problems in many parts of the world (Walling, 1997; cited in Ramos-Scharro´n and MacDonald, 2007).

River morphology deals with the changes in river form and cross-sectional shape due to deposition and erosion processes. Changes in discharge and sediment load may lead to changes in certain parameters including cross sectional shape, channel shape and type, slope and particle size of bed materials (Brandt, 2000; cited by Solaimani et al., 2008). Channel geometry is the cross sectional form of a stream channel (width, depth and cross sectional area) fashioned over a period of time in response to formative discharges and sediment characteristics (Goude, 2004; cited in Solaimani et al., 2008). Changes in channel morphology are the result of interactions of natural and manmade factors such as fluvial processes (e.g. bank erosion, sediment transport) and developments along the river banks (Alam et al., 2007; Shirley and Lane, 1978). “These changes can create significant issues in the riparian zones due to loss of land, changes in biodiversity, impacts on constructions located on the river banks (e.g., bridge crossings, pipes), river pollution etc” (Shirley and Lane, 1978; Bertrand, 2010). Odgaard (1987; cited in Bertrand, 2010) reported that 40% of the suspended sediments found in streams in the US came from the riverbanks. Bank erosion

constitutes an intricate physical, socio-economical, and ecological problem requiring an improved understanding of the key processes governing the phenomenon (Bertrand, 2010).

Assessment of the changes to the river course will facilitate the identification and exploitation of river bank over time and the possible future activities that can significantly affect the river water quality (Shirley and Lane, 1978). Studies in morphological changes in river channels are important to protect agricultural land and ecology of the surrounding area to ensure sustainable development along river corridors (Alam et al., 2007). An evaluation of short-term channel response in the affected river reach is required for planning and design purposes, while an understanding of long-term channel response is needed to predict future project operations and maintenance needs (Scott and Jia, 2002). Few studies have been concerned with the process of fluvial erosion (i.e. the removal of bank sediments by the direct action of the flow), and little progress has been made in understanding fluvial bank erosion of cohesive sediments since the contributions of Arulanandan et al (1980; cited in Bertrand, 2010) and Grissinger (1982, cited in Bertrand, 2010). Although major efforts (e.g. Fox et al., 2007; Langendoen et al., 2009; Lawler, 1991; Papanicolaou et al., 2007) have been made to monitor bank retreat in a channel reach, there is still a lack of available techniques in the literature to assess the erosion rate of banks comprised of cohesive materials in frequent intervals (Bertrand, 2010; Darby et al., 2007; Julian and Torres, 2006; Papanicolaou et al., 2007; Pizzuto, 2009; Prosser et al., 2000; Simon et al., 2000).

Conservation prioritization is an important consideration for planning of natural resources management, allowing decision makers to implement management strategies that are more sustainable in the long-term (Zhang et al., 2010), particularly on soil erosion management. However, soil erosion management in this context can only be achieved when data on sediment sources, sediment yield or erosion risk hazard maps are available on current erosion status.

1.1 Statement of the Research Problem

Soil erosion currently poses a threat to the sustainability of agricultural production in many parts of the world, through soil degradation and reduction of soil productivity (Pimental et al., 1995; cited by Blake et al., 2002). Sedimentation impacts many aspects of the environment among which are water quality, water supply, flood control, reservoir lifespan, irrigation, navigation, fishing, tourism, hydro-power generation, river channel morphology and stability etc (e.g. Alam et al., 2007; Hazarika and Honda, 2001; Shirley and Lane, 1978; Peng et al., 2008; Schwartz and Greenbaum, 2009). Also, watershed sediment transport can lead to a number of environmental problems, including decreases in ecological diversity (FISRWG 1998; cited in Davis and Fox, 2009), and decreases in aesthetic properties of rivers and streams (Davis and Fox, 2009). Consequently, sediment transport problems have attracted increasing attention from the public, scientists/researchers, governments and organizations, local and national policy makers (Jain et al., 2010). This has led to an increasing demand for watershed or regional-scale soil erosion models or a quantitative assessment on the extent and magnitude of soil erosion problems so that sound management strategies can be developed for affected zones (Fistikoglu and Harmancioglu, 2002; Jain, 2010).

Against this background there is a need for reliable information on rates of soil loss and for an improved understanding of sediment transport and storage in catchments to provide a basis for formulating and implementing improved erosion and sediment control strategies (Blake et al., 2002). Watershed conservation management has been a daunting problem for most governments and institutions in charge of water management in most developing countries as a result of high rate of river sedimentation. Information on the physical resources of the watershed, modelling sediment yield of watersheds and the prioritization of watershed for conservation planning are the basic technological ingredients to arrive at any scientific management decisions of watershed conservation (Chakraborti, 1991).

Unfortunately, this information is lacking on most rivers in Ghana including the Pra. This is because rivers situated deep inside tropical rain forests are often poorly gauged and data on sediment load are rare (Restrepo and Kjerfve, 2000). Many of Ghana's reservoirs have been constructed with inadequate watershed data which later showed that actual sediment yield is much in excess of their design capacities. For example, sedimentation impacts are felt in reservoirs/dams such as Akosombo and Kpong on the Volta River, Weija Lake (Densu River) and Pra catchment reservoirs such as Owabi Dam (Owabi River), Barekese Dam (Ofin River) and Brimsu Dam (Kakum River) (e.g. Akuffo, 2003; Kusimi, 2005; Ghana News Agency, 2005a). Siltation of these dams and reservoirs have reduced their water holding capacities which is negatively affecting the ability of Ghana Water Company Limited (GWCL) and Volta River Authority (VRA) to supply potable water to most towns and the generation of hydro-power to meet the growing industrial and domestic energy demand. According to Kusimi (2005), the Densu river channel, especially the middle and lower courses are seriously experiencing erosion and siltation which is threatening the Weija Dam. The Weija Lake is silting up at a rate of 2%, giving it a lifespan of 50 years and is already 27 years old, meaning, it has 23 years life left (Akuffo, 2003). Although low water inflows into the Volta Lake has been the cause of recent power crisis of 1998, 2002 and 2006 (Brew-Hammond and Francis Kemausuor, 2007; Centre for Policy Analysis, 2007), some analysts believe that sedimentation of the Volta Lake could be other reasons accounting for its reduced power generation capacity.

According to Water Resources Commission of Ghana, NGOs (e.g. Friends of Rivers and Water Bodies), District and Municipal Assemblies, chiefs, Assemblymen and residents and other stakeholders within the Pra Basin, the river catchment has come under threat from various activities such as logging, farming, urbanization and illegal mining (e.g. Mensah, 2012). Illegal gold mining along the banks (Plata1.1a) and alluvial mining within the river

bed (Plata1.1b) have been the most destructive activities on water quality and sediment injection into the rivers. These illegal mining activities are so rampant and they are found along all the major tributaries of the Pra Basin and virtually in every community from the source to the mouth at Sekyere Heman. Their activities result in the discharge of large



Plata1.1a: Illegal gold mining along the bank of the Birim River at Kibi



Plata1.1b: Illegal alluvial gold mining of the river bed and bank of the Ofin River at Adwumain

volumes of sediments and chemicals such as mercury into the rivers, thus polluting the water. According to GWCL production costs becomes higher when treating this polluted water as a lot of chemicals have to be applied to get the water to the acceptable standard limits for consumption and this is militating against potable water supply. The high sediment levels are also causing the rapid deterioration of filters in treatment plants. For instance, GWCL shut down its treatment plant at Kibi, a town at the source of the Birim River because the river has become too polluted to be treated for domestic use as a result of the activities of illegal or small scale mining activities (Bentil, 2011).

Similarly, illegal miners have besieged the raw water intake point at Sekyere Heman threatening the water quality of the 41 million Euro Water Treatment Plant as result of mining the bank materials, thereby, injecting sediments into the river (Asiedu-Addo, 2008). Though the Brimsu Dam was dredged at a cost of 1.7 million dollar in 2005 to curb the annual perennial water shortages, which usually faced Cape Coast Municipality and surrounding districts (Ghana News Agency, 2005b), in May, 2013 the level of water in the Brimsu Dam had drastically fallen below 3 m, which is the minimum operation level, compared to its 8 m maximum operation level, making it difficult to pump water from the facility (Ghana News Agency, 2013). The dam was now producing below one million gallons of water per day instead of its daily production capacity of four million gallons resulting in serious water crisis in the municipality (Ghana News Agency, 2013). Due to the deterioration in water quality resulting from these illegal mining activities, most residents within the basin have to depend on boreholes and sachet water as the alternative source of water supply for domestic uses. In smaller communities where they do not have boreholes and have no access to treated water, they have no option but to still depend on this polluted water which has dire consequences on their health.

These illegal mining activities have not only rendered the water of these rivers unwholesome for consumption, but the level of pollution of the rivers have also affected the breeding of fish and crabs which residents within the basin used to depend on for livelihood. Besides, they can no longer swim in the rivers as the level of sediments and chemicals such as mercury and arsenic used in the gold processing react with their skins resulting in skin diseases. Until the recent past when the nation was plunged into power and urban water supply crisis, river sedimentation was not considered as a challenge to water management. Even as of now, what strategic measures have been put in place to arrest the rapid depletion of the vegetative cover of our river corridors which is a strong parameter in controlling soil erosion? Have any efforts been made to assess the sedimentation rates of these rivers and reservoirs that we heavily depend upon so as to develop the right management plans? It is therefore imperative to assess the sediment levels of these rivers for informed river basin management policies to be developed on rivers in the country.

Geographic information system (GIS) and remote sensing (RS) have been used to establish a more quantitative, repetitive strategy to classify sediment sources or soil erosion risk maps using models such as the Universal Soil Loss Equation (USLE) and its modified versions (Biswas, 2012; Chakraborti, 1991; Roy, 2009; Wahyunto and Abdurachman, 2010; Bonilla et al., 2010). Though GIS and RS have been increasingly used to model and predict soil erosion in many landscapes and climatic regimes globally, they have received less application in assessing soil erosion in Ghana. Many studies of sediment yield and sediment sources have been conducted in many parts of the world (Collins et al., 1997; Collins et al., 2001; Nichols, 2006; Restrepo et al., 2006), but in Ghana most sediment studies have been concentrated on sediment load/sediment yield (Akrasi, 2005; Amisigo and Akrasi, 1998; Ayibotele and Tuffour-Darko, 1974; Ayibotele and Tuffour-Darko, 1979) with little research on sediment sources.

River bank erosion has important implication for channel adjustment and long term channel change, meander development, catchment sediment dynamics, riparian land loss and downstream sedimentation problems (Lawler et al., 1997). However, river bank erosion processes are still poorly understood, and therefore weakly specified in models of river dynamics and sediment transport and only loosely integrated into river management strategies (Wang et al., 1997; in Lawler et al., 1997). Downstream changes in retreat rates for individual basins are also poorly documented (Lawler et al., 1997).

Many researchers in fluvial geomorphology have used remote sensing and GIS in studying channel morphology or pattern, bank erosion etc (Alam et al., 2007; Porter and Massong, 2004; Winterbottom and Gilvear, 1997). Simple statistical/regression models for predicting suspended sediment yields of river catchments in Ghana for which no sediment measurements had been undertaken have been developed (Akraasi, 2005; Akraasi, 2011; Akraasi and Ansa-Asare, 2008; Boateng, 2012). However, soil erosion mapping of spatial erosion patterns/vulnerability and the profiling of channel dynamics/bank erosion and deposition are less researched by geomorphologists, engineers, hydrologists etc in Ghana.

Given the limited capacity of the conventional methods (surveys) and the need to rapidly map and frequently monitor soil erosion, bank erosion and sediment sources of Ghana's river basins to make available current data for effective decision making, there is a growing need to employ GIS and related technologies (remote sensing) for speed and accuracy. With the advent of GIS, quantitative analyses necessary for watershed and hydrologic modelling could be carried out rapidly and accurately, allowing for the construction and execution of large-scale geomorphologic investigations (Roy, 2009; Wahyunto and Abdurachman, 2010). To contribute in addressing this research gap, this study aims at assessing river sediment sources and yields from the various sub-basins of the Pra Basin using remote sensing, GIS and erosion models, produce soil erosion/sediment yield maps of the catchment and lastly

undertake bank erosion measurement of river channels in the basin to ascertain the contribution of bank sediments to the riparian sediment budget.

1.1.1 Research Questions

The above problems that have been discussed raise a number of research questions which were the focus of this study and they are:

1. What is the spatial pattern of sediment yield in the Pra Basin?
2. To what extent can the sediment yield in the Pra Basin be modelled using the revised universal soil loss equation?
3. Where are the major sources of sediments in the catchment?
4. What are the morphological characteristics of channel/bank erosion of the river valleys?

1.2 Objectives of the Study

The main objective of this study is to assess the pattern in sediment sources, sediment yield, bank erosion in the Pra River Basin through field data collection and spatial modelling. Specific objectives are:

1. Assess sediment yield of the Pra Basin.
2. Determine the dominant sediment source, whether surface or bank materials in different sub-basins of the Pra catchment.
3. To determine channel stability of selected cross sections by measuring bank erosion.
4. To model sediment yield in the Pra Basin using the revised universal soil loss equation in GIS.

1.3 Hypotheses

Hypotheses guiding this study are:

1. H_0 : There are no significant variations in sediment yield within drainage basins.

H_a : There are significant variations in sediment yield within drainage basins.

2. H_0 : Stream bank erosion is not the main source of sediment transport in the Pra Basin.

H_0 : Stream bank erosion is the main source of sediment transport in the Pra Basin

1.4 Background of the Study Area

This study was carried out in the Pra River catchment which is located between latitudes $5^{\circ}00'N$ and $7^{\circ}15'N$ and longitudes $0^{\circ}03'W$ and $2^{\circ}80'W$ (Fig.1.1). It is one of the south-western drainage basins in Ghana. The Pra is the largest of the four principal rivers that drain the area south of the Volta divide and enters the Gulf of Guinea east of Takoradi. Its main tributaries are the Ofin, Oda, Anum and Birim rivers which drain from the Mampong-Kwahu Ranges. The drainage basin area is $23,188 \text{ km}^2$ with a mean annual discharge of $214 \text{ m}^3 \text{ s}^{-1}$ (Akrasi and Ansa-Asare, 2008). The landscape is generally flat characterised by undulating topography with an average elevation of about 450 m above sea level.

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 and Benneh, 1985).

The basin falls within the wet semi-equatorial climatic belt which is characterized by two rainfall maxima, the first season is from May – June with the heaviest rainfall in June and the second rainy season is from September – October. Relative humidities are highest (75-80%)

during the two rainy seasons and are around 70% during the rest of the year. The basin comes strongly under the influence of the moist south-west monsoons during the rainy

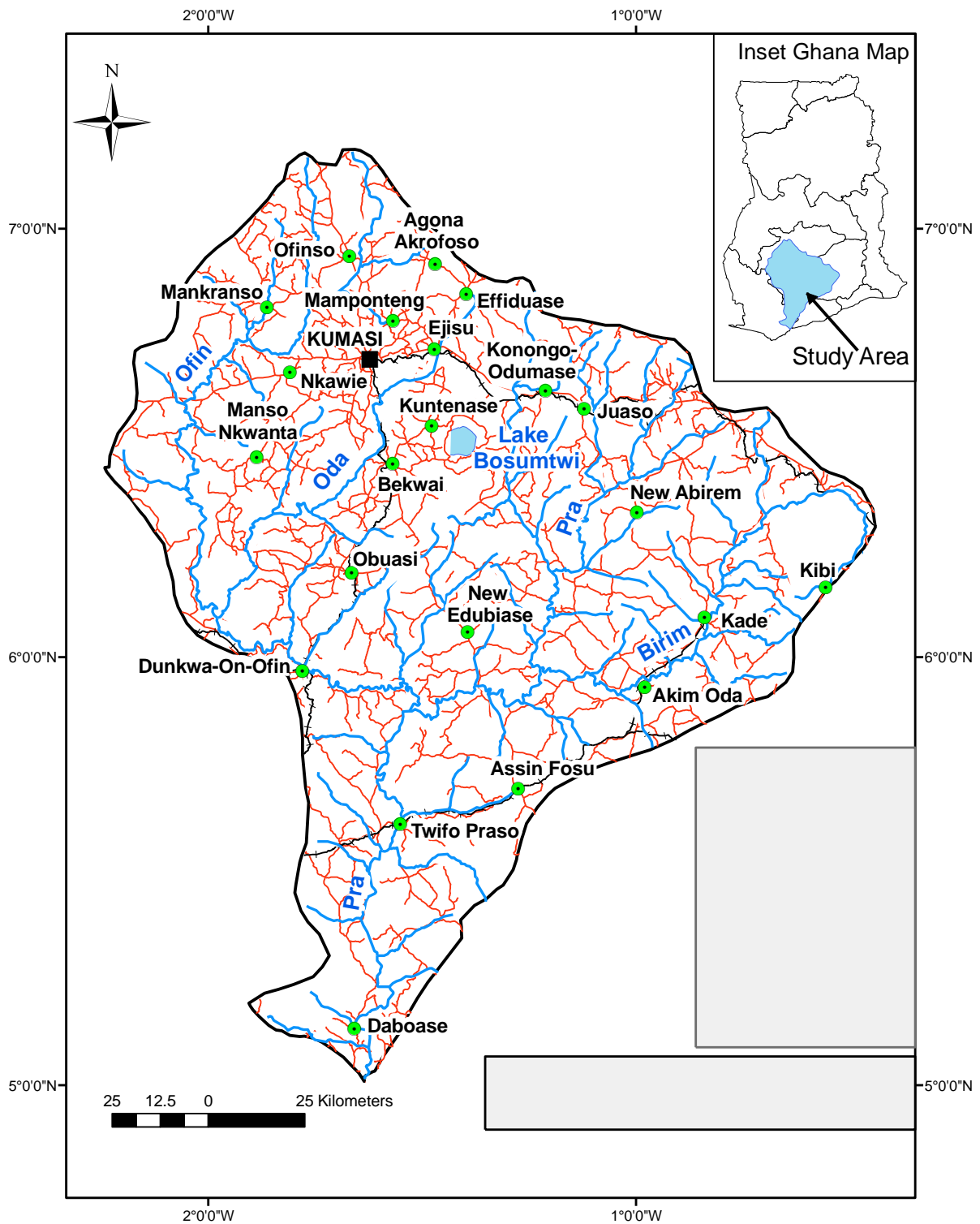


Fig.1.1: Map of the Pra River Basin

season with high annual rainfall amounts of between 125 and 200 cm. Dry season is well marked and spans from November to March. 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 in August (Dickson and Benneh, 1995).

The Pra Basin is covered by the moist-semi deciduous forest vegetation which contains most of the Ghana's valuable timber trees. The climatic environment of high temperatures and heavy rainfall promote the rapid growth of trees particularly in the rainy season. Trees grow to heights of about 35-45 m or more and are of three layers, the upper, middle and lower layer. A typical semi-deciduous forest consists of trees, lianas, climbers and shrubs/bushes which cover the soil from erosion by rain drops and run-off. However in the dry season, certain species of the upper and middle layers shed their leaves during the long dry spell. Due to the rapid expansion of the cocoa industry 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. Near large settlements where the pressure on land is very great, fallow periods may be as short as 3 years, thus the vegetation is reduced to climbers, shrubs/short woody plants and grass species interspersed by isolated tall trees left on the landscape by farmers (Dickson and Benneh, 1995).

The Pra Basin serves as the source of water supply for both industrial and domestic uses for three regional capitals, 41 districts and over one thousand three hundred towns. Of the 41 administrative districts 20 are in the Ashanti Region, 11 in the Eastern Region, 6 in the Central Region, and 4 in the Western Region. The Ofin sub-basin is the main source of water supply to Kumasi and its environs, through two reservoirs, namely Barekese and Owabi dams. The Birim sub-basin is located predominantly in the Eastern Region and has attractive historic places and nine forest reserves. For instance, the Esen Epan Forest Reserve near

Akim-Oda is a tourist site with the biggest tree in West Africa at 12 m in circumference and 66.5 m tall. The major tributaries are perennial and constitute all-year-round reliable water source. However, human activities such as mining, logging etc. are having adverse impacts and degrading the surface water resources of the basin (Ghana Survey Department; Water Resources Commission, 2011).

The Pra Basin is one of the most extensively and intensively used river basin areas in Ghana in terms of settlement, agriculture, logging and mining due to its rich economic tree species, rich mineral ore deposits and conducive environment for farming. The basin contains most of the large cocoa growing areas in the Eastern, Ashanti, and Central regions. Tree cash crop cultivation other than cocoa is mainly oil palm. Food cropping is increasingly becoming more commercialized especially around the medium and large settlements and along the major road arteries. The basin contains the highest density of settlements (both rural and urban) in Ghana. It has a high concentration of mining activities mainly concerned with gold and other minerals. Several large scale mining companies in the basin include AngloGold Ashanti, Perseus Mining Ltd, Newmont Ghana Gold Ltd etc (Water Resources Commission, 2011).

The vegetative cover of the basin is experiencing rapid rate of deforestation due to human activities such as farming, illegal small scale mining and lumbering (saw mills and chain-saw operators) and this is hampering water resources management of the basin. Forest cover outside the reserve areas is negligible and is estimated at less than 2% of the Basin. These forests are heavily logged by both licensed timber firms and illicit loggers. These anthropogenic activities are negatively impacting on the hydrological and geomorphological processes within the basin. The implication of these human activities is sediment transport into the river and channel morphological dynamics. The extensive forest clearance for mining, settlement, and infrastructural development causes considerable loss of soil minerals

and subsequent high sediment transport in the Pra and its tributaries silting up channels and dams (Water Resources Commission, 2011). Large scale and small scale mining with disruptive impact on surface cover including soils occur around Obuasi, Kibi, Dunkwa-on-Ofin, Konongo and most other communities within the basin. Moderate to severe sheet and gully erosion poses a threat for flooding within the basin. For instance in July 2011, the Pra and Birim rivers flooded their banks in the upper and middle courses where these anthropogenic activities are intense destroying lives and property (Bentil, 2011).

1.5. Structure of the thesis

This thesis is organized into seven chapters. The first chapter gives background information on fluvial geomorphology and the underpinning issues that are of focus by scientists. This chapter also discusses the problem under study, questions that the study seeks to address and outlines the objectives and hypotheses guiding the study. Lastly the chapter also introduces the physical settings of the study area by stating the geographical position of the study area and the underlying physical and socio-economic factors prevailing within the basin.

Chapter two encompasses literature review. The chapter reviews existing literature on approaches for measuring/determining sediment yield, sediment sources and bank erosion in fluvial geomorphology and other related fields such as hydrology, glacier geomorphology, and oceanography, among others. The underlying processes involved in these landscape and channel transformation and transportation of landscape materials are also reviewed. The chapter also examines existing models for predicting sediment transport and sediment yield. Chapters three to six are on the research methods and findings of each of the thematic set objectives of the study. The last chapter is chapter seven and in this chapter, a general discussion is done relating all the findings of the study, stating the significance of the results

to decision making and policy formulation, drawing conclusions and making recommendations for future studies and for informed decision making.

Chapter Two

Literature Review

2.0 Introduction

The chapter reviews existing literature on approaches for measuring/determining sediment yield, sediment sources and bank erosion in fluvial geomorphology and other related fields such as hydrology, glacier geomorphology, and oceanography among others. The underlying processes involved in these landscape and channel transformation and transportation of landscape materials were also reviewed. The chapter also examines existing models for predicting sediment transport and sediment yield. Informed by this existing literature, the research methods and materials for the study were designed.

2.1 Stream Bank Erosion Processes and Measurements

Rivers perform three main sediment related activities; erosion, transportation and deposition. These activities lead to the creation of erosional and depositional landforms (Nagle, 2000). Materials are dislodged through the processes of abrasion and solution. Mass failure of river banks due to the fluvial erosion at the toe banks also entrains materials into river channels. The resultant impact of these fluvial processes is the formation of a myriad of fluvial landforms and a change in the landscape in the long term. The morphology of catchment topography and river channels depends to a large extent, on the interaction between hill slope and channel processes. Consequently, many management theories, measurements and modelling have been developed in order to reduce soil loss from basins and sediment transport to hydrologic drainage networks and to explore the drainage basin structure and evolution (Amore, 2004; Tucker and Bras, 1998).

Stream bank erosion rate studies have been undertaken using conventional, manual and field monitoring methods, and these involve erosion pins, cross section resurveys or terrestrial photogrammetry (Lawler, 2005b; Billi, 2008; Bertrand, 2010). The conventional methods present some significant disadvantages as they do not provide continuous measurements of fluvial erosion, but instead provide snapshots of erosion between periods of measurements and do not allow the accurate identification of the critical events triggering fluvial erosion (Bertrand, 2010; Lawler et al., 1997).

New techniques available to estimate fluvial erosion rates or the erodibility parameters are the jet testing device (Thoman and Niezgod, 2008, in Bertrand, 2010), the LIDAR technology and Airborne Laser Scanning (Korpela et al., 2009; Pizzuto et al., 2010; Thoma et al., 2005, in Bertrand, 2010), and the Photo-electronic Erosion Pin (PEEP) (Bertrand, 2010; Lawler, 2005b; Lawler et al., 1997). The advantage of the PEEP over the traditional methods is its ability to continuously monitor bank retreat, which will better pinpoint the exact timing and magnitude of small to moderate erosion events (Bertrand, 2010; Lawler, 2005b; Lawler et al., 1997). For instance, Lawler (2005b) observed that, tidal banks are revealed to be much more dynamic using PEEP measurements than previous conventional monitoring has indicated. Also, by comparing PEEP to low-resolution monitoring of conventional methods, he indicated that, the frequencies of low-resolution monitoring failed to adequately represent the cyclicity, mean, range, variability and trend of bank elevation changes. However, PEEP is saddled with the problem of not being able to record events at night. Also, some of these new methods are expensive for developing countries. Erosion pin and cross sectional re-surveys methods are popular approaches as they are cheap and easily operable (Bertrand, 2010).

2.2 Sediment Source Analytical Techniques

Determining the sources of sediments, and associated nutrients and contaminants, is an important issue for the management of water quality in river systems (Caitcheon, 1998). Spatial sediment tracing can be achieved by measuring the relative contributions of sediments and associated substances at stream junctions, so that a budget of relative contributions for a whole drainage network can be established (Caitcheon, 1998). In addition to spatial source tracing, dated sediment cores from channel, floodplain deposits and reference inventories sampled at stream junctions can provide valuable information about longer term trends in source contributions and sediment erosion (Caitcheon, 1998; Matisoff and Whiting, 2011; Walling, 2004).

Symander and Strunk (1992, in Nagle et al., 2007) described some of the difficulties with the use of suspended sediments to identify source areas. Two of the principal problems are the enrichment of suspended sediments in fines and in organic matter relative to the sources and the transformation of sediment properties within the fluvial system (Nagle et al., 2007). Recently published work on the use of tracers, contend that the use of recent over bank deposits enables the contributions of sediment sources to be identified more reliably and the long-term loading from individual sources to be assessed (Bottrill et al., 2000, in Nagle et al., 2007).

Mapping erosional features in a watershed for sediment source tracking could involve using photos, maps, field surveys, erosion pins and troughs. Assembling information on suspended sediment sources has proved difficult using the traditional direct monitoring techniques (e.g. erosion pins and troughs) due to inherent spatial and temporal sampling constraints and the amount of fieldwork involved (Peart and Walling, 1988). Secondly, these traditional techniques do not permit the derivation of the range of soil redistribution rates such as the mean erosion rate

for the eroding areas, the mean deposition rate for the depositional areas, the net soil loss from the field and the sediment delivery ratio (Walling, 2004).

In response to the problems associated with traditional monitoring and measurement techniques, the fingerprinting approach using tracers has been increasingly employed as a means of establishing the relative importance of potential catchment sediment sources and soil erosion rates (Collins et al., 1997; Collins et al., 2001; Mukundan et al., 2009; Nagle et al., 2007). Sediment fingerprinting relies upon the premise that the physical and chemical properties of suspended sediment will reflect its source (Collins et al., 1997; Collins et al., 2001). Another fundamental condition that must be met by any tracer is that the tracer substance(s) must remain unaltered within the spatial and temporal limits in which the tracing method is being applied, (Caitcheon, 1998), adsorption of the tracer to soil is strong and quick; variation in adsorption to various sizes or mineralogic/organic constituents is minor or can be accounted for (Matisoff and Whiting, 2011).

The most commonly used tracers include; radionuclides (^{137}Cs , ^{210}Pb) (Nagle et al. 2007; Walling, 2004), and cosmogenic isotopes (^7Be) (Schuller et al., 2006; Walling, 2004). ^{137}Cs has a core depth profile not greater than 20 cm and is 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 ($t_{1/2} = 22$ years, with core depth of about 10 cm) and beryllium – 7 ($t_{1/2} = 53$ days 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. ^{137}Cs , ^7Be , 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

and Whiting, 2011). Also these environmental radionuclide tracer methods 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 – 30 cm usually contain little or no traces of the radionuclides (Nagle et al., 2007; Matisoff and Whiting, 2011). However, ^{137}Cs fallout from the atmosphere is currently near zero or near non-detectable limits (Matisoff and 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 ^7Be , it is only suitable for simulating erosion of small catchments.

Other tracers include; stable isotopes (C-13, N-15) sediment carbon and nitrogen (Juracek and Ziegler, 2009; Mukandaun et al., 2009), phosphorous (Wallbrink et al. 2003), clay mineralogy (Youngberg and Klingeman, 1971; Glasmann, 1997, in Nagle et al., 2007), magnetic susceptibility (Blake et al., 2006; Caitcheon, 1998; Gruszowski et al., 2003), and heavy metals (Juracek and Ziegler, 2009) etc. In view of the multiplicity of elements being analyzed in these approaches, they are often very costly hence not employed in most studies.

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 and 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 and Oldfield, 1989; Molinaroli et al., 1991; Walling et al., 1993). For example, suspended sediment tracer values may resemble

those of a particular source, but could also result from various combinations of other sources (Collins et al., 1997). 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 Beryllium-7 (Schuller et al., 2006) have also been used singularly in sediment source tracing. Sediment source tracking 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). Parsons and Wainwright (1993) and Caitcheon (1998) used mineral magnetic properties of sediments in tracing sediment sources.

The use of mixing and unmixing models of multi tracers involving multivariate statistics to identify the relative contributions of surface erosion from different land use types and channel erosion to suspended sediment load in river basins sources has also been demonstrated and examined in detail in the literature (Collins et al., 1997; Collins et al., 2001; Gruszowski et al., 2003). For instance Walling (2004) successfully used environmental radionuclides caesium-137, lead-210, beryllium-7 to trace sediments mobilization and delivery in river floodplains in Devon, UK. Though very effective and efficient in characterizing sediment sources and the redistribution rates of sediments, the multi-tracer model approach is very complex, mathematical and very demanding in terms of data, field work as well as laboratory logistics with huge financial burden. Issues of sample size and the range of tracer properties that are measured have also being raised (Gruszowski et al., 2003).

GIS and remote sensing techniques and other modelling programmes such as USLE, WEPP, DR3M, WFPB, GWLF (Arekhi, 2008; Jain et al., 2010, Nangia et al., 2010; Mongkolsawat, 1994; Roy, 2009; Wahyunto and Abdurachman, 2010) have recently been employed for

sediment source tracking in catchments. Models are appealing because they are cheaper to use. They are also most effective for source analyses where the models have been applied and calibrated. Models are used by reviewing existing data, and consulting with those who are familiar with basin conditions (Gellis, 2010). However with very large basins some models are associated with large errors. Secondly, some are very complex and require very complex input data sets such as the hydrology, rainfall interception by vegetation (e.g. throughfall, stemflow etc), water balance, plant growth and residue decomposition of catchments which make them unsuitable in the developing countries where such explicit data is difficult to generate (e.g. WEPP and EUROSEM).

The latest modelling approaches to overcome the limitations of the empirical USLE concentrate on physically based erosion models such as SWAT (Arnold et al. 1998; Gassman et al., 2007, in Silva et al., 2010), Water Erosion Prediction Project (WEPP) (Amore et al., 2004) and EUROSEM (Morgan et al., 1998). These are physically based models with the basic processes incorporated in them so that they can simulate the individual components of the entire erosion process by solving the corresponding equations; and so it is argued that they tend to have a wider range of applicability (Amore et al., 2004; Silva et al., 2010). Such models are also generally better in terms of their capability to assess both the spatial and temporal variability of the natural erosion processes (erosion and deposition) (Amore et al. 2004). Though these models are transferable to other watersheds, they require huge amounts of input data and many calibration parameters, complex laboratory analyses or hard and expensive field data collection, which are commonly out of reach of many developing countries (Renschler et al., 1999; Silva et al., 2010).

2.3 Sediment Yield Measurements

Sediment yield is the amount of sediment load passing the outlet of a catchment, that is the sediment load normalized for the drainage area and is the net result of erosion and deposition processes within a basin (Jain and Das, 2010; Restrepo and Syvitski, 2006; Verstraeten and Poesen, 2001). These materials are of three different kinds; dissolved load (consisting of soluble materials carried as chemical ions); suspended load (containing clay and silt held up by the turbulent flow), and bed load which includes larger particles moved by saltation, rolling and sliding (Nagle, 2000).

However, on the basis of transport processes, measurement principles, and morphological/sedimentary associations, fluvial sediments are often classified into two; bed materials and washed materials. Bed material is often conflated with bed load (makes up the bed and lower banks of the river channel), and wash material moves in suspension and travels out of the reach once entrained (measured load), but the two classifications are not congruent (Church, 2006). Depending on discharge/flow rate, the medium grain sand particles (saltation materials) could become unmeasured sediments if the popular Helley-Smith sampler is used. Generally, the size of material that moves as bed or suspended load in the flow depends upon the power and turbulence of the flow (Gomez and Church, 1989).

In relatively deep streams of high flows, with bed material that consists of fine sand, the suspended bed material may be 90% or more of the total sediment discharge. However, in shallow streams with medium to coarse sand beds, the unmeasured-sediment discharge may represent 50% or more of the total sediment discharge (Andrews, 1981). Various approaches have been developed to determine river sediment yield and these include field measurements and modelling (physical and empirical). Suspended load and bedload are measured or estimated

separately because the physical processes that govern their rates of transport are dependent on different factors. The sum of suspended load and bedload is the total sediment load (Edwards and Glysson, 1999).

2.3.1 Field Measurements of Sediment Yield

Measuring and estimating suspended sediment yields in rivers has long been subject to confusion and uncertainty (Thomas, 1985) because various methods have been developed to measure suspended sediment yield and they include the measurement of suspended sediment load and water discharge (Akrasi, 2005; Khanchoul et al., 2010; Kusimi, 2008), measuring total eroded soil and deposited sediments in small catchments (Verstraeten and Poesen, 2001), and measuring sediment volumes in ponds, lakes or reservoirs (Nichols, 2006; Verstraeten and Poesen, 2001). For the measurement of sediment volumes in ponds, lakes and reservoirs, radiometric techniques using ^{210}Pb or ^{137}Cs as tracer elements can be employed to reconstruct sediment budgets over a period of time (Foster et al., 1990; Govers et al., 1996; Walling, 1990 cited in Verstraeten and Poesen, 2001).

The ideal situation to estimate the suspended sediment yield of rivers would be to measure suspended sediment concentration and water discharge continuously and use the product function as an estimate of suspended sediment discharge (Lane et al., 1997; Thomas, 1985). Obtaining continuous records of concentration however is practically impossible owing to cost, number of samples and sampling frequency among others (Edwards and Glysson, 1999; Thomas, 1985). Alternative to these issues of cost, remoteness of sites, and technical difficulties is to measure water discharge continuously and to take occasional discrete water samples either

manually or using automatic sampling equipment for gravimetric analysis of suspended sediment concentration (Thomas, 1985).

The use of sediment-discharge rating curve to estimate sediment yield is however problematic because suspended-sediment concentrations are known to be variable for a given discharge because stormflow hydrographs usually, but not always, are characterized by higher suspended-sediment concentrations during the rising limb than the falling limb. Further, the timing between storm events also influences availability of fine-grained sediment from the watershed, such that an initial stormflow following relatively dry conditions usually has a greater suspended-sediment concentration than subsequent flows of similar magnitude (Edwards and Glysson, 1999). Consequently, statistical considerations show that the sediment load of a river is likely to be underestimated when concentrations are estimated from water discharge using least squares regression of log-transformed variables (Asselman, 2000; Cohn et al., 1992; Ferguson, 1986; Jansson, 1985; Singh and Durgunoglu, 1989). Also regardless of how the samples are collected, there remain questions of when the measurements of concentration should be made, how they should be used to estimate the total yield, how close can samples be spaced in time and still be meaningful among others (Edwards and Glysson, 1999; Thomas, 1985).

According to Edwards and Glysson, (1999), spatio-temporal variations in sediment transport can be captured by collecting depth/point-integrated suspended-sediment samples that define the mean discharge-weighted concentration in the sample vertical and collecting sufficient verticals to define the mean discharge weighted concentration in the cross section. Verticals of samples could either be taken using Equal-Discharge-Increment or Equal-Width-Increment Methods. Though both methods have their advantages and disadvantages, if properly used, they yield similar results.

Also the biases in the estimation of sediment loads by rating curve due to using log-transformed estimates can be significantly reduced by using nonlinear regression. Further improvements can be achieved by identifying seasonalities and breaks in slopes of the rating curves and taking samples at the right time. Finally, the underestimation caused by using average daily flows with the rating curve can be eliminated by using sub-daily flow data, if available (Singh and Durgunoglu, 1989). The many methods that have been developed for collecting data and estimating suspended sediment yields indicate each method is characterised by one limitation or the other, thus the method that one employs is subject to availability of equipment, cost, convenience, the kind of results that is sought among others.

2.3.2 Sediment Yield Modelling

Sediment yield and surface erosion at a watershed or regional scale are at present also modelled using empirical models such as the universal soil loss equation (USLE), modified universal soil loss equation (MUSLE) or the revised universal soil loss equations (RUSLE and RUSLE 2) which are sometimes integrated into GIS (Arekhi, 2008; Jain et al., 2010; Mongkolsawat, 1994; Nangia et al., 2010; Roy, 2009; Wahyunto and Abdurachman, 2010). Others include WEPP, SWAT, EUROSEM etc (Amore et al., 2004; Fistikoglu and Harmancioglu, 2002).

Universal Soil Loss Equation (USLE) and its revised versions (RUSLE and RUSLE2) have been used to model soil erosion sometimes integrating the parameters of the model in GIS to produce soil erosion risk maps (Bonilla et al., 2010; Fistikoglu and Harmancioglu, 2002; Kouli et al., 2008; Silva 2004; Silva et al., 2010; Stone and Hilborn, 2000; Roy, 2009; Wahyauto, 2010). The USLE/RUSLE though empirical without spatial dimensions like some of their counterparts, they are however simple and their parametric data can easily be transformed into GIS input data

formats for spatial analysis of phenomena. Secondly, their data requirements are not too complex and literature has shown that they have been successfully used to estimate soil erosion of catchments and farmlands (Arekhi, 2008; Fistikoglu and Harmancioglu, 2002; Jain and Kothyari, 2000; Jain and Das, 2010; Jain et al., 2010; Silva et al., 2010).

However, USLE/RUSLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for soil losses from gully, wind or tillage erosion and deposition (Stone and Hilborn, 2000). Consequently, RUSLE was subsequently revised to include more advanced scientific interface as RUSLE 2 which permits the segmentation of topography to determine sediment yield and deposition based on changes in topography, soil and management systems along a flow path (Dabney et al., 2011; Stone and Hilborn, 2000; USDA-ARS, 2008a, 2008b). Despite these advancements, RUSLE2 cannot predict erosion within concentrated flow channels (gully erosion) (Dabney et al., 2011; USDA-ARS, 2008a). Also, RUSLE2 is too rigorous with a lot of data requirements some of which do not have spatial domain (e.g. surface roughness, sediment detachment, sediment transport and sediment deposition models) and as such cannot be analysed with GIS. Though it has a higher predictability of soil erosion than USLE/RUSLE, it is only applicable to small farm plots hence inappropriate for large river catchments like the Pra River Basin.

The other models (e.g. WEPP, SWAT, EUROSEM, MIKE SHE, ANSWERS, CREAMS etc) are applicable at catchment scale, event based, continuous models spatially and temporally distributed (i.e. 2D) (e.g. Amore et al., 2004; Fistikoglu and Harmancioglu, 2002). As already discussed above, these models require substantial data inputs, many calibration parameters, characterized by complex laboratory analyses or hard and expensive field data collection (Silva

et al., 2010) and thus are inappropriate to apply in developing countries where physical data on river basins are non-existent or very limited.

2.4 Soil Erosion and Sediment Yield Modelling

In order to improve water quality and restore impaired watersheds, managers need to make decisions using data that they are able to gather (Nangia, 2010). Data collection can be expensive, tedious and time consuming, so in such situations using modelling approach makes sense (Nangia, 2010) particularly in the developing countries where institutions and organizations charged with the monitoring and collection of data are ill-equipped in terms of personnel, materials as well as financial. Models for sediment yield provide invaluable information when applied to those areas lacking data, for predicting future impacts of agricultural activities, land use, stream stabilization and sediment storage in reservoirs (Khanchoul et al., 2010). The revised universal soil loss equation has been widely used with very good results, is applicable in a GIS environment and so can provide a spatial distribution of erosion and soil loss, requires a small and simple input data set, is relatively easy to use and is suitable for the study, thus its structure and operating system are being discussed for clarity.

2.4.1 The Revised Universal Soil Loss Equation (RUSLE)

A first attempt to evaluate and quantify the human impact on soil erosion such as land use changes or new cultivation techniques was the universal soil loss equation (USLE) developed by Wischmeier and Smith (1958) (Renschler et al., 1999). Since then, modified versions such as the revised universal soil loss equation (RUSLE) (Renard et al., 1991), modified universal soil loss equation (MUSLE) (Blaszczynski, 2003) have been widely used as tools for predicting soil

erosion in many parts of the world (Renschler et al., 1999). USLE, RUSLE and MUSLE were defined by the following equation whose variables were annually estimated (Wischmeier and Smith 1978):

$$A = R \times K \times LS \times C \times P \dots\dots\dots (2.1),$$

where A represents the potential long term average annual soil loss in tonnes per hectare per year; R is the rainfall erosivity factor (MJ mm ha/h/yr); K is the soil erodibility factor ($\text{t h MJ}^{-1} \text{mm}^{-1}$); LS is the slope length-gradient factor, C is the crop/vegetation and management factor, and P is the support practice factor and these other parameters are all dimensionless.

The rainfall erosivity index (r factor) measures the potential ability of rain to cause soil erosion. The R -factor is the sum of individual storm erosivity index (EI)-values for a year averaged over long time periods (> 20 years) to accommodate apparent cyclical rainfall patterns. Storm erosivity ($\text{EI} = r$) is the product of a storm's total energy (E) and its maximum intensity (I) within a stipulated time frame which in standard time could be 5 min, 10 min, 15 min, 30 min, 60 min etc (Renard and Freimund 1994; USDA-ARS, 2008a). An erosive event is a rainfall event with more than 12.50 mm of total rainfall accumulation or with at least 6 mm of rainfall accumulation in 15 minutes (Petkovšek and Mikoš, 2004; USDA-ARS, 2008a). The three most common mathematical models used to relate the kinetic energy (KE) to rainfall intensity are the logarithmic model, exponential model, and the Hudson (1965) model (Shamshad et al., 2008).

The original method for calculating R values for a storm event requires pluviograph records (Table 2.1) (Wischmeier and Smith, 1978). This kind of information is difficult to obtain in many parts of the world because its processing is time-consuming, labour-intensive, and costly (Eltaif et al., 2010; Silva, 2004). There is also a lack of pluviograph record data in most developing countries. The successful use of the EI_{30} in certain temperate regions (such as its

place of origin) does not guarantee its success as an index of soil loss in regions with substantially different climates, such as the tropics, because erosive rainfall in the tropics differs from that in other regions mainly in intensity and frequency characteristics (El-Swaify et al., 1982).

A number of indices which relate the erosivity of a rainstorm and its associated runoff to soil loss prediction have been established. The most commonly used indices include the Fournier Index (Fournier, 1960), the modified Fournier Index (MFI) (Arnoldus, 1980), Hudson's $KE > 25$ Index (Hudson, 1965), Lal's AI_m Index (Lal, 1976) and the erosivity index (EI_{30}) of the Universal Soil Loss Equation (Renard and Freimund, 1994; Vrieling et al., 2010; Wischmeier and Smith, 1978). In the US, the R -factor can be evaluated or calculated using methodological guides of Wischmeier and Smith (1978). In contrast, lack of rainfall intensity data in some countries makes the calculation of R -factor, especially in the developing world, very difficult.

Although the most accurate estimate of R -values can only be obtained from longterm rainfall intensity data as calculated by Wischmeier and Smith (1978), several works suggest that monthly precipitation data can give reasonable estimates of R -values for many regions throughout the world (Renard and Freimund, 1994; Shamshad et al., 2010; Vrieling et al., 2010). Several authors have derived exponential/regression relationships between R and average monthly precipitation of the wettest month. Also, R is well correlated with the modified Fournier index (Table 2.1). Although very useful for estimating relative erosion hazards, mean annual rainfall is not directly correlated with soil loss in the tropics due to differences in rainfall characteristics and vegetative cover, hence the use of rainfall amounts in deriving R factor is over simplification of soil erosion process (El-Swaify et al., 1982). For example, erosivity index varies from 50 to 650 in the United States, 60 to 300 in Tunisia, 50 to 300 in Morocco, 60 to 340 in the South of

France, and 500 to 1400 in Ivory Coast (Roose, 1977). The works of these scientists indicate that an erosivity variable may be dependent on the climatic conditions of the geographical area, scale of the study area, and type of measurement and that there is no single universal variable better than the others (Irvem et al., 2007, Renard and Freimund 1994; Stocking, 1987).

Table 2.1: Examples of models for the derivation of R values

Number	Equation	Author
1	$R = \frac{\sum_{i=1}^j (EI_{30})_i}{N}$,	Wischmeier and Smith, 1978
2	$R = 0.04830P^{1.610}$	Renard and Freimund 1994
3	$R = 587.8 - 1.219P + 0.004105P^2$	Renard and Freimund 1994
4	$R = 0.07397F^{1.847}$	Renard and Freimund 1994
5	$R = 95.77 - 6.081F + 0.4770F^2$	Renard and Freimund 1994
6	$FI \text{ or } R = \rho^2/P$	Vrieling et al, 2010
7	$MFI \text{ or } R = \sum_{i=1}^{12} \frac{P_i^2}{P_t}$	De Luis et al (2010)
8	$MFIe \text{ or } R = \sum_{i=1}^{12} \frac{Pe_i^2}{P_t}$	Smithen and Schulze (1982).
9	$R = 0.577H - 5.766$	Roose, 1977
10	$R = (0.0158H \times I_{30}) - 1.2$	Roose, 1977
11	$EI_{30} = 227MFI^{0.548}$	Shamshad et al, 2010

$(EI_{30})_i$ is EI_{30} for storm i , j no. of storms in an N year period, ρ the average rainfall (mm) of the month with the highest rainfall, P the average annual rainfall (mm), F the modified Fournier Index, H rainfall amount, P_i monthly precipitation of month i , Pe_i effective monthly precipitation of month i , P_t annual rainfall amount (mm), I_{30} maximum intensity in 30 minutes. (Angulo-Martínez and Beguería 2009; Diodato and Bellocchi, 2007).

Soil erodibility factor (K) is the average soil loss in tonnes/hectare for a particular soil in cultivation under continuous fallow on a plot with a slope length of 22.13 m and slope steepness of 9%. K is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff (Stone and Hilborn, 2000). The LS factor represents a ratio of soil loss under given conditions to that at a site with the “standard” slope steepness of 9% and slope length of 22.13 m. The steeper and longer the slope, the higher is the risk for erosion (Stone and Hilborn, 2000). Slope length has been defined as the distance from the point of origin of overland flow to

the point where either the slope gradient decreases enough that deposition begins or the flow is concentrated in a defined channel (Wischmeier and Smith, 1978). Traditionally estimates for L were obtained from field measurements, however, this method requires high financial and human resources which are not feasible at regional scale (Van Remortel et al., 2001; Hickey et al., 1994). With advancement in computers, there are several algorithms that have been packaged into GIS softwares that make the derivation of slope length and steepness simpler. These include using either unit stream power (Moore and Burch, 1986) or upslope area (Desmet and Govers, 1996) as a surrogate for slope length, the neighbourhood method and the best fit plane method (Srinivasan and Engel, 1991), grid-based methods and the maximum downhill slope angle (Hickey et al., 1994; Hickey, 2000; Van Remortel et al., 2001), network triangulation (Cowen, 1993) techniques (cited by Hickey, 2000), quadratic surface, maximum slope and maximum downhill slope techniques (Van Remortel et al., 2001). Among these, the one that is best suited for integration with GIS is the theoretical relationship proposed by Moore and Burch (1986) and Moore and Wilson (1992) based on unit stream power theory, given as (Jain and Das, 2010; Jain and Kothyari, 2009; Silva et al., 2010):

$$\left(\frac{A_s}{22.13}\right)^{0.4} \cdot \left(\frac{\sin \phi}{0.0896}\right)^{1.3} \dots\dots\dots (2.2)$$

where A_s is the specific area ($=A/b$), defined as the upslope contributing area for an overland cell (A) per unit width normal to the flow direction (b); ϕ is the slope gradient in degrees.

The cover management factor C is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. The C factor is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land (Stone and Hilborn, 2000). The support practice factor P reflects the effects of practices that will reduce the amount and rate of the water runoff and thus

reduce the amount of erosion. The P factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The most commonly used supporting cropland practices are cross slope cultivation, contour farming and strip cropping (Stone and Hilborn, 2000).

The genesis of RUSLE is USLE (Universal Soil Loss Equation) introduced in 1958 by W. H. Wischmeier and D. D. Smith with the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Soil Conservation Service (SCS), and Purdue University. USLE was an empirical model of simple structure that captured the main effects of rainfall intensity, soil type, topography, and management on sheet and rill erosion, with no attempt to account for sediment deposition nor gully erosion (Dabney et al., 2011; Renard et al., 1991). USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion (Stone and Hilborn, 2000).

In the early 1980s a programme to develop technology to replace the USLE was initiated, resulting in the computer-based revised universal soil loss equation (RUSLE) model, documented in written form in 1997 (Renard et al., 1997, cited by Dabney et al., 2011). RUSLE incorporated significant advances over the USLE and this permitted the application of soil erosion estimation for a great variety of crops and management practices beyond those in the original USLE data base. Some other changes include a sub factor method for computing values for the cover-management factor, improved factor values for the effects of contouring, terracing, strip cropping, and management practices for rangeland (Dabney et al., 2011; Renard et al., 1991; Stone and Hilborn, 2000). In addition, RUSLE introduced new slope length and steepness (LS) algorithms reflecting rill to inter-rill erosion ratios and the capacity to calculate LS products

for slopes of varying shape (Renard et al., 1991; Stone and Hilborn, 2000) and thus is a better estimate of soil erosion and sediment yield in landscapes than USLE.

2.5 Justification for Research Methodologies

Many published soil loss and sediment yield models, sediment yield, bank erosion and sediment source tracking approaches were reviewed to understand their techniques and applications. Relative merits and shortcomings of these methodological approaches in soil erosion and sediment yield studies were discussed. It was realised that there is no universally acceptable method or approach to modelling a catchment's soil erosion and sediment yield as well as field data collection of sediment discharge measurements. The choice of any methodology depends on the availability of resources (secondary data, financial, equipment etc) at the disposal of the researcher.

However, for soil erosion and sediment yield modelling, the literature showed that, RUSLE has been widely used with very good results, is applicable in a GIS environment and so can provide a spatial distribution of erosion and soil loss in catchments. The model also requires a small and simple input data set and is relatively easy to use and thus suitable for this study. Hence, the RUSLE model was chosen to model soil erosion and sediment yield in the basin. However, a slight modification to the model was made. Due to the high intensity of tropical rains as compared to temperate regions, two rainfall erosivity events were adopted; the standard 12.5mm erosive event and then 12mm event, to see whether a lower rainfall event will have any significant impact on soil erosion and sediment yield in the basin. The thunderous tropical raindrops (high intensity and large rain drops) will have more destructive impact on soil aggregates as compared to temperate raindrops, hence the need to examine this effect. For

instance, observations made in the savannah and forest regions of Nigeria indicate that rains with median drop size in excess of 2.5 mm and energy load of $100 \text{ J m}^{-2} \text{ mm}^{-1}$ are common (Lal, 1985). The energy load of rains in western Africa is generally more than that of the subtropical rains of Zimbabwe (Elwell & Stocking, 1975). Also, the mass of soil detached per unit area by tropical rains was observed to be more closely related to the momentum than to the kinetic energy of a rainfall in East Africa (Rose, 1960).

In situ field data collection involved suspended sediment yield measurements, erosion pin to measure bank erosion and the simple mixed model using one fingerprint (^{210}Pb) to track sediment source trajectory in the basin. Suspended sediment concentration measurements were undertaken; coupling depth integrated and dip sampling in order not to miss critical flows. Gauge readers were engaged to undertake dip sampling when there are significant changes in flows. Despite its inability to capture continuous bank erosion data, the traditional erosion pin measurement was employed to measure bank erosion due to financial constraints to acquire PEEP equipment.

Considering the size of the Pra Basin, much of ^{7}B would be decayed in view of the resident time to outlets of sub-catchment basins, hence ^{7}B at the outlets of sub-basins will contain only tracers of eroded surfaces close to sub-basin outlets. There is also no equipment available for the analysis of ^{137}Cs and ^{7}B in the laboratory. Lead-210 was therefore used as the tracer to determine the dominant sediment source in this study.

Chapter Three

Sediment Concentration and Yield Measurement in the Pra Basin

3.0 Introduction

Information on sediment yield of a river basin is an important requirement for water resources development and management (Akrasi, 2011), because high sediment loads affect water quality and silt reservoirs. However, data on fluvial sediment are very limited because it is very expensive to collect such data and also for lack of logistic support (Amisigo and Akrasi, 1998; Akrasi, 2005). The amount of sediment yield generated within a catchment is a function of a number of anthropogenic and physical factors including farming, mining, construction, slope, basin area and rainfall intensity. This chapter presents methods and results of sediment yield measurements undertaken in selected sampling stations within the Pra Basin to ascertain sediment discharge levels and derived rating curves for the stations.

3.1 Research Materials and Methods

To determine the annual temporal variability in sediment yield for the year, fluvial sediment samples were collected from March (low flows at the beginning of the rainy season) to December at the end of the season at 7 monitoring stations (Fig.3.1) as suspended sediment concentration in streams can change appreciably over seasonal timescales and during high flow events (Lawler et al., 2006a). In order not to miss critical flows, gauge readers were engaged where possible to take dip samples when there were significant changes in gauge heights. Dip samples were taken simultaneously alongside depth-integrated samples during field visits and correlated with the integrated samples to obtain a correction factor which was used to adjust dip

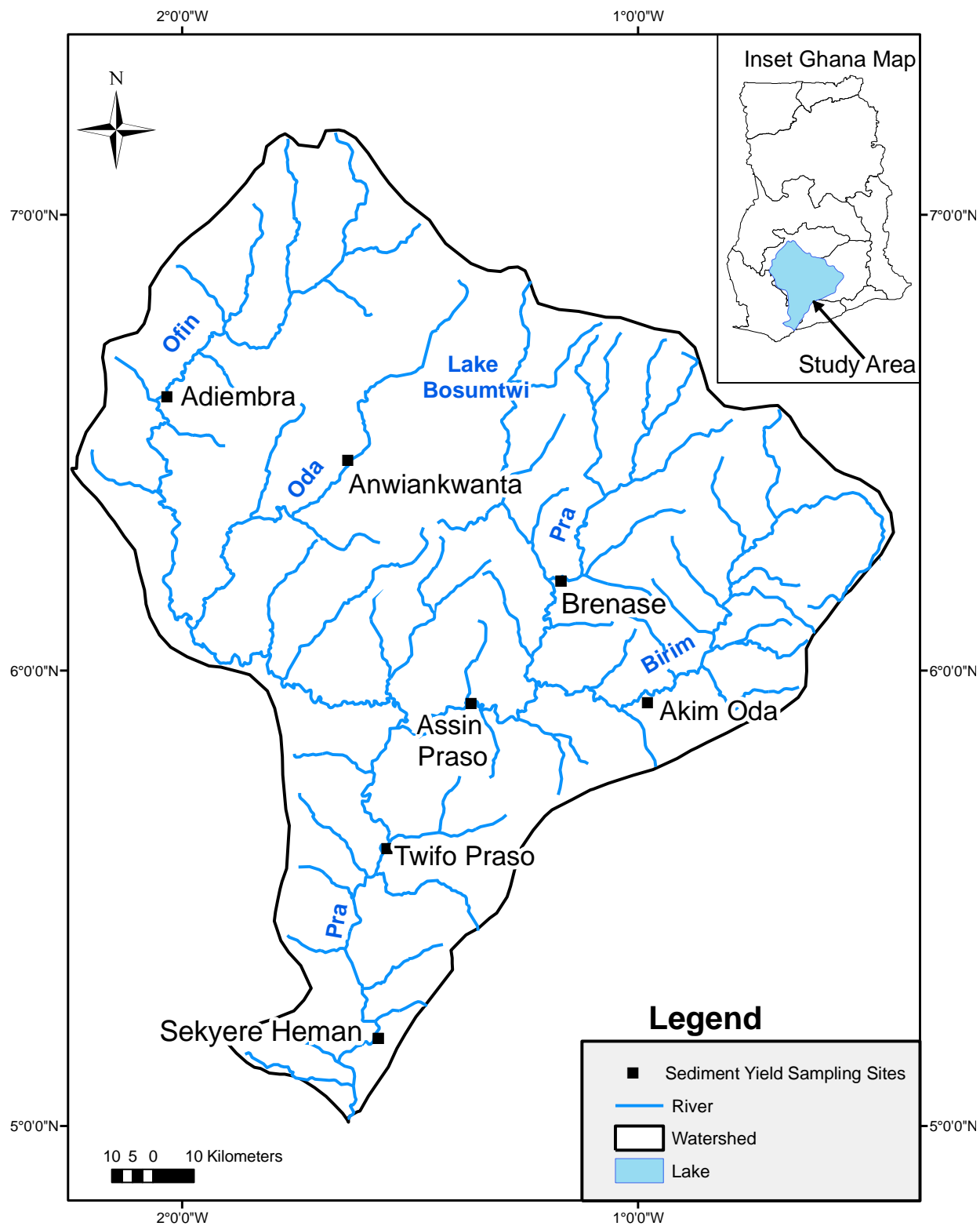


Fig.3.1: Sediment Yield Sampling Stations

samples taken by gauge readers (e.g. Akraasi, 2011; Edwards and Glysson, 1999). To account for lateral and vertical variability in sediment concentration, sampling was cross sectional (equal-width-increment) using the depth-integrated sampler as sediment varies vertically and laterally within the river channel. Samples were taken at the midpoints of intervals (Edwards and Glysson, 1999). In the absence of a bridge at Sekyere Hemang, dip samples were taken across the channel in a canoe. At gauged stations, gauge heights were read when sampling. The suspended sediment samples were analyzed in the Ecological Laboratory at the Department of Geography, University of Ghana, Legon, using the evaporation method.

Suspended sediment samples were flocculated using magnesium chloride ($MgCl_2$), allowed to settle for 24 hours, and the supernatant decanted (e.g. Kusimi, 2008; Schoonover, 2007). Sediments at the bottom of the container were emptied into dishes of known tare weights and oven dried at $85^{\circ}C$ (e.g. Di Stefano et al. 2000; Kusimi, 2008). The gross weights of the glass dishes were taken after cooling in a desiccator. The tare weights of dishes were deducted from gross weights to obtain sediment weight of each sample (e.g. Sengtaheuanghoung et al., 2007). The weight of each sediment was divided by the weight of the water-sediment mixture and then multiplied by one million converting it to parts per million to obtain suspended sediment concentration of the sample (Porterfield, 1972). Samples at each point interval were added to determine mean sediment concentration for that cross section in milligrams per litre.

The daily suspended sediment discharge/sediment load was computed using instantaneous concentration and flow equation;

$$L = 0.0864CQ_w, \dots\dots\dots (3-1)$$

where, L = sediment load in tonnes/day; 0.0864 = conversion factor assuming a specific weight of 2.65 for sediment; C = instantaneous concentration/sediment concentration, in mg/l; and Q_w = instantaneous water discharge, in m^3/s (Osten, 1979; Yüksel et al., 2008).

Water discharge at gauged stations was derived using water discharge rating curves (Table 3.1) whiles at ungauged stations (i.e. Assin Praso and Anwiankwanta) flow measurements were undertaken using the current meter and float methods to determine water discharge. The float method was employed during high flows and current meter when flows were low. Equations for the water discharge rating curves were obtained from the Hydrological Services Department - Accra. A water discharge rating curve was derived for Anwiankwanta using the log transform power function (Table 3.1).

Table 3.1: Discharge Rating Curves

No.	Station	Equation	Source
1	Sekyere Hemang	$Q_w = 45.14(h - 0.2)^{1.93}$	Hydrological Services Department - Accra
2	Twifo Praso	$Q_w = 16.56(h + 0.09)^{2.64}$	
3	Akim Oda	$Q_w = 10.47(h - 0.46)^{1.45}$	
4	Adiembra	$Q_w = 6.79(h - 0.37)^{1.6}$	
5	Praso-Brenase	$Q_w = 6.14(h - 0.42)^{1.57}$	Hydrological Services Department - Accra
6	Anwiankwanta	$Q_w = 3.468h^{1.7968}$	Author – Fieldwork, 2012

NB: h is gauge height

Sediment rating curves were then derived from graphical plots of the daily water discharges and the daily cross sectional mean suspended sediment discharges. The sediment rating curves are derived using a log transformed power function equation in the form (Achite and Ouillon, 2007; Asselman, 2000; Khanchoul et al., 2010);

$$Q_s = aQ^b \dots\dots\dots (3-2);$$

where Q_s is the daily mean suspended sediment discharge in $t \text{ day}^{-1}$, Q is the daily mean water discharge in $m^3 s^{-1}$, and a and b are constant and exponent of the rating curve.

Mean monthly sediment load and yield, annual suspended sediment yield and annual specific sediment yield for the period were derived from the daily sediment discharge data of the monitored stations. Mean monthly suspended sediment load is an average of the daily sediment discharge per month (t day^{-1}) while the monthly sediment yield was determined by multiplying mean monthly suspended sediment load by number of days of the month (t/month). Annual suspended sediment yield is the sum of monthly sediment yield for the year (t/yr^{-1}). The annual specific sediment yield was obtained by dividing annual suspended sediment yield by catchment area ($\text{t km}^{-2} \text{ year}^{-1}$) (e.g. Akrasi, 2011; Akrasi, 2005).

3.2 Results and Discussion

Trends in the daily mean sediment concentration are shown in Figs.3.2 – 3.8. Generally sediment concentrations in all stations have been fluctuating staggered by series of sharp rises and declines in concentration amounts from March to December. At Anwiankwanta the lowest concentration 109 mg/l was observed in November and at Brenase it was about 106 mg/l in March with the highest concentrations occurring in October at Anwiankwanta (869 mg/l) and June at Brenase (1216 mg/l) (Figs. 3.2 and 3.3). There was a sharp rise in sediment concentration at the beginning of the rainy season at Akim-Oda reaching 652 mg/l in May and thereafter, there was a gradual decline to below 750 mg/l at the beginning of August. From August however, concentration amounts rose again reaching 736 mg/l which was the highest for the year and declined from this month onwards till the end of the year (Fig.3.4). At Adiembra maximum sediment concentration 295 mg/l was also recorded in August whereas the minimum concentration 44 mg/l was in November (Fig.3.5). At Twifo Praso there was a dip in sediment concentration from 992 mg/l at the beginning of the year to about 357 mg/l in July followed by a

rise to nearly 1500 mg/l in September (Fig.3.6). At Assin Praso and Sekyere Heman, there was a gradual rise in sediment concentration from March, peaking in September at Assin Praso and

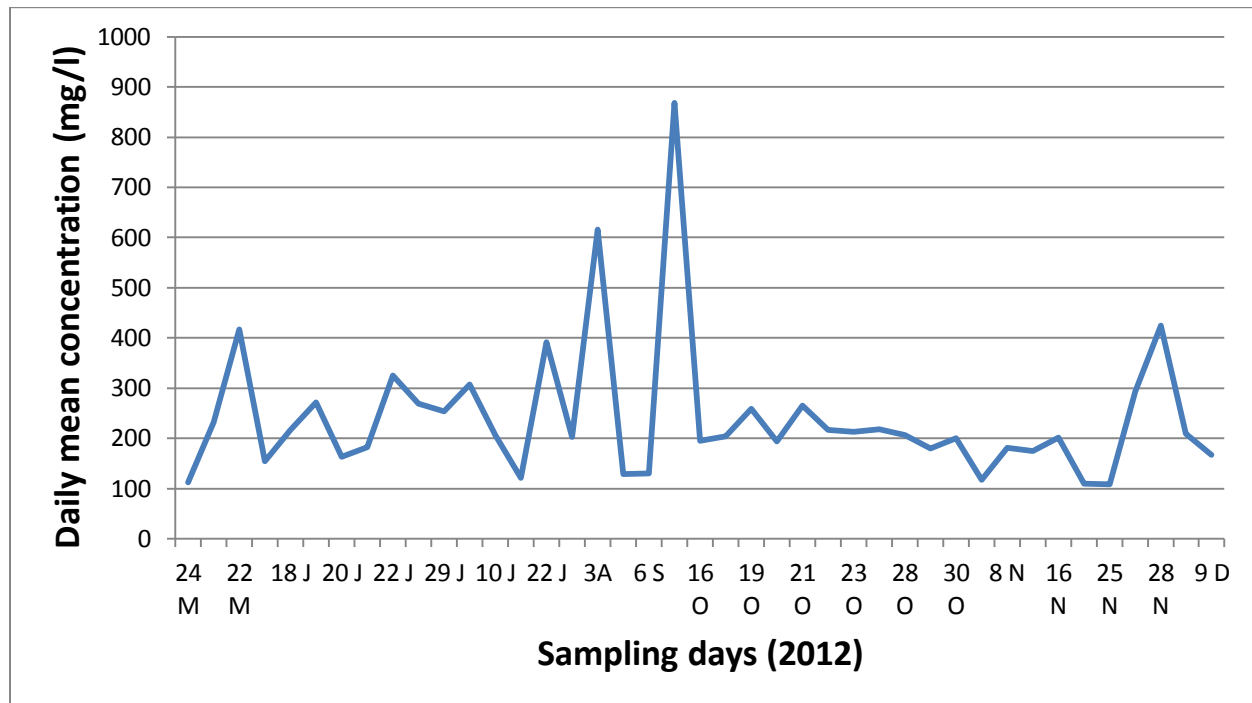


Fig.3.2: Daily mean concentration of samples at Anwiankwanta

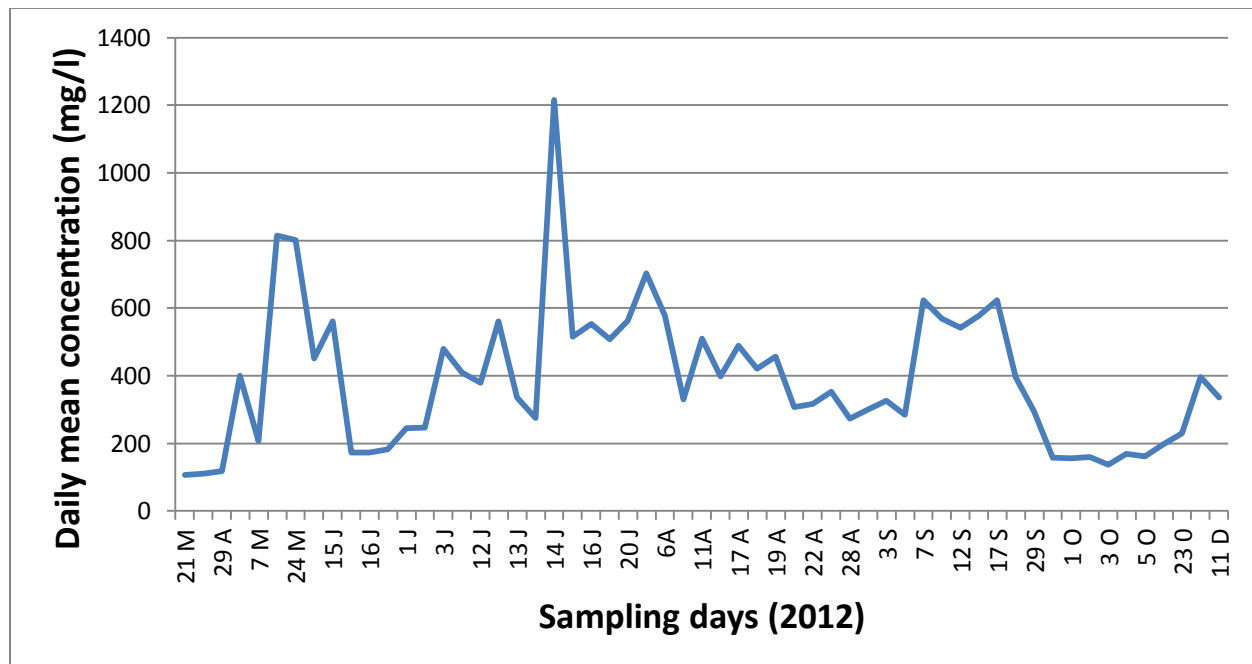


Fig.3.3: Daily mean concentration of samples at Brenase

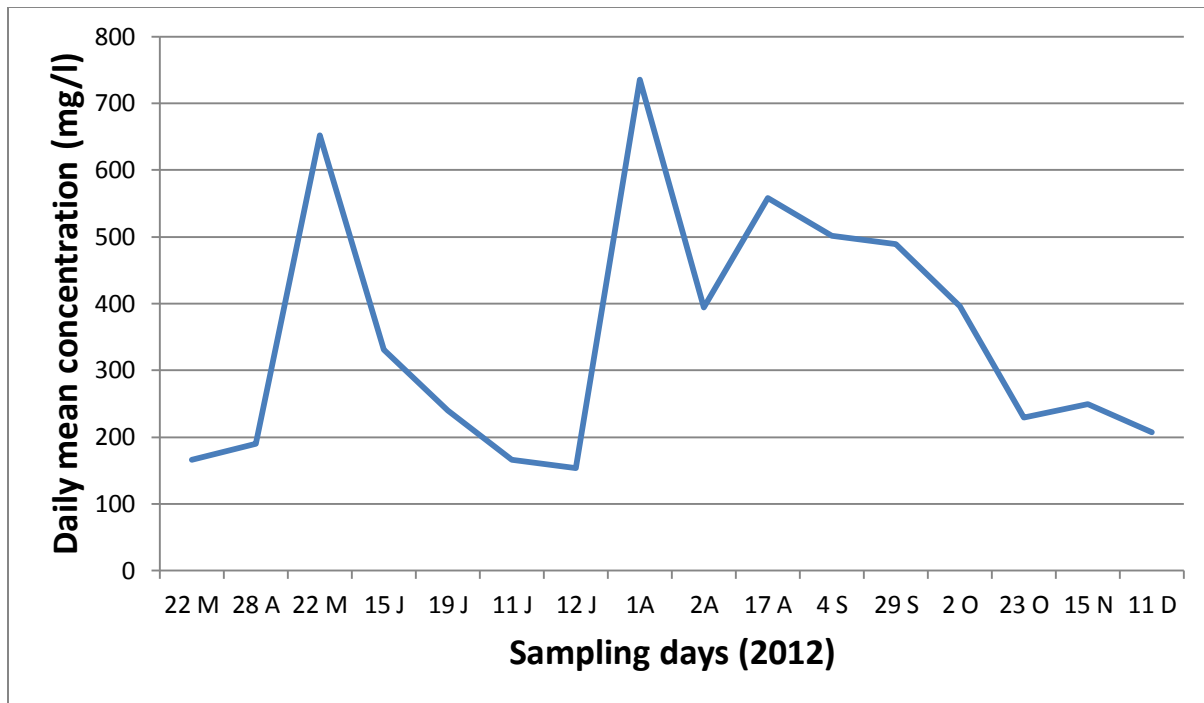


Fig.3.4: Daily mean concentration of samples at Akim Oda

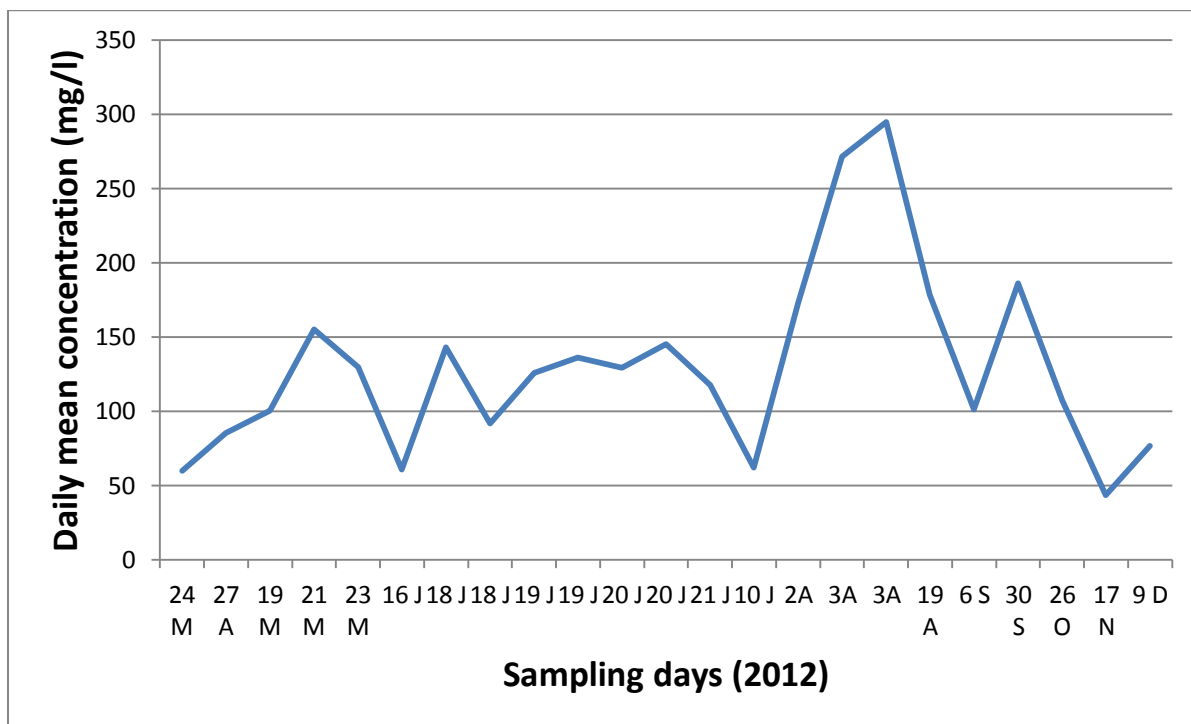


Fig.3.5: Daily mean concentration of samples at Adiembra

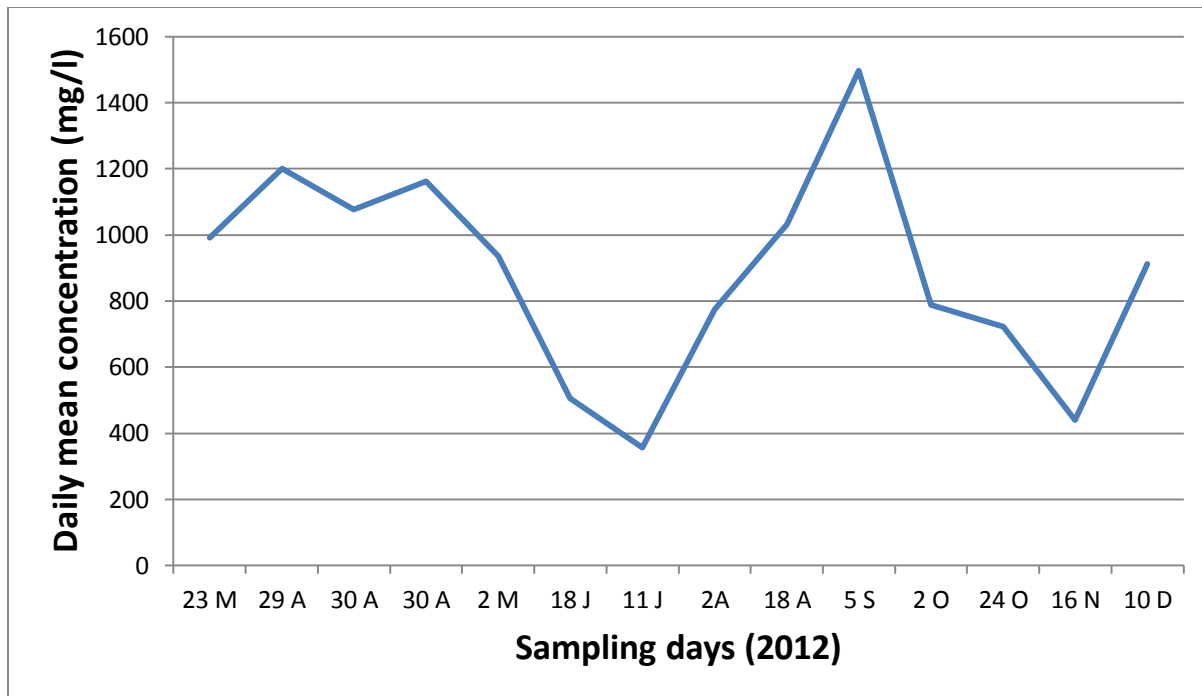


Fig.3.6: Daily mean concentration of samples at Twifo Praso

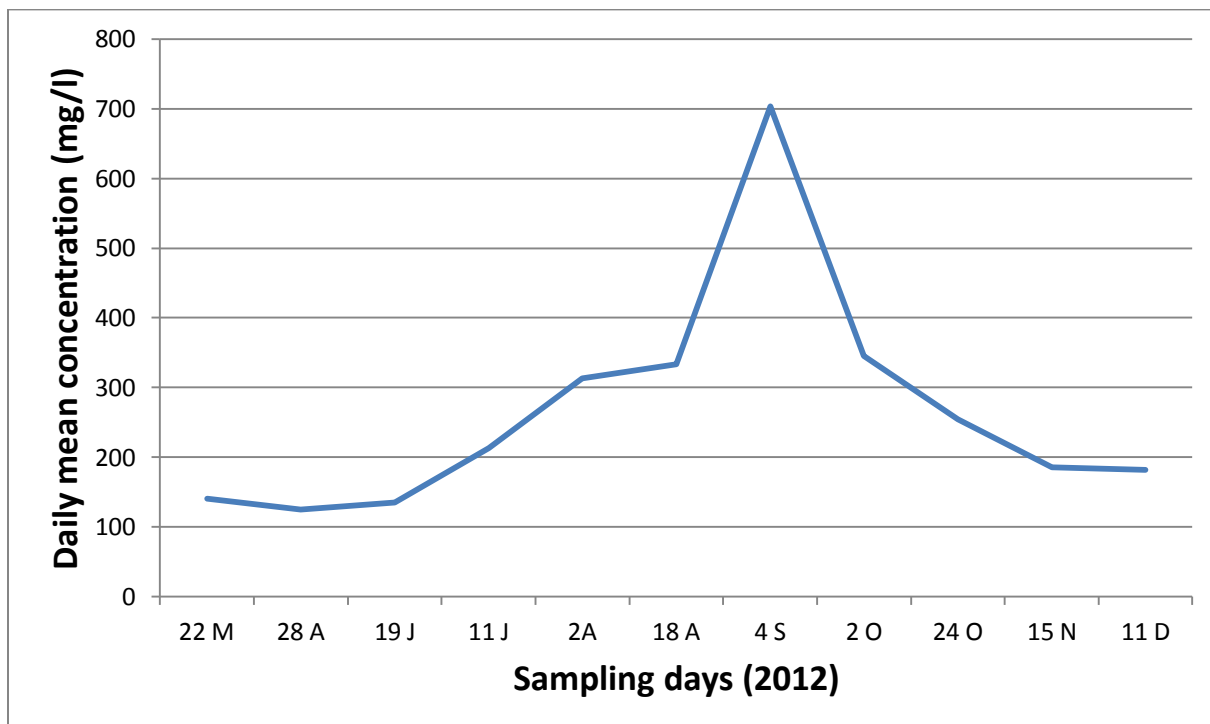


Fig.3.7: Daily mean concentration of samples at Assin Praso

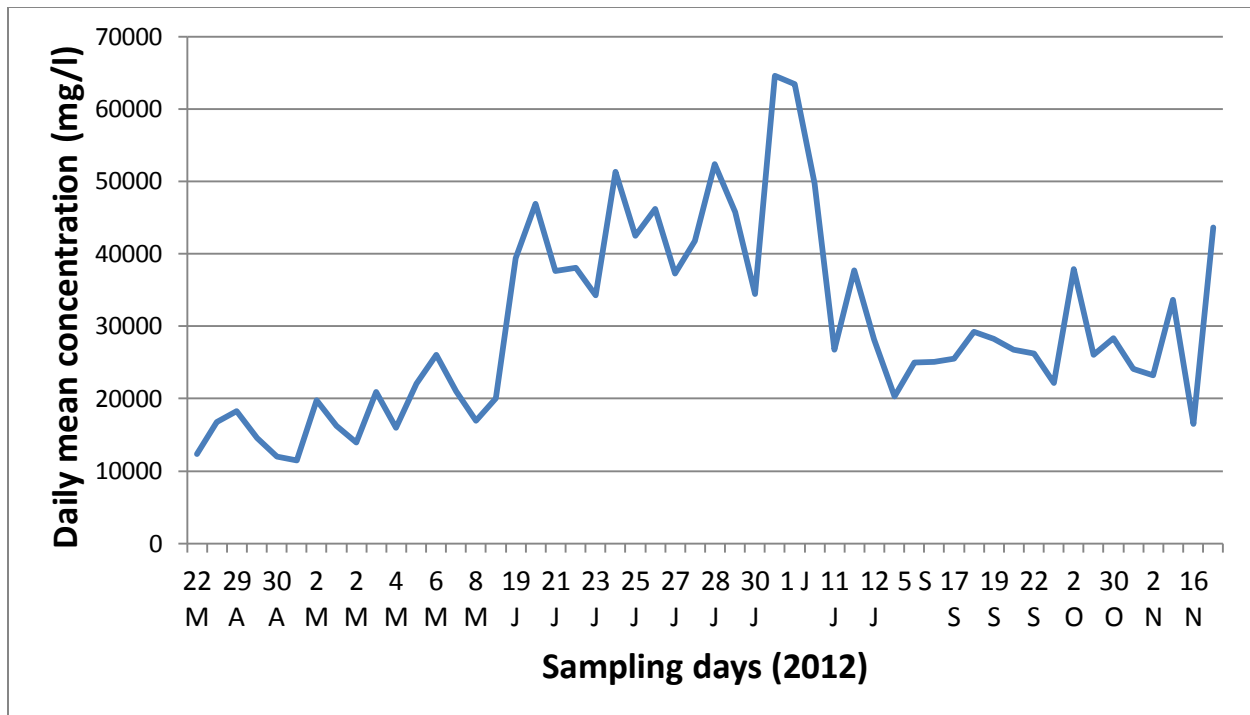


Fig.3.8: Daily mean concentration of samples at Sekyere Heman

July at Sekyere Heman (Figs. 3.7 and 3.8). At Assin Praso sediment concentration ranged between 125 and 703 mg/l and at Sekeyere Heman concentrations have been relatively high with a value of more than 12,300 mg/l as the minimum occurring at the beginning of the rainy season and a maximum of about 65,000 mg/l in June, the peak of the rainy season.

Field investigations showed very little anthropogenic activities that could discharge more sediments into the rivers at Adiembra and Anwiankwanta and this accounts for the relatively uniform and low sediment concentrations at these stations. Upstream of these stations, such as Ejisu and Asaago on the Oda River and Adiembra, Ntensere and Ahenkro on the Ofin River, the water was of good clarity or good transparency (Plate 3.1, A & B), though sediment concentration levels were not measured, the level of transparency of the water is an indication of low sediment levels. However, within the catchments of the other stations (Akim-Oda, Brenase,

Assin Praso etc), the activities of illegal alluvial gold miners are very intense consequently, as rainfall amounts increases, run-off entrains a lot of sediments into the rivers accounting for the relatively high concentrations marked by sudden rise and falls in concentration levels. The colour of the water at these stations was of low virtual clarity or low transparency, that is, it looked very turbid (grayish/brownish), an indication of high sediment levels (Plate 3.1, C & D). Other human activities such as farming could also expose the land and accelerate soil erosion of sediments into the rivers, but field observations revealed that most farms along the rivers had a buffer of 3 m or more and besides most of the crops along the rivers were tree crops such as cocoa and oil palm except a few locations such as Atwidie Waterworks on the Annum River and Denso on the Pra



A: Ejesu on Oda River



B: Adiembra on Ofin River



C: Bepotenten on Oda River



D: Ekorso Brimsu on Birim River

Plate 3.1: A and B show colour of water in the upper courses before gamamsey activities. C and D show colour of water at gamamsey sites.

River where vegetables, plantain and cassava were cultivated. These lands were therefore, well covered and erosion was less, hence sediment discharge from these farms into streams or the rivers was less than what pertains to the illegal mining sites. Other potential sediment sources such as urban erosion and gulling were also observed not to be severe; hence water bodies within these locations did not look that turbid as compared to the illegal small scale (galamsey) sites.

Figs.3.9 – 3.15 show the mean monthly sediment load of the various sampling stations with their standard errors. Sediment transport at all sampling stations increased from March to December coinciding with the rainfall pattern of the climatic zone, thus sediment discharge increased with corresponding increase in water discharge as expected (refer to rating curves Table 3.3). At Akim-Oda on the Birim River (Fig.3.9) and Brenase on the Pra River (Fig.3.10) sediment discharge increased from 97 t day^{-1} and 29 t day^{-1} in March, peaked in September at $2,741 \text{ t day}^{-1}$ and 979 t day^{-1} respectively. On the other hand, the highest sediment transported values of above $20,500 \text{ t day}^{-1}$ and $3,500 \text{ t day}^{-1}$ were recorded at Twifo Praso (Fig.3.13) and Assin Praso (Fig.3.14), respectively, in October. The monthly suspended sediment yield generated for those periods were above $637,800 \text{ t/month}$ and $108,500 \text{ t/month}$. At Adiembra and Anwiankwanta however high discharges of sediments were recorded during the first half of the year May ($1,089 \text{ t day}^{-1}$) and June (604 t day^{-1}) yielding nearly $34,000 \text{ t/month}$ and $18,200 \text{ t/month}$ of suspended sediments. At the mouth of the river at Sekyere Heman, sediment transport was relatively very high, with the lowest discharge being more than $11,000 \text{ t day}^{-1}$ occurring at the beginning of the year in March and the highest was nearly $43,000 \text{ t day}^{-1}$ which was recorded in June.

Suspended sediment concentration increased from upstream of the rivers downstream with the highest values being recorded at Sekyere Heman, followed by Twifo Praso. This reflected trends

in annual sediment yield which also increased from the sub-basins towards the mouth (Fig.3.16). The least annual sediment yield was recorded at Anwiankwanta ($66,094 \text{ t yr}^{-1}$) and the maximum was $7,489,290 \text{ t yr}^{-1}$ at Sekyere Heman, the mouth of the basin. The estimated annual

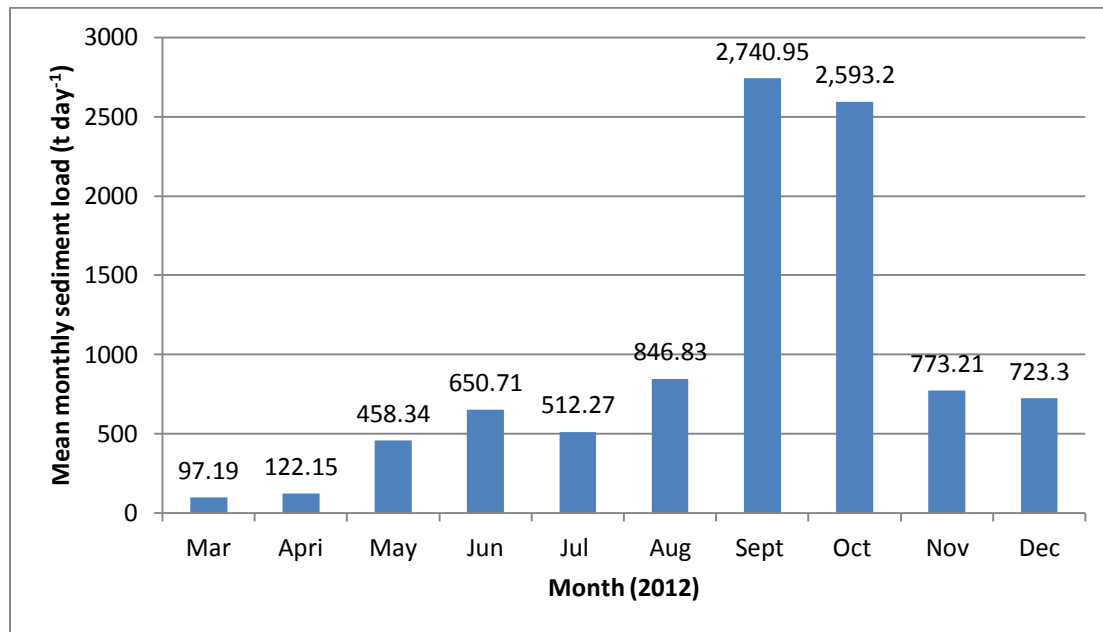


Fig.3.9: Mean monthly sediment load at Akim Oda

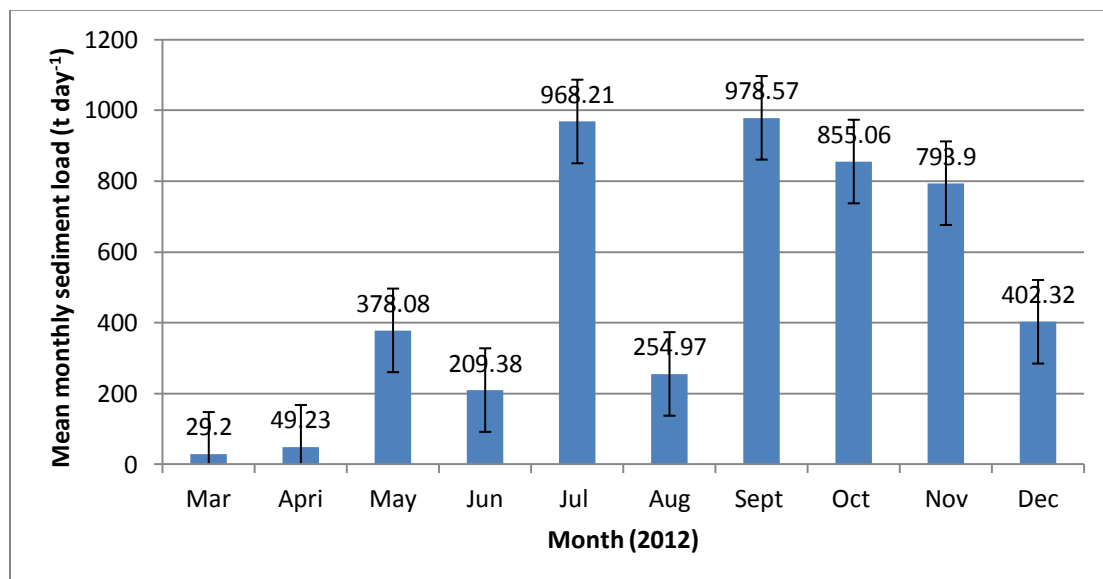


Fig.3.10: Mean monthly sediment load at Brenase

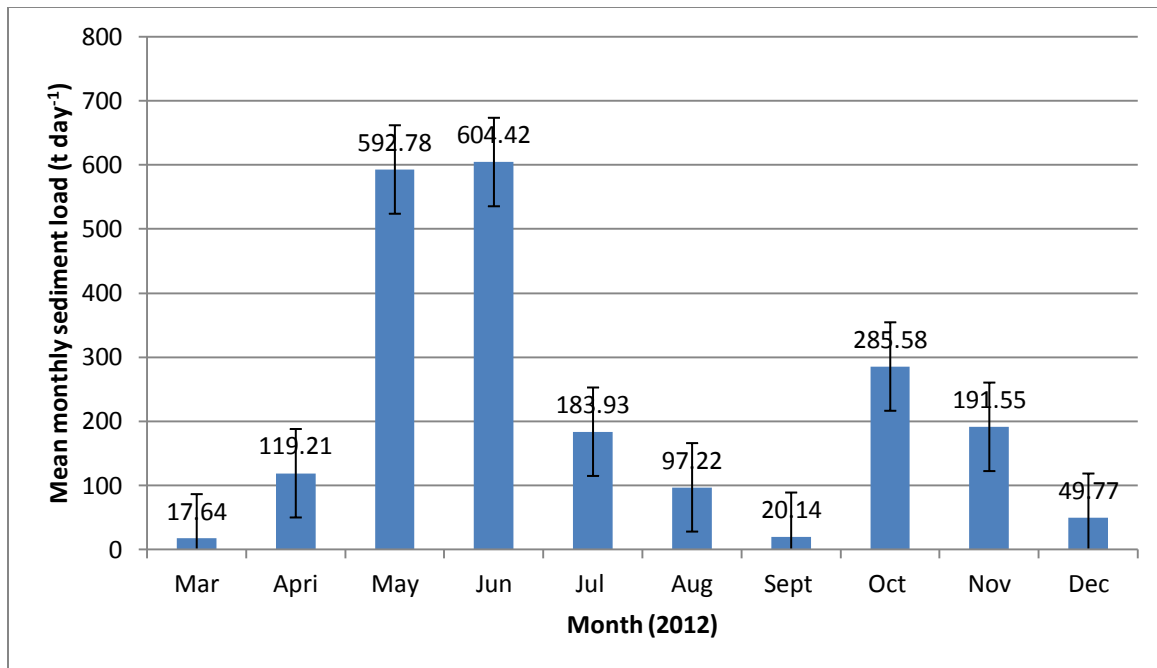


Fig.3.11: Mean monthly sediment load at Anwiankwanta

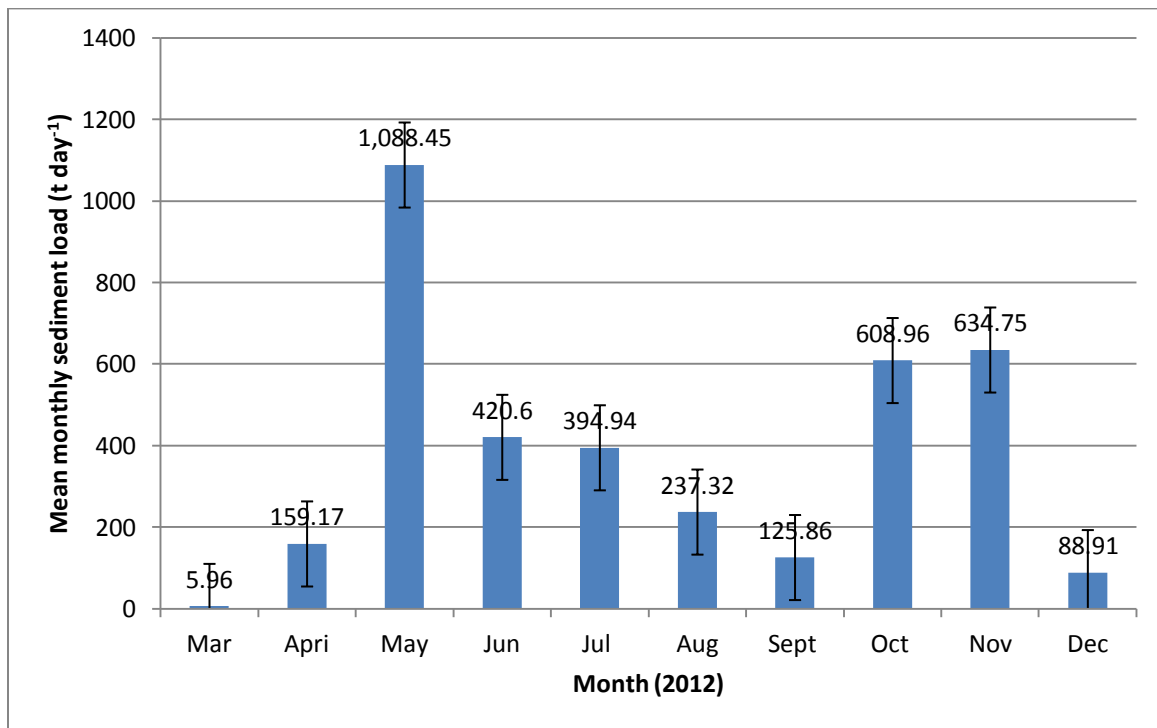


Fig.3.12: Mean monthly sediment load at Adiembra

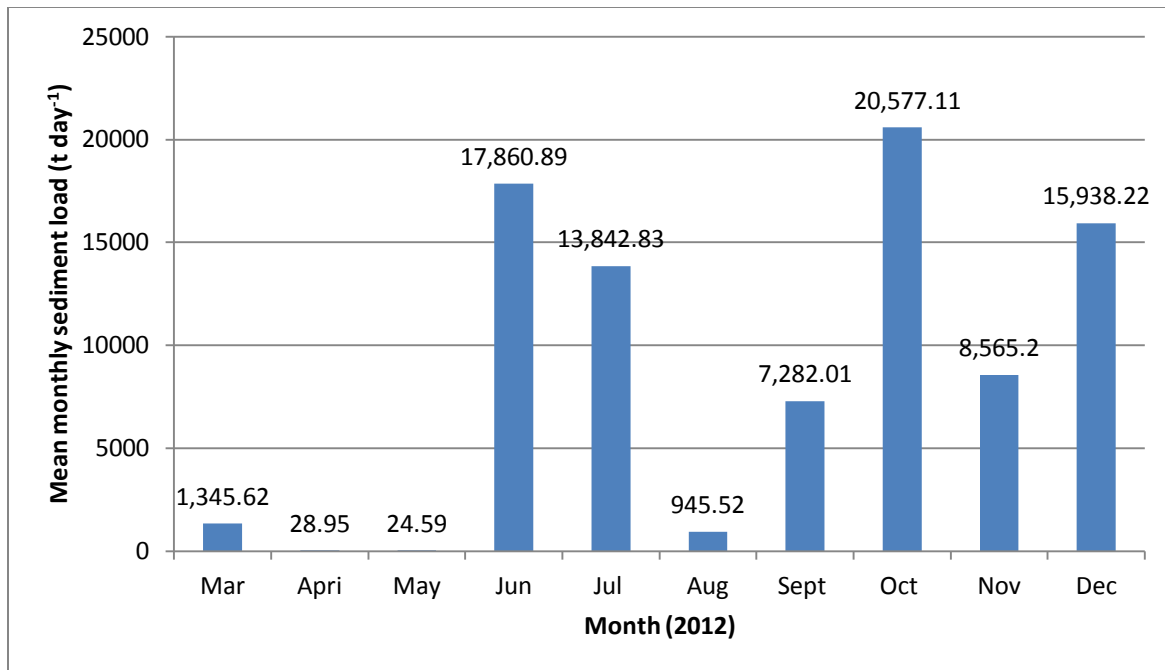


Fig.3.13: Mean monthly sediment load at Twifo Praso

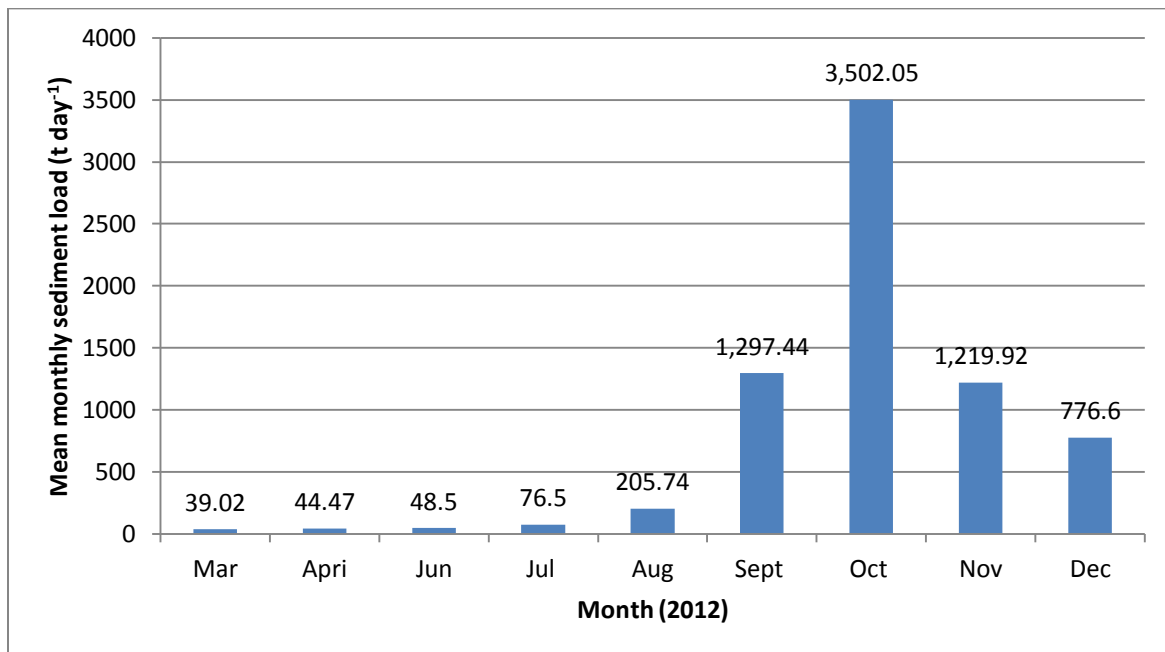


Fig.3.14: Mean monthly sediment load at Assin Praso

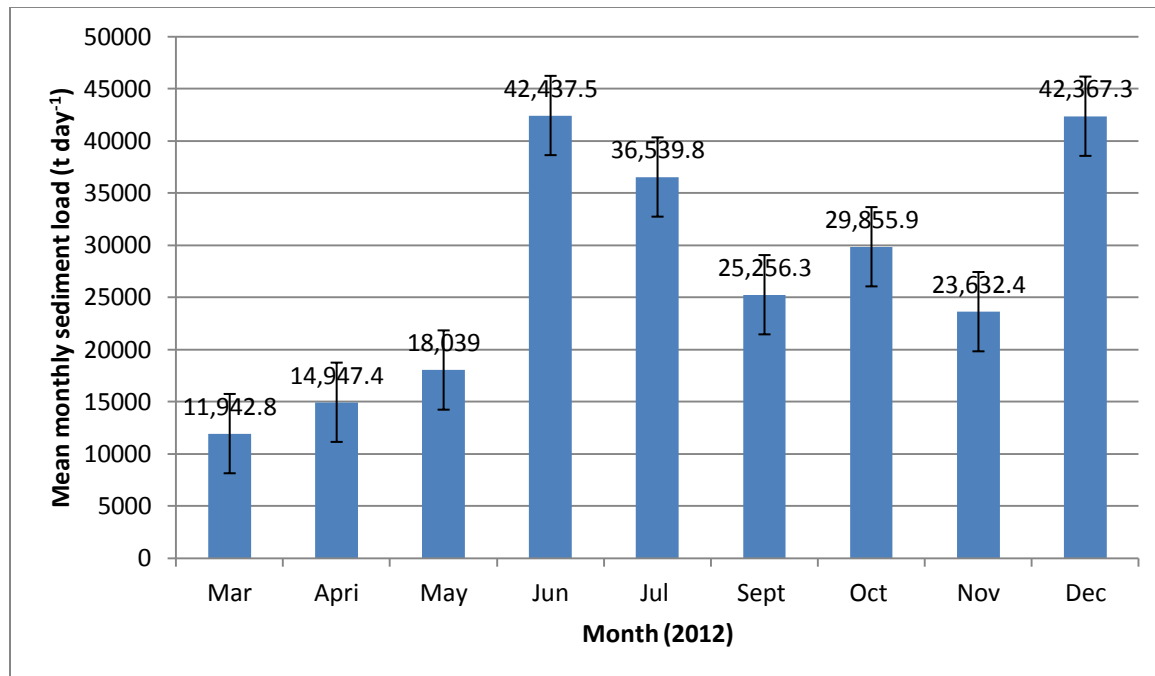


Fig.3.15: Mean monthly sediment load at Sekyere Heman

specific suspended sediment yield for the whole Pra Basin at Sekyere Heman station was $329 \text{ t km}^{-2} \text{ yr}^{-1}$ (Table 3.2). At Adiembra for the Ofin Basin the specific suspended sediment yield was slightly above $37 \text{ t km}^{-2} \text{ year}^{-1}$, nearly $94 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Birim at Akim-Oda, about $51 \text{ km}^{-2} \text{ year}^{-1}$ for the Oda at Anwiankwanta, and above $69 \text{ km}^{-2} \text{ yr}^{-1}$ at Brenase. The specific suspended sediment yield of the drainage basin at Sekeyere Heman and that of the Birim Basin are higher compared to those of other major drainage basins in Ghana and other tropical rivers. The yields in these basins are higher than those obtained for the Black Volta ($28 \text{ t km}^{-2} \text{ yr}^{-1}$), White Volta ($33 \text{ t km}^{-2} \text{ yr}^{-1}$), and Oti ($63 \text{ t km}^{-2} \text{ yr}^{-1}$) in Ghana (Akrasi, 2005). They are also higher than the suspended sediment yields for other major rivers in Africa and South America including the Niger (about $5 \text{ t km}^{-2} \text{ yr}^{-1}$), Congo ($16 \text{ t km}^{-2} \text{ yr}^{-1}$), Nile ($37 \text{ t km}^{-2} \text{ yr}^{-1}$), and the Amazon ($63 \text{ t km}^{-2} \text{ yr}^{-1}$). These values are; however, lower than that of the Ganges whose specific suspended sediment yield is above $1,350 \text{ t km}^{-2} \text{ yr}^{-1}$ (Akrasi, 2005).

Model results of a hypothesis test indicate a significant variation in sediment yield within drainage basins with a p -value of 0.01 and an R^2 to be 0.70 (Model1; Appendix A). Spearman and Kendall correlation analyses showed very strong positive correlations between sediment yield and drainage basin area with r values of 0.93 and 0.81 (Models2 & 3, Appendix A). These models results are; however, in contrast with the inverse relationship model between sediment delivery ratio and basin area. The inverse relationship has been explained in terms of decreasing slope and channel gradients with increasing basin size and this increases opportunities for either a temporary/permanent deposition to be associated in river channels, floodplains, valleys or the base of slopes. Literature shows that mostly between 10-30% of gross erosion is transported into river channels and this is what ends up at basin outlets (Golubev, 1982; Hadley and Shown, 1976; Walling, 1983). For instance, there is a 17% loss in sediment load along the Nile River from Sudan to Egypt and along the Nazus River in Mexico, the conveyance loss in total suspended sediment load is 25% (Walling, 1983).

The increasing levels of suspended sediment concentration and sediment yields downstream are explained by the increasing human activities along and within the rivers particularly illegal small scale mining. These illegal small scale mining activities become very intensive towards the mouth of the Pra at Sekyere Heman because of increased volume of the river. At the upper sections of the rivers such as Kibi (refer to Plate.1a in chapter one), Anyinam, Brenase, Konongo etc the illegal mining is basically restricted to land fringing the banks due to the small river channel but towards the middle sections such as Akim Oda, Assin Praso, Dunkwa-on-Ofin, Twifo Praso and the mouth, the illegal mining activities take two forms; alluvial mining within the river bed and channel bank mining (bank full stage) because the river channel is now wider and deeper which enables the miners to ply within the channel (see Plate.1b in chapter one).

There is virtually no community without these miners, particularly from the middle section to the mouth. On the Pra River they are found in every community from Sekyere Heman to Brenase, on the Birim River from Assin Praso to Kibi, on the Ofin River from Foso downstream of Adwumain to Adiembra and on the Oda River they are found from Bepotenten to Anwiankwanta. These activities are primarily responsible for the entrainment of large quantities of sediments into the rivers even at low flows from both bank mining activities and the discharge of mine wastes into the rivers. Thick plumes of sediments are observed in transport in these mine sites and the intensity of their activities does not promote much deposition of fluvial sediments. For instance at Sekyere Heman and Twifo Praso, the illegal mining activities were just about 200 m upstream of the sampling stations and this is the major explanation to the exceptionally high sediment levels in these stations. Interaction with locals in these communities indicated that, this level of pollution of the rivers has been as a result of the illegal mining activities. Hitherto, the water was very clean, clear of sediments and they used to depend on it for domestic chores, but now that is impossible because the water looks very dirty and they cannot drink it any more.

The implication of the level of sediment load and transport patterns in the entire Pra Basin is that, it poses a great threat to the sustainability of dams/reservoirs on these rivers and water quality of the rivers in general as was discussed in the problem statement in chapter one. According to managers of Ghana Water Company Limited in the Pra Basin particularly at Kibi, Twifo Praso, Dunkwa-on-Ofin, Beposo and Sekyere Heman, the level of sediment and chemical pollution of the water by these galamsey activities is increasing their cost of operation as more chemicals have to be used in treating the water before it is supplied to consumers. The situation is also causing the frequent break down of their equipment and this have therefore raised serious concerns about these illegal mining activities as these illicit activities are threatening the water

treatment plants. Due to the deteriorated state of the water, most communities that do not have access to potable water along the rivers now have to depend on boreholes for their domestic water needs. Residents along the rivers complained of reduced stock of fish and crabs in the rivers owing to the pollution resulting from the illegal mining. Also owing to the turbid state of the water, residents are scared of swimming or bathing in the rivers for fear of contracting diseases. These illegal mining activities have also been a great concern to Water Resources

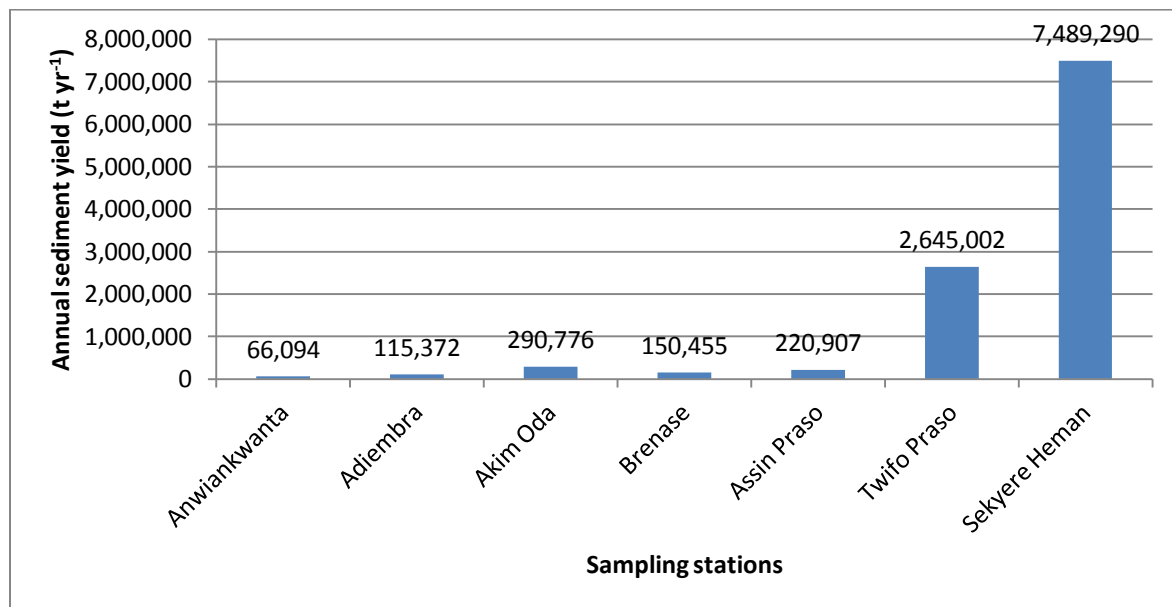


Fig.3.16: Annual sediment yield.

Table 3.2: Annual suspended sediment load and specific suspended sediment yield for the monitored stations in the Pra River Basin

River and station	Drainage Area (km ²)	Annual suspended sediment yield (t y ⁻¹)	Annual specific sediment yield (t km ⁻² year ⁻¹)
Oda at Anwiankwanta	1,288	66,094.1	51.3
Ofin at Adiembra	3,101	115,372.1	37.2
Birim at Akim Oda	3,104	290,775.6	93.7
Pra at Brenase	2,168	150,455.4	69.4
Pra at Assin Praso	9,235	220,907.1	23.9
Pra at Twifo Praso	2,0625	2,645,002.1	128.2
Pra at Sekyere Heman	22,758	7,489,290.1	329.1

NB: Drainage areas composed of upstream of stations draining into the station and these were extracted in ArcGIS.

Commission, which has set up the Pra River Basin Management Board to help manage human activities such as farming, mining, industrial activities, among others, that are impinging on the water bodies.

The sediment ratings established between suspended sediment discharges and water discharges are shown in Table 3.3. Each relationship was statistically tested to be significant at 5% level and the coefficients of determination (R^2) associated with the relationships, ranged between 0.66 and 0.98. For instance, at Sekyere Heman over 60% of the suspended sediment discharge is explained by water discharge. This implies that, largely a greater percentage of the suspended sediment discharges are explained by water discharges. However, the low magnitude of the rating exponents ranging from 0.67 – 1.15 reflect the insensitivity of suspended sediment

Table 3.3: Parameters for suspended sediment rating curves

No.	Station	River	Equation	R^2
1	Sekyere Hemang	Pra	$Q_s = 429.48Q^{0.67}$	0.66
2	Twifo Praso	Pra	$Q_s = 100.38Q^{0.90}$	0.98
3	Assin Praso	Pra	$Q_s = 14.638Q^{1.12}$	0.92
4	Akim Oda	Birim	$Q_s = 31.626Q^{0.95}$	0.73
5	Adiembra	Offin	$Q_s = 10.914Q^{0.97}$	0.86
6	Brenase	Pra	$Q_s = 31.608Q^{0.97}$	0.73
7	Anwiankwanta	Oda	$Q_s = 13.676Q^{1.15}$	0.86



A: Water colour at Bepotenten



B: Water colour at Ekorso Brimsu

Plate 3.2: Colour of water near galamsey sites at low flows

concentration to increases in discharges, which implies the rivers remain turbid over a wide range of flows, and the suspended sediment concentrations remain relatively high even during low flows. The insensitive nature of sediment discharge to water discharge could be attributed to the alluvial illegal gold mining activities practiced within the river channel and the basin resulting in the remobilization of deposited channel sediments. This results in constant discharge of sediments into the fluvial sediment transport. See how turbid the rivers are at two galamsey sites; Bepotenten and Ekorso Brimsu on the Oda and Birimsu Rivers respectively at low flows (Plate 3.2).

Since the curves were derived from one year flows, they are likely to be associated with errors. The use of only one year of data means the curves may not provide accurate estimates of long term mean sediment discharges of the basins. Sediment concentrations were determined using both the integrated and dip samplings with the dip samples being corrected by a correction factor of the integrated samples. This will definitely introduce some errors. Also sampling was also not according to the hydrological regime/seasonality of flow but calendar based; hence certain critical flows were missed irrespective of the number of samples taken particularly in stations where people could not be engaged to undertake dip sampling. For lack of previous flows and concentration data, the accuracy of these curves could not be evaluated but could be associated with error margins due to the reasons outlined above. According to Horowitz (2003) and Walling (1977a; 1977b), the sediment rating-curve method tends to under predict high, and over predict low suspended sediment concentrations when flow is not constant throughout the day. As such, the range of errors associated with concomitant flux estimates for relatively short time-frames (e.g. daily, weekly) are likely to be substantially larger ($\pm 20\%$) than those associated with longer time-frames (e.g. quarterly, annually) because the over and under predictions do not have

sufficient time to balance each other. The evaluations indicate that over periods of 20 or more years, errors of <1% can be achieved using a single sediment rating curve based on data spanning the entire period. In either case, hydrologically based sampling, as opposed to calendar-based sampling is likely to limit the magnitude of flux estimation errors.

3.3 Conclusion

The annual specific sediment yield measurements in the Pra Basin are higher than most tropical rivers including those in Ghana. Illegal alluvial gold mining within the rivers and the basin is one of the likely underlying forces injecting sediments into the rivers as compared to other forces. This large sedimentation levels have socio-economic and environmental implications as this is increasing the cost of potable water supply, and break down of water equipment. Also residents are denied of their cheap sources of protein needs as a result of the reduced stock of fish and crabs in the water bodies.

Chapter Four

Sediment Source Analysis

4.0 Introduction

There is an increasing need to determine sources of sediments in fluvial sediment transport owing to their environmental impacts. For instance, in Africa, the on-site problems caused by enhanced soil erosion include a reduction of soil depth and organic matter content (El Wakeel & Astatke, 1996; Lal, 1996a), the depletion of plant-available nutrients (Ghuman & Lal, 1991; Lal, 1996b) and a reduction of water storage capacity in the root zone (El-Swaify, 1993). These can all reduce crop yields (Lal, 1993) and are compounded by the inability of the typical subsistence farmer to provide the inputs necessary to restore soil quality (El-Swaify, 1993).

In response to these sediment-related environmental problems, major soil conservation programmes have been established in several African countries, including Kenya (Wenner, 1980), Zimbabwe (Elwell, 1978) and Zambia (Bezuneh et al., 1995). Such schemes have, however, been hampered by a multitude of physical, socioeconomic, demographic and political constraints, and by limited resources (Collins et al., 2001).

Information on sediment sources is required to design effective sediment and non-point pollution control strategies. This will provide an improved understanding of erosion and suspended sediment transport within a basin which is an essential precursor to establishing sediment budgets, developing distributed sediment yield models, and interpreting sediment yields in terms of landscape evolution (Walling et al., 1993). As observed in the previous chapter, sediment yield levels in the Pra Basin are high and this calls for public concern due to the environmental and health related impacts. Traditional methods of watershed monitoring for suspended sediments are inadequate to provide

information on fluvial processes taking place within a watershed (Mukundan et al., 2009). The fingerprinting approach has proved to be an effective way for tracking sediment movement within a watershed in terms of both source type and spatial origin (Walling, 2005). Consequently, the fingerprinting technique was adopted to identify sediment sources and quantify the various pathways of sediment origin within the Pra Basin. The chapter presents research materials and methods employed in carrying out this tracer study and findings of the study.

4.1 Research Materials and Methods

Sediment source tracking 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, path/untarred roads leading to rivers, gullies and gutters from settlements and farms into streams) and for bank erosion (channel banks). Sampling sites of these potential sediment sources were determined through field investigations and interviews with the local communities to identify areas of active sediment erosion (Davis and Fox, 2009).

To accommodate local spatial variability in ^{210}Pb in the surface soil, core samples of depth 10 cm within plot sizes of $15 \times 15 \text{ m}^2$ at grid intervals of $3 \times 3 \text{ m}$ were taken at each site with an improvised 5 cm pvc pipe as a corer. Samples were composited for analysis (Nagle et al., 2007; Walling, 2004). Bank sediments were collected by scrapping channel wall sediments (Davis and Fox, 2009). Suspended sediments were sampled at the catchment outlets of sub-basins using the depth integrated sampler based on the equal-width-incremental approach across a channel transect (Davis and Fox, 2009; Edwards and Glysson, 1999; Matisoff and 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 polyethene bags while those of suspended sediments were in plastic bottles which were 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 when flows were high because ^{210}Pb environmental radionuclides are known to fallout highest with increasing precipitation (Matisoff and Whiting, 2011).

All source material samples were air-dried, ground in a mortar and dry-sieved to $63\mu\text{m}$ because radionuclides tend to have higher sorption to finer soils (Matisoff and 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. Samples were then analyzed for ^{210}Pb using Atomic Absorption Spectrophotometer (AAS). The AAS digestion procedure for lead 210 was as follows:

0.5g of sample was measured into labelled 100 ml polytetrafluoroethylene PTFE Teflon bombs. 6ml of Concentrated HNO_3 and 5ml of concentrated HCL 38% were added in a fume chamber. Samples were then loaded on a microwave carousel. The vessel cap was secured tightly using an appropriate screw tool. The complete assembly was microwave irradiated for 21min in a Milestone microwave Labstation (Ethos 900) using the following operation parameters; 250w for 5 min, 0w for 1 min, 250 w for 10 min, 450w for 5 min, and 5 min allowed for venting (Milestone Cook Book, 1996). After digestion the Teflon bombs mounted on the microwave carousel were cooled in a water bath to reduce internal pressure and to allow volatilized material to re-solubilize. The digest was made up to 20 ml with ddH_2O and assayed for the presence of metals on a Varian AA240FS Atomic Absorption Spectrophotometer in an acetylene –air flame. Typical count times on gamma detectors were in the order of $\sim 84 \text{ k s}^{-1}$ (Wallbrink et al. 2003).

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

$$C_s = \frac{Pr - Pb}{Ps - Pb} \times 100 \dots\dots\dots (4.1),$$

where C_s (%) 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.

4.2 Results and Discussion

Tables 4.1 - 4.4 illustrate the mean concentration of ^{210}Pb for each of the surface sample types as well as the average concentration of all the surface samples captioned mean surface soil. The mean concentration levels of bank sediments and stream sediments are also provided for each sub-catchment. Results of individual surface and bank samples are illustrated in Appendix B. Mean concentration levels of ^{210}Pb for bank sediments were generally lower than most surface samples (Table 4.1 – 4.4) except at Oda Basin. The lowest mean concentration of ^{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 4.3 and 4.4). However the lowest mean surface soil value was recorded in Birim Basin (1.34 Bq/kg) while the highest was in the Pra Sub-basin (3.40 Bq/kg) (Tables 4.2 and 4.3).

Roads that are not tarred and settlements (urban landscapes) were found to have the highest mean value of ^{210}Pb in surface samples as compared to other surface samples. The rationale for this high concentration of ^{210}Pb in these samples is due to the well exposed and less disturbed state of these landscapes as compared to soils of farms,

Table 4.1: Mean ^{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 surface soil (n = 47)	Bank Sediment (n = 12)	Stream Sediment
^{210}Pb Bq/kg	1.45	1.79	1.43	1.65	1.06	0.74	1.34	0.89	1.10

Table 4.2: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in the Pra main basin

Tracer	Galamsey (n = 9)	Road & Bridge (n = 21)	Farm (n = 7)	Settlement (n = 9)	Gully (n = 1)	Gutter (n = 10)	Mean surface soil (n = 72)	Bank Sediment (n = 15)	Stream Sediment
^{210}Pb Bq/kg	2.32	4.02	2.88	3.31	0.68	4.25	3.40	3.09	3.18

Table 4.3: Mean ^{210}Pb Concentration levels for stream sediment and potential source materials in Oda Sub-basin

Tracer	Galamsey (n = 5)	Road & Bridge (n = 2)	Settlement (n = 4)	Gully (n = 2)	Gutter (n = 4)	Mean surface soil (n=29)	Bank Sediment (n=12)	Stream Sediment
^{210}Pb Bq/kg	0.44	0.55	1.01	2.34	2.96	1.77	2.12	2.24

Table 4.4: 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
^{210}Pb Bq/kg	2.25	2.22	1.13	2.84	0.85	0.52	1.54	1.01	1.16

Table 4.5: Contribution of bank material and surface soil sources to suspended sediment load in the various sub-catchments

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

galamsey, and gullies which are frequently being mixed/tilled or eroded. The exposed urban soils promote the accumulation of ^{210}Pb radio-nuclide fallouts. Samples from gutters were also high in ^{210}Pb concentration levels with a minimum value of 0.52 Bq/kg in the Ofin Basin and a maximum of 4.25 Bq/kg in the main Pra Sub-basin (Table 4.2 and 4.4). Generally lower levels of ^{210}Pb in surface samples were found in sites of active erosion. In all the basins, ^{210}Pb mean levels in bank sediments were found to be lower than mean ^{210}Pb samples of most surface sites. For instance except gutter samples in the Birim Basin and then gully and gutter samples in the Ofin Basin, all other surface samples had a higher ^{210}Pb levels than bank materials (Tables 4.1 and 4.4). However, in the Pra and Oda Basins, bank sediments were relatively high in ^{210}Pb concentration than most surface materials (Tables 4.2 and 4.3).

Lower levels of bank sediment samples and surface samples were recorded in localities of very active bank erosion and surface erosion (Tables 4.6; 4.8 and 4.9; Appendix B). 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 levels of an environmental radionuclide ^{137}Cs in bank sediments to active bank erosion. Also recent illegal mines sites (galamsey) also recorded lower values of ^{210}Pb (Tables 4.6 – 4.9; Appendix B). For instance at Kibi, an abandoned illegal mined site had 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 4.6; Appendix B). Soils are dug from pits of 20 m or more by the 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 lead 210 values. Thus samples of

adjacent soils had higher values than those of galamsey site. These observations are in line with literature. According to Walling et al., (1993), in undisturbed soils, ^{210}Pb are concentrated in 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 was explained by soil mixing due to cultivation (Nagle and Ritchie, 1999).

The simple sediment mixing model results derived using equation (4.1) show that a higher percentage contribution of sediments into the fluvial sediment transport is coming from bank sediments with a range of 53 – 72% (Table 4.5). The lowest estimated bank sediments contribution is in the Birim Basin (53%) while the highest is recorded in the Ofin Basin (72%). Conversely, the lowest surface soil sediment source (28%) is in the Ofin Basin while the highest surface sediment source is in the Birim Basin (47%) (Table 4.5). The model results are buttressed by the hypothesis test 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 (Appendix B). 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 (Appendix B).

Due to the good vegetative cover (details in chapter 6), soils are well protected and coupled with low gradient of the catchment which is less than 20 degrees, surface erosion is very low. Collins et al., (2001) also made a similar observation that, due to the increased cover density provided by natural vegetation soil erosion from surface soils declined from the dry to wet season. 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 material tracer sources. At the peak of the rainy season river banks were flooded making them susceptible to mass failure and slumping. Bank toe undercutting during the falling limb



A: Illegal mining along the banks of a stream of the Ofin River.



B: Illegal mine waste water draining into the Birim River at Kibi.

Plate 4.1: Evidence of direct sediment and mine waste water entrainment into the rivers.

stage of flow hydrograph resulted in the removal of bank material and bank collapse into the river channel. Bank erosion was observed to be very severe in the middle course of the tributaries.

This result is in common with findings of chapter three and chapter five. It was observed in the previous chapter that in the upper sections of the river where there are no activities of illegal mining, river water was of low turbidity and of low suspended sediment concentration. However at the middle and lower sections where small scale alluvial gold mining is intense, the colour of the rivers tended to be gray or brown and are characterised by very high suspended sediment levels. The underlying reason accounting for the high sediment injection into the rivers as discussed earlier is because, most of the miners undertake alluvial mining within the river bed and channel banks and this entrains sediments directly into the river or it results in the remobilization of deposited sediments into the sediment transport system.

Besides this practice, other miners who are along the river/stream banks, discharge both their mine waste sediments or water into nearby streams and rivers to avoid the flooding of their sites (Plate 4.1). These mine waste water are very turbid and thus generate plumes of sediments in the rivers which discolours the water. And there are hundreds of these miners strung along all the major tributaries and most streams within the basin. Also due to the exposed nature of these galamsey landscapes (Plate 1), rain drops dislodge soil particles (rain splash) causing sheet erosion. Hence run-off/overland flow drains directly as flash floods into the streams and rivers increasing the sediment concentration levels. Similarly, it has been observed that significant soil erosion by rainsplash, sheetwash and rilling is prominent in exposed areas of bare soils (Collins et al., 1997; Collins et al., 2001). Such erosion is accentuated by high rainfall erosivities during frequent thunderstorms which are characteristic of the tropics (Stocking & Elwell,

1976; Obi & Salako, 1995). In fact, the nature of the sediment entrainment from these mine sites can not in any way be compared to bank erosion by hydraulic processes.

4.3 Conclusion

In this chapter a tracer technique using ^{210}Pb environmental radionuclide has been employed to determine that much suspended fluvial sediments in transport are originating from bank materials. The method used in this study did not allow the discrimination between the contributions of the various subsurface sources to the fluvial sediment in transport. A combination of human activities (galamsey) and bank erosion are however, the plausible explanatory factors accounting for the entrainment of bank sediment into the sediment transport budget. Though the study could not differentiate between fingerprints of galamsey materials from those of bank erosion, however the relatively high levels and trends in suspended sediment discharge throughout the season even at low flows as shown in the previous chapter attest to the fact that, illegal mining could be the major source of bank sediments discharge into the rivers. Additional information is provided in the next chapter on the state of bank erosion of channel walls within the river valleys.

Chapter Five

Changes in River Channel

5.0 Introduction

Changes in river channels as a result of bank erosion and deposition cause significant damage to infrastructure (e.g., bridge crossings, pipes), losses of fertile agricultural soil, and a degradation of stream water quality (Bertrand, 2010) because erosion and deposition highly impact the amount of sediment transported to a stream (Hayes, 2004).

Bank erosion plays a very important role in river channel dynamics, meander development, and catchment sediment systems (Church and Slaymaker, 1989). Channels are widened; meander loops are severed to form ox-bow lakes and large volumes of sediments can be entrained into channels due to bank erosion and bank failure of river valleys. River banks have been shown to act as key sediment sources and sinks; in many different types and sizes of drainage basins, and can supply over 50% of catchment sediment output (Church and Slaymaker, 1989; Lawler et al., 1999).

As demonstrated in chapter four, bank materials are the main source of suspended fluvial sediments in the Pra Basin. Bank erosion; therefore, constitutes an intricate physical, socio-economical, and ecological problem requiring an improved understanding of the key processes governing bank erosion (Bertrand, 2010). Knowledge of the rates, patterns and dynamics of bank erosion events that release sediment and any associated contaminants to the fluvial system is fundamental, therefore, to a complete understanding of the fluvial sediment transport regime, including fluxes to estuarine zones (Lawler et al., 1999) and channel stability. In this chapter, an attempt is made to quantify the rates and spatial variability in bank erosion and channel stability in order to evaluate the relative importance of bank sediment supplies to the sediment budget in transport in the

Pra Basin and its sub-catchments by undertaking bank erosion measurements at selected cross sections. The underlying fluvial and sub-aerial processes influencing the dynamics in channel stability were also investigated.

5.1 Research Materials and Methods

Bank erosion was assessed using erosion pin approach (e.g. Bertrand, 2010; Billi, 2008; Lawler et al., 1997; Schoonover et al., 2007). Galvanized steel rods of 6 mm thick and 45 cm long were inserted into channel walls and their levels of exposure measured with a ruler (Plate.5.1). Depending on the depth of the bank face, pins were inserted at each bank face at 1×1 m or 0.5×0.5 m horizontal and vertical grid intervals. Pins were pressed into the soil or lightly tapped with a hammer until 5 cm of the pin remained exposed.



Plate.5.1: Erosion Pin at the bank of the Birim River at Akim Oda

Pins were identified at cross sections with bench marks and numbered sequentially in downstream direction. The first pin in each cross section was placed on the bank toe approximately 3 cm above base flow water surface elevation and the last pin was placed below bankfull of the stream channel.

This elevation was chosen to allow pin measurement during normal flow conditions. Pins were inserted in March when flows were low and monitored during low flows for one year. The first measurement was taken in August/September of the same year at sites where it was possible and in March the following year when flows were low. The level of exposure of the rod is an indication of the extent of bank erosion. Pins were reset to the 5 cm after monitoring visits (e.g. Bartley et al., 2008; Lawler, 1993; Staley et al., 2006).

Soil surface disturbance was minimized as much as possible while placing pins and when measurements were being taken. Reaches that were chosen for the bank erosion measurements were based on reconnaissance survey to identify areas of active channel erosion (Bertrand, 2010). Also, channel reaches undisturbed by human activities and artificial structures; as much as possible, were chosen to avoid impact of human activities on bank retreat (Lawler et al., 1997; Schoonover et al., 2007).

To estimate the amount of bank sediments into the river sediment transport, the mass of sediments eroded into the river channel was estimated by determining the volume of eroded sediments using equation (5-1), multiplying this volume by soil density (ρ), ρ density of wet soil (1920 kg/m^3) (Freeze and Cherry, 1979):

$$\text{Volume} = \text{length} \times \text{height} \times \text{width} \dots\dots\dots(5-1),$$

To determine the susceptibility of bank sediments to erosion, bank sediment samples were collected at each site and analysed to determine the median grain size (D_{50}) and the percent clay and silt (Bartley et al. 2008) of bank sediments.

5.2 Results and Discussion

Tables 5.1 – 5.6 show the annual rate of bank erosion and deposition analyses from erosion pin measurements. Significant channel erosion was recorded at Akim Oda (Birim River), Ejesu (Oda River) and Adiembra (Ofin River) whiles at Anyinam (Birim River), Amuanda Praso and Brenase both on the Pra River, bank erosion was low.

River channel at Anyinam was characterized by very low bank erosion and deposition, even two erosion pins never receded and the maximum annual mean erosion recorded was about 4 cm whiles deposition was very intense, with alluvial deposits of between 2 – 65 cm (Table 5.1). Akim Oda; however, experienced very active bank erosion characterized by bank failure (Tables 5.3). Here all erosion pins receded with the lowest eroded pins recession being nearly 4 cm and the highest about 20 cm of exposure. On the Birim River, mean annual bank erosion increased downstream from 1.3 cm at Anyinam to 9.9 cm at Akim Oda (Tables 5.1 and 5.3).

The increase in bank erosion downstream is attributed to an increase in flow/discharge downstream resulting in bank wearing and weakening, bank collapse by flood waters, especially at bankfull stage. This observation is in line with findings of Lawler et al (1997, 1999) who observed that, from mid-basin downstream the optimum combination of water surface slope, channel cross- section geometry and discharge is obtained, hence available stream energy is likely to peak resulting in the dominance of stream entrainment processes such as bank wearing and mass failure of channel banks. In the upper reaches of river basins, stream power is low because of low discharges, despite steep bed slopes, thus limiting the available energy for fluid entrainment of bank materials and banks are also too small to be susceptible to mass failure (Lawler et al.,

1997; Lawler et al., 1999) (Plate.5.2). This promotes channel bed incision with low bank erosion characterised by step-pools and bars in the dry season (Plate.5.2).

Monitored channel banks of the main Pra River were also characterized by both erosion and deposition (Tables 5.2 and 5.4). At Amuanda Praso, the right bank was more erodible than the left bank, whereas at Brenase it was the vice versa. Mean annual bank erosion at Amuanda Praso (4 cm) was almost twice the bank wearing at Brenase (2.3 cm). Bank toe erosion at both stations was greater than towards the bankfull stage. However, on the Pra River, bank erosion decreased downstream by 1.6 cm between Amuanda Praso and Brenase.

Just like Anyinam, the river channel at Ejesu on the Oda River was experiencing both erosion and accretion with the mean annual bank erosion almost 11 cm (Table 5.5). The lowest eroded pin was just above 2 cm and the highest eroded point was above 26 cm. The opposite bank was; however, undergoing sediment deposition. Unlike the other river channels, both banks of the Ofin River at Adiembra was subjected to bank erosion and the annual mean erosion at both right and left banks was above 2 and 8 cm respectively.

In a nutshell, the retreat magnitudes observed in this study are lower than rates such as 8.3 – 44 cm obtained by Lawer et al., (1999) on Swale-Ouse system, northern England. These values are also lower than the global average, and lower than expected for a tropical river system, particularly when compared with other tropical rivers such as the Luangwa River in Zambia, where erosion is as high as 33 m yr⁻¹ (Bartley et al., 2008; Gilvear et al., 2000).

Table 5.1: Annual bank erosion or deposition rates at Anyinam

Date				5 th March 2013				
				Length of exposure/deposition of pins/cm (“+” erosion and “-” deposition)				
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4	Pin 5
Birim	Anyinam	Left	Top	0.0	0.0	0.5	3	1
		Left	Bottom	1.0	0.5	2.0	1.5	3.7
		Right	Top	Deposition of sediments of depth between 2 – 17cm				
		Right	Bottom	Deposition of sediments of depth between 20 – 65cm				
Average annual bank erosion (cm)				1.3				
Volume of eroded sediments (cm ³)				33,800				
Mass of eroded bank sediments (tonnes/yr)				64,896				

Gridded interval: Horizontal (1 m), Vertical (0.65 m)

Table 5.2: Annual bank erosion or deposition rates at Amuanda Praso

Date				5 th March 2013		
				Length of exposure/deposition of pins/cm (“+” erosion and “-” deposition)		
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3
Pra	Amuanda Praso	Right	Top	5.8	1.5	3
		Right	Middle	3	1	5
		Right	Bottom	5.5	4	6.4
		Left	Top	buried	buried	buried
		Left	Middle	buried	buried	2.5
		Left	Bottom	6	6	5.5
Average annual right bank erosion (cm)				3.9		
Volume of eroded sediments (cm ³)				156,000		
Mass of eroded bank sediments (tonnes/yr)				299,520		

Gridded interval: 1 m by 1 m

Table 5.3: Annual bank erosion or deposition rates at Akim Oda

Date				5 th March 2013			
				Length of exposure/deposition of pins/cm ("+ erosion and "-" deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4
Birim	Akim Oda	Left	Top	12	4	17	Bank failure
		Left	Middle	3.3	20	4.5	buried
		Left	Bottom	10.5	8	buried	buried
Average annual bank erosion (cm)				9.9			
Volume of eroded sediments (cm ³)				594,000			
Mass of eroded bank sediments (tonnes/yr)				1,140,480			

Gridded interval: 1 m by 1 m

Table 5.4: Annual bank erosion or deposition rates at Brenase

Date				5 th March 2013		
				Length of exposure of pins/cm ("+ erosion and "-" Deposition)		
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3
Pra	Brenase	Right	Top	0	0.5	buried
		Right	Bottom	buried	buried	buried
		Left	Top	1.2	2.0	2.9
		Left	Bottom	2.2	3.0	2.7
Average annual right bank erosion (cm)				2.3 cm		
Volume of eroded sediments (cm ³)				37,260		
Mass of eroded bank sediments (tonnes/yr)				71,539.2		

Gridded interval: 0.9 m by 0.9 m

Table 5.5: Annual bank erosion or deposition rates at Ejesu

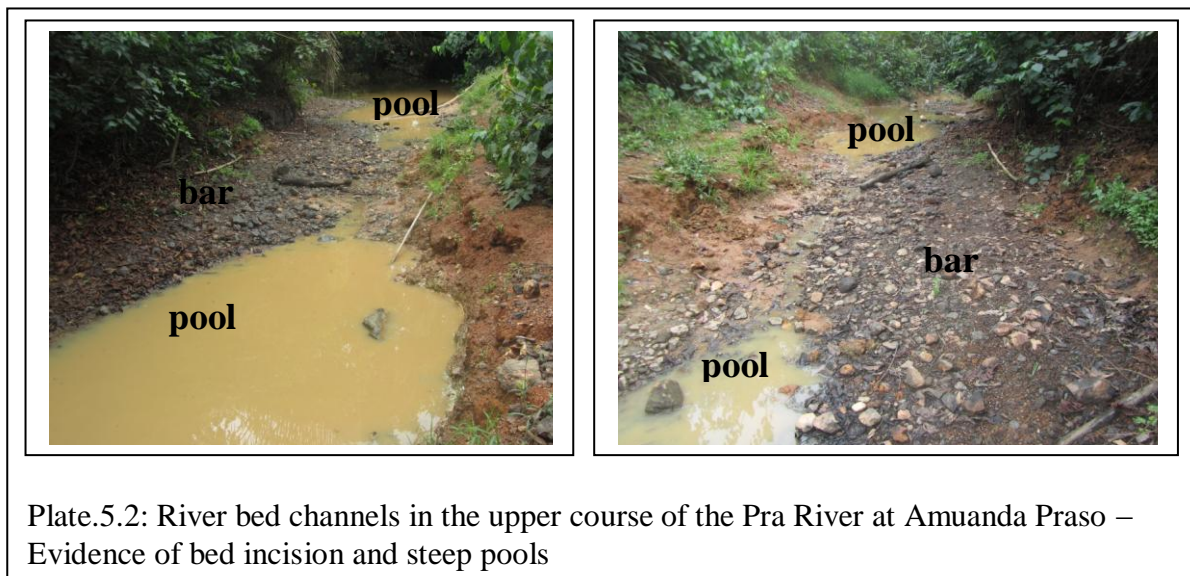
Date				6 th March 2013			
				Length of exposure of pins/cm ("+ erosion and "-" Deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4
Oda	Ejesu	Right	Top	3	3.2	7.8	26.7
		Right	Middle	2.4	4.3	7.9	6.2
		Right	Bottom	2.1	26.3	25.3	10.7
		Left	Top	Buried	Buried	Buried	
		Left	Middle	Buried	Buried	Buried	
		Left	Bottom	Buried	Buried	Buried	
Average annual right bank erosion (cm)				10.5			
Volume of eroded sediments (cm ³)				630,000			
Mass of eroded bank sediments (tonnes/yr)				1,209,600			

Gridded interval: 1 m by 1 m

Table 5.6: Annual bank erosion or deposition rates at Adiembra

Date				6 th March 2013			
				Length of exposure of pins/cm ("+" erosion and "-" Deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4
Offin	Adiembra	Right	Top	1	4.7	4.6	
		Right	Middle	1.2	1.6	3.9	
		Right	Bottom	1.1	1.3	1.8	
		Left	Top	3.3	3.8	3.1	9.5
		Left	Middle	3.4	3.6	3.3	24.7
		Left	Bottom	4.5	5.9	7.8	25.1
Average annual right bank erosion (cm)				2.36			
Volume of eroded sediments (cm ³)				94,400			
Mass of eroded bank sediments (tonnes/yr)				181,248			
Average annual left bank erosion (cm)				8.17			
Volume of eroded sediments (cm ³)				122,550			
Mass of eroded bank sediments (tonnes/yr)				235,296			
Total Mass of eroded bank sediments (tonnes/yr)				416,544			

Grid interval: right bank (1m by 1 m), left bank (Horizontal = 1 m, Vertical = 0.5 m)



Outer banks were characterized by pronounced erosion and there was deposition at the inner banks. For instance at Anyinam the left bank (outer bank) was being eroded whiles at the right bank (inner bank) deposition was occurring. Deposited sediments ranged 2 – 65 cm thick (Table 5.1) with the depth of deposited materials increasing from the top of the bank towards bank toe. Similarly at Ejesu erosion was prevalent at the rightside (outer bank) whiles deposition was dominant at the left bank (inner bank) (Table 5.5). Also

bank incision increased towards bank toe due to increases in flow particularly at the middle course where flows are generally at the mid-bank section throughout the year, bank undercutting is very pronounced resulting in cantilever failures. For instance, at Amuanda Praso, there is active bed incision as illustrated by the level of recession of the bottom pins on both banks (Table 5.3 and Fig.5.3).

According to Bertrand (2010) and Lawler et al (1999) bank toe erosion is triggered due to shear stress exerted by the flow, which can lead to bank undercutting near the toe or mid-section region. This undercutting over-steepened the bank height making the bank more susceptible to mass failure and slumping (Lawler et al., 1999). These findings are similar to results of Lawler (1999), that bank retreat is the integrated product of three interacting processes (i.e. weathering and weakening, fluvial erosion and mass-wasting), with mass failures and fluvial erosion typically dominating in the middle to lower portions of a drainage basin. This reinforces the point that fluvial erosion and mass failures are both significant contributors to the total volume of fluvial sediment transport as observed by Luppi et al (2009) along the Cecina River (Central Italy).

Steep banks were also subjected to cantilever bank failure due to undercutting and bank toe erosion while on gentle slopes erosion is by soil creep and this results in sediment deposition at the base of channels and burial of erosion pins. Active bank incision was also very serious along outer banks of meander loops than straight channels. Buried pins due to either bank failure or deposition could not be measured and insertion of new pins was not possible in the unconsolidated sediments. There were also erosion measurement sites close to the mouth of Ofin and Oda Rivers at Adeboa and Bepotenten which were vandalised by galamsey activities and new pins could not be inserted. The vandalization of sites by galamsey operators downstream of the Oda and Ofin Rivers at Bepotenten and Adeboa respectively prevented the downstream variability trend assessment in bank

erosion and channel stability along these rivers. However, field observation showed active channel erosion downstream due to increase in discharge resulting in particle detachment and large-scale mass failure of channel banks as a result of similar processes discussed above (Plate.5.3A & 5.3B). At Asaago and Akim Oda (Plate.5.3A & 5.3B) active bank toe erosion is pronounced leading to under-cutting of bank profiles causing cantilever failures.



Plate.5.3A: Evidence of cantilever bank failure along the bank of the Oda River at Asaago – Kumasi.



Plate.5.3B: Evidence of cantilever bank failure along the bank of the Birim River at Akim – Oda.

From the grain size analyses, most bank sediments were of coarser particle sizes with over 50% of coarser diameter greater than 0.1 mm except bank sediments of Adiembra which had about 60-80% of particle sizes less than 0.1 mm in diameter (Fig.5.1). The D_{50} for Akim Oda B, Brenase, Amuanda Praso and Anyinam are greater than 0.1 mm; D_{50} for Ejisu and Akim-Oda A are 0.1 mm and that of Adiembra are less than 0.1 mm. Adiembra site B had the finest grain sizes of finer particles of less than 0.1 mm diameter while Akim Oda site B had the coarsest grain particles greater than 0.1 mm. The finer particles were made of fine sand, silt and clays while the coarser materials were composed of coarse sand, gravel and cobbles.

Apart from the shear stress of flows and the morphology of the river channel (bank geometry), the physical characteristics of the bank materials such as the nature of the

bank materials (texture/particle sizes) and plant cover strongly influenced the degree of bank erosion. High cohesive forces of finer particles particularly silt and clay made certain banks a bit resistant to erosion as compared to the coarser zones. This is because cohesive materials resist erosion by a complex set of characteristics related to the existence of electro-chemical bonds between individual particles (Simon and Collison, 2001). For instance, at Akim Oda site B, due to the looseness of bank materials, bank toe erosion and bank failure were very pronounced resulting in accelerated bank erosion along this section of the bank. Though, channel walls at Adiembra were being eroded, due to the fine nature of the particle sizes, the rate of erosion was low as a result of the strong cohesive bonds of the silt and clay soils, hence the channel walls were less susceptible to bank wearing. The coarse texture of the right bank materials at Ejisu was also much prone to bank wearing.

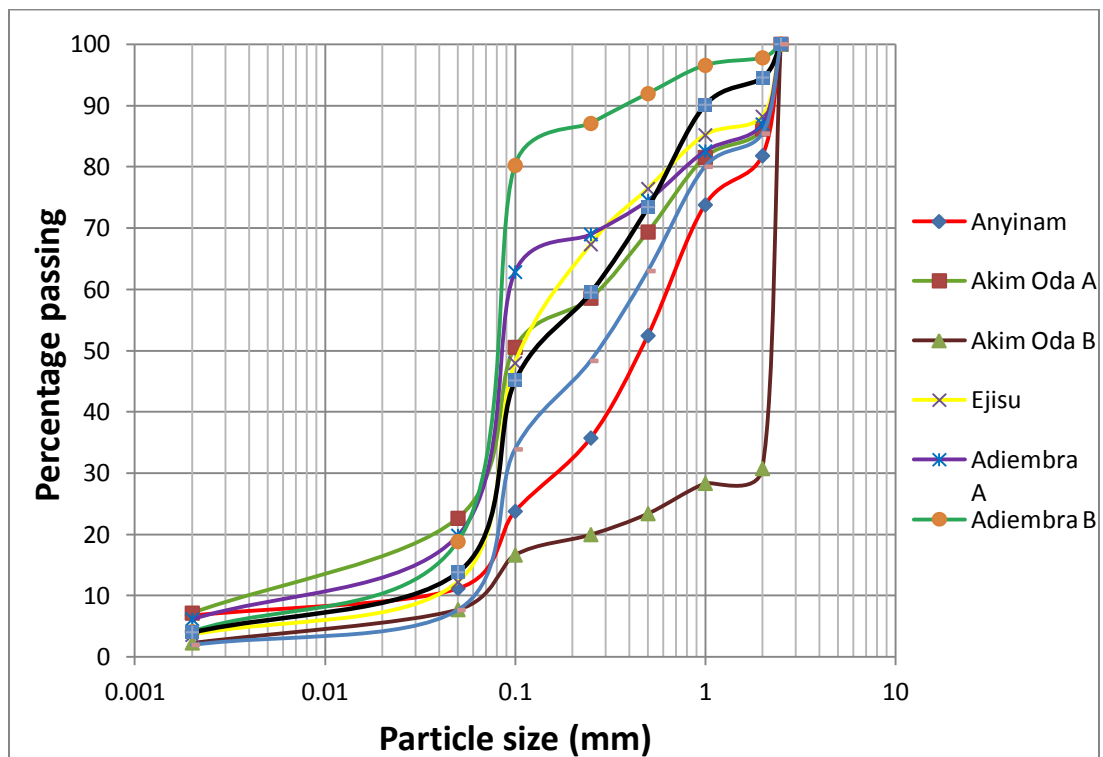


Fig.5.1: Particle size distribution curves of bank sediments

Dense fibrous root network created by bank-top grasses/trees effectively held soil particles against bank collapse. In some instances, large soil peds were completely suspended by roots (e.g. Akim Oda). According to Simon and Collison (2002), vegetation increases bank stability by intercepting rainfall that would otherwise have infiltrated into the bank, and by extracting soil moisture for transpiration. These processes enhance shear strength by reducing positive pore-water pressure and encouraging the development of matric suction (Simon and Collison, 2002).

The annual tonnage of eroded sediments estimated at each monitored site based on the erosion pin measurements is graphically represented in Fig.5.2. The lowest eroded bank sediments into the fluvial sediment transport was just above 37,200 tonnes/yr and it occurred in Brenase whereas the highest was 1.21 million tonnes/yr at Ejisu. Along the Birim River sediment yield from bank erosion increased from about 65,000 tonnes/yr at Anyinam to just above 1.14 million tonnes/yr at Akim Oda due to higher bank erosion at Akim Oda. On the contrary sediment yield from bank erosion at Amuanda Praso about 300, 000 tonnes/yr was nearly four times higher than what was generated at the river bank downstream at Brenase which was about 72,000 tonnes/yr. The low sediment yield at Brenase was on account of lower bank erosion within this cross section as it was characterized by more bank deposition of alluvial sediments.

Temporal analyses of results showed variability in bank erosion. Much bank erosion was recorded after the retreat of the floods of the second rainy season from September – December. This is in common with findings of Chapter Three which shows that most stations recorded higher and relatively stable sediment concentrations and sediment transport during this last quarter of the year's flood. Also sediment source tracking analyses in chapter four shows a higher percentage of sediment transport to be coming

from bank materials. However as noted in chapter 4, galamsey activities along the river bank is also a major factor in entraining bank sediments into the rivers.

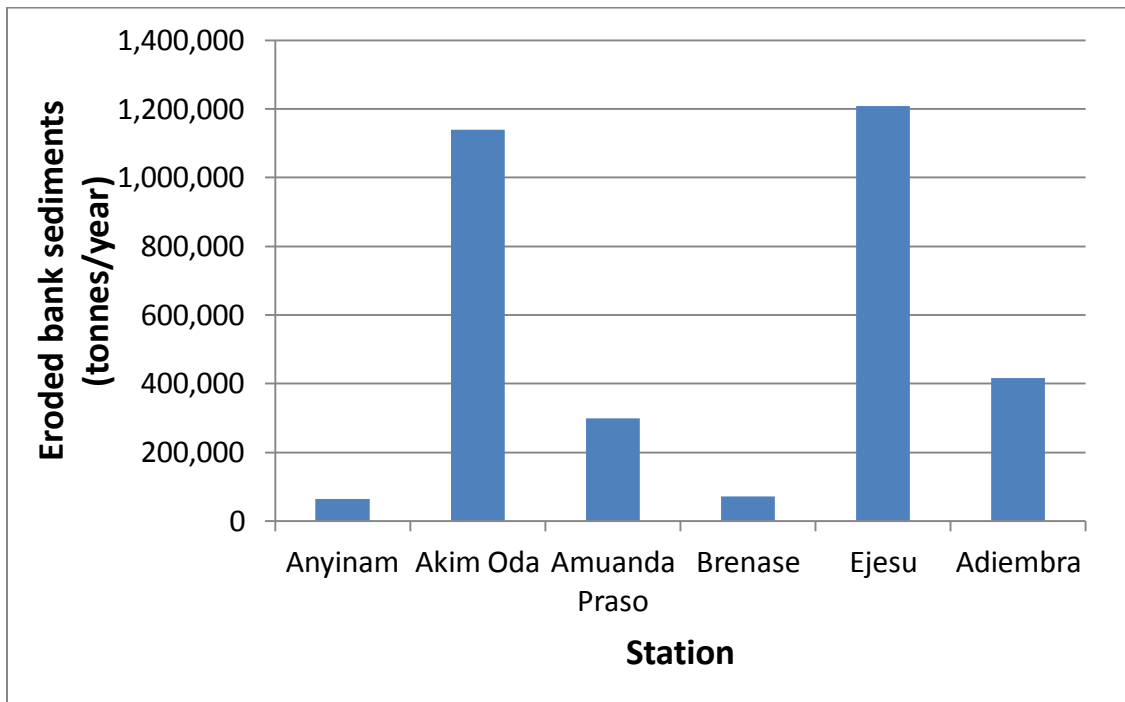


Fig. 5.2: Eroded bank sediments

5.3 Conclusion

Results of the study shows a spatial variability in river channel dynamics; very active channel and bank erosion within the three major tributaries of the Pra Basin namely, the Birim River, Oda River and the Ofin River and deposition of fluvial materials along channel walls. Bank erosion is low at the upper courses of the river but increases downstream and deposition is concentrated at the inner bends of meander loops. Channel geometry, discharge/fluvial hydraulics or processes and bank materials are the major driving forces governing channel and bank dynamics which is entraining significant amount of sediments into the rivers. Bank material texture was found to influence the degree of bank stability as coarser bank materials were more prone to erosion than finer textured grains.

Chapter Six

Catchment Scale Soil Loss and Sediment Yield Modelling

6.0 Introduction

Accelerated soil erosion is a worldwide problem because of its economic and environmental impacts. To minimise the cost of field measurements of soil erosion and river sediment loads many computer models have been developed and used to effectively estimate soil erosion which aid in developing soil erosion management plans in many river basins. The Revised Universal Soil Loss Equation (RUSLE) has been used in many countries, and input parameter data for RUSLE have been well established over the years (Lim et al., 2005). In this chapter, the spatial patterns in soil erosion and sediment yield in the Pra catchment has been assessed using the revised universal soil loss equation (RUSLE) model. Research materials and methods used in deriving the RUSLE parameters, how the parameters of RUSLE were integrated in GIS as well as results of the RUSLE model are presented.

6.1 Materials and Methods

The revised universal soil loss equation (RUSLE) model has been used to model soil erosion in the Pra Basin. It is defined as (Bonilla et al., 2010; Kouli et al., 2008; Renard et al., 1997);

$$A = RKLSCP \dots\dots\dots (6-1),$$

where; A is the soil loss ($t/km^2/yr$); R the rainfall run-off erosivity factor ($MJ \text{ mm } km^2/h/yr$); K the soil erodibility factor; LS the slope steepness and slope length factor; C the vegetative cover factor; and P the conservation practice factor are dimensionless.

Vector maps of parameters of equation 6-1 were generated and then converted to raster layers. The raster maps were multiplied using raster calculator module in ArcGIS to generate soil erosion and sediment yield maps of cells of varying magnitude of soil loss in the catchment (Fig.6.1). The approach for deriving each parameter is discussed below.

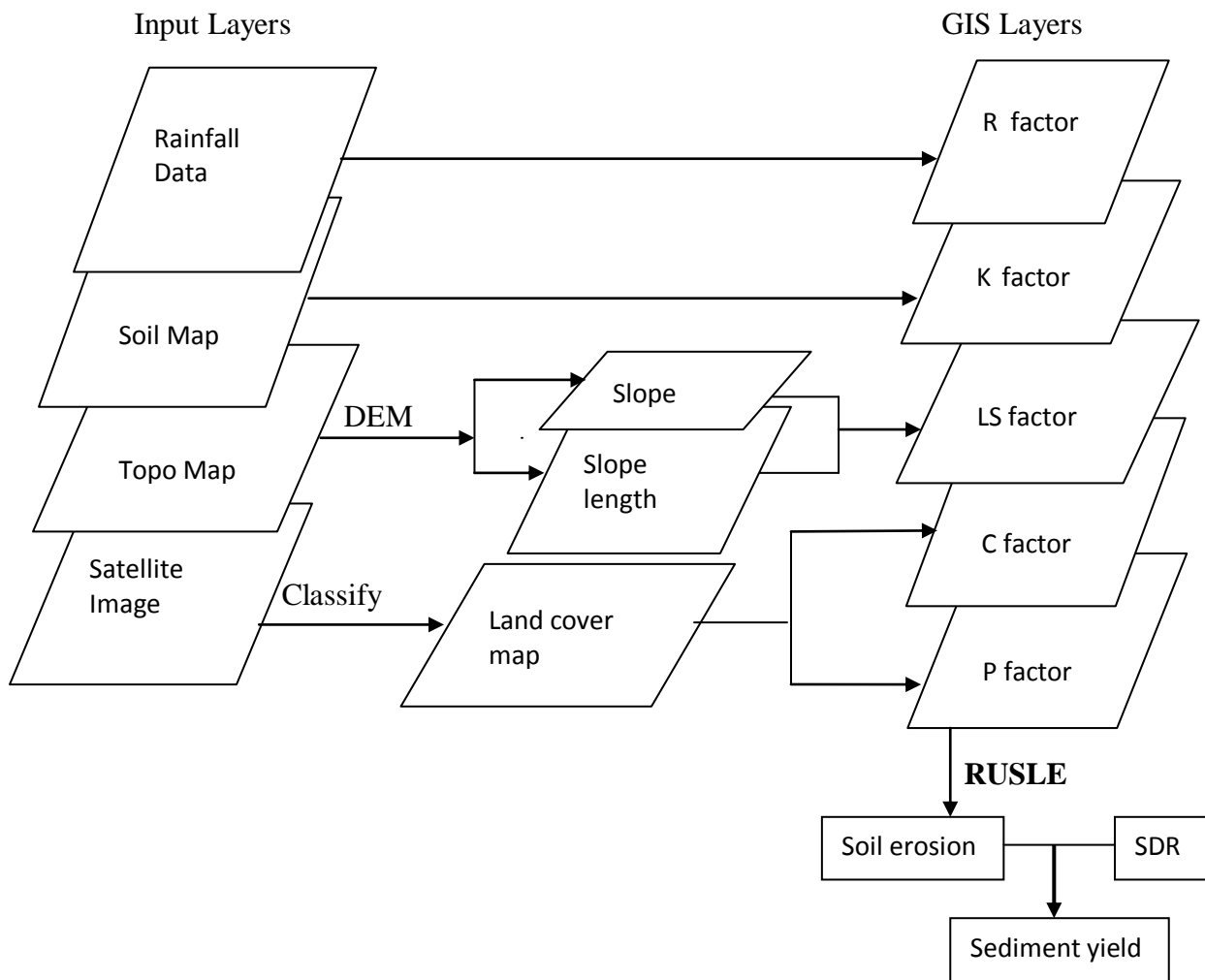


Fig.6.1: Schematic chart of GIS applications to soil erosion mapping and the derivation of Sediment Delivery Ratio, SDR (Modified from Mongkolsawat et al., 1994).

The rainfall erosivity index R measures the potential ability of rain to cause soil erosion. High R values mean, high rainfall intensity with a higher potency of dislodging soils, hence the expected soil erosion from the land surface and subsequent sediment yield will be high. Low R

value implies low rainfall intensity and run-off, consequently erosion and sediment yield will be low. R factor map was derived from monthly EI_{30} values using the modified Fournier index (MFI) (Shamshad, 2010);

$$R = 227MFI^{0.548} \dots\dots\dots (6-2).$$

The modified Fournier index (MFI) was estimated using total monthly erosive rainfall amounts (Smithen and Schulze, 1982);

$$MFIe = \frac{Pe_i^2}{P_t} \dots\dots\dots (6-3);$$

where: Pe_i , monthly erosive precipitation of month i , P_t , annual rainfall amount (mm). The rationale for the choice of these equations is due to the fact that, they were developed in humid tropics such as West Africa and Malaysia which are characterised by similar rainfall conditions (intensity and amounts) like the study area. The mean annual erosivity map (isoerodent map) was then produced in ArcGIS for the erosivity index (i.e, Re). Two erosivity maps were generated, 12 mm and 12.5 mm maps of total rainfall accumulation within 24 hours. Though an erosive event has been defined as rainfall event with more than 12.50 mm of total rainfall accumulation (Petkovšek and Mikoš, 2004; USDA-ARS, 2008a), however due to the thunderous nature of humid tropical storms (large particle sizes, quantity and greater intensity) than the temperate zones, 12.0 mm of total rainfall accumulation was also employed to determine its impact on soil erosion.

K is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff (Stone and Hilborn, 2000). When K value is high, it implies deterioration in the physical properties of the soil such as low organic matter, coarse soil texture, coarse granular structure etc; thus the soil is more prone to erosion. Therefore, the higher the K value the more the soil is prone to erosion. When K values are low, it implies an enhancement in the physical properties of

the soil such as increase in organic matter, fine soil texture, fine granular structure etc which increases the cohesiveness of soil particles to resist erosion. This will result in low soil erosion and sediment yield. The FAO *K* factor values of soils in the basin; (Table 6.1A) were used to produce a raster layer of *K* factor map. Table 6.1B shows the susceptibility classes of soils.

Soil Type	Area (Km ²)	K factor
Acrisols	18,328.8	0.00090
Alisols	213.4	0.00000
Arenosols	1.2	0.00000
Ferralsols	1.4	0.02800
Leptosols	206.2	0.00002
Lixisols	3,564.9	0.00000
Fluvisols	854.1	0.06460
Luvisols	11.0	0.00400

Soil erodibility Classes	Soil <i>K</i> Factor
Very High	>0.70
High	0.50-0.70
Moderate	0.25-0.50
Low	0.13-0.25
Very Low	<0.13

Source: Hagos (2004)

LS measure the effects of topography on soil erosion and the steeper and longer the slope, the higher is the risk for erosion and vice versa. The *LS* factor map for a cell area was computed with equation 6-4 below in ArcGIS using upslope contributing area and slope gradient computed from the digital elevation model (DEM) of the watershed. The DEM was generated from 1:50,000 scale contour map sourced from the Ghana Survey Department. The contours were interpolated at 30 m pixel resolution using ‘topo to raster’ command in ArcGIS to create a hydrologically correct DEM (e.g. Jain et al., 2010; Jain and Das, 2010). The generated DEM was further reconditioned to a depressionless DEM using ‘fill sink’ command to determine the maximum downhill slope and the flow direction which will maintain continuity of flow to catchment outlet (e.g. Jain et al., 2010; Jain and Das, 2010). The slope (*S*) factor and flow accumulation were then derived from the depressionless DEM and then *LS* map was generated based on equation 6-4 in ArcGIS using the raster calculator module; (Jain et al., 2010; Jain and Das, 2010; Engel, 2003);

$$LS = \left(\frac{A_s}{22.13} \right)^{0.4} \cdot \left(\frac{\sin \phi}{0.0896} \right)^{1.3} \dots \dots \dots (6-4);$$

where; A_s is upslope contributing area for overland grid per unit width normal to flow direction, θ is the slope angle in degrees. On the basis of total length of stream channels of a 1:50,000 topographic map of the basin and the basin area, a channel initiation threshold value of 0.65 km^2 was extracted and used to define channel cells (e.g. Jain and Das, 2010).

The cover management factor C is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. High C factor implies low vegetation cover in the catchment, hence there is an increased opportunity for rainfall to detach sediments, overland flow to scour and transport sediments, ultimately causing an increase in sediment production and when C values are low, it implies good vegetative cover and erosion will be low. Cover management factor map for C was determined using classified land cover and land use map of landsat ETM + 2008 image (e.g. Jain et al., 2010; Jain and Das, 2010; Jain and Kothyari, 2000). The image was classified with reference to topographical maps, Google Earth and training areas of sites taken in the field using a global positioning system (GPS). Seven land cover types were classified using the maximum likelihood classifier module in Idrisi (Table 6.2). C factor values suggested by Wischmeier and Smith (1978), were assigned to cells of the respective classes as shown in Table 6.2.

The basin covers two landsat scenes (Table 6.3). The images were downloaded from the Global Land Cover Facility website glovis.usgs.gov. This date was chosen based on the availability of good satellite images covering the study area because due to thick cloud cover most images were not suitable for usage. The 2008 images had no cloud cover, however due to the failure of the Scan Line Corrector (SLC) of Landsat ETM+, there were gap marks on the 2008 images and these gaps were filled using the NASA gap filling software IDL 7.0 based on 1985/1986 images of the same locations. The images were merged and cropped to size using the

geographic coordinates of the basin. The classified image was then exported to ArcGIS, and cropped to size using the vector layer of the drainage basin.

Table 6.2: Land cover types and cover management (C) factor values

Land Cover Type	Area (km ²)	C Factor
Closed canopy	10,760.5	0.0001
Water bodies	3,109.4	0.0000
Built-ups & Barelands	1,160.6	0.3500
Open forest with shrubs & mixed arable tree Crops	10,412.1	0.0003
Open savannah woodland with shrubs & grassland	9,593.1	0.0020
Coastal scrub & grassland	9,855.9	0.0400
Bush fallows & cropland with natural vegetation mosaic	4,929.0	0.5429

Table 6.3: Attributes of Landsat ETM+ 2008

Year & Image Scene	Date of Acquisition	Row	Path	Resolution	Level of Processing
2008 Landsat ETM+ (Kumasi and Pra's Mouth Scenes)	01/02/08 (for both scenes)	055 and 056	194	30m	L1T

P factor reflects the effects of soil erosion support practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. Cross slope cultivation, contour farming and strip cropping intercept flow paths and flow hydraulics of run-off. These soil conservation practices will minimise soil erosion and sediment yield. *P* factor map was determined in the field by finding out the kind of soil erosion management practices (i.e. contouring, mulching, crop rotation etc) being practiced by land users (e.g. farmers, miners etc) with reference to land cover classified landsat image of the catchment. Since in the study area, no major conservation practices are followed, the *P* factor was taken as 1 for all land use and land cover categories as majority of land areas have not been provided with any conservation support (Jain and Das, 2010).

Soil erosion potential map of the basin was developed by multiplying the factor maps of K , LS , C and P (Jain et al., 2010), while that of gross soil loss was determined by multiplying all the derived factor maps of RUSLE (equation 6.1 and Fig.6.1).

The annual sediment yield of the watershed was estimated by multiplying soil loss map and the sediment delivery ratio map (Fig.6.1) as expressed by equation 6.5 (Fistikoglu and Harmancioglu, 2002):

$$Y = RKLSCP \times SDR \dots\dots\dots(6-5);$$

where Y is the sediment yield (t/km^2), SDR is the sediment delivery ratio, and $RKLSCP$ is gross erosion per unit area above a measuring point (Arekhi, 2008; Silva et al., 2010; USDA-ARS, 2008a).

SDR is defined as the ratio of sediment delivered at a given area in a stream system (sediment yield) to the gross erosion or the fraction of gross erosion that is transported from a given catchment in a given time interval. For each land cell, SDR depends upon several physical characteristics of the watershed including surface roughness, land slope, soil hydrologic conditions, and length of the travel path (flow length) to the stream and vegetative cover (Kothyari and Jain, 1997).

The sediment delivery ratio for each cell i (SDR_i) is a function of travel time (Jain and Kothyari 2000; Fu et al., 2006);

$$SDR_i = \exp(-\beta t_i) \dots\dots\dots (6.6);$$

where t_i is the travel time (h) for each cell _{i} to the nearest channel cell down the drainage path and β is a watershed-specific parameter regarded constant. The total travel time along a flow path is expressed as (Jain and Kothyari, 2000);

$$t_i = \sum_{i=1}^m \frac{l_i}{v_i} \dots\dots\dots (6-7);$$

where: l_i is the flow length (i.e. the length of segment i in the flow path (m) and is equal to the length of the side or diagonal of a cell depending on the flow direction in the cell, and v_i the flow velocity for the cell (m/s).

Flow length was derived from the digital elevation model (DEM). Flow velocity is derived from Manning's equation which is a function of the land surface slope and the land cover characteristics (Jain and Kothyari, 2000; Fu et al., 2006);

$$v_i = a_i S_i^{0.5} \dots\dots\dots (6-8);$$

where: S_i is the slope of the i th cell and a_i is a land use coefficient. The land use co-efficient values (Table 6.4) were assigned to each grid cell in the land cover image. The final flow velocity for the overland flow was calculated from Equation 6.8; i.e. by multiplying the assigned land cover map and the square root of slope for each grid cell.

Table 6.4: Land cover co-efficient values

Land use/land cover type	a_i value/velocity co-efficient
Closed canopy	0.7600
Water bodies	0.1250
Built-ups & barelands	6.3398
Open forest with shrubs & mixed arable tree crops	0.6401
Open savannah woodland with shrubs and grassland	0.4267
Coastal scrub and grassland	0.4572
Bush fallows & cropland with natural vegetation mosaic	0.3962

Source: Jain & Kothyari, 2000 & Mutua and Klik, 2006

Substituting equations 6-7 and 6-8 into 6-6;

$$SDR_i = \exp\left(-\beta \sum_{i=1}^m \frac{l_i}{a_i S_i^{0.5}}\right) \dots\dots\dots (6-9).$$

Sediment yield was simulated within a β range of 0.1 to 1.5 with an incremental value of 0.1 and it was found that sediment yield was insensitive to β value (e.g. Fu et al., 2006; Jain and Kothyari, 2000, Mutua and Klik, 2006), so β value was taken as 1 for computation.

6.2 Results and Discussion

The generated GIS layers of RUSLE for the determination of the magnitude of soil erosion in the Pra Basin are shown in Figs. 6.2 – 6.6. Annual rainfall erosivity ranges from 456 – 1,181 and 553 – 1,166 MJ mm/ha/h/yr for the 12 and 12.5 mm erosivity events respectively with higher intensities prevailing around Praso-Konongo-Juaso, a reflection of the climatic trend within the basin (Fig.6.2 and Fig.6.3). Similar patterns in rainfall erosivity of the basin was observed in an erosivity map produced by Oduro-Afriyie (1996) of Ghana and Roose (1977) of West Africa. The 12 mm event map has the least and the highest erosivity values while the 12.5 mm map least erosivity is higher than that of 12 mm event, because larger events were used to produce the 12.5 mm map, thus it will be more erosive due to the higher intensity of rainfall events. With reference to the annual rainfall erosivity index (R) classification; $R \leq 2,452$ low erosivity, $2,452 < R \leq 4,905$ medium erosivity, $4,905 < R \leq 7,357$ medium-strong erosivity, $7,357 < R \leq 9,810$ strong erosivity, $R > 9,810$ very strong erosivity (Silva, 2004), the rainfall erosivity indices of the basin are low.

The Pra catchment is underlain by 8 major soil types (aliosols, acrisols, arenosols, ferralsols, fluvisols, leptosols, lixisols and luvisols), with aliosols, acrisols, lixisols having erodibility values of 0 and fluvisols being most erodible ($0.0646 \text{ t h MJ}^{-1} \text{ mm}^{-1}$) (Fig.6.4). All these soils are classed as having very low erodibilities when exposed with the most erodible types being concentrated in the river valleys (Table 6.1B).

Forest reserves making up the closed canopy had the best vegetative cover while urban centres and barelands (mine sites) had sparse vegetative cover (Fig.6.6). Over 81% of the catchment was protected by vegetative cover composing of forest reserves, open/secondary growth, savannah and coastal scrub/grassland with only about 22% being covered by

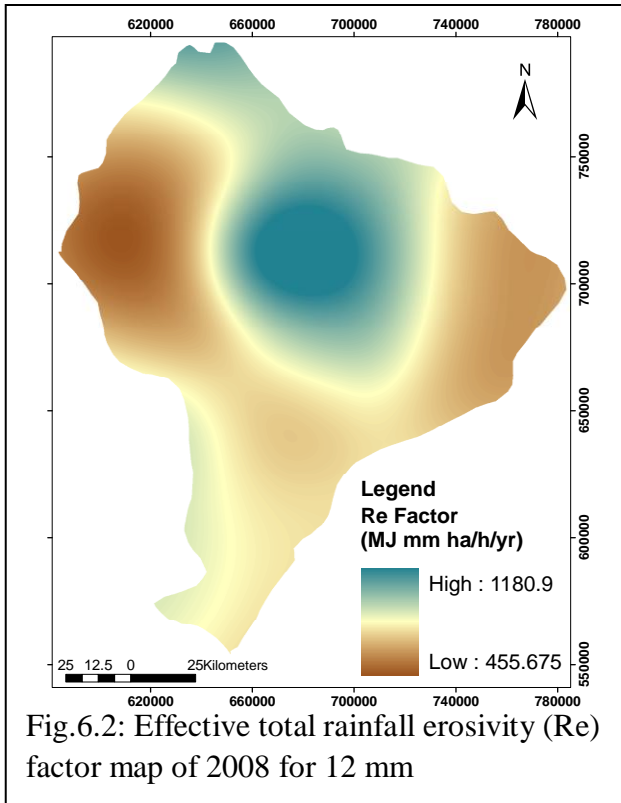


Fig.6.2: Effective total rainfall erosivity (Re) factor map of 2008 for 12 mm

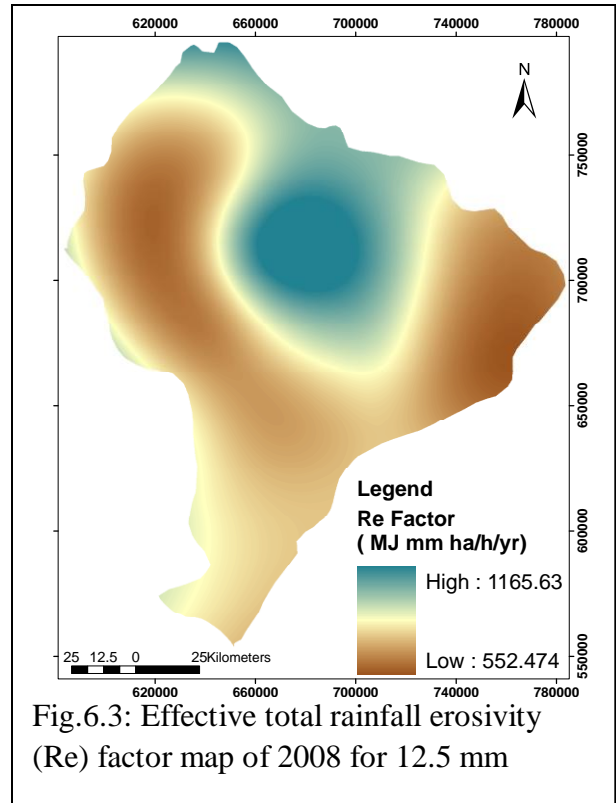


Fig.6.3: Effective total rainfall erosivity (Re) factor map of 2008 for 12.5 mm

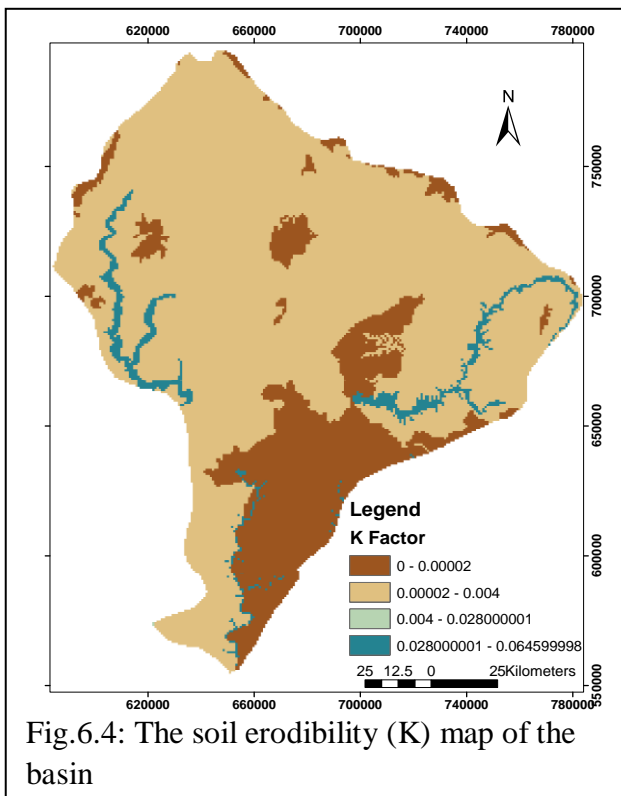


Fig.6.4: The soil erodibility (K) map of the basin

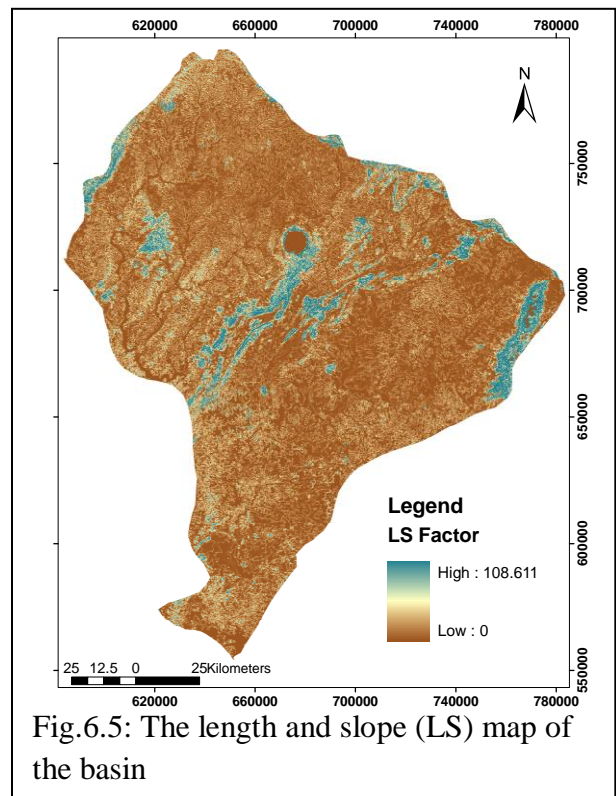
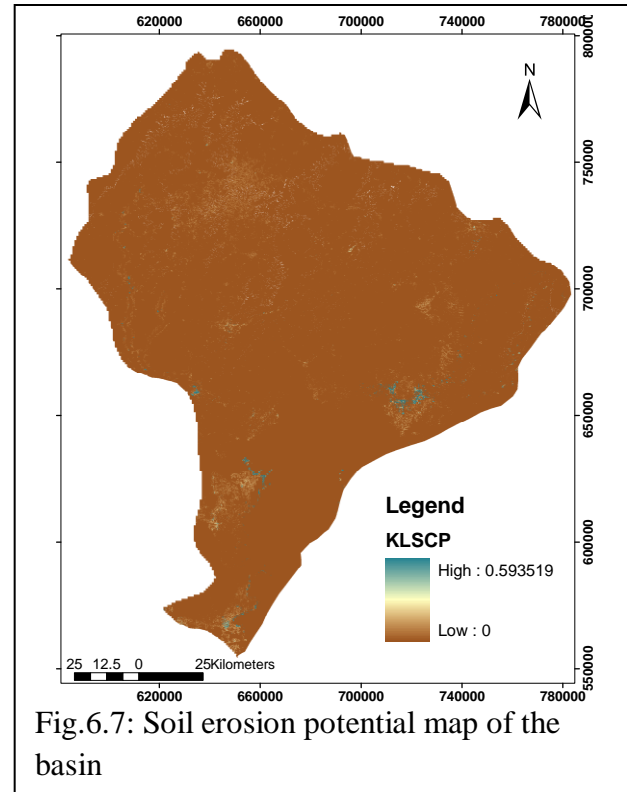
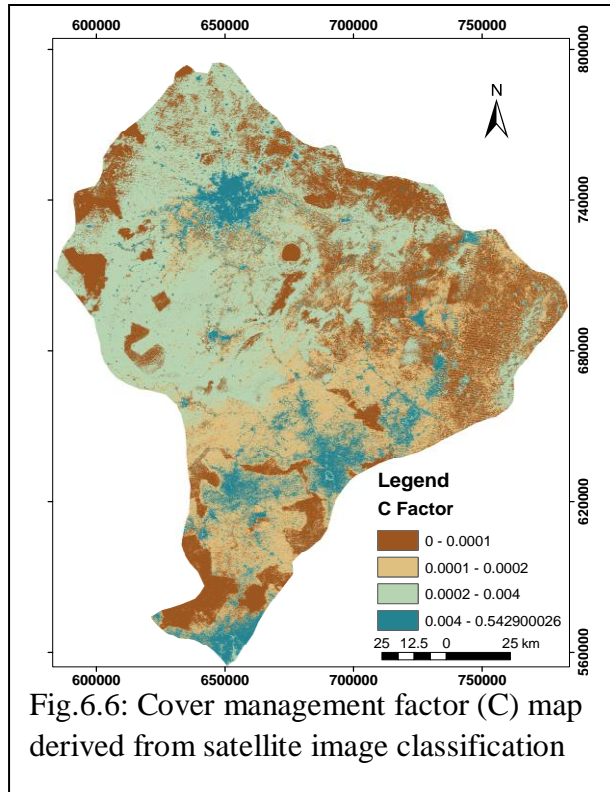


Fig.6.5: The length and slope (LS) map of the basin



bushes/cropland and built-ups/barelands.

The length and steepness of slopes is high at the source of the basins such as the Atewa Forest Reserve watershed and the Ashanti Mampong-Kwahu Scarps which serves as the source of the Pra, Birim and Oda Rivers, and around Lake Bosomtwi due to the mountain formations, whereas the *LS* of the other parts of the basin particularly the southern part is very low (Fig.6.5). Much of the basin area is characterised by low values of *LS* and transport of eroded materials will be very limited owing to the low gradient.

Fig.6.7 shows areas of varying *KLSCP* values and hence the soil erosion potential in the different cells of the river catchment. Values of potential soil loss ranged between 0 and 0.59 tonnes/year. Overlay of Fig.6.6 on slope, rainfall erosivity and landuse/landcover maps revealed that higher cell values of soil erosion coincide with steep slopes, higher rainfall intensity zones

and cells of urban centres. High values of this term indicate a higher potential of soil erosion in those cells and vice-versa.

Figure 6.8 and 6.9 illustrate the gross soil erosion for the annual rainfall year 2008. Estimated annual soil loss from a cell ranged from 0 to 3.91 and 0 – 3.96 t/ km²/yr for both 12 and 12.5 mm events with a mean of 0.001 t/ km²/yr and a standard deviation of 0.02 t/ km²/yr. The relative higher soil erosion by 12.5 mm is attributable to the higher intensity of the event. Generally, the catchment is characterised by low soil loss risk based on the four classes of basin soil loss proposed by FAO (1967, cited by Silva et al., 2010) in t/km²/yr: (a) < 0.10 = very low, (b) 0.10–0.50 = moderate, (c) 0.50–2 = high, and (d) >2 = very high. The low soil erosion is due to the well protected landscape by the vegetative cover, and low gradient of the topography. Zones susceptible to moderate-high erosion risks are very few and these occur in built-ups, exposed landscapes (galamsey areas) and also along steep slopes and within the river valleys underlain by fluvisols which are very susceptible to erosion.

The highest soil loss occurs in river valleys and the erosion tends to increase downstream as a result of increase in flow accumulation down slope from the source towards catchment outlet. Most urban centres are characterized by moderate soil erosion and this is due to the exposed nature of these urban landscapes (unpaved and not grassed). High run-offs generated during rainfalls cause serious urban erosion creating rills/gullies and entraining sediments into gutters/gullies which are channelled into nearby streams and rivers. These results are akin to other RUSLE/USLE model estimates of soil erosion in a number of basins in Brazil all in the tropics. Annual soil loss was estimated to be 0-0.032 and 0-0-2.93 in Guaraíra and Tapacurá catchments (Silva et al., 2007; 2010). Field investigations confirm the model results, that there is

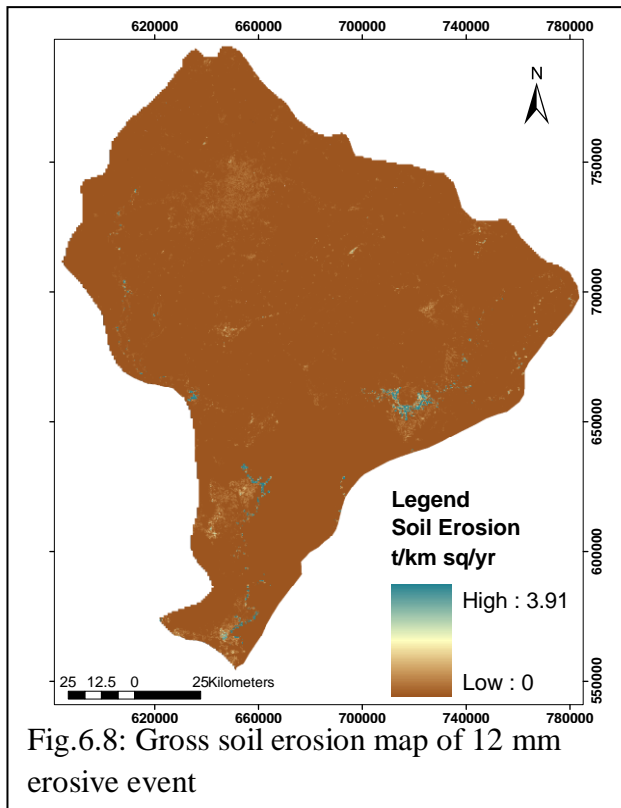


Fig.6.8: Gross soil erosion map of 12 mm erosive event

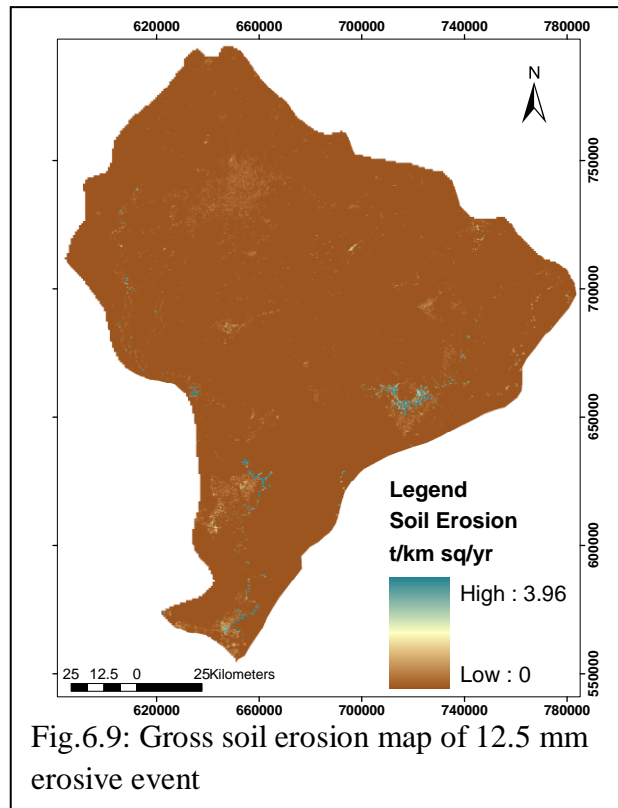


Fig.6.9: Gross soil erosion map of 12.5 mm erosive event

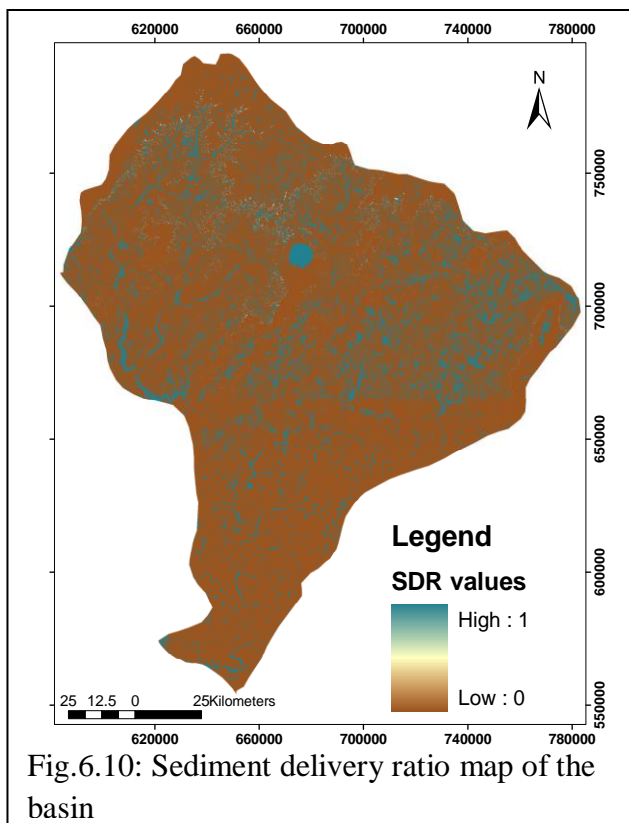


Fig.6.10: Sediment delivery ratio map of the basin

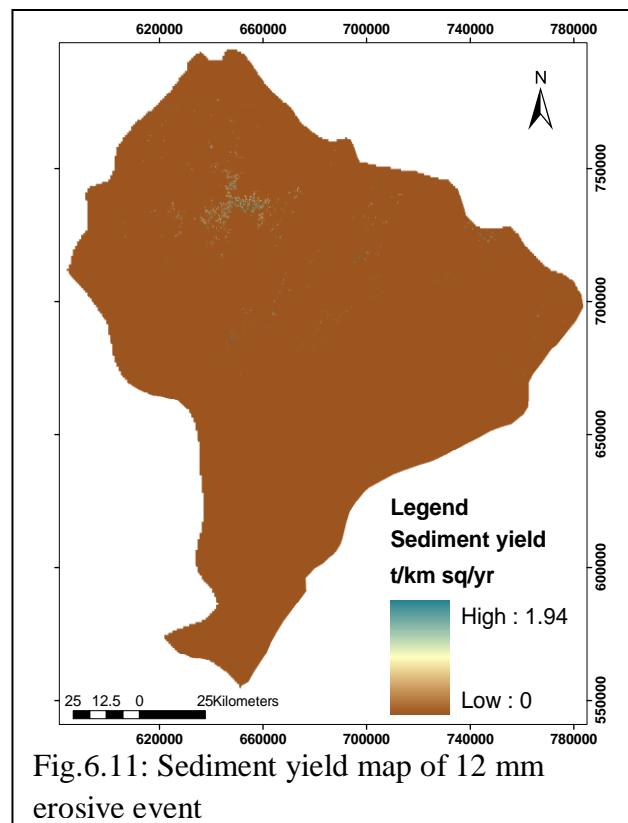
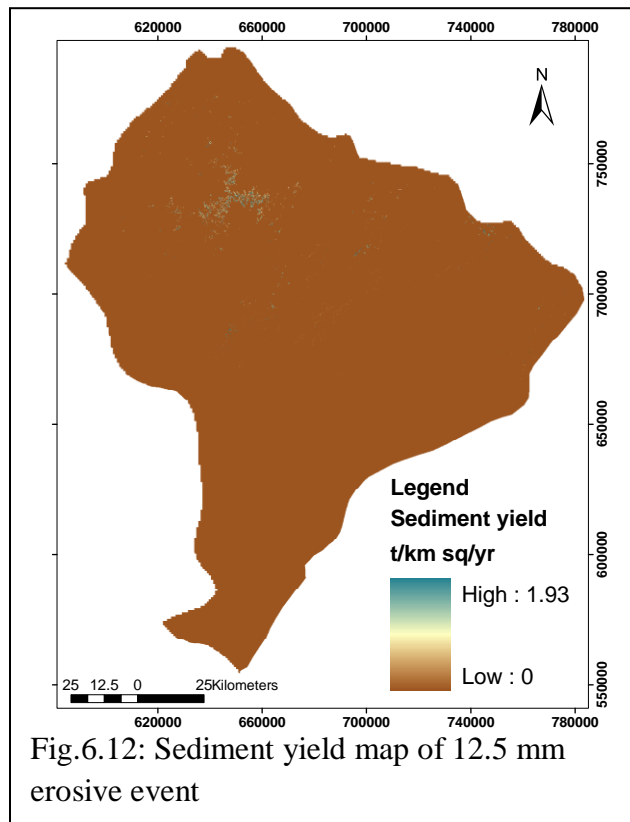


Fig.6.11: Sediment yield map of 12 mm erosive event



very active urban erosion in most towns within the basin. Plate.6.1 and 6.2 illustrate cases of urban erosion at Konongo-Odumase where field measurements showed that most building foundations and structures have been eroded to depths of between 0.6 – 1.5m.

The sediment delivery ratio values range from 0 – 1 (Fig.6.10). At mean annual temporal scale, *SDR* generally assumes values ≤ 1 , but for a given event, *SDR* can be >1 because sediments deposited on the hillslopes or stored into the channel network, in some previous events, can be remobilised (Ferro and Porto, 2000). Higher values are found in river channels while lower values are recorded in the overland regions outwards river channels. These findings conform to the observation by Novotny and Chesters (1989, cited by Hagos, 2004) that the *SDR* of a river basin is more affected by the characteristics of the drainage system than by its land use. The

insensitivity of *SDR* to sediment yield means there is not much deposition within the catchment, thus much eroded surface sediments are entrained into the river channels.

The spatial variations in sediment yield across the entire catchment is very low (Fig.6.11 and 6.12) with a range of 0 – 1.94 and 0 – 1.93 t/km²/yr for both erosive events. Higher sediment yield values occur in residential areas particularly in Kumasi and on steep slope landscapes of the catchment. There is virtually no sediment yield from surface erosion except in a few built-up environs and along slopes of the Atewa Range, Ashanti Mampong and the Kwahu Scarps. The sediment yield estimates are however higher than values 0-0.55 t/km²/yr obtained in Henley Catchment in the Kwazulu-Natal Province of South Africa (Hagos, 2004).

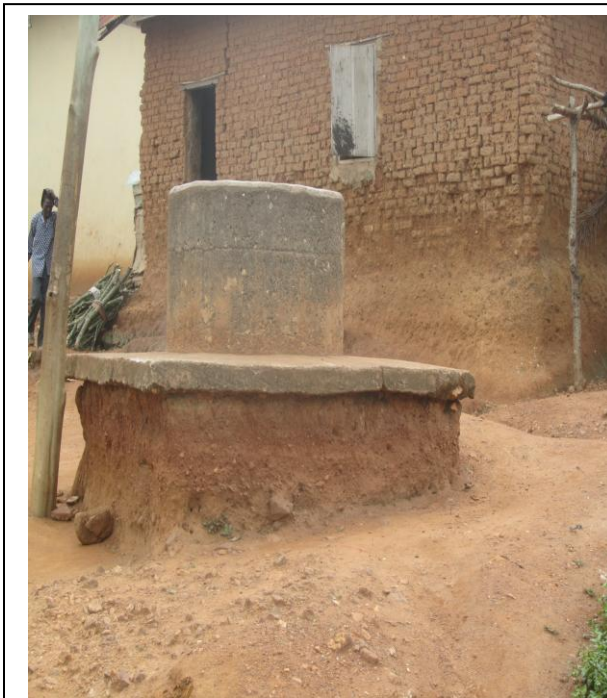


Plate.6.1: Erosion of a well and house foundations at Odumase



Plate.6.2: Eroded plant root at Konongo

The low sediment yield is as a result of the protective vegetative cover which covers over 80% of the entire basin and the low relief of the basin. The vegetative cover protects the soil from the erosive power of the torrential tropical rains which is capable of dislodging particles into

concentrated channels. Also except at the source of the rivers which are characterised by steep slopes, the topography is gentle with much of catchment slope being less than 20 degrees, thus the decrease in slope with increasing basin size downstream will lead to low-energy levels of run-offs which will facilitate sediment storage rather than surface erosion. Similarly Akraasi (2011), attributed the low specific sediment yield in Ghanaian Rivers including the Pra to low gradients of the river basins and the associated low-energy conditions and low efficiency of sediment delivery from the catchment surface to, and through, the channel system.

Sediment yield measurements in chapter three however show that the annual specific suspended sediment yield of the entire catchment as well as the sub-catchments are very high, ten of tonnes higher than the model results. These large variations between the modeled results and that of observed data could be attributed to an increase in human activities within the basin for the past four years. According to stakeholders within the basin, galamsey activities have been on the ascendency in the basin for the past decade and this has greatly affected the water quality in most communities in the basin. Also analysis of the provisional results of 2010 population and housing census report and that of 2000 shows an increase in population of all urban centres with an annual growth rate of between 3 – 7%. The population growth will lead to an increase in demand for land for housing and farming, and an increased in land clearance will accelerate soil erosion and sediment yield within the basin. These changing environmental conditions of the Pra Basin will impact on its sediment yield; however input model data such as satellite imagery and rainfall were of 2008 and therefore model results are expected to be lower. Thirdly, the model predicts only surface erosion and does not account for bank/gully erosion, but observed data is a composite of both surface and channel erosion data and since previous chapters indicate that bank erosion contributes more sediment to the total sediment load of the rivers, observed sediment yield is expected to be higher than predicted yields. However, the model has not been

able to capture the impact of illegal small scale mining activities in the basin consequently the development of a model that is capable of capturing both surface and concentrated soil erosion should be explored in the future.

Results of the two models, the 12 mm and 12.5 mm erosive events do not vary much, the 12 mm modelled results is just about 0.5% higher than that of 12.5 mm, hence the use of any of these events in predicting soil erosion will produce similar results which will not be statistical different from each other hence any of these events can be adopted for soil erosion and sediment yield mapping in the basin. The level of accuracy of each event could only be ascertained if the model had been calibrated, but due to the time lag between the observed data and the model results, and considering the extent of increase in human activities within the basin over the past four years as well as the lack of current rainfall and land cover/use data of the basin, the use of the observed that in calibrating the model could result in greater errors and high levels of uncertainty.

6.3 Sediment Yield Sensitivity Analysis

Sensitivity analysis is the study used to ascertain how a given model output depends upon the information (input data) fed into it, upon its structure and upon the framing assumptions made to build it (Saltelli et al., 2000; Hagos, 2004). Sensitivity analysis is used to increase the confidence in the model and its predictions, by providing an understanding of how the model responds to changes in the input parameters (Saltelli et al., 2000; Hagos, 2004).

In this research, a sensitivity analysis of RULSE parameters (R , K , C , LS , P and SDR) was done to measure the sensitivity of the model prediction to a change in the variable value (Hagos, 2004). The means and standard deviations of each of the input RULSE data layers were extracted

in ArcGIS and their co-efficient of variability (CV) calculated (Table 6.5). The sensitivity analyses were undertaken by increasing and decreasing the RUSLE variables by a fixed percentage (20%) of their standard deviation from their mean.

Table 6.5: Statistics of the different sediment yield model variables

Variable	Mean	Standard deviation	Coefficient of variation
<i>R</i> (12mm)	768.240	160.560	0.208997
<i>R</i> (12.5mm)	780.850	143.830	0.184197
<i>K</i>	0.003	0.012	4
<i>LS</i>	1.69	3.47	0.694
<i>C</i>	0.054	0.155	2.87037
<i>P</i>	1.0	0.04	0.04
<i>SDR</i>	0.176	0.380	2.159091

6.3.1 Sensitivity of sediment yield to overestimation and underestimation of model variables

From the results of the sensitivity analysis in Tables 6.6 and 6.7, model prediction of sediment yield was found to be most sensitive to changes in the *K* variable both 12 and 12.5 mm erosivity events. For example, a 20% of standard deviation increase in the mean *K* value resulted in 271 and 250% increase in the sediment yield of 12 and 12.5 mm erosivity events respectively. This implies that as the value of *K* increases, the amount of sediment yield predicted by the model and delivered to the catchment outlet increases. The second most sensitive variable was *R*, whose increment resulted in a 37 and 23% increase in the sediment yield of both erosive events. *LS* and *SDR* were the next sensitive parameters with 8% increase in sediment yield as a result of the percentage increase in their values. The fifth sensitive variable was found to be the cover factor, *C*, where a 20 % of standard deviation increase from the mean in the *C* value resulted in 5% increase in sediment yield for both erosive events. *P* is the least sensitive variables and it shows

just a marginal increased (1%) in sediment yield over the wide range of percentage of standard deviation change from the mean.

With respect to underestimation of RUSLE parameters, similar trends in the sensitivity of the variables to sediment yield were obtained as in the overestimation. The most sensitive variable in the model is the *K* factor. For example, a 20% of standard deviation decrease from the mean of the *K* value resulted in a more than 50% decrease in predicted sediment yields. This implies that as the value of *K* decreases, the amount of sediment yield predicted to be delivered to the catchment outlet also decreases. Also the second most sensitive variable in the model is again the *R* factor. A decrease of 20% of standard deviation in the value of *R* from its mean caused a decrease of 27 and 13% in the predicted sediment yields. There were however reductions in sediment yield of 8 and 7 % respectively for both events when *LS* and *SDR* values were reduced

Table 6.6: Estimates of sensitivity analysis of sediment yield for 12 mm event

Predicted sediment yield		1.94 (t/ km ² /yr)		
Variable	Overestimation (t/ km ² /yr)	Percentage Change	Underestimation (t/ km ² /yr)	Percentage Change
<i>R</i> (12mm)	2.67	38	2.47	27
<i>K</i>	7.19	271	0.90	13
<i>C</i>	2.04	5	1.82	-54
<i>P</i>	1.96	1	1.92	-6
<i>LS</i>	2.09	8	1.79	-8
<i>SDR</i>	2.09	8	1.79	-8

Table 6.7: Estimates of sensitivity analysis of sediment yield for 12.5 mm event

Predicted sediment yield		1.93 (t/ km ² /yr)		
Variable	Overestimation (t/ km ² /yr)	Percentage Change	Underestimation (t/ km ² /yr)	Percentage Change
<i>R</i> (12.5mm)	2.39	23	2.20	13
<i>K</i>	6.75	250	0.90	-53
<i>C</i>	2.03	5	1.82	-6
<i>P</i>	1.95	1	1.91	-1
<i>LS</i>	2.08	8	1.79	-7
<i>SDR</i>	2.08	8	1.79	-7

by 20% of the standard deviation of their values. *C* and *P* factors were the fifth and sixth sensitive variables and their level of sensitive is very low. Generally, overestimated model was much sensitive to sediment yield prediction and the level of sensitivity was much higher with 12 mm rainfall erosivity than with 12.5 mm index. The most sensitive factors in sediment yield prediction of the Pra Basin are *K* and *R* whiles the least sensitive variables are *C*, *P*, *LS* and *SDR*. Therefore in prediction sediment yield in the basin, *K* and *R* parameter values need to be estimated with very good accuracy and so be given more attention in estimating their values as errors in their input data will have much impact on the outcome of the results. However errors in the input data of the *C*, *P*, *LS* and *SDR* parameters will have less impact on the output results.

6.4 Conclusion

Given the elements and processes prevailing in the basin in 2008, surface soil erosion and sediment yield is very low but this condition could degenerate into very severe surface soil erosion if the current state of land degradation, particularly by galamsey activities are allowed to continue. These results reflect findings of chapter four which indicates that much of fluvial sediment transported is from bank materials. However, results of the sensitivity analyses shows variables such as *K*, and *R* to be very sensitive to predicted sediment yield particularly when overestimated. This calls for high accuracy in the estimation of *K*, and *R* input data to ensure precision of model results. A synthesis of the various chapters will be discussed in the next chapter.

Chapter Seven

A Synthesis of Results, Conclusion and Recommendations

7.0 Introduction

Soil erosion and sediment transport are subject to highly complex processes that are very cumbersome to study; because these processes and their interactions with each other influence soil loss and sediment yield (Hagos, 2004). Owing to the importance of these processes a number of models that use these processes to simulate catchment soil loss and sediment yield have been developed over the years (Hagos, 2004). In this study, soil erosion and sediment yield patterns were modelled using the revised universal soil loss equation. In situ sediment yield and bank erosion measurements were also undertaken to ascertain the level of sediment discharge in the river basin and channel stability. Lastly, a finger print approach was also employed to determine the source of sediments whether from bank materials or surface soils. As a concluding chapter, the relationship between findings of the various chapters have been synchronised and discussed. Other sections of the chapter include a discussion on the policy implication of the findings, limitations/challenges encountered in the study, conclusion and recommendations for policy makers and future studies.

7.1 The Nexus between Field Measurements and Modelling of Soil Loss and Sediment Delivery

This study was undertaken in the Pra River Basin to assess the level of soil erosion/sediment yield and bank erosion using the revised universal soil loss equation (RUSLE) and field data collection. The model was able to determine the spatial variability in soil erosion and sediment

yield. Model results showed that the Pra Basin was characterized by a low surface soil erosion and sediment yield generation owing to the relatively low risk factors such as low topography of the landscape and the thick vegetative cover. Thus soil erosion and sediment yield were concentrated in exposed landscapes such as urban centres and steep slopes characterized by intense rainfall activity. The model could not be validated as it predicts only surface sediments and does not account for channel/gulley erosion and sediment yield. Therefore it will be inappropriate to use sediment load or sediment yield measurements which consist of both surface and bank/gully/channel eroded sediments for validating the model.

For instance the sister model USLE which does not also account for gully/channel erosion was used by Simanton et al. (1980, cited by Lim et al., 2005) to predict soil loss of four watersheds. They found that USLE estimated soil losses matched reasonably for two watersheds that had no gullies or significant alluvial channels, while USLE results did not match well for the other two watersheds with significant gullies and channels. These results indicate that USLE should not be applied to large watersheds, experiencing significant gully and channel erosion (Lim et al., 2005). Also predicted soil loss was less than the measured sediment yield for two basins using MUSLE (Modified Universal Soil Loss Equation) and for three basins using RUSLE (Erskine et al., 2002), because they do not account for gully erosions.

Besides, the satellite image and rainfall data used for the model was that of 2008 and the sediment yield studies were carried out in 2012 so it will not be appropriate to use sediment yield data of 2012 to calibrate a model predicting sediment yield of 2008 in the midst of lot of environmental changes taking place within the basin. As indicated in previous chapters, the activities of the illegal small scale mining has increased tremendously over the past decade and this will impact greatly on sediment yield hence sediment transport in 2012 is expected to be

higher than that of 2008 and this also explains the variability in sediment yield between observed and predicted.

Results of sediment yield measurements however show that the suspended sediment yield of the sub-catchments and the main Pra system are very high. Suspended sediment discharge indicates high suspended sediment transported throughout the season even at low flows. This high variability in sediment yield between model results and that of observed data implies that, there is more bank erosion than surface erosion within the basin and since the model does not account for bank erosion, sediments from bank materials are not captured in the modelling. This observation is buttressed by sediment source tracking analyses which showed that bank sediment materials were more dominant tracers than surface soils in all the tributaries studied including the main Pra catchment. Bank materials accounted for over 60% of suspended sediment loads in all sub-basins, and this explains the great variation between the model results and observed field sediment yield data measured. The strong positive correlation between sediment yield and basin area is also indicative of high fluvial sediment transport from the sources of the rivers through the basin system to the outlet.

These high discharges are attributable to human activities along the river corridor, most likely illegal alluvial gold mining activities taking place within the Pra Basin particularly those undertaken in the rivers. As discussed in the previous chapters, these activities result in the continuous entrainment of sediments from the river bank, mine wastes and the remobilization of deposited bed materials. Though surface sediments entrainment into streams are lower than bank materials, there is the need to manage land use activities in these basins to avoid over exploitation/degradation of the vegetation especially in the upsurge of mining activities coupled with farming. This is because the sensitivity analyses showed that predicted sediment yield was

very sensitive to C variable especially when the vegetative cover is reduced. The magnitude of the sediment delivery ratio for a particular basin is influenced by a wide range of geomorphological and environmental factors including the nature, extent and location of the sediment sources, relief and slope characteristics, the drainage pattern and channel conditions, vegetation cover, land use and soil texture (Walling, 1983). High sediment yields are known to pertain in smaller basins where sediments from source areas are easily moved into channels or downstream without significant deposition because the channel network of a small basin is generally constituted of channels having narrow cross sections and short channel lengths (Erskine et al. 2002; Ferro and Porto, 2000). High yields are also common in catchments that have either been extensively disturbed by agriculture or have experienced high density gulling (e.g. Erskine et al., 2002).

Though there is active bank erosion by hydraulic processes of flow which also contributes to sediments in the rivers, the proportion of sediment emanating from these processes is small as compared to the galamsey activity. This is because bank erosion measurements showed that much bank erosion occurred during high flows, but the relatively high sediment discharges that occurred during low flows as revealed by the suspended sediment concentration values cannot be attributed to the hydraulic erosional processes, but galamsey. Apart from those who operate on the rivers, there are other operators who dig pits which are often along the bank of the river or a stream and they create channels through which the mine waste is discharged into the rivers, so even at low flows there are thick plumes of sediments from mine waste water that are discharged into the streams/rivers. In communities where these galamsey activities are on-going, they indicated that due to the large sediment discharge and chemicals used in these operations, the water has become too polluted and they cannot use it any longer. According to them, the

situation has even led to the reduction in stock of aquatic species such as fish and crabs which they used to depend on for food.

The implication of the level of sediment load and transport pattern in the entire Pra Basin is that, it poses a great threat to the sustainability of the dams built on the rivers and water quality of the rivers in general. Dams built on these rivers (e.g. Owabi Dam, Barekese Dam and Brimsu Dam etc) are all silting up rapidly and Government has to spend lot of money in de-silting them to ensure potable water supply to communities within the basin. Ghana Water Company Limited is always complaining of the increasing cost of treating water for potable purposes along these rivers due to the high sedimentation levels of the water bodies. Also sediment load affects water turbidity. Turbidity determines the degree of scattering or absorption of light in the water and thus influences water temperature and the growth of aquatic plants and algae which can increase water loss (evapo-transpiration) or cause eutrophication which will worsen the water stress situation of communities in these basins.

From the above syntheses, it is obvious that sediment yield prediction within the Pra Basin using the RUSLE does not complement data from in situ sediment yield measurements due to the large amount of sediments generated within river channels. The inability of RUSLE to capture sediments generated from concentrated flow channels is a major limitation of the model and future research in modelling sediment yield within the basin should consider addressing this problem. However, as has been noted in literature the model is user friendly as its data input is very simple to generate and can be incorporated into GIS to give a spatial dimension to the phenomena under study. Though the field measurement of the sediment yield is reflective of the trends of sediment transport within the catchment, in situ data collection of sediment yield has been observed to be expensive and time consuming, consequently the application of a model

capable of capturing concentrated sediment transport will make sediment yield assessment within the basin faster, easier, cheaper and more convenient.

7.2 Limitations of the study

In the collection and analysis of data for this project a number of setbacks were encountered which need to be enumerated to guide future studies of this kind. This included the lack of certain logistics and data.

One major challenge that confronted this study was the unavailability of good satellite images covering the study area to enable a decadal/temporal modelling of soil erosion and sediment yield of the basin. Most of the available Landsat images had much cloud cover and could not be used for the study except that of the 2008. Thus it was impossible to model soil loss and sediment yield between different periods to determine trends in these processes within the basin. Another limitation of the model is its inability to model bank/gully erosion of channels and as discussed in literature it is unsuitable for large basins. As revealed by sediment yield measurements and source analyses, much of the fluvial sediments in transport are from bank materials hence an accurate sediment yield model of the Pra Basin will require a model that could also predict bank erosion.

A study of this kind required the use of a boat to facilitate movement along the river for a better assessment of processes and field data collection. The researcher could not however acquire/access this facility for lack of funds; consequently field measurements of bank erosion and bank sediment source analysis had to be restricted to the sub-basins whose channels were easily accessible due to the small volumes of water they carried. Though certain sections of the

river were undergoing active channel erosion, they were not accessible for lack of a boat to navigate these courses. This therefore limited the number of monitoring sites of bank erosion.

At some stations such as Sekyere Heman and Adwumain, stream gauges were vandalized by galamsey operators and at Akim Oda, the readings of lower gauge staffs were also worn-out and not legible. Readings taken during these stages were only estimates and in Adwuman sampling was impossible because all gauges had been removed as a result of illegal mining activities along the river bank. Also at Sekyere Heman some gauge staffs had also been removed by the illegal miners and this affected gauge readings at those stages of flow. These challenges were known to the Ghana Hydrological Services Department through their gauge readers, but the Service complained that, they lacked funds to maintain the defaced gauges and also had no control over the illegal miners. Insufficient funding from the state also affected their ability to undertake flow measurements regularly.

Erosion pins unlike PEEP is incapable of determining the magnitude, timing, spatial variability and dynamics of erosion events, consequently spatio-temporal comparison of bank erosion with respect to rainfall events/flows was impossible. The lack of bank erosion monitoring at high resolution intervals using PEEPS prevented a better characterization of the fluvial erosion processes with hydrograph events. Thus bank erosion could not be associated with fluvial events and processes and the detection of critical erosion events during the period of observation. That is the timing and magnitude of specific erosion events could not be captured. PEEP could not be deployed for the study for lack of funds to purchase the equipment and there was none for hiring as well.

Sediment concentrations were determined using both the integrated and dip samplings with the dip samples being corrected by a correction factor of the integrated samples. This will definitely

result in some marginal errors in the concentration levels. Also sampling was not done strictly according to the hydrological regime of flow due to the small number of visiting times, thus certain critical flows were missed irrespective of the number of samples taken particularly in stations where people could not be engaged to undertake dip sampling. Nevertheless, though a strict hydrological regime was not followed, the field work was scheduled in such a way that more samples were taken during the rising and peak stages of the season than the falling stages and this could provide a fair idea of the sediment discharge regime of the catchments. Also error margins are said to be low with larger basin sizes, so the expected associated errors related to sediment rating curves will be low (e.g. Walling, 1977a and 77b; Horowitz, 2003).

As indicated earlier, some bank erosion sites were vandalised due to the illegal mining activities and this prevented the empirical assessment of the level of bank erosion at those stations.

7.3 Conclusion

The study shows a very effective combination of spatial data of RUSLE parameters into GIS in mapping the spatial patterns in soil erosion and sediment yield. Simulated results showed that soil loss and sediment yield for 2008 in the Pra were generally low with zones susceptible to moderate-high erosion risks being few and these occurred in built-ups, high rainfall intensity and exposed landscapes (galamsey) areas and also along steep slopes and within the river valleys underlain by fluvisols which are very susceptible to erosion. Results of sediment yield derived from the integration of RUSLE into GIS gives a vivid spatial dimensions in sediment yield in the Pra Basin, however due to the unavailability of observed data the model could not be calibrated and validated. There is therefore the need to calibrate and validate the RUSLE model in the

future with respect to its application in the basin. The low erosion and sediment yield risk patterns are as a result of the well protected nature of the landscape by vegetative cover; consequently, measures must be put in place by state institutions to maintain a good vegetative cover of the basin especially in the light of serious threat from galamsey operations. Urban greening to protect the soil and the construction of good drains to carry run-off should also be encouraged by District Assemblies to protect the soil from urban erosion. Results of sensitivity analyses showed variables such as K , and R to be very sensitive to predicted sediment yield particularly when overestimated. This calls for high accuracy in the estimation of K , and R input data to ensure precision of model results.

The suspended sediment yield of the Pra Basin has been found to be higher than most tropical rivers including those in Ghana and illegal gold mining is the major force entraining large volumes of sediments into the rivers. These high yields are negatively impacting on the ability of Ghana Water Company to produce and distribute potable water to communities within the Pra Catchment. The deteriorative quality of the water is also causing aquatic life to perish. Communities are therefore getting stressed in terms of good quality water supply and protein need from fish.

A fingerprinting technique involving ^{210}Pb analyses showed that a greater percentage of fluvial sediments are emanating from bank materials. Human activities (galamsey) and bank erosion are the driving forces injecting bank sediments into the rivers. Field investigations and sediment yield results however indicate that much of the bank sediment injection is as a result of galamsey activities. Bank erosion studies revealed that, there is much channel instability along most cross sections particularly along meander bends and confluences. Other sections of river channels

characteristic of inner curves of meanders and banks of cohesive particles sizes and good vegetative cover are very stable.

7.4 Recommendations

In view of the lack of decadal modeling of soil erosion and sediment yield of the basin, it is recommended whenever it is possible (availability of two time period of satellite images) any study of this kind should attempt a temporal analyses of the sediment yield to decipher changing patterns in soil erosion and sediment yield in the basin. Also due to the current high intensity of human activities along and within the river banks which is entraining more sediments into the rivers than surface processes, future research works in sediment yield modelling should consider deploying models such as WEPP, EUROSEM that could model both bank and surface erosion within a basin. This will give a better perspective to the nature of soil erosion and sediment yield within the Pra Basin.

As has been acknowledged in the study, the number of bank erosion sites and sediment source sampling was limited to only the major tributaries of the basin for lack of funding. It is therefore recommended that, future studies should consider increasing the number of sampling sites if possible to include the whole Pra Basin. This will give a better reflection of bank erosion and sediment source characterization of the basin. Also to build on this initial study on bank erosion measurements, it is suggested that future work should focus on understanding the dynamics of bank erosion events through use of the Photo-Electronic Erosion Pin (PEEP) automatic erosion monitoring system, which gives a sharper picture of the intensity, timing and frequency of specific channel retreat episodes in relation to transient fluctuations in the driving forces.

Though results of fingerprinting involving one tracer was found to be effective in detecting sediment sources of the Pra Basin, suspended sediment sources, could also be determined using composite source fingerprints but this is expensive. However where the necessary funding is available such a study would give a much better assessment/definitive assessment of the sources as the tracers are many.

One critical challenge for sediment yield analyses which has been acknowledged in literature is the expensive nature of these studies. The Government needs to resource financially and improve staff strength of the Hydrological Services Departments to enable them maintain and monitor critical stations for flow and sediment discharge measurements. This calls for a replacement and re-graduation of vandalized and defaced gauges and the installation of automatic samplers, or use of turbidimeters to ensure continuous assessment of suspended sediment concentration data of Ghana's rivers. Another institution that also needs to be resourced is the Sediment Unit of the Water Research Institute of CSIR to continuously monitor sediment discharges of our rivers. This will ensure a trend assessment of the sediment yield of Ghana's rivers for proper management measures to be instituted. It will also make available data for scientific research such as model validation and calibration.

The activities of illegal mining in the Pra Basin and for that matter the whole country need to be controlled as they do not only directly inject sediments into the rivers, but the activities are also not sustainable. This is because most illegal miners do not control/contain their mine wastes and these are discharged into streams polluting them. They do not also undertake reclamation after mining and these facilitate soil erosion by running water into water bodies increasing their sediment levels. The Inter-Ministerial Task Force to flush out Ghanaians and foreigners engaged in illegal mining (galamsey) in the country is a good step by Government. However the

traditional authorities (chiefs) and landowners who give out lands for such activities should also be prosecuted. The mode of acquisition of the license and operations of these people also need to be scrutinised and supervised. This calls for a lot of supervision from the appropriate state agencies (EPA, Water Resources Commission, Minerals Commission and local assemblies). Therefore, there is the need to create more offices of these agencies in these localities where galamsey is rampant. When these agencies are properly resourced, there is the possibility of nipping this canker in the bud.

Generally, there is the need for Government to enforce 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 these policies will ensure the sustainable exploitation of the natural resources of the Pra Basin without compromising its water quality. For instance, enforcement of regulations governing buffer strips along surface water bodies needs to be strictly adhered to; to protect the quality of the basin's water. Also enforcement of legislation against mining in water bodies will also minimise pollution of the basin's water bodies. A major problem of the law enforcement has been Government's failure to establish the prescribed institutions and committees at the local level to assist the central agencies to implement policies. Though Government's excuse has always being the lack of funds to decentralised these regulatory agencies, it is highly recommended that much effort and commitment need to be shown by Government in this regard as the nation stands to gain in the long-run irrespective of the financial implications of these policies.

References

- Achite, M., and Ouillon, S. (2007). Suspended sediment transport in a semiarid watershed, Wadi Abd, Algeria (1973-1995). *Journal of Hydrology*, 343, pp.187-202.
- Akrasi, S. A. (2011). Sediment Discharges from Ghanaian Rivers into the Sea. *West African Journal of Applied Ecology*, Vol. 18, pp.1-13.
- Akrasi, S. A. and Ansa-Asare, O. D. (2008). Assessing Sediment and Nutrient Transport in the Pra Basin of Ghana. *West African Journal of Applied Ecology*, Vol. 13, pp.1-11.
- Akrasi, S.A. (2005). The assessment of suspended sediment inputs to Volta Lake. *Lakes & Reservoirs: Research & Management*, Vol. 10, Issue 3, pp. 179 – 186.
- Akuffo, S.B. (2003). *The Imminent Water Supply Crisis in Accra: The Silting Up of the Weija Lake*, Accra Mail - Accra.
- Alam, J. B., Uddin, M., Ahmed, J. U., Cacovean, H., Rahman, M. H., Banik, B. K., Yesmin, N. (2007). Study of Morphological Change of River Old Brahmaputra and Its Social Impacts by Remote Sensing, *Geographia Technica*, No.2, pp.1-11.
- Amisigo, B. A. and Akrasi, S. A. (1998). A Preliminary Assessment of the Suspended Sediment Yields of Rivers in the Volta River Basin System of Ghana. *Ghana Journal of Science*, Vol.38, pp.7-13.
- Amore, E., Modica, C., Nearing, M. A., Santoro, V. C. (2004). Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. *Journal of Hydrology*, 293, pp.100–114.
- Andrews, E. D. (1981). Measurement and Computation of Bed-Material Discharge in a shallow sand-bed stream, Muddy Creek, Wyoming. *Water Resources Research*, Vol. 17, No. 1, pp.131-141.
- Arekhi, S. (2008). Evaluating Long-Term Annual Sediment Yield Estimating Potential of GIS Interfaced MUSLE Model on Two Micro-Watersheds. *Pakistan Journal of Biological Sciences*, 11 (2), pp.270-274.
- Asselman, N.E.M. (2000). Fitting and Interpretation of Sediment Rating Curves. *Journal of Hydrology*, 234, pp.228-248.

- Asiedu-Addo, S. (2008). Illegal Miners Invade Water Treatment Plant. Retrived from: <http://shirleyasiedu-addo.blogspot.com/2008/09/illegal-miners-invade-water-treatment.html>: 10th June, 2013.
- Ayibotele, N.B., and Tuffour-Darko, T. (1974). *Report on Sediment Measurement in the Densu River at Manhia*, Water Resources Unit, Accra.
- Ayibotele, N.B., and Tuffour-Darko, T. (1979). *Sediment Loads in the Southern Rivers of Ghana*, Water Resource Unit (CSIR), Accra.
- Bartley, R., Keen, R. J., Hawdon, A. A., Hairsine, P. B., Disher, M. G., and Kinsey-Henderson, A. E. (2008). Bank erosion and channel width change in a tropical Catchment. *Earth Surface Processes and Landforms*, 33, pp.2174–2200.
- Bentil, N. L. (2011). Kyebi Water Plant Shut Down as a Result of Evil Effects of Galamsey. *Daily Graphic*, 2 August 2011.
- Bertrand, F. (2010). *Fluvial Erosion Measurements of Streambank using Photo-Electronic Erosion Pins (PEEP)*. MSc Thesis, University of Iowa, Theses and Dissertation, paper 642. <http://ir.uiowa.edu/etd/642>.
- Billi, P. (2008). Bedforms and Sediment Transport Processes in the Ephemeral Streams of Kobo basin, Northern Ethiopia. *Catena*, 75, pp. 5–17.
- Blake, W. H., Wallbrink, P. J., Doerr, S. H., Shakesby, R. A., and Humphreys, G. S. (2006). Magnetic Enhancement in Wildfire-affected Soil and its Potential for Sediment-source Ascription. *Earth Surface Processes and Landforms*, 31, pp.249–264.
- Blake, W. A., Walling, D. E., and He, Q. (2002). Using Cosmogenic Beryllium-7 as a Tracer in Sediment Budget Investigations. *Geografiska Annaler*, 84 A (2), pp.89–102.
- Blaszczynski, J. (2003). Estimating Watershed Runoff and Sediment Yield Using a GIS Interface to Curve Number and MUSLE Models. *The Bureau of Land Management Resource Notes*, No.66, US.
- Boateng, I., Bray, M., and Hooke, J. (2012). Estimating the fluvial sediment input to the coastal sediment budget: A case study of Ghana. *Geomorphology*, 138, pp.100–110.
- Bonilla, C. A., Reyes, J. L., and Magri, A. (2010). Water Erosion Prediction Using the Revised Universal Soil Loss Equation (RUSLE) in a GIS Framework, Central Chile. *Chilean Journal of Agricultural Research*, 70(1): pp.159-169.

- Brew-Hammond, A., and Kemausuor, F. (2007). Energy Crisis in Ghana-Drought, Technology or Policy? Kwame Nkrumah University of Science and Technology (KNUST)–College of Engineering, Kumasi, Ghana, ISBN #: 9988-8377-2-0.
- Bezuneh, M., Ames, G. C. W., & Mabbs-Zeno, C. C. (1995). Sustainable agricultural development using a farming systems approach in Zambia. *Ecological Economics*, 15, pp.149–156.
- Caitcheon, G.G. (1998). The Significance of Various Sediment Magnetic Mineral Fractions for Tracing Sediment Sources in Killimicat Creek. *Catena*, 32, pp.131–142.
- Centre for Policy Analysis (2007). The Energy Crisis and Growth Performance of the Economy, *CEPA*, Issues Paper No. 15, pp.1-19.
- Chakraborti, A.K. (1991). *Sediment Yield Prediction and Prioritisation of Watershed Using Remote Sensing Data*. *GISdevelopment.Net*, AARS - ACRS 1991 - Poster Session.
- Chorley, R. J., Schumm, S. A., and Sugden, D. E. (1984). *Geomorphology*. Methuen & Co. Ltd, London.
- Church, M. (2006). Bed Material Transport and the Morphology of Alluvial River Channels. *The Annual Review of Earth and Planetary Science*, 34: pp.325–354.
- Church, M., and Slaymaker, O. (1989). Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature*, Vol. 337, pp.452 – 454.
- Cohn, T. A., Caulder, D. L., Gilroy, E. J., Zynjuk, L. D., and Summers, R. M. (1992). The Validity of a Simple Statistical Model for Estimating Fluvial Constituents Load: An Empirical Study involving Nutrient Loads entering Chesapeake Bay. *Water Resources Research*, Vol.28, No. 9, pp.2353-2363.
- Collins, A.L., Walling, D.E., Leeks, G.J.L., (1997). Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena*, 29, pp. 1-27.
- Collins, A.L., Walling, D.E., Sichingabula, H.M., and Leeks, G.J.L. (2001). Suspended sediment source fingerprinting in a small tropical catchment and some management Implications, *Applied Geography*, 21, pp.387–412.

- Dabney, S. M., Yoder, D. C., Vieira, D. A. N., and Bingner, R. L. (2011). Enhancing RUSLE to include runoff-driven phenomena. *Hydrological Processes*, 25, pp.1373–1390.
- Davis, C. M., and Fox, J. F. (2009). Sediment Fingerprinting: Review of the Method and Future Improvements for Allocating Nonpoint Source Pollution, *Journal of Environmental Engineering*, Vol. 135, No. 7, pp.490 – 504.
- Darby, S.E., Rinaldi, M., Dapporto, S. (2007). Coupled simulations of fluvial erosion and mass wasting for cohesive river banks. *Journal of Geophysical Research*, Vol.112, pp.1-15.
- Desmet, P.J.J., and Govers, G. (1995). GIS-based simulation of erosion and deposition patterns in an agricultural landscape: a comparison of model results with soil map information. *Catena*, 25, pp.389-401.
- Dickson, K.B., and Benneh, G. (1995). *A New Geography of Ghana*. Longman, England.
- Di Stefano, C., Ferro, V., Porto, P. (2000). Length Slope Factors for applying the Revised Universal Soil Loss Equation at Basin Scale in Southern Italy. *J. Agric. Engng Res*, Vol.75, pp.349-364.
- Dogbevi, E. K. (2008). 'Ghana's Forests Under Threat' What is the Way Out? Retrieved March 31, 2008 from <http://www.illegal-logging.info/item>
- Edwards, T. K., and Glysson, G. D. (1999). Field Methods for Measurement of Fluvial Sediments. In: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, U.S. Geological Survey, Information Services, Reston, Virginia.
- El-Swaify, S. A. (1993). Soil erosion and conservation in the humid tropics. In D. Pimental, *World soil erosion and conservation* (pp. 233–255). Cambridge: Cambridge University Press.
- El Wakeel, A., & Astatke, A. (1996). Intensification of agriculture on vertisols to minimise land degradation in parts of the Ethiopian Highlands. *Land Degradation and Development*, 7, pp.57–67.
- El-Swaify, S. A., Dangler, E. W., and Armstrong, C. L. (1982). Soil Erosion by Water in the Tropics, Research Extension Series 024, 630 US ISSN 0271-9916.
- Eltaif, N. I., Gharaibeh, M. A., Al-Zaitawi, F., Alhamad, M. N. (2010). Approximation Of Rainfall Erosivity Factors In North Jordan. *Pedosphere*, 20(6), pp.711–717.

- Elwell, H. A. (1978). *Soil loss estimation: compiled works of the Rhodesian multi-disciplinary team on soil loss estimation*. Harare: Institute of Agricultural Engineering.
- Elwell, H.A., and Stocking, M.A. (1975). Parameters for estimating annual runoff and soil loss from agricultural lands in Rhodesia. *Water Resources Research*, 11 (4), pp.60-605.
- Engel, B. (2003). Estimating Soil Erosion Using RUSLE (Revised Universal Soil Loss Equation) Using ArcView. Accessed: 20th October 2011.
<http://pasture.ecn.purdue.edu/~abe526/resources1/gisrusle/gisrusle.html>
- Erskine, W. D., Mahmoudzadeh, A., Myers, C. (2002). Land use effects on sediment yields and soil loss rates in small basins of Triassic sandstone near Sydney, NSW, Australia. *Catena*, 49, pp. 271–287.
- Ferguson, R. I. (1986). River Loads underestimated by Rating Curves. *Water Resources Research*, Vol. 22, No. 1, pp.74-76.
- Ferro, V., and Porto, P. (2000). Sediment Delivery Distributed (SEDD) Model. *Journal of Hydraulic Engineering*, Vol. 5, No. 4, pp.411-422.
- Fistikoglu, O., and Harmancioglu, N.B. (2002). Integration of GIS and USLE in assessment of soil erosion. *Water Resources Management*, 16, pp.447–467.
- Fox, G.A., Wilson, G. V., Simon, A., Langendoen, E. J., Akay, O., Fuchs, J. W. (2007). Measuring streambank erosion due to ground water seepage: correlation to bank pore water pressure, precipitation and stream stage. *Earth Surface Processes and Landforms*, 32: pp.1558-1573.
- Freeze, R.A., and Cherry, J.A. (1979). *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.
- Fu, G., Chen, S., McCool, D. K. (2006). Modeling the impacts of no-till practice on soil erosion and sediment yield with RUSLE, SEDD, and ArcView GIS. *Soil & Tillage Research*, 85, pp.38–49.
- Gellis, A., (2010). Methods to identify sources of sediments. Accessed: 29/11/10.
http://www.mwcog.org/environment/potomacforum/Forum_PPTs/Gellis_Methods_to_ID_Sediment_Sources.pdf
- Ghana News Agency (2013). Cape Coast MCE Visits Brimsu Dam. Published: Wednesday, May 1, 2013.

Retrieved from: <http://www.ghananewsagency.org/social/cape-coast-mce-visits-brimsu-dam-59614>

Ghana News Agency (2005a). Owabi Dam to be de-silted, Modern Ghana News: Published: Thursday, March 17, 2005.

Retrieved from: <http://www.modernghana.com/news/74031/1/owabi-dam-to-be-de-silted.html>: 13th June, 2010.

Ghana News Agency (2005b). Work begins on the dredging of Brimsu dam.

Published: Wednesday, September 7, 2005. Retrieved from: <http://ghanaweb.net/GhanaHomePage//soccer/artikel.php?ID=89656>

Ghana Survey Department. Extract from Geographic Information System Data of Ghana. Unpublished Document.

Ghuman, B. S., & Lal, R. (1991). Land clearing and use in the humid Nigerian tropics II: soil chemical properties. *Soil Science Society of America Journal*, 55, pp.184–188.

Gilvear, D., Winterbottom, S., and Sichingabula, H. (2000). Character of Channel Planform Change and Meander Development: Luangwa River, Zambia. *Earth Surface Processes and Landforms*, 25, pp.421- 436.

Gomez, B., and Church, M. (1989). An Assessment of Bed Load Sediment Transport Formulae for Gravel Bed Rivers. *Water Resources Research*, Vol. 25, No. 6, pp.1161-1186.

Golubev, G.N. (1982). Soil erosion and agriculture in the world: an assessment and hydrological implications. IAHS Publ. 137, pp. 261- 268.

Gruszowski, K. E., Foster, I. D. L., Lees, J. A., and Charlesworth, S. M. (2003). Sediment sources and transport pathways in a rural catchment, Herefordshire, UK. *Hydrological Processes*, 17, pp.2665–2681.

Hadley, R.F. and Shown, L.M., 1976. Relation of erosion to sediment yield. In: Proceedings of the Third Federal Inter-Agency Sedimentation Conference. U.S. Water Resources Council, Washington, D.C., pp. 1-139.

Hagos, D. B. (2004). Distributed Sediment Delivery Ratio Concept for Sediment Yield Modelling. MSc Thesis to University of KwaZulu-Natal Pietermaritzburg, South Africa.

- Hassan, M. A. (2003). Tracers for Sediment Movement. *Encyclopedia of Sediments & Sedimentary Rocks*, pp.752-753.
- Hayes, P. J. (2004). Watershed modeling and uncertainty analysis for the north fork broad river, georgia, USA. MSc Thesis, The University of Georgia.
- Hazarika, M. K., and Honda, K. (2001). Estimation of Soil Erosion Using Remote Sensing and GIS, Its Valuation and Economic Implications on Agricultural Production, p.1090-1093. Inc. D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds.).
- Hickey, R. (2000). Slope Angle and Slope Length Solutions for GIS. *Cartography*, Vol. 29, No. 1, pp.1-8.
- Hickey, R., Smith, A., and Jankowski, P. (1994). Slope Length Calculations from a DEM within Arc/Info Grid. *Computers Environment and Urban Systems*, Vol. 18, No. 5, pp. 365-380.
- Horowitz, A. J. (2003). An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrological Processes*, 17, pp.3387–3409.
- Irvem, A., Topaloğlu, F., and Uygur, V. (2007). Estimating Spatial Distribution of Soil Loss Over Seyhan River Basin in Turkey. *Journal of Hydrology*, 336, pp.30-37.
- Jain, M. K., and Das, D. (2010). Estimation of Sediment Yield and Areas of Soil Erosion and Deposition for Watershed Prioritization using GIS and Remote Sensing. *Water Resources Management*, 24: pp.2091–2112.
- Jain, M. K., Mishra, S. K., and Shah, R. B. (2010). Estimation of Sediment Yield and Areas Vulnerable to Soil Erosion and Deposition in a Himalayan Watershed Using GIS. *Current Science*, Vol. 98, No.2, pp.213 – 221.
- Jain, M.J. K., and Kothyari, U. C. (2000). Estimation of Soil Erosion and Sediment Yield using GIS. *Hydrological Sciences Journal*, 45:5, pp.771-786.
- Jansson, M. (1985). A Comparison of Detransformed Logarithmic Regressions and Power Function Regressions. *Geografiska Annaler*, 67A, pp.1-2.
- Julian, J.P., Torres, R. (2006). Hydraulic erosion of cohesive riverbanks. *Geomorphology*, 76, pp.193–206.
- Juracek, K. E., and Ziegler, A. C., (2009). Estimation of sediment sources using selected chemical tracers in the Perry lake basin, Kansas, USA. *International Journal of Sediment Research*, 24, pp.108–125.

- Khanchoul, K., Benslama, M., and Remini, B. (2010). Regressions on Monthly Stream Discharge to Predict Sediment Inflow to a Reservoir in Algeria. *Journal of Geography and Geology*, Vol. 2, No.1; pp.36 – 47.
- Kothyari, U. C., and Jain, M.J. K. (1997). Sediment yield estimation using GIS. *Hydrological Sciences*, 42 (6), pp.833 – 843.
- Kouli, M., Soupios, P., and Vallianatos, F. (2008). Soil erosion prediction using the Revised Universal Soil Loss Equation (RUSLE) in a GIS framework, Chania, Northwestern Crete, Greece. *Environmental Geology*, DOI 10.1007/s00254-008-1318-9.
- Kusimi, J.M. (2005). *A Geomorphological Study of the Densu Basin*. MPhil Thesis, Dept of Geography and Resource Development, University of Ghana, Legon.
- Kusimi, J.M. (2008). Analysis of Sedimentation Rates in the Densu River Channel: The Result of Erosion and Anthropogenic Activities in the Densu Basin. *West African Journal of Applied Ecology*, Vol. 14, pp.1-13.
- Lal, R. (1985). Soil erosion and sediment transport research in tropical Africa. *Hydrological Sciences Journal*, 30: 2, pp.239-256.
- Lal, R. (1993). Soil erosion and conservation in West Africa. In D. Pimental, *World soil erosion and conservation* (pp. 7–25). Cambridge: Cambridge University Press.
- Lal, R. (1996a). Deforestation and land-use effects on soil degradation and rehabilitation in Western Nigeria I: soil physical and hydrological properties. *Land Degradation and Development*, 7, pp.19–45.
- Lal, R. (1996b). Deforestation and land-use effects on soil degradation and rehabilitation in Western Nigeria III: runoff, soil erosion and nutrient loss. *Land Degradation and Development*, 7, pp.99–119.
- Lane, L. J., Hernandez, M., and Nichols, M. (1997). Processes Controlling Sediment Yield from Watersheds as functions of Spatial Scale, *Environmental Modelling and Software*, Vol.12, No.4, pp.355 - 369.
- Langendoen, E.J., Lowrance, R.R., Simon, A. (2009). Assessing the impact of riparian processes on streambank stability. *Ecohydrology*, 2(3): pp.360-369.
- Lawler, D. M. (2005a). Turbidimetry and Nephelometry, in Worsfold P.J; Townshend A; and Poole C. F. (Eds), *Encyclopaedia of Analytical Science*, Elsevier 2nd ed, pp.343-351.

- Lawler, D. M. (2005b). The importance of high-resolution monitoring in erosion and deposition dynamics studies: examples from estuarine and fluvial systems. *Geomorphology*, 64, pp.1 –23.
- Lawler, D. M., Foster, I. D. L., Petts, G. E., Harper, S., and Morrissey, I. P. (2006). Suspended sediment dynamics for June storm events in the urbanized River Tame, UK. Proceedings of a symposium held in Dundee, UK. *IAHS Publ.* 306, pp.96-103.
- Lawler, D. M., Grove, J. R., Couperthwaite, J. S., and Leeks, G. J. L. (1999). Downstream change in river bank erosion rates in the Swale-Ouse system, Northern England. *Hydrological Processes*, 13, pp.977 – 992.
- Lawler, D. M., Couperthwaite, J., Bull, L. J., Harris, N. M. (1997). Bank Erosion Events and Processes in the Upper Severn Basin. *Hydrology and Earth System Science*, 1 (3), pp.523 – 534.
- Lawler, D.M. (1993). Needle ice processes and sediment mobilization on river banks: the River Ilston, West Glamorgan, UK. *Journal of Hydrology*, 150, pp.81-114.
- Lillesand, T.M., and Kiefer, R.W. (1994). *Remote Sensing and Image Interpretation*. 3rd Edition, New York: John Wiley and Sons inc., University of Madison.
- Lawler, D.M. (1991). A New Technique for the Automatic Monitoring of Erosion and Deposition Rates. *Water Resources Research*, 27(8): pp.2125-2128.
- Lim, K. J., Sagong, M., Engel, B. A., Tang, Z., Choi, J., Kim, K. (2005). GIS-based sediment assessment tool. *Catena*, 64, pp.61–80.
- Luppi, L., Rinaldi, M., Teruggi, L. B., Darby, S. E., and Nardi, L. (2009). Monitoring and numerical modelling of riverbank erosion processes: a case study along the Cecina River (central Italy). *Earth Surface Processes and Landforms*, 34, pp.530–546.
- Matisoff, G., and Whiting, P. J. (2011). Measuring Soil Erosion Rates Using Natural (⁷B, ²¹⁰Pb) and Anthropogenic (¹³⁷Cs, ^{239,240}Pu) Radionuclides, In Baskaran M. (ed.), *Handbook of Environmental Isotope Geochemistry*, Advances in Isotope Geochemistry, pp.487 - 519, DOI 10.1007/978-3-642-10637-8 25.
- Mensah, K. (2012). Pra River basin under threat-Nana Sarpong. Business and Financial Times, 31 October, 2012. Retrieved from: <http://www.ghheadlines.com/agency/business-and-financial-times/20121031/399941/prariverbasinunderthreat>: 20th June, 2013.
- Milestone Cook Book (1996). Digestion report code 240. Milestone Application lab. Mineral Lab. USA, 1989. Supplied data.

- Mongkolsawat, P., Thirangoon, S., Sriwongsa, S. (1994). *Soil Erosion Mapping with Universal Soil Loss equation and GIS*, GISdevelopment.net, AARS - ACRS 1994 – Disaster.
- Molinaroli, E., Blom, M., and Basu, A. (1991). Methods of Provenance Determination Tested with Discriminant Function Analysis. *Journal of Sedimentary Petrology*, Vol. 61, No. 6, pp. 900-908.
- Moore, I. D., and Burch, G. J., (1986). Physical Basis of the Length-slope Factor in the Universal Soil Loss Equation. *Soil Science Society of America Journal*, Vol.50: pp.1294-1298.
- Morgan, R. P. C., Quinton, J. N., Smith, R. E., Govers, G., Poesen, J. W. A., Auerswald, K., Chisci, G., Torri, D., and Styczen, M. E. (1998). The European Soil Erosion Model (Eurosem): A Dynamic Approach for Predicting Sediment Transport from Fields and Small Catchments. *Earth Surface Processes and Landforms*, 23, pp.527–544.
- Motha, J. A., Wallbrink, P. J., Hairsine, P. B., and Grayson, R. B. (2002). Tracer properties of eroded sediment and source material. *Hydrological Processes*, 16, pp. 1983–2000.
- Mukundan, R., Radcliffe, D. E., and Ritchie, J. C. (2009). Sediment Source Tracking in the Georgia Piedmont. *Proceedings of the 2009 Georgia Water Resources Conference*, April 27–29, 2009, The University of Georgia, pp.186 – 190.
- Mutua, B. M. and Klik, A. (2006). Estimating Spatial Sediment Delivery Ratio on a Large Rural Catchment. *Journal of Spatial Hydrology*, Vol.6, No.1. pp.64-80.
- Nagle, G., (2000). *Advanced Geography*. Oxford University Press, Oxford, UK.
- Nagle, G.N. and Ritchie, J. C., (1999). The use of tracers to study sediment sources in three streams in North-eastern Oregon. *Physical Geography*, 20, 4, pp.348-366.
- Nagle, G.N. and Ritchie, J. C., (2004). Wheat field erosion rates and channel bottom sediment sources in an intensively cropped Northeastern Oregon Drainage Basin. *Land Degradation & Development*, 15: 15–26.
- Nagle, G.N., Fahey, T. J., Ritchie, J. C., and Peter, B., Woodbury, P. B., (2007). Variations in sediment sources and yields in the Finger Lakes and Catskills regions of New York. *Hydrological Processes*, 21, pp.828–838.

- Nangia, V., Wymar, P., and Klang, J, (2010). Evaluation of a GIS-based watershed modeling approach for sediment transport. *International Journal of Agricultural and Biological Engineering*, Vol. 3, No.3, pp. 43-53.
- Nichols, M. H. (2006). Measured Sediment Yield Rates from Semiarid Rangeland Watersheds. *Rangeland Ecology & Management*, 59(1), pp.55-62.
- Obi, M. E., & Salako, F. K. (1995). Rainfall parameters influencing erosivity in southeastern Nigeria. *Catena*, 24, pp.275–287.
- Oduro-Afriyie, K. (1996). Rainfall erosivity map for Ghana. *Geoderma*, 74, pp.161-166.
- Ohio EPA (2001). Sediment Sampling Guide and Methodologies, 2nd Edition, <http://www.epa.ohio.gov/portals/35/guidance/sedman2001.pdf>: Accessed: 11th June, 2011.
- Osten, A. T. (1979). Sediment Transport in Streams: Sampling, Analysis and Computation, *Man. Proc. opl Hydrol.* 5. Ministry of Water Energy and Minerals (Tanzania) and Norwegian Agency for International Development (NORAD).
- Papanicolaou, A.N., Elhakeem, M., Hildale, R., (2007). Secondary current effects on cohesive river bank erosion. *Water Resources Research*, 43, pp.1-14.
- Parsons, A. J., and Wainwright, J. (1993). Tracing Sediment Movement in Interrill Overland Flow on a Semi-Arid Grassland Hillslope Using Magnetic Susceptibility. *Earth Surface Processes and Landforms*, Vol. 18, pp.721-732.
- Peart, M. R., and Walling, D. E. (1988). Techniques for Establishing Suspended Sediment Sources in Two Drainage Basins in Devon, UK: A Comparative Assessment, Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). *IAHS Publ.* No. 174, pp.269 – 279.
- Peng, W., Zhou, J., He, Z., and Yang, C. (2008). Integrated Use of Remote Sensing and GIS For Predicting Soil Erosion Process, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVII. Part B4. Beijin.
- Petkovšek, G., and Mikoš, M. (2004). Estimating the R factor from daily rainfall data in the sub-Mediterranean climate of southwest Slovenia. *Hydrological Sciences Journal*, 49(5), pp.869-877.
- Pizzuto, J. (2009). An empirical model of event scale cohesive bank profile evolution. *Earth Surface Processes and Landforms*, 34, pp.1234–1244.

- Porter, M.D., and Massong, T.M. (2004). Analyzing Changes in River Channel Morphology Using GIS for Rio Grande Silvery Minnow Habitat Assessment, Fishery and Aquatic GIS Research Group, New Mexico, US.
- Porterfield, G. (1972). Computation of Fluvial Sediment-Discharge. In: Applications of Hydraulics. United States Government Printing Office, Washington.
- Prosser, I.P., Hughes, A.O., Rutherford, I.D. (2000). Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms*, 25, pp.1085-1101.
- Ramos-Scharro´n, C. E., and MacDonald, L. H. (2007). Development and application of a GIS-based sediment budget model. *Journal of Environmental Management*, 84, pp.157–172.
- Renard, K. G., and Freimund, J. R. (1994). Using monthly precipitation data to estimate the R-factor in the revised USLE. *Journal of Hydrology*, 157, pp.287- 306.
- Renard, K. G., Foster, G. R., Weesies, G. A., and Porter, J. P. (1991). Revised universal soil loss equation (RUSLE). *Journal of Soil and Water Conservation*, Vol.46, No.1, pp.30-33.
- Renschler, C.S, Mannaerts, C., and Diekkruiger, B. (1999). Evaluating spatial and temporal variability in soil erosion risk—rainfall erosivity and soil loss ratios in Andalusia, Spain. *Catena*, 34, pp.209–225.
- Restrepo, J. D., and Kjerfve, B. (2000). Water Discharge and Sediment Load from the Western Slopes of the Colombian Andes with Focus on Rio San Juan. *The Journal of Geology*, volume 108, pp.17–33.
- Restrepo, J. D., and Syvitski, J. P. M. (2006). Assessing the Effect of Natural Controls and Land Use Change on Sediment Yield in a Major Andean River: The Magdalena Drainage Basin, Colombia, *AMBIO: A Journal of the Human Environment*, 35(2): pp.65-74.
- Roose, E. J. (1977). Use of the universal soil loss equation to predict erosion in West Africa. in *Soil Erosion – Prediction and Control: Soil Conservation Society of America*. Ankeny, Iowa, pp.60-73.
- Rose, C.W. (1960): Soil detachment caused by rainfall. *Soil Science*, Vol.89, Issue 1, pp.25-35.
- Roy, P. (2009). Detection of Land Use/Land Cover Change and its Impact on Soil Erosion, using Satellite Remote Sensing and GIS, *Proceedings of International*

Conference on Energy and Environment, March 19-21, 2009 ISSN: 2070-3740, Enviroenergy.

- Saltelli, A., Chan, K., and Scott, M. (2000). Sensitivity Analysis. Wiley Series in Probability and Statistics. New York: John Wiley and Sons.
www.cs.ubbcluj.ro/~per/C6%20Vs/C6_Ms.pdf. Accessed: 10th April 2013.
- Schoonover, J. E., Lockaby, B. G., Shaw, J. N. (2007). Channel morphology and sediment origin in streams draining the Georgia Piedmont. *Journal of Hydrology*, 342, pp.110– 123.
- Schwartz, U., and Greenbaum, N. (2009). Extremely high sediment yield from a small arid catchment—Giv'at Hayil, northwestern Negev, Israel. *Israel Journal of Earth Science*; Vol.57: pp.167–175.
- Schuller, P., Iroume', A., Walling, D. E., Mancilla, H. B., Castillo, A., and Trumper, R E. (2006). Use of Beryllium-7 to Document Soil Redistribution following Forest Harvest Operations. *Journal of Environmental Quality*, 35: pp.1756–1763.
- Scott, S. H., and Jia, Y. (2002). Simulation of Sediment Transport and Channel Morphology Change in Large River Systems, US-China Workshop on Advanced Computational Modelling in Hydroscience & Engineering, September 19-21, Oxford, Mississippi, USA, pp.1-11.
- Sengtaheuanghoung, O., Valentin, C., Ribolzi, O., De Rouw, A., Thiebaut, J-P., (2007). The impact of rapid land use changes upon sediment yields from agricultural catchments in Northern Lao PDR. *Actes des JSIRAUF*, Hanoi, pp.1-6.
- Shamshad, A., Azhari, M.N., Isa, M.H., Wan Hussin, W.M.A., Parida, B.P. (2008). Development of an Appropriate Procedure for Estimation of RUSLE EI₃₀ Index and Preparation of Erosivity Maps for Pulau Penang in Peninsular Malaysia. *Catena* 72, pp.423-432.
- Shirley, E. D., and Lane, L. J. (1978). A Sediment Yield Equation from an Erosion Model. *Hydrology and Water Resources in Arizona and the Southwest*, Vol 8. pp. 90-96.
- Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., (2000). Bank and near-bank processes in an incised channel. *Geomorphology*, 35, pp.193-217.
- Silva, A. M. (2004). Rainfall Erosivity Map for Brazil. *Catena*, 57: pp.251–259.
- Silva, R. M., Santos, C. A. G., Montenegro, S. M. G. L., and Silva, L. P. E. (2010). Spatial Analysis of Vegetal Cover and Sediment Yield in Tapacurá River

- Catchment Based on Remote Sensing and GIS. *Annals of Warsaw University of Life Sciences – Land Reclamation*, No 42 (1): pp.5–16.
- Silva, R.M., Santos, C.A.G., Silva, L.P., Silva, J.F.C.B.C. (2007). Soil loss prediction in Guaraira river experimental basin, Paraíba, Brazil based on two erosion simulation models. *An Interdisciplinary Journal of Applied Science*, Vol.2, No.3, pp.19–33.
- Simon, A., and Collison, A. J. C. (2001). Pore-water pressure effects on the detachment of cohesive streambeds: Seepage forces and matric suction. *Earth Surface Processes and Landforms*, 26, pp.1421–1442.
- Simon, A., and Collison, A. J. C. (2002). Quantifying the Mechanical and Hydrologic Effects of Riparian Vegetation on Streambank Stability. *Earth Surface Processes and Landforms*, 27, pp.527–546.
- Singh, K. P., and Durgunoğlu, A., (1989). Developing accurate and reliable stream sediment yields. Sediment and the Environment (Proceedings of the Baltimore Symposium), *IAHS Publ.* No. 184, pp.193-199.
- Smithen, A.A., and Schulze, R.E. (1982). The Spatial Distribution in Southern Africa of Rainfall Erosivity for use in the Universal Soil Loss Equation. *Water SA*, Vol.8, No.2, pp.74-78.
- Solaimani, K., Omidvar, E., and Kelarestaghi, A. (2008). Investigation of Check Dam's Effects on Channel Morphology – Case Study: Chehel Cheshme Watershed. *Pakistan Journal of Biological Sciences*, 11 (17), pp.2083 – 2091.
- Srinivasan, R., and Engel, B. A. (1991). Effects of Slope Prediction Methods on Slope and Erosion Rates. *Purdue Agricultural Experiment Station Journal*, Paper No. 12806, pp.1-15.
- Staley, N. A., Wynn, T., Benham, B., Yagow, G. (2006). Modeling Channel Erosion at the Watershed Scale: Model Review and Case Study, BSE Document Number 2006-0009. Center for TMDL and Watershed Studies, Biological Systems Engineering, Virginia Tech. Virginia.
- Stocking, M.A. (1987). A methodology for erosion hazard mapping of the SADCC region. Rep. No. 9, Maseru, SADCC, Maseur, Lesotho, Africa.
- Stocking, M. A., & Elwell, H. A. (1976). Rainfall erosivity over Rhodesia. *Transactions Institute of British Geographers NS*, 1, pp.231–245.

- Stone, R. P., and Hilborn, D. (2000). Universal Soil Loss Equation (USLE), Ministry of Agriculture Food and Rural Affairs, Ontario, Factsheet Order No. 00-001.
- Thomas, R. B. (1985). Estimating Total Suspended Sediment Yield with Probability Sampling. *Water Resources Research*, Vol. 21, No. 9, pp.1381-1388.
- Tucker, G. E., and Bras, R. L. (1998). Hillslope Processes, Drainage Density and Landscape Morphology. *Water Resources Research*, Vol. 34, No. 10, pp.2751-2764.
- UNDP Ghana (2004). *Liquefied Petroleum Gas (LPG) Substitution for Wood Fuel in Ghana – Opportunities and Challenges*. Unfolink No.1, pp1-7.
- USDA-ARS (2008a). DRAFT USER'S REFERENCE GUIDE - Revised Universal Soil Loss Equation Version 2 (RUSLE2), Prepared for USDA-Agricultural Research Service, Washington D.C.
http://www.ars.usda.gov/sp2UserFiles/Place/64080510/RUSLE/RUSLE2_User_Ref_Guide.pdf. Accessed: 8th March, 2011.
- USDA-ARS (2008b). DRAFT SCIENCE DOCUMENTATION - Revised Universal Soil Loss Equation Version 2 (RUSLE2), Submitted to USDA-Agricultural Research Service, Washington D.C.
ftp://fargo.nserl.purdue.edu/pub/RUSLE2/RUSLE2_Program_File/RUSLE2_Science_Doc.pdf. Accessed: 8th March, 2011.
- Van Remortel, R., Hamilton, M., and Hickey, R. (2001). Estimating the LS factor for RUSLE through iterative slope length processing of digital elevation data. *Cartography*, v. 30, no. 1, pp. 27-35.
- Verstraeten, G., and Poesen, J. (2001). Factors controlling sediment yield from small intensively cultivated catchments in a temperate humid climate. *Geomorphology*, 40, pp.123–144.
- Vrieling, A., Sterk, G., de Jong, S. M. (2010). Satellite-based estimation of rainfall erosivity for Africa. *Journal of Hydrology*, 395, pp.235–241
- Wahyunto, K. D., and Abdurachman, A. (2010). Quick Mapping of Soil Erosion Risks by Remote Sensing and GIS in East Java, Indonesia. *International Journal of Geoinformatics*, Vol. 6, No, 2, pp.27 – 33.
- Wallbrink, P.J., Martin, C.E., and Wilson, C.J. (2003). Quantifying the contributions of sediment, sediment-P and fertiliser-P from forested, cultivated and pasture areas at the landuse and catchment scale using fallout radionuclides and geochemistry. *Soil & Tillage Research*, 69, pp.53–68.

- Walling, D. E. (1977a). Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers. pp.34 – 47. Retrieved from: http://itia.ntua.gr/hsj/redbooks/122/iahs_122_0034.pdf: 15th Sept, 2011.
- Walling, D. E. (1977b). Assessing the Accuracy of Sources Sediment Rating Curves for a Small Basin. *Water Resources Research*, Vol.13, No.3, pp.531 – 538.
- Walling, D.E. (1983). The Sediment Delivery Problem. *Journal of Hydrology*, 65, pp. 209-237.
- Walling, D. E., Woodward, J. C., and Nicholas, A. P. (1993). A Multi-Parameter Approach to Fingerprinting Suspended-Sediment Sources, Tracers in Hydrology (Proceedings of the Yokohama Symposium, July 1993) *IAHS, Publ. No. 215*, pp.329-338.
- Walling, D. E. (2004). Using environmental radionuclides to trace sediment mobilisation and delivery in river basins as an aid to catchment management. *Proceedings of the Ninth International Symposium on River Sedimentation*, October 18 – 21, 2004, Yichang, China.
- Walling, D.E. (2005). Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment*,. 344: pp.159-184.
- Water Resources Commission (2011). Basins – Pra Basin. Retrieved from: <http://wrc-gh.org/en/basins/17/pr-a-basin>: 14th May, 2013.
- Wenner, C. G. (1980). *Soil conservation in Kenya* (6th ed.). Nairobi: Soil Conservation Extension Unit, Ministry of Agriculture.
- Winterbottom, S. J., and Gilvear, D. J. (1997). Quantification of Channel Bed Morphology in Gravel-Bed Rivers Using Airborne Multispectral Imagery and Aerial Photography Regulated Rivers. *Research & Management*, Vol. 13, pp.489 – 499.
- Wischmeier, W. H., and Smith, D. (1978). *Predicting Rainfall Erosion Losses. A Guide to Conservation Planning*. USDA. Agricultural Handbook 537. Washington D.C.
- Yu, L., and Oldfield, F. (1989). A Multivariate Mixing Model for Identifying Sediment Source from Magnetic Measurements. *Quaternary Research*, 32, pp.168-181.
- Yüksel, A., Akay, A. E., Gundogan, R., Reis, M., and Cetiner, M. (2008). Application of GeoWEPP for Determining Sediment Yield and Runoff in the Orcan Creek Watershed in Kahramanmaras, Turkey. *Sensors*, 8, pp.1222-1236.

Zhang, X., Wu, B., Ling, F., Zeng, Y., Yan, N., and Yuan, C. (2010): Identification of priority areas for controlling soil erosion. *Catena*, 83, pp.76–86.

Appendices

Appendix A: Sediment rating curves of monitored stations in the Pra Basin

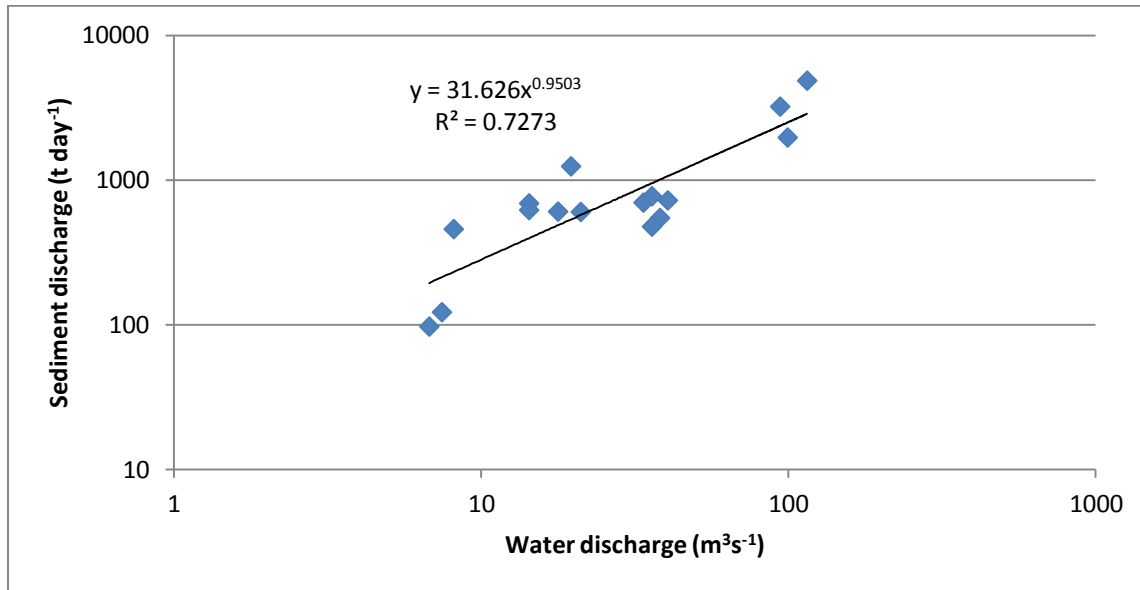


Fig.3.17: Suspended sediment rating curve for Akim Oda

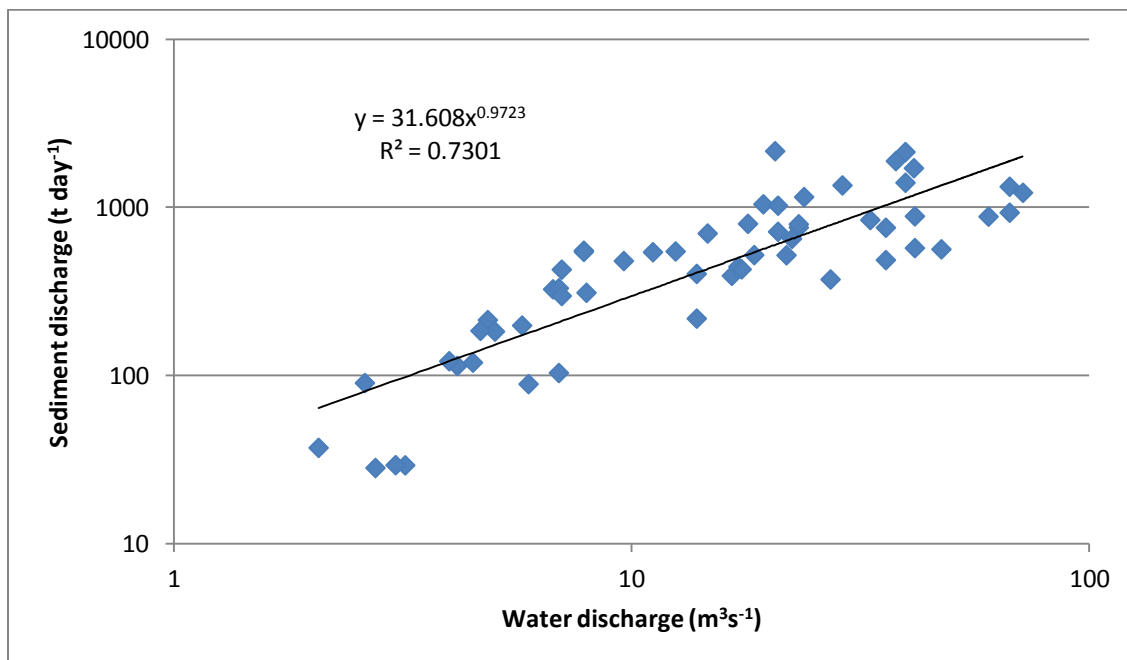


Fig.3.18: Suspended sediment rating curve for Brenase

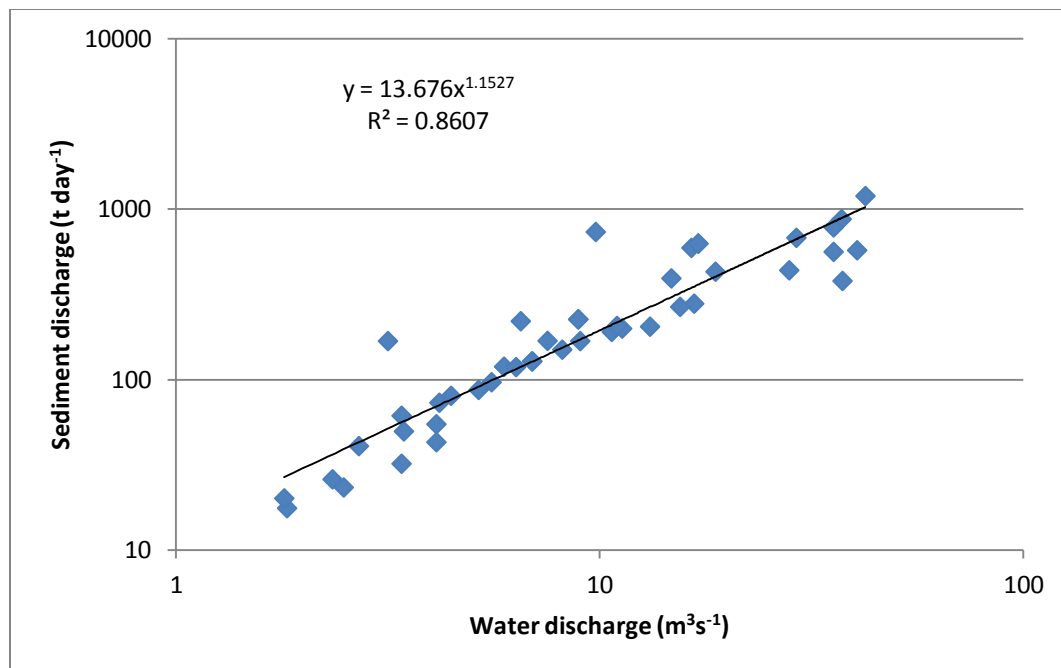


Fig.3.19: Suspended sediment rating curve for Anwiankwanta

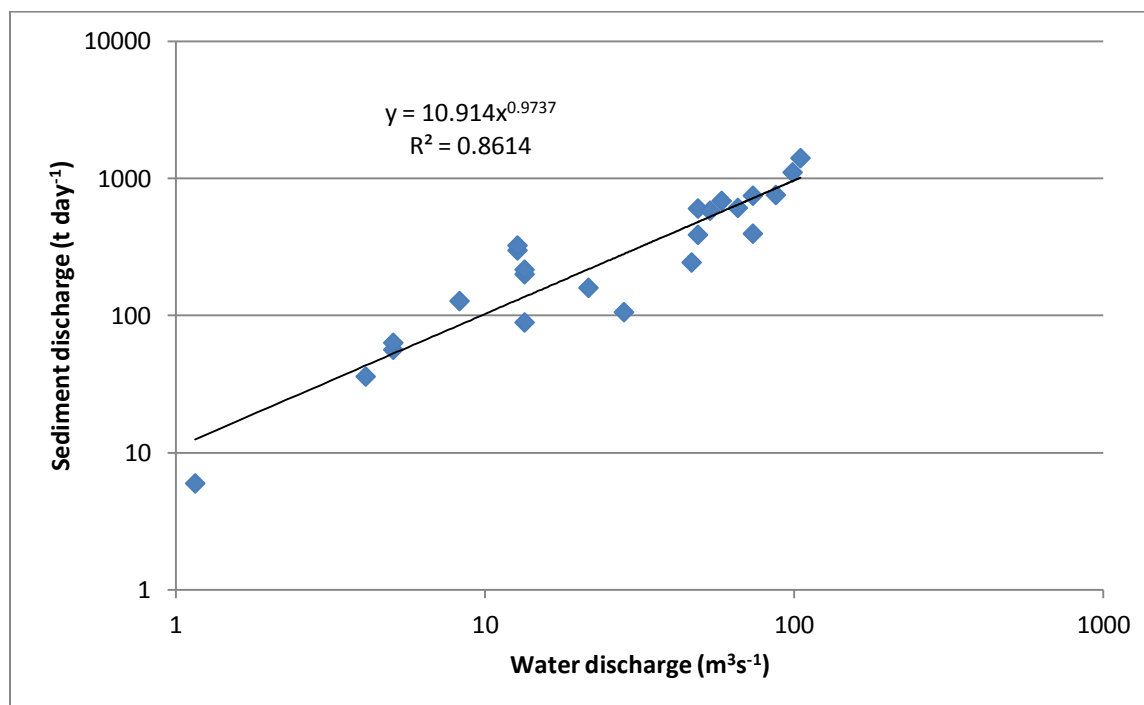


Fig.3.20: Suspended sediment rating curve for Adiembra

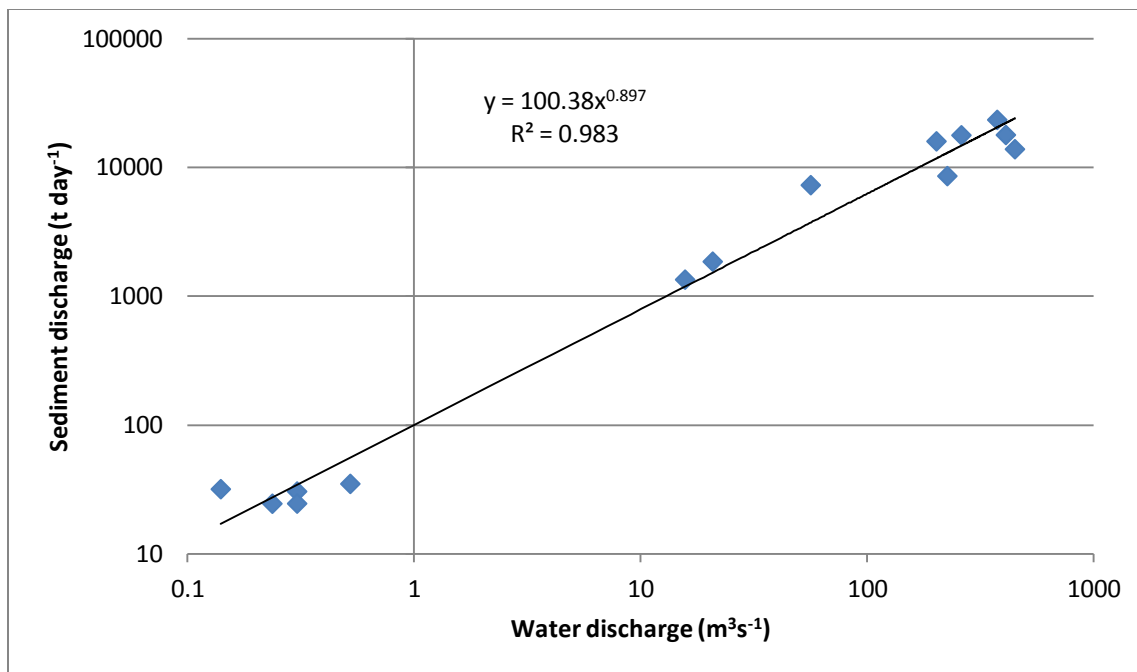


Fig.3.21: Suspended sediment rating curve for Twifo Praso

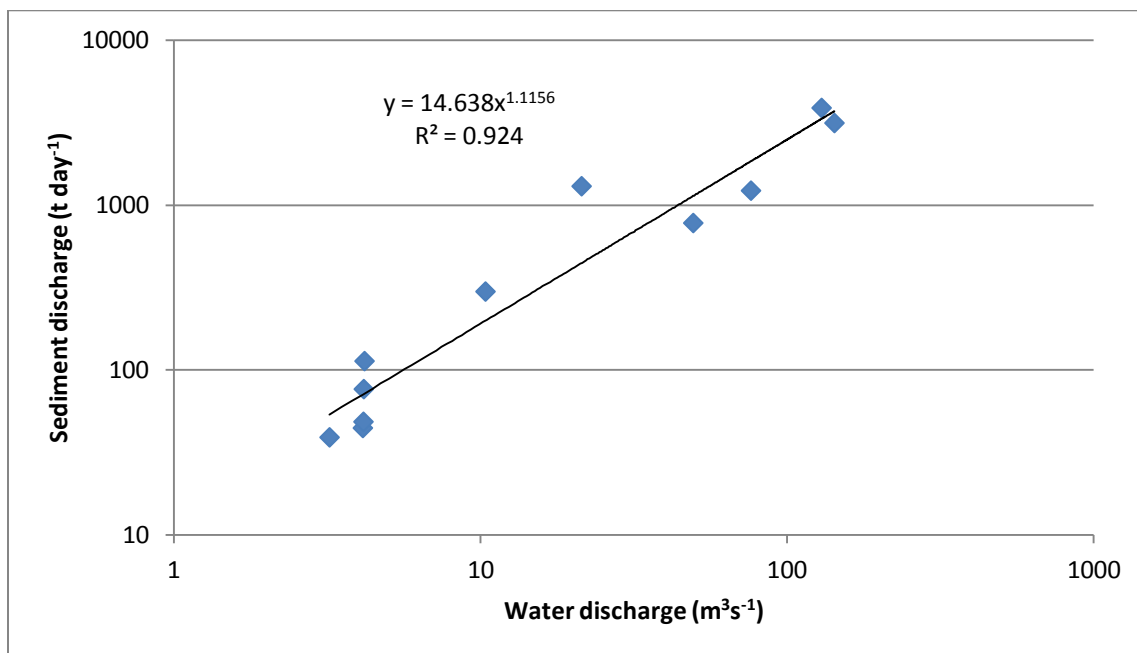


Fig.3.22: Suspended sediment rating curve for Assin Praso

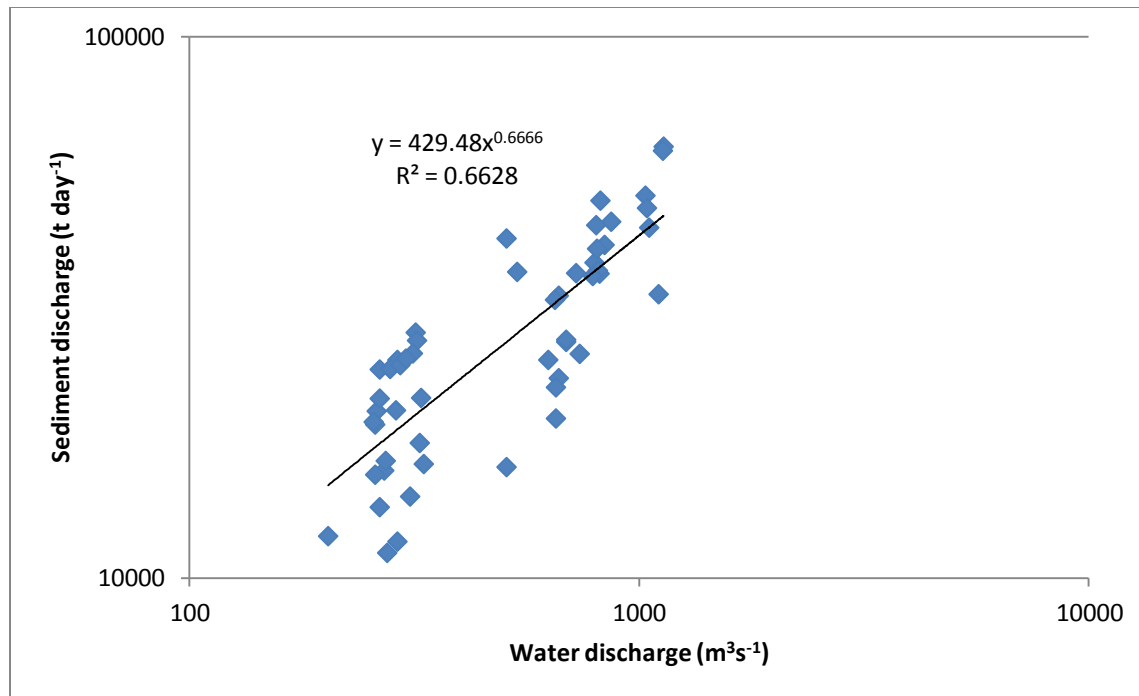


Fig.3.23: Suspended sediment rating curve for Sekyere Heman

Hypothesis Testing

Model1:

Yield ~ AREA

Df Sum of Sq RSS AIC F value Pr(>F)

<none> 1.1710e+13 201.02

AREA 1 3.4333e+13 4.6043e+13 208.60 14.659 0.01226 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> summary(model1)
```

Call:

```
lm(formula = Yield ~ AREA, data = Sedimentyield_BasinArea)
```

Residuals:

```
 1    2    3    4    5    6    7
491506 65663 240257 345277 -1435865 -1996171 2289334
```

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -762798.44 839798.72 -0.908 0.4054

AREA 262.01 68.43 3.829 0.0123 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1530000 on 5 degrees of freedom

Multiple R-squared: 0.7457, Adjusted R-squared: 0.6948

F-statistic: 14.66 on 1 and 5 DF, p-value: 0.01226

Model2:

```
>cor(Sedimentyield_BasinArea, method = "kendall")
```

	No.	Yield	AREA	SSY
No.	1.0000000	0.8095238	0.8095238	0.4285714
Yield	0.8095238	1.0000000	0.8095238	0.6190476
AREA	0.8095238	0.8095238	1.0000000	0.4285714
SSY	0.4285714	0.6190476	0.4285714	1.0000000

Model3:

```
> cor(Sedimentyield_BasinArea, method = "spearm")
```

	No.	Yield	AREA	SSY
No.	1.0000000	0.8928571	0.8928571	0.5714286
Yield	0.8928571	1.0000000	0.9285714	0.7500000
AREA	0.8928571	0.9285714	1.0000000	0.5357143
SSY	0.5714286	0.7500000	0.5357143	1.0000000

Appendix B: Results of sediment source analysis

Table 4.6: 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						

Units ((Bq/kg)

Table 4.7: 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				

Units ((Bq/kg)

Table 4.8: 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					

Units ((Bq/kg)

Table 4.9: 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				

Units ((Bq/kg)

Hypothesis Testing

Modell:

Stream_Sediment ~ Surface_soil + Bank_sediment

Df Sum of Sq RSS AIC F value Pr(>F)

<none> 0.00156 -25.3984

Surface_soil 1 0.00002 0.00158 -27.3412 0.0144 0.92395

Bank_sediment 1 0.43321 0.43477 -4.8769 277.7630 0.03815 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

>

> summary(modell)

Call:

```
lm(formula = Stream_Sediment ~ Surface_soil + Bank_sediment,
    data = SedimentSource_testing)
```

Residuals:

```
    1    2    3    4
0.027706 0.003396 -0.003368 -0.027734
```

Coefficients:

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.21719   0.05469   3.971 0.1570
Surface_soil  0.00752   0.06265   0.120 0.9240
Bank_sediment 0.94946   0.05697  16.666 0.0382 *
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.03949 on 1 degrees of freedom
Multiple R-squared: 0.9995, Adjusted R-squared: 0.9984
F-statistic: 942 on 2 and 1 DF, p-value: 0.02303

Model 2:

```
Stream_Sediment ~ Bank_sediment
```

```
            Df Sum of Sq  RSS   AIC F value  Pr(>F)
<none>                0.00158 -27.3412
Bank_sediment  1    2.9384 2.94000  0.7685 3714.6 0.0002691 ***
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

>

```
> summary(model2)
```

Call:

```
lm(formula = Stream_Sediment ~ Bank_sediment, data = SedimentSource_testing)
```

Residuals:

```
    1    2    3    4
0.028245 0.005552 -0.007351 -0.026447
```

Coefficients:

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.22112   0.03122   7.082 0.019359 *
Bank_sediment 0.95577   0.01568  60.947 0.000269 ***
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.02813 on 2 degrees of freedom
Multiple R-squared: 0.9995, Adjusted R-squared: 0.9992
F-statistic: 3715 on 1 and 2 DF, p-value: 0.0002691

Model3:

```
Stream_Sediment ~ Surface_soil
```

```
      Df Sum of Sq  RSS   AIC F value Pr(>F)
<none>          0.43477 -4.8769
Surface_soil 1    2.5052 2.94000  0.7685  11.524 0.0769 .
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

>

```
> summary(model3)
```

Call:

```
lm(formula = Stream_Sediment ~ Surface_soil, data = SedimentSource_testing)
```

Residuals:

```
      1      2      3      4
-0.16729 -0.08666  0.55536 -0.30141
```

Coefficients:

```
      Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.03327   0.62081  -0.054  0.9621
Surface_soil  0.97057   0.28590   3.395  0.0769 .
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Residual standard error: 0.4662 on 2 degrees of freedom

Multiple R-squared: 0.8521, Adjusted R-squared: 0.7782

F-statistic: 11.52 on 1 and 2 DF, p-value: 0.0769

Appendix C: Data sheet of erosion pin measurements and grain size analysis

Table 5.7: Measurements of bank erosion and deposition at Akim Oda

Date				4 th September 2012				6 th March 2013			
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4	Pin 1	Pin 2	Pin 3	Pin 4
Birim	Akim Oda	Left	Top	1	1	Bank failure	Bank failure	11	3	17	Bank failure
		Left	Middle	1.3	15	buried	buried	3	5	4.5	buried
		Left	Bottom	10.5	8	buried	buried	buried	buried	buried	buried

Table 5.8: Measurements of bank erosion and deposition at Amuanda Praso

Date				4 th September 2012			5 th March 2013		
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)			Length of exposure of pins/cm (“+” erosion and “-“ Deposition)		
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3
Pra	Amuanda	Right	Top	-1	0.7	buried	buried	buried	buried
		Right	Middle	-2	1	buried	buried	buried	2.5
		Right	Bottom	-0.5	buried	buried	6	6	5.5
		Left	Top	3	-2	1.5	2.8	1.5	1.5
		Left	Middle	buried	buried	buried	3	1	5
		Left	Bottom	1	submerged	1.4	4.5	4	5

Table 5.9: Measurements of bank erosion and deposition at Praso

Date				17 th August, 2012			5 th March, 2013		
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)			Length of exposure of pins/cm (“+” erosion and “-“ Deposition)		
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3
Pra	Praso	Right	Top	-3.0	-2.5	buried	0	0.5	buried
		Right	Bottom	-4.0	buried	buried	buried	buried	buried
		Left	Top	1.0	1.0	1.4	0.2	1.0	1.5
		Left	Bottom	1.2	1.5	1.0	1.0	1.5	1.7

Table 5.10: Measurements of bank erosion and deposition at Anyinam

Date				5 th March 2013				
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)				
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4	Pin 5
Birim	Anyinam	Left	Top	0.0	0.0	0.5	3	1
		Left	Bottom	1.0	0.5	2.0	1.5	3.7
		Right	Top	Deposition of sediments of depth between 2 – 17cm				
		Right	Bottom	Deposition of sediments of depth between 20 – 65cm				

NB: Due to high flows, measurements were only possible once in the year

Table 5.11: Measurements of bank erosion and deposition at Ejisu

Date				6 th September 2012				6 th March 2013			
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4	Pin 1	Pin 2	Pin 3	Pin 4
Oda	Ejesu	Right	Top	0	-1.5	4	24	3	3.2	3.8	2.7
		Right	Middle	Buried with wasted materials upslope				2.4	4.3	7.9	6.2
		Right	Bottom	0	25	11.5	3	2.1	1.3	13.8	7.7
		Left	Top	3	-2	1.5		Buried	Buried	Buried	
		Left	Middle	Buried	Buried	Buried		Buried	Buried	Buried	
		Left	Bottom	Buried	Buried	Buried		Buried	Buried	Buried	

Table 5.12: Measurements of bank erosion and deposition at Adiembra

Date				6 th September 2012				6 th March 2013			
				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)				Length of exposure of pins/cm (“+” erosion and “-“ Deposition)			
River	Station	Bank	Bank Location	Pin 1	Pin 2	Pin 3	Pin 4	Pin 1	Pin 2	Pin 3	Pin 4
Oda	Ejesu	Right	Top	-1.5	3	3		1	1.7	1.6	
		Right	Middle	-1.6	-1	2		1.2	1.6	1.9	
		Right	Bottom	Buried with materials crept from upslope				1.1	1.3	1.8	
		Left	Top	1	1.6	0	6.8	2.3	2.2	3.1	2.7
		Left	Middle	In water	In water	-1	20.5	3.4	3.6	3.3	4.2
		Left	Bottom	In water	In water	In water	In water	4.5	5.9	7.8	25.1

Table 5.13: Grain size analyses of bank sediments at Anyinam and Ejisu

Sieve Opening(mm)	Anyinam				Ejisu			
	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing
0.002	35.3	6.8	100	6.8	52.6	3.8	100	3.6
0.05	22.9	4.4	93.2	11.2	127	8.6	96.4	12.2
0.1	65.6	12.6	88.8	23.8	526.6	35.8	87.8	47.9
0.25	62.4	12.0	76.3	35.72	285.4	19.4	52.1	67.3
0.5	87.1	16.7	64.3	52.4	133.9	9.1	32.7	76.4
1	111.3	21.4	47.6	73.8	129	8.8	23.6	85.2
2	41.8	8.0	26.2	81.8	44.6	3.0	14.8	88.2
2.5	94.9	18.2	18.2	100	173.9	11.8	11.8	100
Total	521.3				1473			

Table 5.14: Grain size analyses of bank sediments at Akim Oda

Sieve Opening(mm)	Sample A				Sample B			
	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing
0.002	79.2	7.1	100	7.1	38.8	2.3	100	2.3
0.05	171.8	15.5	92.9	22.6	92.9	5.4	97.7	7.7
0.1	309.6	27.9	77.4	50.5	152.1	8.9	92.3	16.6
0.25	89.1	8.0	49.5	58.6	56.8	3.3	83.4	20.0
0.5	119.9	10.8	41.5	69.4	58.5	3.4	80.1	23.4
1	135.1	12.2	30.7	81.5	84.3	4.9	76.6	28.3
2	51.5	4.6	18.5	86.2	41.2	2.4	71.7	30.7
2.5	153.5	13.8	13.8	100	1182.4	69.3	69.3	100
Total	1109.7				1707			

Table 5.15: Grain size analyses of bank sediments at Adiembra

Sample A (left bank)					Sample B (right bank)			
Sieve Opening(mm)	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing	Weight on Sieve/gm	% Remaining on sieve	Cumulative % remaining on sieve	Cumulative % passing
0.002	0.002	67.80	6.14	100	0.002	50.5	4.1	100
0.05	0.05	150.90	13.66	93.86	0.05	179.5	14.7	95.9
0.1	0.1	475.20	43.01	80.21	0.1	750.8	61.4	81.2
0.25	0.25	67.90	6.15	37.20	0.25	83.7	6.9	19.8
0.5	0.5	61.20	5.54	31.05	0.5	59.5	4.9	12.9
1	1.0	88.90	8.05	25.51	1	56.4	4.6	8.1
2	2.0	48.60	4.40	17.47	2	15.1	1.2	3.5
2.5	2.5	144.40	13.07	13.07	2.5	27.1	2.2	2.2
Total	1104.9				1222.6			