KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

Estimation of the Rate of Sediment Transport into the Bui Hydropower Reservoir

By

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A Thesis submitted to the Department of Civil Engineering, College of Engineering in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

WATER RESOURCES ENGINEERING AND MANAGEMENT

June, 2016

DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ACKNOWLEDGEMENT

My first gratitude goes to the Almighty God who has made my dream of achieving an MSc degree a reality. I would like to thank Dr. Kwabena Kankam-Yeboah, Head of Surface Water Division – (CSIR-WRI), who gave me the opportunity to pursue this MSc. Study.

My sincere appreciation goes to my Supervisors Dr. F. O. K. Anyemedu (KNUST) and Dr. Emmanuel Obuobie (CSIR-WRI) for providing supervision for my thesis. I would also like to thank Dr. G. K. Anornu (KNUST) who provided initial supervision to my thesis.

I thank all the lecturers who took me throughout the entire WRESP programme. My appreciation goes out to Dr. Ruby Asmah, Head of Fisheries Division (CSIR-WRI) and the Coordinator of the DANIDA funded project "Effects of Climate Change on Lake Volta Resources-VOLTRES" for admitting me into the project and sponsoring my field work. I thank Mr. Gabriel Appiah, Mr. Frank Teye Oblim and Mr. Serapis Appiah for their great support during my field data collection. I am grateful to Ms. Fati Aziz (PhD student, WASCAL) for sharing part of her data with me to compliment my own data.

A special appreciation to my beloved wife, Mrs, Roberta Akofa Asante-Sasu for her love, patience and support throughout my studies. I thank my mother Comfort Dankyi and siblings, Mrs. Caroline Ansah-Akrofi and Mr. Kwabena Dankwah Asante-Sasu for their love, financial support and prayers. God bless you all.

ABSTRACT

The knowledge of sediment yields in water infrastructures like reservoirs is necessary to be able to plan for long-term water resources development and management. The Black Volta Basin houses the recently constructed hydropower reservoir at Bui, which supplies 400 MGW of power to the national grid, but lacks recent sediment information for outstanding changes in sediment transport and sedimentation in the Bui reservoir. This study analysed the current rate of sedimentation in the Bui reservoir by establishing discharge and sediment rating curves at Chache (upstream of the reservoir) and Bamboi (downstream of reservoir), and using empirical equations together with suspended sediment data collected through a one year (2014/2015) monitoring programme. The results show maximum suspended sediment concentrations of 328.15 mg/l and 51.28 mg/l measured at Chache and Bamboi, respectively. This gives an indication that the Bui reservoir is effective in trapping sediment from upstream of the reservoir catchment area.

Current gross annual sediment yield in the reservoir was estimated at 1,370,007 t/yr. Compared to the designed rate of sediment yield for the reservoir (968,000 t/yr), the current estimate depicts an increase in annual sediment yield of about 41.5 %, which has negative impact on hydropower generation, aquatic life including fishery, and the lifespan of the reservoir. The increase in sediment yield over the designed figure could worsen in the near future if changes in land use, particularly illegal small scale mining activities upstream and close to the reservoir are not properly managed by regulating or enforcing the laws governing illegal small scale mining.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER 1:

INTRODUCTION

1.1 Background

Reservoirs are designed to store water from upstream of catchments for various purposes including irrigation, flood control, navigation, power generation and water supply. Reservoir capacities are basically divided into three components namely; dead storage, active storage and the flood control storage (Rijn, 2013). Generally, the dead storage is usually about 10 - 25% of the total reservoir capacity and it is usually designed to impound sediments. This is located between the lowest outlet level and the normal surface level and it is equivalent to the total volume of sediments expected to be deposited in the reservoir during its designed life span.

Reservoir sediment is characterized by the watershed sediment production, rate of transportation and the mode of deposition (Sumi & Hirose, 2005). Principally, most of the sediments transported into rivers and subsequently into reservoirs are as a result of erosion from land surfaces. A number of factors are usually responsible for the rate of sediment transport in rivers. Major contributing factors to sediment transport in rivers include geomorphology and land use practices in the river basin as well as the prevailing rainfall regime. Other activities that influence sediments transport are climate change impacts, particularly changes in rainfall intensity, and urbanization.

The most suitable method used in determining sediment yield of a catchment is the Direct Method approach. The direct method can be achieved in one of two ways; computing the sediment load of a river through sampling and by resurveying existing reservoirs (Akrasi, 2008).

It is essential to have knowledge on sediment transport in rivers because it is one way of providing information for water resource planning thus, designing the dead storage of a reservoir, evaluating whether or not water is suitable for drinking purposes, knowledge of catchment erosion and subsequent morphological changes.

One definite impact of reservoir sedimentation is the raising of the bed causing loss of storage volume and consequently a reduction in its storage capacity. Worldwide around 40,000 large reservoirs suffer from sedimentation and it is estimated that between 0.5% and 1% of the total storage capacity is lost per year (White, 2001). Effective and sustainable management of the Bui hydropower facility requires the proper understanding of sediment deposition into the Bui reservoir. This is because sediments deposition in the reservoir at a rate faster than designed for can significantly reduce the reservoir‟s total storage, reduce the life span of the reservoir in the long term and hence reduce its total power generation capacity.

The study therefore seeks to estimate the amount and rate of sediment deposition into the Bui reservoir and to compare with the designed rate to determine whether or not the designed useful life of the reservoir is sustainable.

1.2 Problem Statement

The Bui reservoir impounds water from the Black Volta River. A greater percentage of land use upstream of the Bui reservoir on the Black Volta River is Agriculture. Land degradation activities upstream and conversion of forest lands into agriculture farmlands makes the soils susceptible to erosion. Recent illegal mining upstream and around the reservoir is likely to increase the rate of sedimentation in the reservoir.

Also, heavy intensive rainfall upstream has the capability of loosening the soil cover and promote the soils transportation into the river and consequently into the reservoir.

The above enumerated problems will cause an increase in the rate of siltation in the Bui reservoir, possibly resulting in the reduction in the storage capacity of the reservoir whose primary objective is to generate hydropower to supplement the nation‟s total hydropower generation. Also, other purposes of the reservoir (irrigation, drinking water supply and fishery) will be impacted negatively.

1.3 Justification of Study

Currently there has been no ongoing research work being done to quantify the rate of sediment yield into the Bui Reservoir. This study will estimate the rate at which sediments are deposited into the Bui reservoir and will provide initial data for future assessments of sedimentation in the reservoir. The results can be useful for informing catchment management practices in the Black Volta basin.

1.4 Main and Specific Objectives

The main objective of this study was to estimate the amount and rate of sedimentation in the Bui reservoir as contribution to the effective and sustainable management of the reservoir and its catchment areas.

The specific objectives were to;

- Establish a flow rating curve for the Black Volta River at Chache gauge station to update the existing one.

- Develop suspended sediment rating curve for the Black Volta at Chache gauge station.
- Estimate the annual sediment yield into the Bui Reservoir.

1.5 General Overview of Report

Chapter one gives general introduction to sedimentation in reservoirs and associated effects, the problem statement, justification, and the main and specific objectives of this study. Chapter two provides the theoretical background of sediment production, transport and deposition as well as the review of some sediment analysis work done on the Black Volta and other Rivers. Chapter three describes the study area, including the sampling monitoring stations and the Bui Reservoir. Chapter four entails detailed explanation of the research methodology used and chapter five deals with the results and discussion of the results. The conclusions and recommendations of the study are provided in chapter six.

CHAPTER 2:

LITERATURE REVIEW

2.1 General Sedimentation in Rivers and Reservoirs

2.1.1 Sediment Production

Sediments are derived as a result of weathering of parent rocks. Agents responsible for this weathering process break down the parent rock into fragments to form boulders, gravel, sand, silt and clay. These agents are in the form of mechanical and chemical agents. Other factors that aid in the process of sediments production are temperature changes, wind activities and water or solvent activities. These activities form the natural processes of sediment formation.

Certain man-made activities influence the rate at which sediments are produced in a watershed. These are deforestation, unrestricted grazing and cultivation on steep slopes are some of these man-made activities which causes sediment production (Tilrem, 1979). Other activities such as urbanization, drainage of wetlands and Climate Change which is caused by human‟s anthropogenic activities accelerate the production of sediment. Agriculture and grazing for example reduce water infiltration into the soil and causes an increase in the rate and magnitude of surface runoff (Julien & Vensel, 2005).

Stream channel can also be a source of sediment production. Scouring of stream bed can occur during periods of high flow velocity. The high flow velocity overcomes the resistive forces of the river bed and dislodges the particles. The dislodged particles are then transported within the river channel either in suspension or as bedload until they are deposited when the flow velocity reduces (Simon *et al.,*

2003).
The significance of sedimentation in rivers and reservoirs is not only characterized by the production of these sediments either by natural means or by man-made, but also the means of transportation and deposition (Sumi & Hirose, 2005).

2.1.2 Sediment Transport

Erosion from disturbed land surfaces is the primary means of sediment transport into streams and eventually reservoirs. The magnitude of sediment from eroded land surfaces is directly related to the land cover and eventually land use. Runoff from rainfall erode loose soil particles from the land surface of the catchment and are conveyed through the processes of rill, sheet and gully erosion into river systems which eventually deposits them into reservoirs, lakes or seas.

Land cover, land use and the hydrology of a river basin are so closely linked and because of that erosion and sediment transportation processes are rendered sensitive to changes in climate and land cover as well as human activities to a large extent (Walling, 2009). Such activities include deforestation and land-clearing, land use practices, expansion of agriculture, urbanization and infrastructural development, sand mining, dam and reservoir construction, mining extraction and programmes for soil conservation and sediment control (Walling, 2009).

The fluvial system of sediment transport is divided into two main types. (Brandes *et al.*, 2009) defines suspended load as particles continuously entrained in water column during turbulent flows. Suspended load mostly consists of clay and silt with varying amounts of sand derived from the channel bed. Bedload however refers to the material that moves along or near the stream bed. Their movement is either by rolling, sliding and sometimes skipping along the stream bed. Bedload includes sand grains and gravels. Fluvial sediment may be classified according to particle size of which is the most significant factor with respect to water transportation (Tilrem, 1979).

2.1.3 Sediment Deposition in Reservoirs

The primary focus in this context is sediment deposition into reservoirs. A greater quantity of sediments produced within the watershed is transported by the river systems and end up in reservoirs. This is because the nature of dams forming reservoirs on natural rivers is such that, they are subjected to some level of sediment inflow and deposition.

As the sediment laden water approaches the reservoir, within the area of the dam, the turbulent velocity of the flow greatly reduces. This is due to the wide surface area of the reservoir. The coarsest (bed load and larger suspended load) particles are immediately deposited in the reservoir headwater vicinity. This leaves the smaller sediment particles to remain in suspension for a longer while until they are gradually deposited further down the reservoir.

Morris & Fan (1998) described the modes of sediment deposition in three different classes (Figure 2.1). The “topset” bed is made up of the heavy sediment particles that are deposited at the entry into the reservoir. The “foreset” bed consists of the relatively medium sized particles and is deposited at the toe of the topset bed.

Finally the "bottomset" bed comprises of the finer components which do not settle until they travel a sufficient distance within the reservoir. They are deposited in thin layers (Morris & Fan, 1998).

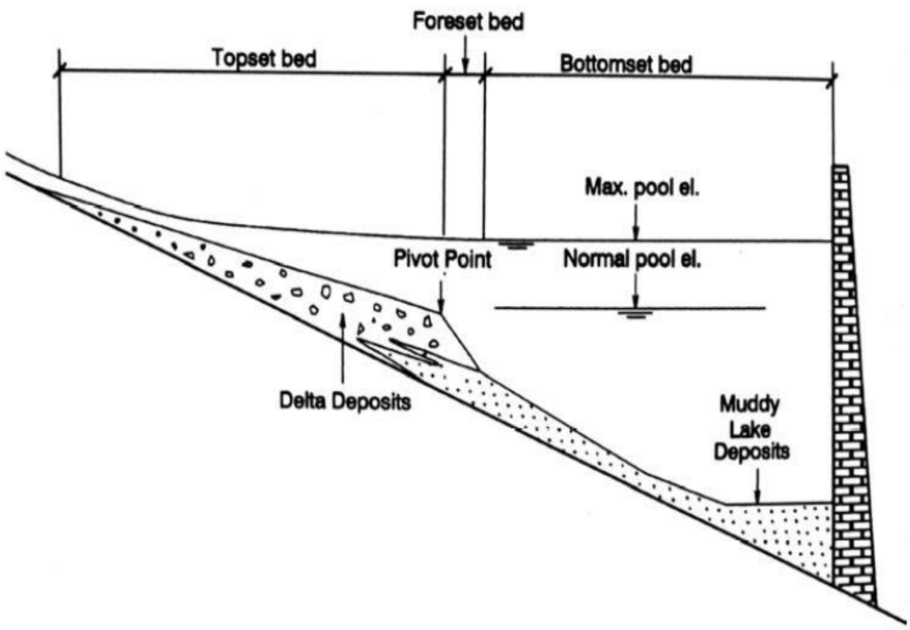

Figure 2.1 Generalized depositional zones in a reservoir (Morris & Fan, 1998).

After the various depositions have taken place, the water in the reservoir reduces in turbidity. Continuous inflow of sediment laden water flows towards the dam structure under the influence of gravity within the channel. The clear water flows on top of the turbid water. This phenomenon is known as stratified flow. The flow of sediment laden water under the clear water is also known as density current.

2.2 Trap Efficiency

The trap efficiency of a reservoir is defined as the ratio of sediments retained in the reservoir to the total sediment that is brought into the reservoir. The trap efficiency depends on the volume and particle size analysis of the incoming sediment, water discharge flowing through the reservoir and the operation levels in the reservoir. Brune (1953) developed the best known empirical trap efficiency relationship which was later supported by Murthy (Murthy, 1977) (Figure 2.2).

Brune defined the trap efficiency of a reservoir as a function of the ratio of the reservoir capacity (V_R) to the total inflow (Q_A) of water in a given time (usually one year) Equation (2.1). Generally, most reservoirs trap about 95-100 % of the sediments inflow.

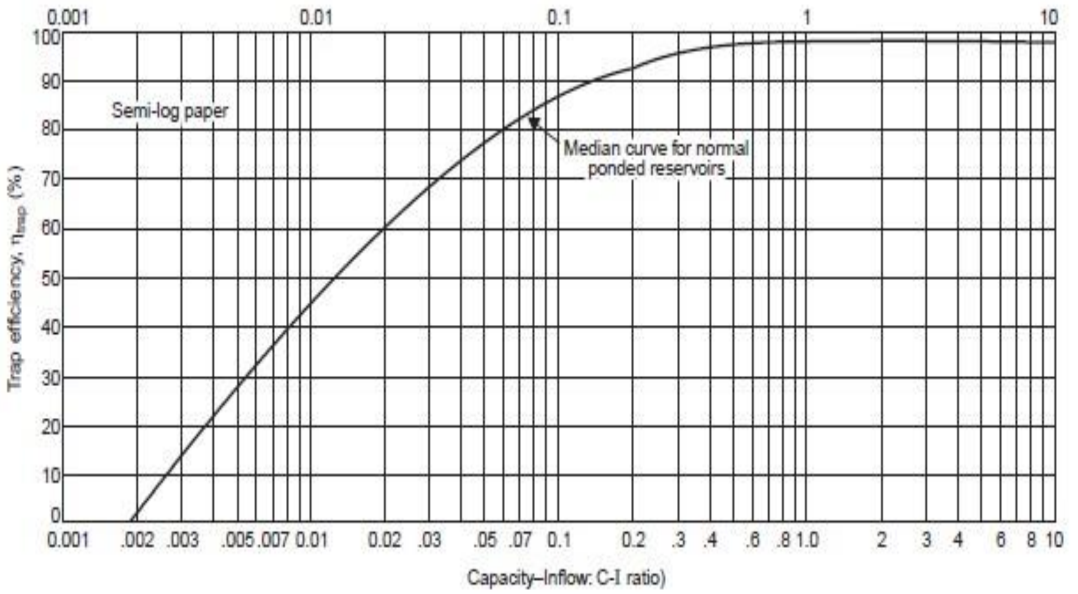

Figure 2.2 Trap efficiency curve for estimating sediment trapping in a conventional impounding reservoir (Brune, 1953).

Trap Efficiency ( ) $f\left[\frac{V_R}{Q_A}\right]$ (2.1)

2.3 Reservoir Storage Capacity

2.3.1 Loss of Storage Capacity

Reservoirs are susceptible to loss of storage capacity over several years. This is due to sediment inflow deposited by these rivers. As the river approaches the reservoir, velocity of flow reduces which brings about the onset of sediment deposition. This causes the active and the dead storage of the reservoirs to lose their capacity over time. The active storage loses its capacity to the coarse components of the sediments whiles the suspended and finer components of the sediments reduces the dead storage capacity as explained in Section 2.1.3.

The estimation of sedimentation is essential for predicting the useful life of reservoirs. The term useful life of a reservoir describes the time it takes for 90% of the live reservoir storage to be depleted (Water, 2001). The magnitude of sediment load deposited is a determinant for the useful life of the reservoir. Preliminary studies on sediment inflows into reservoirs are usually carried out before their construction. After the construction, future investigations could prove otherwise a much higher deposition of sediments than previously estimated for during or before the design process.

Worldwide, studies (e.g., Nordin, 1991; Palmeiri *et al*., 2001; Nagle *et al*., 1999) have shown various degrees of loss of reservoir storage capacities as a result of sedimentation. White (2001) and Mahmood (1987) estimated that the worldwide reservoir sedimentation rate is 1 percent per year. Most reservoirs are designed to be usable for 50 to 100 years, before they are rendered useless by sedimentation (Hotchkiss *et al.,* 1995).

The mean annual sediment load of the Sanmenxia reservoir in China was 1.6 billion tonnes. However, after less than two years of its operation, the reservoir lost a total of about 18 billion m^3 of its total storage capacity to sedimentation (IRTCES, 2005). Onwuegbunam *et al*., (2013) estimated that the initial design capacity of a small reservoir in Kaduna, Nigeria, reduced from 16, 400 m^3 to 10, 665 m^3 (storage loss of 35%) within 10 years of operation. In Puerto Rice., an impoundment of Lago Loíza in 1953 to supply San Juan with drinking water lost 47% of its total storage capacity due to sediment by 1994 (Gellis *et al.,* 2001).

2.3.2 Other Effects of Sedimentation in Reservoirs

There are a wide range of other problems associated with sedimentation in dam reservoirs apart from loss in storage capacity. An increase in flood risk on contributing streams, loss of flood storage for downstream channels and increased spillway flows are probable effects on reservoirs due to sedimentation. Continuous sediment deposition can adversely affect the stability of the dam structure and as well increase water loss to evaporation. In cases where sediments accumulate closer to power intakes, the sediment load passing through the turbine can bring about turbine wear. Sedimentation in reservoirs also cause bottom-feeding fish species to diminish in numbers because their habitation is taken over by sedimentation. This subsequently causes the loss of their food supply.

2.4 Upland Contribution

Within a wide range of sediment contribution in lakes and rivers, agriculture is considered as the major cause worldwide from the upstream. Continuous tillage of lands for agriculture leaves the land bare loose and therefore is rendered susceptible to anthropogenic erosion. Two main key processes are responsible for agricultural pollution; precipitation and runoff. High Rainfall intensity causes soil detachment which makes soil particles available for sediment runoff into rivers and lakes.

Anthropogenic activities and land-use pressure extremely increase the rates of erosion and sediment deposition in a watershed to very high levels. Apart from Agricultural practices, other such activities may include modification of stream channels, land clearing, urbanization, construction of roads, highways, buildings and reservoirs. Stream bank erosion is also a significant contributor of sedimentation in rivers even though its contribution may not be quite huge as compared to those
stated earlier.

Contribution from upland sources through erosion can be explored as a probabilistic problem (Julien & Frenette, 1985; Julien & Dawod, 1987). However the primary method to calculate average soil erosion losses is the use of the Universal Soil-Loss Equation (USLE) Equation (2.2), which relates the mean annual soil erosion losses (A) to the physical characteristics of upland areas in terms of rainfall erosivity (R), soil erodibility (K), surface runoff length (L), slope steepness (S), croppingmanagement factor (C) and soil conservation practice (P) (Frenette & Julien, 1996).

$$A \quad R \quad K \quad L \quad S \quad C \quad P \tag{2.2}$$

2.5 River Morphology

A river develops several landforms through channel processes. The major channel processes happen in three forms namely; erosion, transportation and sedimentation. Erosion causes a river channel to be broader and deeper and these can also be referred as lateral erosion and deepening erosion respectively. A canyon is formed out of the predominance of deepening erosion.

Rivers with higher velocities have higher capacities for transporting sediments. Corrosion, suspension and traction are three different processes through which a river transports sediments. When water in river channel comes into contact with rocks, it corrodes the rocks and brings them into solution invisibly. Suspension takes place when clay, silt and fine sand particles lighter than water are transported on the water surface or in the water without contact with the river bed. In the case of transporting gravels they slide, rolls or hops on the river bed. This happens through traction.

Heavy rains cause flood. Floods carry vast volumes of sediment materials from mountains to plains at which the transport capacity reduces. An alluvial plain is formed when bed loads are deposited in order of their sizes. An alluvial fan is created at the upmost reaches of the alluvial plain. The alluvial fan is composed mainly of gravel. Fine materials and sand are deposited near a river mouth to form a delta.

River morphology is explained by channel patterns and channel forms, and is decided by such factors as discharge, water surface slope, water velocity, depth and width of the channel, and river bed materials. These factors are not independent but inter-related to each other (Matsuda, 2004).

2.6 Sediment Measurement

Generally, the sampling requirements for sediment in motion (suspended sediment) differ from those that are deposited (bed load). The major purpose of sampling suspended sediment is to determine the quantity (concentration) of the sediment in suspension. In the case of the deposited sediment, sampling is mainly done to determine particle size distribution or the grain size in the cross section.

2.6.1 Bed Load

The bed load or unmeasured load defines the part of the sediment material that moves on or near the stream bed either by rolling or sliding and sometimes making some momentary jaunts into the flow a few diameters above the stream bed. Proper analysis of total sediment yield for a drainage area requires that the bed load is added to the suspended sediment load.

The Meyer-Peter and Muller (1948) Equation (2.3), has been used on two previous occasions in Ghana by Ayibotele & Tuffour-Darko (1974) on the Densu river and on some rivers in the south western and coastal basin systems (Ayibotele & TuffourDarko, 1979). (NEDECO, 1959), also applied the equation on the hydraulic parameters on the Niger and Benue rivers in Nigeria. In the original equation, the coefficient was 8; the 6.5 value was used due to the temperature deviation of the river water in Nigeria.

$$q_s \quad . \, d_m^{\;/2} \sqrt{\Delta g} \left[\frac{V^{3/2}(d_{90}S)^{1/4}}{96 d_m \Delta} - . \quad \right] \qquad (2.3)$$

where, q_s = bed load transport (m^3/sec/unit width)

d_m = arithmetic mean particle diameter (m) = d_{50}

submerged specific gravity of sediment . 8 g =
acceleration due to gravity = 9.81 m^2/s V = flow
velocity (m/s)
d_{90} = particle size for which 90% of the bed material is finer S
= slope of the stream bed.

The bed load can also be computed as a percentage of the measured suspended load. On the average, it is taken as 10% of the suspended load. Appendix E gives the approximation values of bed load from the suspended load based on certain recommended conditions, Subramanya (2013).

2.6.2 Suspended Sediment Concentration

Suspended sediment concentration represents the ratio of the mass of the dry sediment of a water sediment mixture to the mass of the mixture. It is usually expressed in parts per million or grams per litre of the total mixture. Concentration of suspended sediments is influenced by dam construction which traps sediments therefore reducing the concentrations downstream. Overgrown grass and bushes along river channels and hydrological stations have the tendency of trapping sediments from the catchment and therefore preventing them from entering these rivers. This reduces sediment concentrations at such stations.

Monitoring stations which record higher concentrations are likely influenced by upland contributions and anthropogenic activities (Akrasi & Amisigo, 1993). These sediment concentrations are progressively utilized in computing the sediment yield

(tonnes/year) of a catchment area.

a) Suspended Sediment Samplers

Suspended sediment samplers are classified into three types; integrating samplers, instantaneous samplers and pumping samplers. The Integrating type of sampler collects the water-sediment mixture through a small nozzle from the ambient flow over a time period. For the instantaneous sampler, the mixture is trapped by the closing in of the ends instantaneously within a flow-through chamber. Through a pumping action, an intake in the pumping type of sampler withdraws the mixture of the suspended sediment and water.

Generally, the integrating is preferred when the applications of the three are appropriate for a number of reasons: (i) the sediment-water mixture is obtained from a long filament of flow and it does not require any energy input and (ii) the sampler can also be traversed through the flow and so more than a point can be sampled.

Two types of integrating samplers are presently available; the depth and the point integrating samplers.

- The depth-integrating type of suspended samplers (Plate 2.1) comprises of a streamlined „fish" fitted with a nozzle positioned directly into the current. The streamlined fish holds the sampled bottle which collects the samples. Through a process of transiting the entire stream vertical at a uniform velocity (transit rate), the sampler samples the water-sediment mixture over the entire depth (Tilrem, 1979).
- The point-integrating type of sampler is designed to be lowered to any depth prior to the opening of its inlet. It is fitted with a remotely operated valve. It is held at a particular depth and it is operated to obtain a time-integrated sample.

Plate 2.1 Depth Integration sampler.

b) Laboratory determination of suspended sediment concentration In the laboratory, two methods are often used for analyzing water-sediment mixture to determine the suspended sediment concentration. These are the evaporation method and the Filtration method. For high concentrations of sediment, the better of the two is usually the evaporation method. With this method, a conventional oven is used to dry the sediment from the water-sediment mixture to determine the concentration. The filtration method works better for low concentrations of the water-sediment mixture. The procedure involved uses a Gooch crucible with an appropriate filter material to filter out the sediment from the mixture.

2.7 Sediment Yield

The term sediment yield of a catchment describes the total sediment outflow from a drainage basin within a specific period of time. It includes bedload as well as suspended load and expressed in terms of mass, or volume per unit of time. It is dependent on the soil erosion and transporting characteristics of the drainage area as well as the river channels.

The sediment yield is determined by either of the following methods: (i) direct measurement, and (ii) prediction method. The direct measurement method is achieved by sampling the sediment load of the river or resurveying the existing reservoirs. The prediction method uses techniques such as evaluation of gross erosion rate equations, mathematical models, empirical relations from measurements and application of sediment transport equations. Out of the two methods, the direct measurement method is well-thought-out to be the most reliable for sediment yield determination. However, the use of mathematical equations is common because it is less time consuming, relatively cheaper and allows the projection of future scenarios of sediment yield for future planning.

The specific sediment yield (Y_s) of a catchment area is an expression of the ratio of the sediment yield measured in that catchment to the catchment area. It is expressed in tonnes per square kilometres per year (t/km²/yr). Equation (2.4) depicts Ys,

$$\text{Specific Sediment Yield } (Y_s) = \frac{\text{Sediment Yield (t/yr)}}{\text{Catchment Area (km}^2\text{)}} \tag{2.4}$$

2.8 Reservoir Sampling

To be able to determine the sediment yield of a catchment, the most reliable method is to measure the sediment accumulation in a reservoir. After the construction of a dam, a plan to monitor sediment accumulation is necessary to know the actual rate of sediment accumulation in the reservoir.

To determine the actual volume of sediment accumulation in a reservoir, two different surveys for storage volumes are made. They are compared with each other and the difference in capacities between the two surveys gives the measured volume of sediment accumulation.

2.9 Rating Curves

2.9.1 Stage Discharge Rating Curves

In the field, hydrologists often record measurements of stream flows at a known point in a stream and the water level usually called the stage. These two data points are used to develop a rating curve (Figure 2.3), which is a graphical or mathematical expression of the water stage and the stream flow at that same stage. With the rating curve, it is easier to determine a stream flow value if the stage value is known. This is so because the stage reading is much less labour- intensive and less expensive to obtain as compared to the continuous stream flow measurement at that river section.

Rating curves are applicable only over a period of time when it is assumed that there are no significant changes in the cross-sectional area of the stream. High flows sometimes cause substantial changes in the cross-sectional area of streams since it flows with high velocities. Therefore rating curves must be continually updated to reflect physical changes of streams.

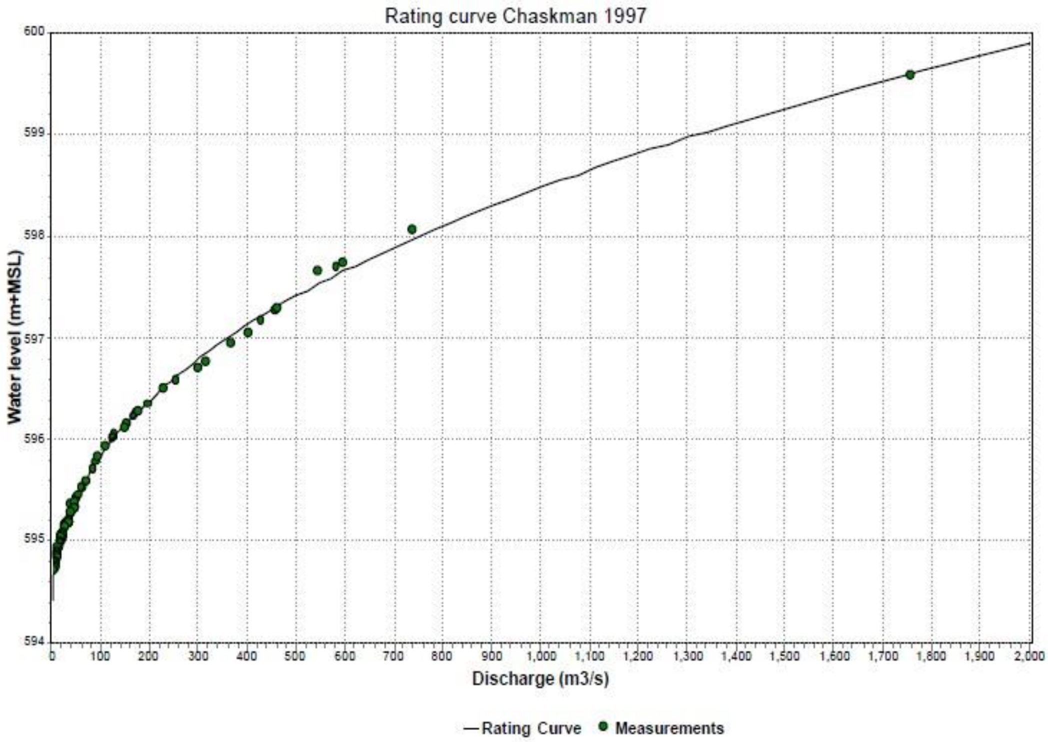

Figure 2.3 Stage discharge rating curve. (Hydrology Project Technical Assistance, 1999).

2.9.2 Suspended Sediment Rating Curve

Suspended sediment rating curves are usually obtainable in one of two different forms. Suspended sediment concentration versus stream flow or suspended sediment discharges versus stream flow (Walling, 1977). Both curves are used to estimate suspended sediment loads in cases where there is insufficient sampling programme.

Generally, the sediment rating curve equation is a power function, Equation (2.5), which either can be in the form of linear or non-linear model. The curve is used to estimate the parameters (***k*** and ***n***) of Equation (2.5).

Amisigo and Akrasi, (1996) established suspended rating curves for Lawra (upstream) and Bamboi (now downstream) of the Bui dam using rating curves that took the form of power functions.

$$S \quad kQ^n \tag{2.5}$$

where *S* is suspended sediment discharge in (t/day), ***k*** is the index of erosion severity, ***n*** is an exponent equal to the slope of the curve and *Q* is the stream flow in (m^3/s).

Usually, sediment rating curves are established using data collected over multiple hydrological years. However, it is possible and adequate to develop an excellent sediment rating curve for one hydrological year sampling programme (Ndomba *et al*., 2008). Results from the study which was conducted in the upstream of Pangani river basin in Tanzania (1DD1 sub-catchment) suggested that for a hydrological year of a sediment sampling programme, an excellent rating curve could be developed.

CHAPTER 3:

STUDY AREA

3.1 Black Volta

3.1.1 Geographical Location

The Black Volta Basin lies between Latitude 7.2 N and 14.50 N and Longitude 5.20 W and 2.10 W (Figure 3.1). The Black Volta River originates from the Sudanian zone of the basin in Burkina Faso and flows between Ghana and Cote D"Ivoire along the western borders of Ghana, from where it flows finally into the Volta Lake. The total length of the Black Volta River is about 1,363.3 km and drains a total area of about 149,015 km², out of which about 35,107 km² (representing about 23.6%) is located in Ghana.

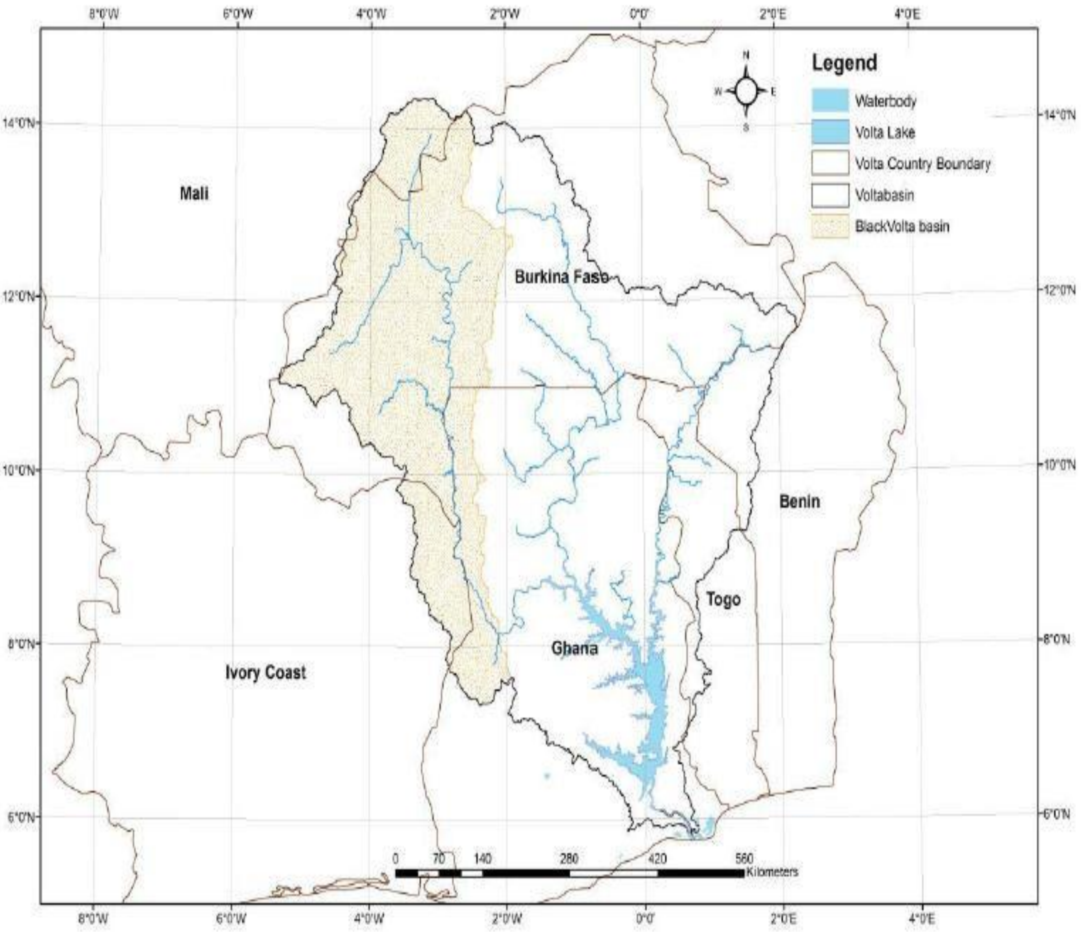

Figure 3.1 Black Volta Basin. (Allwaters, 2012).

3.1.2 Climate

The climate of the Black Volta Basin is dominantly the semi-arid tropical climate with single rainfall season that peaks in August. The extreme southern portions of the basin experience bi-modal rainfall pattern with peaks in June and August. The mean annual rainfall ranges from approximately 1,023.3 mm in the north to 1,348.0 mm in the south. A greater percentage (about 80%) of rainfall within the basin occurs from June to September (Barry *et al.,* 2005).

The pan evaporation is estimated at 2,540 mm per year with a potential evapotranspiration of between 1,450 mm and 1800 per annum (Barry *et al.,* 2005). This is to show that evaporation is high in the basin. The mean annual temperature in the basin is approximately 27 ºC. In the Ghanaian portions of the basin, the mean daily temperatures ranges from range from 25.0 ºC to 27.8 ºC, with high temperatures of about 32 ºC to 44 ºC during the day and as low as 15 ºC in the night. Relative Humidity figures vary between 59% and 77% (Barry *et al.,* 2005).

3.1.3 Land Use

Within the Black Volta Basin, the main land use is Agriculture which is done under extensive bush fallow cultivation of food crop. The predominant food crops under cultivation are yams, millet, sorghum, maize, cassava, beans and groundnuts. Livestock production is a major activity in the basin and this is done at free range grazing.

The insurgence of small scale mining activities in the basin has become a menace to deal with because these miners engage in mining for gold in the main channel river. Land degradation to support crop cultivation and urbanization in the northwest of the basin, mostly in the Lawra district, is a major concern. This causes the destruction of the soil both physically and in terms of its fertility levels which results in its inability to support meaningful cropping.

3.1.4 Geology

The major geological formations in the Black Volta Basin are Granites, Birimian and consolidated sedimentary rocks (Voltaian systems). Some portions of the basin are underlain by the Tarkwaian formation but only to a minor extent. The fundamental rocks of the basin essentially do not have primary porosity which implies the fractured zones in the rocks are where storage of groundwater takes place.

.

3.1.5 Soils

The major soil groups in the Black Volta basin are the Luvisols and the Gleysols (Figure 3.2), based on the FAO soil classification of soils (Allwaters, 2012). On the Ghanaian side of the basin, Ferric Luvisols dominates the soils.

3.1.6 Water Resources in the Black Volta Basin

The two major water resources in the basin are surface water and groundwater. The main surface water resource is the Black Volta River. The mean runoff in the Black Volta River is 7 km^3 per annum. Its driest and wettest months are March and September, respectively. There are three hydrological stations on the main channel of the Black Volta river in Ghana, namely, Lawra, Chache and Bamboi. Lawra and Chache are upstream of the Bui reservoir while Bamboi is located at the downstream.

Groundwater resource is mostly tapped during the dry season when most part of the basins surface systems dry out. Borehole yields ranges between 0.1 m^3/h - 36 m^3/h while the depth to aquifer also ranges from 4.3 m - 82.5 m (Allwaters, 2012). In the Volta river system, the average annual recharge is about 5% - 12% of the annual rainfall in weathered rocks. Annual rainfall beyond 380 mm in the weathered rocks goes to recharge the groundwater system. Groundwater is able to satisfy the domestic needs of the predominantly rural nature of the Black Volta basin.
Therefore monitoring the quality of groundwater is frequently carried out.

The main problems with groundwater in the basin are excesses in fluoride and iodine deficiencies (< 0.005 mg/l) coupled with hardness. The use of water in the Black Volta basin is primarily for agriculture, fishing, livestock, domestic purposes, the environment and currently mining (legal and non-legal).

3.2 Bui Hydroelectric Power Dam

3.2.1 Bui Dam

The Bui hydroelectric dam project (Plate 3.1) was designed mainly for hydropower generation. In spite of that it also involves the provision of improved water supply for the development of an irrigation scheme for agricultural development and domestic use. It also extends to presenting a prospect for improved ecotourism and fisheries development.

Plate 3.1 Structure of the Bui Dam

3.2.2 Reservoir

The Bui Reservoir (Plate 3.2) is located on the border of Bole in the Northern region and Wenchi in the Brong-Ahafo region with coordinates 8º 16' 42" N and 2º 14' 9" W. Maximum and minimum temperatures at the Bui Reservoir are 29.6 ºC and 20.6 ºC respectively with a mean annual temperature of 25.5 ºC. Total annual rainfall is about 967 mm (FAO, 2005).

The reservoir at Maximum Operating Level has a height of 183 m NLD (National Level Datum) and a surface area of approximately 440 km^2. The reservoir impounds water on the Black Volta River with a total capacity of 12.35 billion cubic metres (m^3). The reservoir operates at a Minimum Operating Level of 167 m NLD. At this level, the reservoir will have a surface area of 288 km^2 at a total storage volume of 6.6 billion cubic metres (m^3).

Plate 3.2 Bui Reservoir

3.2.1 Power Generation

The power intake of the dam consists of three penstocks on the downstream face of the dam to convey water from the reservoir into the powerhouse. In the powerhouse (Plate 3.3) are three vertical shaft Francis-type turbines, each having an installed capacity to generate 133 MW of power. The maximum power generational capacity is 400 MW.

Plate 3.3 Bui Power Generation station showing the three penstocks

3.3 Sampling Stations

3.3.1 Chache

The sampling point for which this study will be carried out is Chache discharge gauge station (Plate 3.4). It is located at latitude 09° 10' N and longitude 02° 43' W in the Bole District of the Northern Region of Ghana, approximately 110 km upstream of the Bui reservoir. The station is located on the Black Volta River and it discharges water directly into the Bui Reservoir.

The annual mean temperature for the sampling station is 26.4 °C with maximum and minimum temperatures of 31.6 °C and 20.5 °C respectively. Total annual rainfall is about 1118 mm (FAO, 2005). The gauge station experiences a weak bi-modal rainfall pattern, with a minor peak in June and a major peak in September.

 

Plate 3.4 Automatic Gauge recorder and Staff Gauges at Chache gauged station

3.3.2 Bamboi

Bamboi gauge station (Plates 3.5 and 3.6) is located about 26 km downstream of the Bui dam with coordinates, latitude 08° 09' N and longitude 02° 02' W, on the Black Volta River. The mean annual temperature is 25.5 °C with annual maximum temperature of 29.6 °C and annual minimum temperature of 20.6 °C. The sum of annual rainfall for Bamboi is 1259 mm (FAO, 2005).

Below in Figure 3.3 shows the map of Ghana and its regions with the sampling stations, the Black Volta basin and river and the Volta Lake. The sampling stations; Chache and Bamboi gauge stations are located upstream and downstream respectively of the Bui reservoir.

Plate 3.5 Staff Gauges at Bamboi

Plate 3.6 Bridge and small scale miners (Galamsey operators) at Bamboi gauged station.

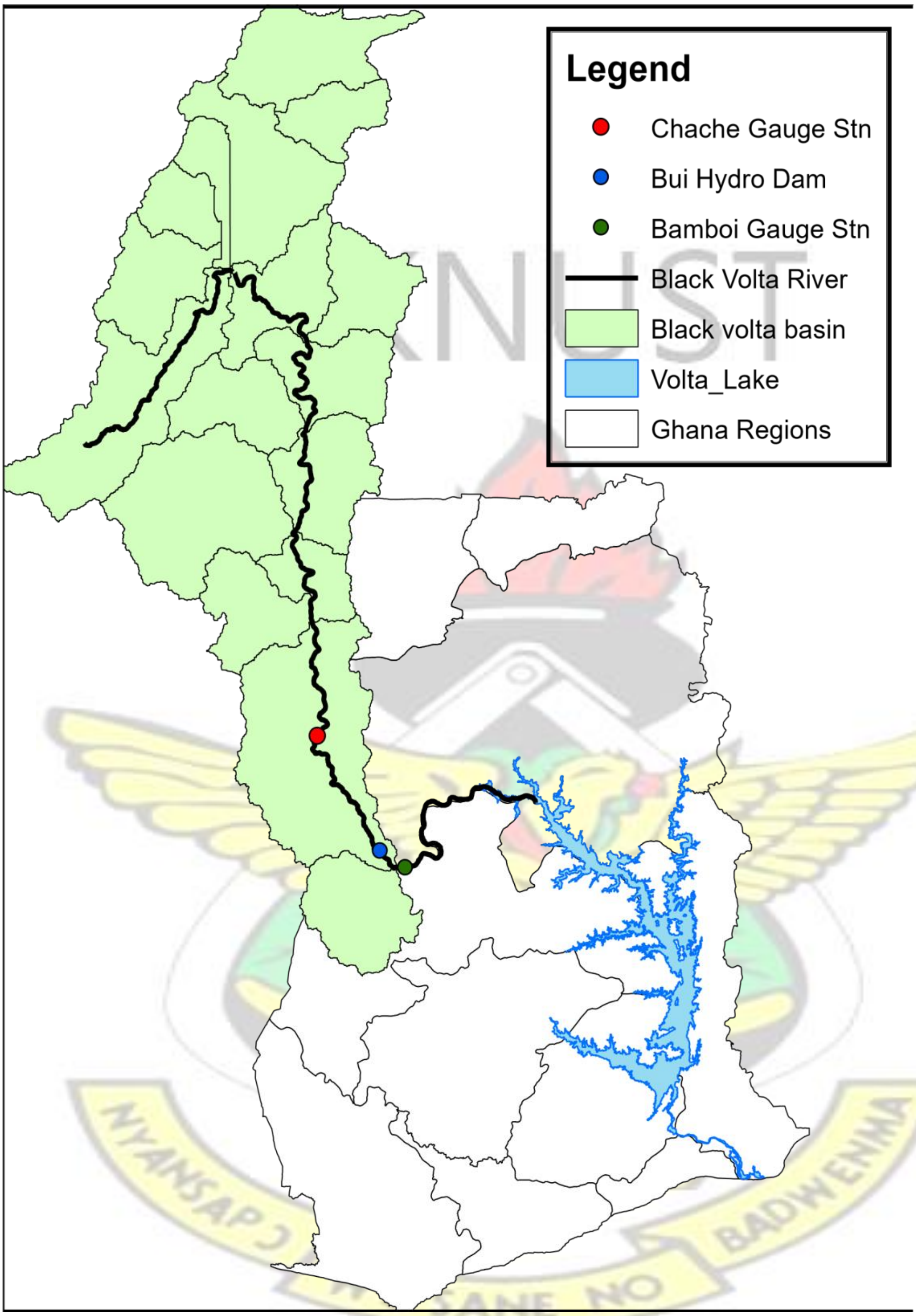

Figure 3.2 Map of study area showing sampling stations.

CHAPTER 4:

RESEARCH METHODOLOGY

4.1 Stage Discharge Rating Curve

A stage-discharge rating curve was established for Chache and compared to an existing one that was developed in the 1970s to determine the validity of the old curve which is still used by the Ghana Hydrological Services Department. The development of the rating curve was based on Equation (4.1) (Hydrology Project Technical Assistance, 1999), which expresses the discharge as a power function of the river stage.

The assumptions associated with the use of Equation (2.5) are that: (i) the discharge contained in the main channel section is fairly steady, (ii) there is no backwater effect to affect the nature of the relationship, (iii) observational errors are not significant, and (iv) there is no significant change in the river bed which could distort the stage-discharge relationship. The type of equation usually recommended for stage discharge rating curves is the power type of equation in the form

$$Q \quad a\,h - c^{\,b} \qquad (4.1)$$

Where ***Q*** is the discharge, ***h*** is the gauge height, ***'a'*** and ***'b'*** are rating curve coefficients and ***c*** is the datum correction, which is the value of the stage for which the discharge Q is zero. This value was determined using the Johnson method

Boiten, as shown in Appendix C.

The values of ***a*** and ***b*** were determined using the method of least squares of linear regression as described by Raghunath (2006). By denoting Q as Y, and (h-c) as X, Equation (4.1) was re-written in the form of a linear relationship as shown in Equation (4.2). The least square line was then obtained from a log-log plot of discharges and stages that were obtained through field measurements. The values of $\boldsymbol{\alpha}$ and **β** were then estimated by solving equations 4.3 and 4.4 simultaneously.

log loga blog (4.2)

The least square line was obtained by solving for ***a*** and ***b*** with the following two equations;

$$\sum^{N} \log \quad n \quad \sum^{N} \log \qquad 4.3)_{i} \quad _{i}$$

$$\sum^{N} \log \log \quad \sum^{N} \quad \sum^{N} \log X^{2}\ 4.4)_{i} \quad _{i\ i}$$

Where, N is the number of pairs of observed values of X and Y, $\boldsymbol{b} = \beta$ and$\boldsymbol{a} =$ 10^{α}.

4.1.1 Discharge Measurements

Discharge measurement was carried out at Chache and Bamboi monitoring stations on monthly basis from August, 2014 to February, 2015. In order to have data for a complete hydrological year, the rest of the data from February, 2014 to November, 2014 for Chache monitoring station was collected from Ms. Fati Aziz (PhD student, WASCAL) who had already began sampling and measurement.

The discharge measurements were done with the OTT Qliner 2 (Plate 4.1) using the classic vertical processes. The cross-section of the river channels were divided into numerous verticals at five (5) metres intervals using a calibrated rope. At each of these specific intervals across the river channel, the OTT Qliner 2 measured the water depth and the vertical velocity distribution using the ultra sound technology.

The water depths and vertical velocities data obtained were then used to calculate the average flow velocity of each vertical and as well the partial discharge of a discharge segment defined in accordance with EN ISO 748 (mid-section method). After completing the measurement of all verticals, the complete discharge of the river channel was calculated as the sum of all partial discharges. In addition to the discharge, the Qliner calculated the cross-sectional area, the average water depth as well as the average velocity of the cross-section.

Plate 4.1 Discharge measurement with Qliner

4.1.2 Stage Measurement

Monthly and bi-monthly data of the stages of the channel were obtained by taking from reading the staff gauges installed by the Ghana Hydrological Services Department at Chache (Plate 3.5).

4.2 Suspended Sediment Rating Curve

A suspended sediment rating curve was developed for the Chache monitoring station based on Equation (2.5). A set of suspended sediment load and the discharge measured at the time of sampling were plotted on a double log sheet and the coefficients k and n determined using the method of least squares of linear regression as described in Equations (4.2), (4.3) and (4.4). The input into Equation (2.5) involved, the instantaneous discharge and the sediment load computed using Equation (4.5) (Akrasi, 2008).

$$Q_{is} \quad . 8 \quad C_sQ_{iw} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. } 4.5$$

Q_{is} = instantaneous suspended sediment load in t/day
Q_{iw} = instantaneous water discharge (m^3/s)
C_s = integrated mean suspended sediment concentration (mg/l).

4.2.1 Suspended Sediment Sampling

The depth integrating sampler (plate 2.1) was used (plate 4.2), as described in Section 2.6.2 (a), in collecting samples of water-sediment mixture for laboratory analysis to determine the suspended sediment concentration. Four suspended sediment samples were collected across the cross-section of the river channel at different locations in order to have a fair distribution of the sediment across the channel. The integrated mean of the four samples was then determined and used in Equation (4.5).

Plate 4.2 Suspended sediment sampling with the depth-integrating sampler

4.2.2 Laboratory Analysis for Suspended Sediment Concentration

From the field, the samples were transported into the Water Research Institute Sediment laboratory, weighed to the nearest gramme and kept in a dark cool place in order to reduce evaporation losses and growth of organisms. The weighed samples were left undisturbed for the sediment to settle at the bottom of the sampling bottles. A period of three weeks was used during the settling period.

The sediment concentration was determined using the Oven Dry Method developed by Tilrem (Tilrem, 1979). After the settling period, the samples were weighed to record the gross sample weight in grammes. The supernatant water was decanted (Plate 4.3) and the remaining sediment (usually same amount for a particular gauging station) was washed into a known weight of empty evaporating dish. The supernatant water was carefully decanted in such a manner that, none of the sediments was removed from the bottom of the container.

The samples were weighed and dried in a convection-type drying oven at a temperature of 95^0C in order to prevent the loss of sediment through spattering at higher temperature above boiling point. After all the visible moisture had evaporated, the temperature was raised to 110 ^{0}C for about an hour to complete the drying process. The evaporating dishes were removed after the drying process and were kept dried in a desiccator to cool. After cooling, the samples were weighed immediately to the nearest 0.1 mg to determine the net sediment weight.

The sample bottles were cleaned, air dried and weighed to determine the net weight of the water-sediment mixture in grammes. The suspended sediment concentration was calculated in parts per million (ppm) and then converted into milligrammes per litre (mg/l) as in Equations (4.6) and (4.7), using a conversion factor C.

$$\frac{\text{Dry weight of sediment g}}{\text{Net sample weight g}} \quad (4.6) \text{ ppm}$$

From ppm to mg/l as

$$\text{mg/l} \quad C \quad \text{ppm} \qquad (4.7)$$

The factor C (Appendix A) is based on the assumption that the density of water is 1000 kg/m^3, plus or minus 0.005, the range of temperature is 0 – 29 ^{0}C, the specific gravity of sediment is 2.65, and the dissolved solids concentration is less than 10,000 ppm (Tilrem, 1979).

Plate 4.3 Decantation of supernatant water.

4.3 Total Annual Sediment Load and Yield

The suspended sediment load was computed for all of the months using Equation (4.5). The maximum suspended sediment load in t/day was used to compute the total annual suspended sediment load in tonnes per year at Chache. The total annual bed load was taken as 10% of the suspended load, using the Maddock"s classification for estimating bedload (Maddock, 1975) as shown in appendix E. The maximum suspended load computed in parts per million was less than a thousand, the type of bed material was rocky with the texture of suspended material of small amount of sand. The total annual sediment yield was further computed as the summation of the annual suspended sediment load and the annual bed load for Chache.

Following from the computation of the total annual sediment yield at Chache, the specific sediment yield (t/km²/yr) was computed as shown in Equation (2.4). Due to lack of specific yield data for Bui, it was assumed that Bui and Chache have the same specific sediment yield and therefore resulting specific sediment yield at

Chache was multiplied by the catchment area of the Black Volta Basin at Bui to determine the quantity of sediment deposited annually in the Bui Reservoir. The catchment areas of the Black Volta Basin at Chache and Bui are 109,078 km^2 and 121,026 km^2 respectively.

CHAPTER 5:

RESULTS AND DISCUSSIONS

5.1 Analysis of Discharge and Sediment

The results of river water stages, discharge measurements, suspended sediment concentrations (SSC), and suspended sediments (SS) loads collected from and computed for Chache and Bamboi for the 2014/2015 hydrological year are shown in Tables 5.1 and 5.2. For the Chache location, the data collected in this study was complimented by data obtained from an on-going work of a PhD student at the same location.

In the 2014/2015 hydrological year, the level of water in the Black Volta River measured at Chache varied from a minimum of 0.92 m in April, which is the end of the dry season and beginning of the wet season in the basin, to a maximum of 4.78 m in September, which is the peak month of the rainy season. The corresponding measured discharges ranged from 4.44 m^3/s in April to 508.41 m^3/s in September. At Bamboi, the minimum water level measured was 2.10 m in August and the maximum level was 4.40 m in April. The corresponding discharges computed were 53.42 m^3/s for August and 274.87 m^3/s for April.

Suspended sediment concentration measured at Chache varied from a minimum of 10.10 mg/l in February to a maximum of 328.15 mg/l in August. Suspended sediment (SS) loads at the same point ranged from 5.17 t/day in February to 3075.36 t/day in August. At Bamboi, the minimum and maximum SSC obtained were 13.87 mg/l in February and 51.28 mg/l in October, respectively. The SS loads calculated was a minimum of 42.44 t/day in December and a maximum of 529.77 t/day in

October.

Table 5.1 Hydrology and sediment data collected and computed at Chache for the 2014/2015 hydrological year.

Dates of Sampling	Gauge Heights (m)	Discharge Q (m^3/s)	SSC (mg/l)	SS Load (t/day)
15/03/2014	1.06	6.91	14.10	8.42
18/04/2014	0.92	4.44	16.69	6.45
30/05/2014	1.18	8.95	14.70	11.37
20/06/2014	1.74	17.92	142.57	220.73
23/07/2014	2.62	98.22	112.57	955.26
07/08/2014	3.00	108.47	328.15	3075.36
19/08/2014	3.25	240.85	66.77	1389.38
17/09/2014	4.60	409.25	79.65	2816.36
26/09/2014	4.78	508.41	40.97	1799.53
15/10/2014	4.40	233.12	33.33	671.22
21/10/2014	3.44	270.52	47.10	1100.86
19/11/2014	1.54	29.47	35.25	89.75
27/11/2014	1.43	22.83	31.00	61.15
19/12/2014	1.20	13.31	20.35	23.40
15/01/2015	1.10	8.11	18.40	12.89
18/02/2015	1.00	5.92	10.10	5.17

Table 5.2 Hydrology and sediment data collected and computed at Bamboi for the 2014/2015 hydrological.

Dates of Sampling	Gauge Heights (m)	Discharge Q (m^3/s)	SSC (mg/l)	SS Load (t/day)
07/08/2014	2.10	53.42	24.92	115.02
17/09/2014	3.00	114.53	46.00	455.19
15/10/2014	3.00	119.57	51.28	529.77
18/11/2014	3.90	204.79	27.30	483.04
18/12/2014	2.80	26.71	18.39	42.44
14/01/2015	3.20	64.69	14.72	82.27
17/02/2015	3.20	94.18	39.74	323.37
17/03/2015	3.00	104.66	15.75	142.42
26/04/2015	4.40	274.87	13.87	329.49

5.1.1 Discharge Hydrograph

The Figure 5.1 below shows the results of the discharge measurements at Chache during the monthly sampling programme in relation to the rainfall pattern. Both charts show a similar trend. Discharge rises gradually from the beginning of the hydrological year with increase in rainfall. Rainfall has a minor peak in June and a major peak in September. This shows that rainfall experiences a bi-modal pattern in the lower portions of the Volta basin. The rainfall from March to June had very little influence on the discharges. Its main purpose is to replenish the soil moisture and very little goes for runoff.

From June, as the rainfall further increased, the runoff from the land surfaces increased as the soil moisture increased. This caused a significant rise in discharges in the channel with increasing runoff. The increases in the runoff and hence the discharges also caused increases in the suspended sediment concentration although they were in lower quantities, thus less than 1000mg/l.

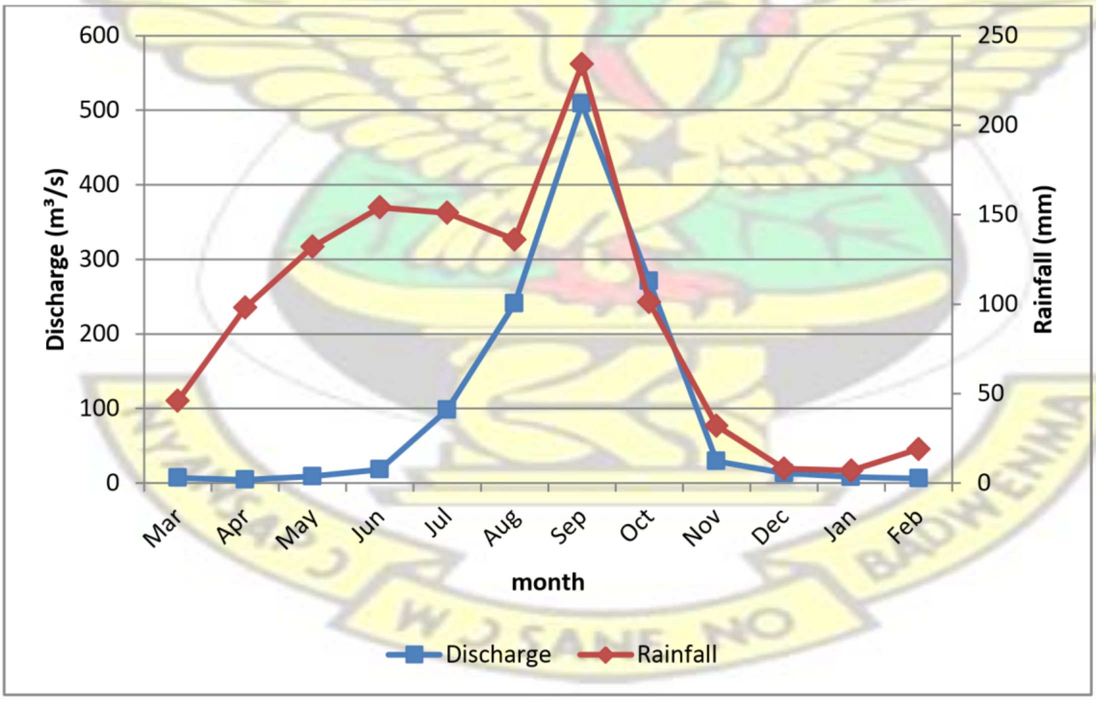

Figure 5.1 Discharge, Rainfall Hydrograph for Chache

5.1.2 Stage Discharge Rating Curve

Figure 5.2 shows the rating curve developed for Chache on a double log scale. The curve depicts the relations between discharge and stage height at that location. After fitting the best line to the set of discharge and stage data, the coefficient of determination (R^2) for the rating curve was computed as 0.87, which is an indication of a very good correlation between the discharge and stage height at Chache.

Based on Equations (4.4) and (4.5), the rating curve in Figure 5.2, and data in Table 5.3, a rating curve equation that shows the relationship between discharge and stage height was established at Chache as depicted by Equation 5.1. The value of the datum correction in Equation (4.4), ***(c)*** was calculated to be ***1.04***. The other parameters in Equations (4.4) and (4.5) were computed as follows: **α** = 1.9065, **β** = 0.8789, ***a*** = 80.631 and ***b*** = 0.8789.

Q 8 . h - . .8 8 (5.1)

where Q = discharge, and h = stage height.

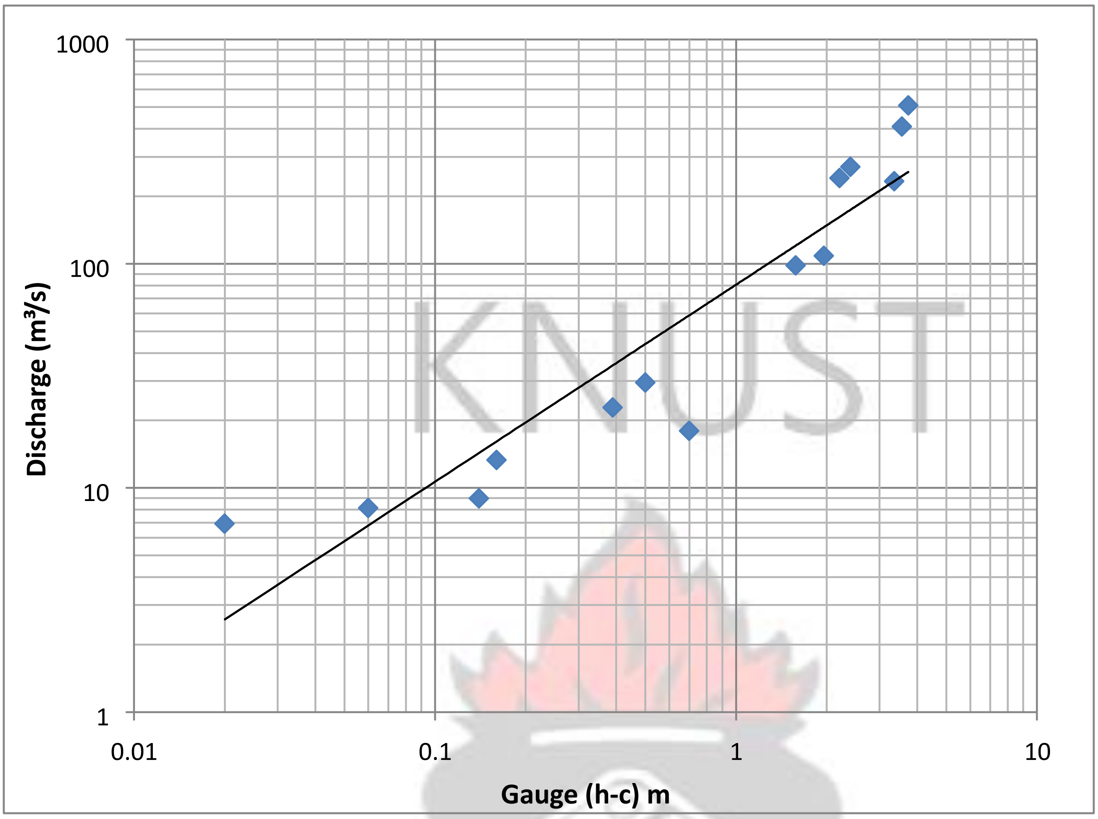

Figure 5.2 Stage Discharge Rating Curve for Black Volta River at Chache.

Table 5.3 Data for computing rating curve coefficients

X (h-c)	Y (Q)	Log X	Log Y	Log X*Log Y	Log X²
0.02	6.91	-1.6990	0.8395	-1.4262	2.8865
0.14	8.95	-0.8539	0.9518	-0.8127	0.7291
0.70	17.92	-0.1549	1.2533	-0.1941	0.0240
1.58	98.22	0.1987	1.9922	0.3958	0.0395
1.96	108.47	0.2923	2.0353	0.5948	0.0854
2.21	240.85	0.3444	2.3817	0.8203	0.1186
3.56	409.25	0.5514	2.6120	1.4404	0.3041
3.74	508.41	0.5729	2.7062	1.5503	0.3282
3.36	233.12	0.5263	2.3676	1.2462	0.2770
2.40	270.52	0.3802	2.4322	0.9247	0.1446
0.50	29.47	-0.3010	1.4694	-0.4423	0.0906
0.39	22.83	-0.4089	1.3585	-0.5555	0.1672
0.16	13.31	-0.7959	1.1242	-0.8947	0.6334
0.06	8.11	-1.2218	0.9090	-1.1107	1.4929
Σ20.78		**-2.5693**	**24.4330**	**1.5361**	**7.3211**

The rating curve equation derived from the 2014/2015 hydrological year was compared to that of the existing one being used by the Ghana Hydrological Services (HSD) for Chache (Table 5.4). The HSD rating curve was developed in the 1970s. It can be noted that the datum correction and the constants ***'a'*** and ***'b'*** have changed since the HSD equation was established. The implication is that, the continuous use of the HSD rating curve equation for computing discharges at Chache will lead to results that do not reflect the true discharges.

Table 5.4 Comparing Parameters for Rating Curve Equations at Chache

Chache	**a**	**b**	**C**
Existing	13.4109	2.4503	0.3965
New	80.631	0.8789	1.0433

5.1.3 Suspended Sediment Concentration

The suspended sediment concentrations (SSC) measured at Chache and Bamboi (Tables 5.1 and 5.2) were relatively low, with the maximum SSC being lower than 1000mg/l. Similar results were obtained by Amisigo & Akrasi (1996) for several locations in the Volta basin. The maximum concentration computed within the sampling period was 328.15 mg/l in August 2014 for Chache and 51.28 mg/l in October 2014 for Bamboi. The minimum SSC for Chache was 10.10 mg/l measured in February 2015 while a minimum value of 14.72 mg/l was measured at Bamboi in December 2014.

Figure 5.3 shows a scatter plot of suspended sediment concentration with its corresponding gauge height. There appeared to be a very low correlation between the

SSC and gauge height at Chache. There was no significant increase in the SSC as the stage height increased and the maximum concentration did not correspond to the highest stage measurement. A possible cause of this happening could be as a result of heavy rainfall or flood event having occurred prior to the time of sampling. The low concentration values were directly connected to low gauge heights which were noted to have been the case during the dry season within the Black Volta Basin.

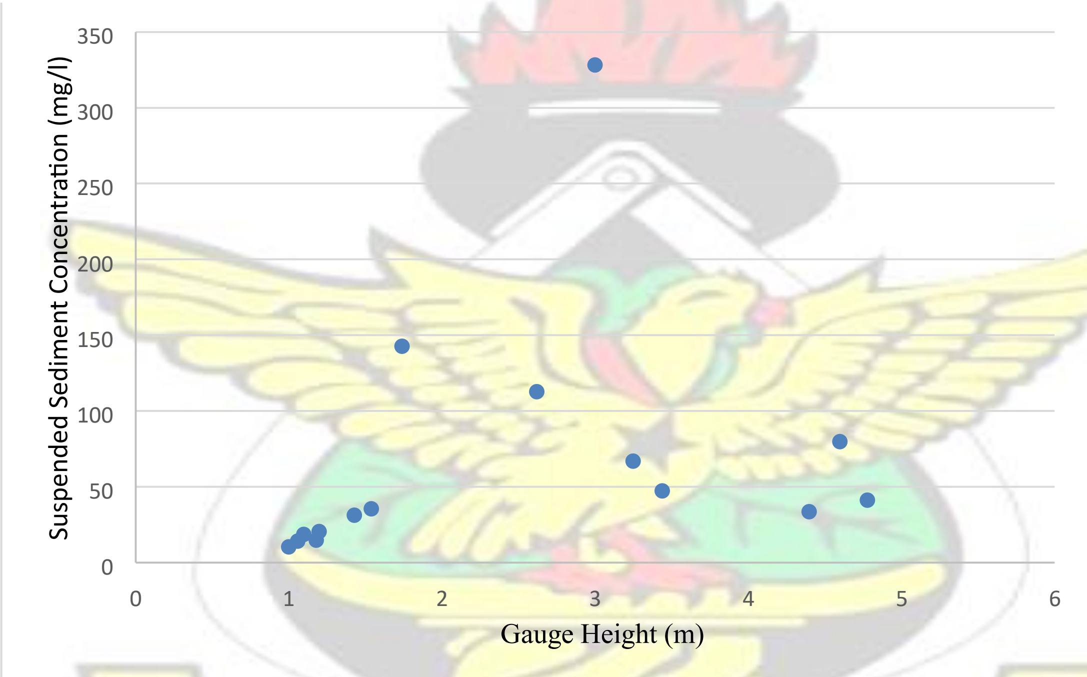

Figure 5.3 Suspended sediment concentration versus stage for Black Volta River at Chache.

Figures 5.4 and 5.5 show hydrographs of suspended sediment concentrations and discharges at Chache and Bamboi, respectively. For both locations, suspended sediment concentration increases with increasing discharge. However, it can be noted that the peaks of both suspended sediment concentrations and discharge do not coincide for both Chache and Bamboi.

The time lag between the peak discharges and peak suspended sediment concentrations in both Figures (5.4 and 5.5) could be as a result of the differences between the density of water and that of sediments. The difference in their densities leads to differences in their velocities.

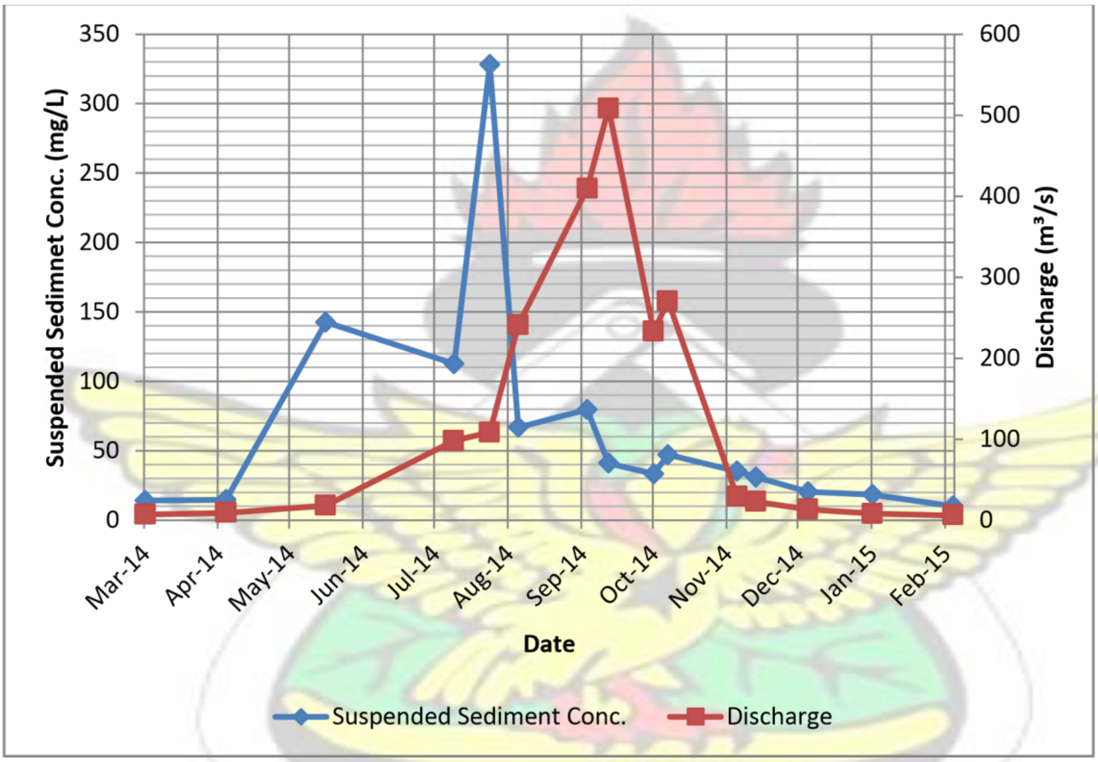

Figure 5.4 Hydrograph of suspended sediment and discharge at Chache.

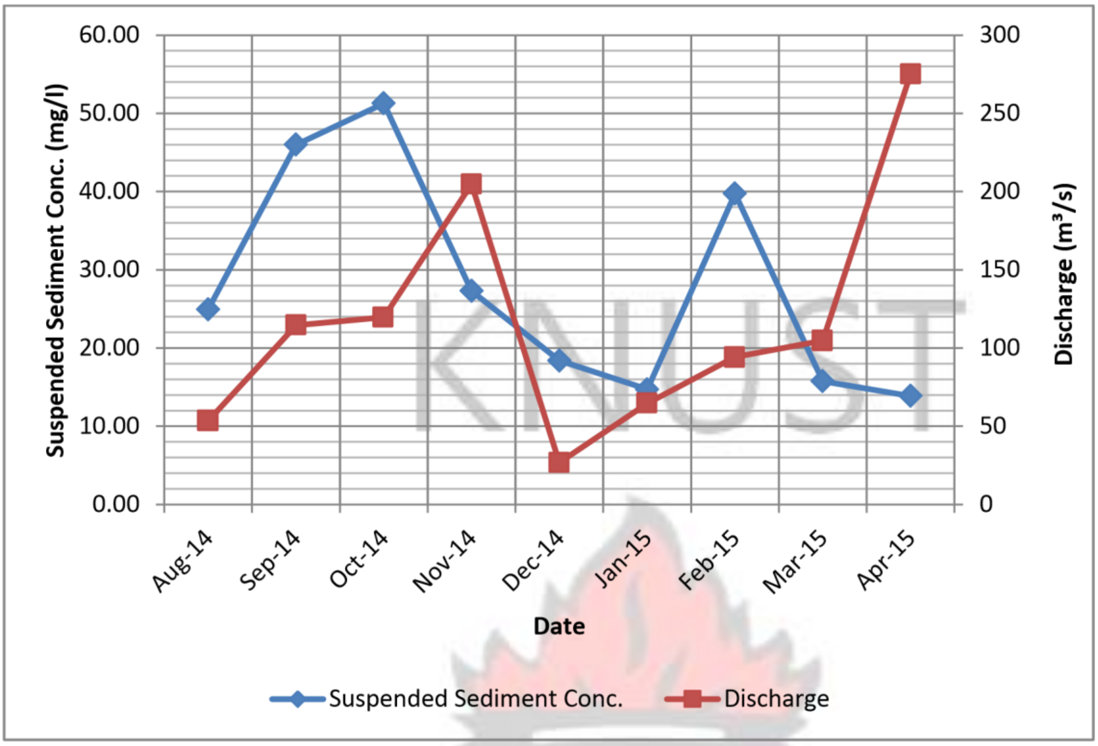

Figure 5.5 Hydrograph of suspended sediment and discharge at Bamboi.

5.1.4 Suspended Sediment Load

To overcome the scatter nature of the suspended sediment concentration values, the sediment concentrations were converted to sediment load in tonnes per day using Equation (4.5).

The resulting suspended sediment loads were used, together with the stream channel discharges measured at the time of sediment sampling (Table 5.1) to establish a suspended sediment rating curve on a double log scale (Figure 5.6).

5.1.5 Suspended Sediment Rating Curve

The equation of the suspended sediment rating curve established for Chache (Figure

5.6) is depicted by Equation (5.2):

S . Q . 8 (5.2)

where S is the suspended sediment load (tons/day) and Q is the discharge (m^3/s). The coefficients (***k*** =1.0923 and ***n*** =1.3478) in the general form of the Equation (2.5) were determined using the linear regression as explained earlier under Section 4.1, together with Table 5.5. The value of R^2 obtained for the rating equation is 0.89, which is an indication of a strong correlation between sediment loads and discharge at Chache.

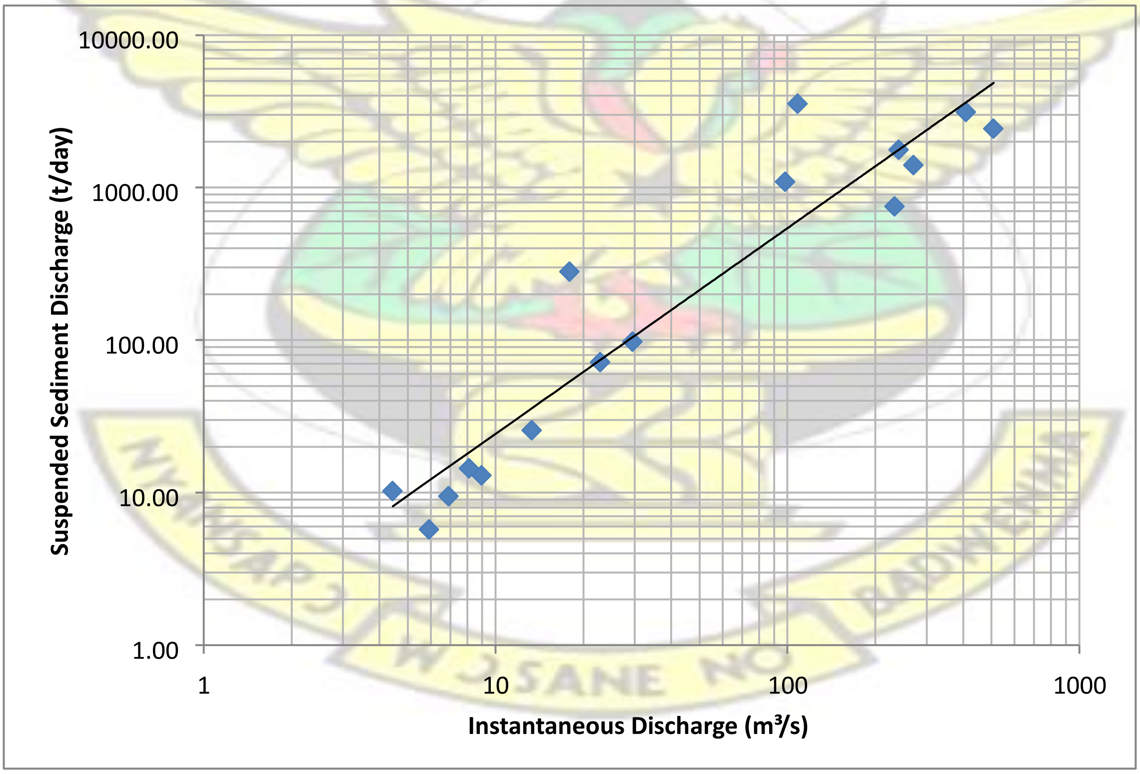

Figure 5.6 Suspended sediment rating curve for the Black Volta River at Chache.
Table [1].5 Data for computing suspended sediment rating curve coefficients

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[1] .1.6 Total Annual Sediment Yield at Chache

6.91	9.46	0.84	0.98		0.70
4.44	10.24	0.65	1.01	0.65	0.42
8.95	12.99	0.95	1.11	1.06	0.91
17.92	280.70	1.25	2.45	3.07	1.57
98.22	1089.71	1.99	3.04	6.05	3.97
108.47	3537.01	2.04	3.55	7.22	4.14
240.85	1763.60	2.38	3.25	7.73	5.67
409.25	3124.69	2.61	3.49	9.13	6.82
508.41	2435.73	2.71	3.39	9.16	7.32
233.12	752.49	2.37	2.88	6.81	5.61
270.52	1402.84	2.43	3.15	7.65	5.92
29.47	97.80	1.47	1.99	2.92	2.16
22.83	71.78	1.36	1.86	2.52	1.85
13.31	25.68	1.12	1.41	1.58	1.26
8.11	14.40	0.91	1.16	1.05	0.83

The total annual sediment yield was computed to know the total amount of sediment being transported by the Black Volta River at Chache. The maximum suspended sediment concentration recorded during the monitoring period of this study was used to compute the maximum suspended sediment load in t/day. The annual suspended sediment load at Chache was estimated to be 1,122,506 t/yr. The bed load at Chache was approximated at 112,250 t/yr, based on Maddock"s classification for estimating bedload and the characteristics of the river bed material as mentioned under Section 4.3. Therefore, the total annual sediment yield (annual suspended sediment load plus bedload) at Chache was estimated at 1,234,756 t/yr.

5.92	5.72	0.77	0.76	0.59	0.60	**X (Q)**
Σ 1986.70		**25.85**	**35.46**	**68.03**	**49.74**	**Y (Q_s)**

Log

	LogX*LogY	
X Log Y	0.82	**Log X²**

5.1.7 Specific and Total Sediment Yield

The specific sediment yield for the Black Volta at Chache was computed to be 11.3 t/km²/yr using Equation (2.4). Based on the assumption in Section 4.3, the total annual sediment yield in the Bui Reservoir was estimated at 1,370,007 t/yr.

5.2 Discussion

The new discharge rating curve equation was used to compute the long term monthly average historic discharges (Appendix B) at the Chache monitoring station and was compared with using the existing rating equation as in Table 5.6. The effects of continuous use of the existing rating equation to compute discharges from recorded stage heights showed some level of disparity in the results when the new equation was used (Figure 5.7). During the wet season, the new equation indicated relatively lower discharge values than that of the existing equation. In the dry season, the new equation resulted in no discharges whereas the existing equation recorded values of discharges.

These effects in using existing rating curves without periodically updating them do not take into account the changes that occur in the river channel. The values of discharges predicted from using the existing rating equation will therefore not give a true reflection of the discharges within the channel and also liable to a number of errors.

Table 5.6 Comparison of Existing and New Rating Equation using long-term average data at Chache

Month	Q (m^3/s), Using Old Rating Equation	Corresponding Gauge Height (m)		Q (m^3/s), Using New Rating Equation
		h	(h-c)	
Mar	2.61	0.61	-0.43	0.00
Apr	4.32	0.71	-0.33	0.00
May	14.87	1.08	0.04	4.96
Jun	31.42	1.44	0.40	36.11
Jul	87.92	2.17	1.13	89.66
Aug	280.28	3.47	2.43	175.65
Sep	547.47	4.55	3.51	243.06
Oct	259.97	3.36	2.32	169.00
Nov	40.19	1.59	0.55	47.47
Dec	12.31	1.01	-0.03	0.00
Jan	5.46	0.76	-0.28	0.00
Feb	3.60	0.67	-0.37	0.00

The Black Volta River discharge at Chache is seasonal and shows a trend that depicts the rainfall pattern in the basin (Figure 5.1). There is a linkage between the annual rainfall pattern and the annual discharges in the study area. This was corroborated by (Giesen *et al*., 2001), that there is a correlation between monthly rainfall and river discharges in the Volta Basin.

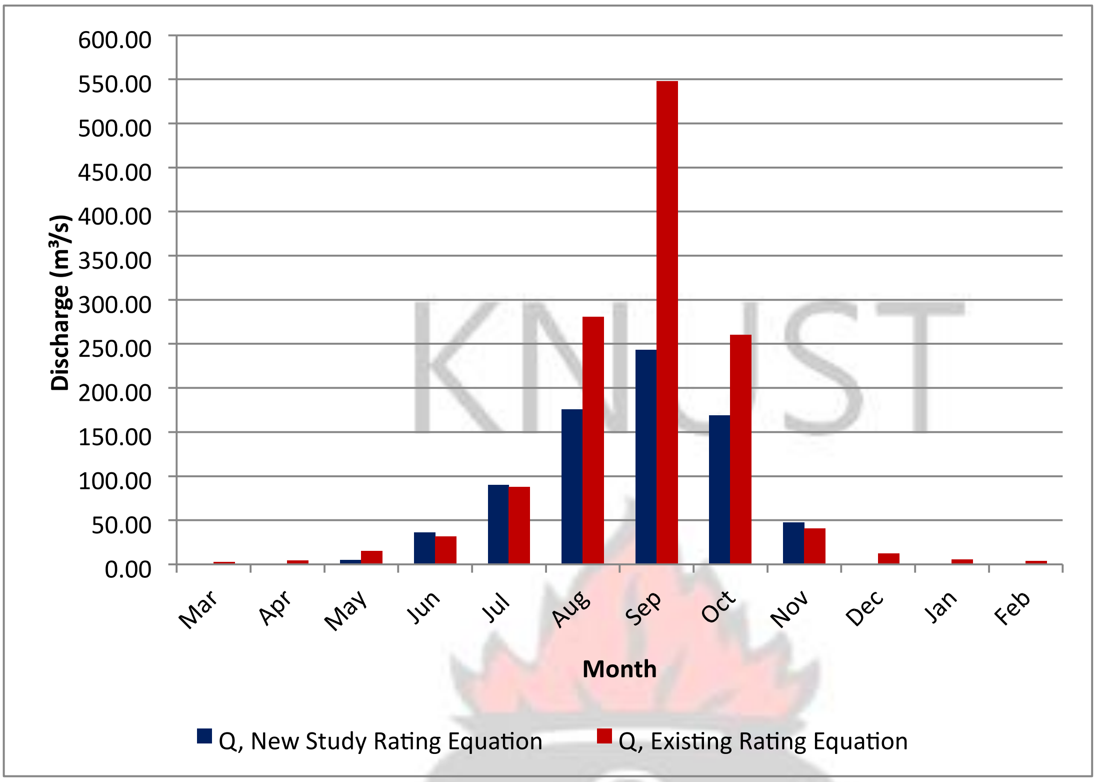

Figure 5.7 Computed long term monthly mean discharges using both existing and new rating curve equations at Chache Gauge station.

The analysed suspended sediment concentrations recorded were compared with previous works done on the Black Volta River by Amisigo and Akrasi in 1996 for Lawra and Bamboi monitoring stations (Appendix D2). No previous studies have been done at Chache. The maximum suspended concentration recorded at Lawra (upstream) was 470.0 mg/l and a higher concentration recorded at Bamboi (downstream), thus 568.0 mg/l. This suggested that sediment load and suspended sediment concentration increases as one move downstream of the river.

Maximum concentrations at both upstream and downstream of the Bui dam for this study were 377.41 mg/l and 51.28 mg/l, respectively. Their respective suspended sediment loads were 3537.01 t/day and 529.77 t/day. Comparing the results at

Bamboi with the 1996 study by Amisigo and Akrasi clearly indicates the impacts caused by the construction of the Bui dam since suspended sediment concentrations have significantly reduced. The expectation that, lower suspended sediment concentrations and loads would be recorded at Bamboi due to the construction of the dam was proven to be true, in that, dams act as effective traps to sediments.

A similar occurrence was established at Akosombo and Akuse dams (Akrasi and Amisigo, 1993). These dams had served as effective sediment traps for sediment produced upstream hence reducing the suspended concentrations as well as sediment loads downstream.

In the 1996 study (Appendix D1), concentrations in the White Volta at Pwalugu and Nawuni were much higher than those in the Black Volta. Relating those figures with the results captured under this study at Chache again show a similar trend. The maximum suspended sediment concentrations in other major rivers in Ghana such as Daka, Afram, and Pru at Ekumdipe, Afram, Pruso and Prang were lesser than that of the Black Volta at Chache.

There has not been any suspended sediment rating curve developed for the study area at (the Chache gauged station, which is the last gauged station upstream of the Bui Reservoir). Therefore the sediment and flow data collected in this study have been used to establish a sediment rating curve to aid in predicting future sediment discharges. The value of the goodness of fit (R^2) for the established sediment rating curve at Chache was higher than the corresponding values for Lawra and Bamboi but was slightly lower than what was obtained by Akrasi, (2005) for Bamboi.

Unfortunately, the sediment rating curve developed by Akrasi (2005) for Bamboi is no longer valid due to the creation of the Bui Dam.

The exponent value (n) of the suspended rating curve is considerably low as compared with typical values which range between 2.0 and 3.0, as quoted by Gregory and Walling (1973). Such cases with low exponential values propose that the Black Volta River remains turbid throughout an extensive range of discharges. This suggestion agrees with the various activities in the catchments especially the recent emergence of illegal small scale mining in the Upper and Northern regions of Ghana.

Another past sediment study done on the Black Volta River in Ghana was undertaken by Opoku-Ankomah, (1996) to estimate the gross annual suspended sediment yield and the specific annual suspended sediment yield. The research work was done at Lawra and Bamboi and the results were used for the estimation of sedimentation in the construction of the Bui dam. During that period, he evaluated the gross annual suspended sediment yield to be 1,079,175.2 t/yr and 1,018,029.9 t/yr for Lawra and Bamboi, respectively. The results showed a decrease in the yields as one moves from Lawra to Bamboi and this he attributed to a possible deposition of the suspended sediment in the river bed during periods of low discharges where there is sluggish or no flows.

Other studies had been done in previous years before the one that has just been discussed. Hydroproject USSR (1964) and C & B (1993) estimated the gross annual suspended sediment yield at Bui to be 800,000 t/yr and 760,000 t/yr respectively.

These results were used together with that by Opoku-Ankomah (1998) for Bamboi to estimate the expected sediment yield for the Bui reservoir by applying the area ratio method with the assumption that similar conditions existed for both locations. Therefore the estimated gross annual sediment yield was computed to be 968,000 t/yr (ERM , 2007). This was used as the designed rate of expected annual sediment yield in the Bui Reservoir,

Comparing the estimated total annual sediment yield from Section 5.1.7 with the designed rate of 968,000 t/yr shows a marginal increase of 402,007 t/yr. This represents an increase in 41.5% of annual sediment yield.

The specific annual sediment yield for the Chache catchment computed under this study was 11.3 t/km²/yr, same for Bui as was assumed and Bamboi was 1.7 t/km²/yr. The same parameter was computed for by Amisigo and Akrasi in 1996 for Lawra and Bamboi. The figures were 12.0 t/km²/year and 8.0 t/km²/year for Lawra and Bamboi, respectively. The figure for that of Bamboi had hugely reduced and this is as a result of the construction of the Bui hydroelectric power dam.

The decrease in the results can be attributed to the construction of the Bui dam which traps most of the suspended sediment load therefore reducing the yield at Bamboi. The mean annual suspended sediment yield will eventually reduce. The other rivers in Africa and India show huge averages of annual suspended sediment loads due to the large catchment areas they cover.

CHAPTER 6:

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The objective of this study was to estimate the current rate of sediment deposition in the Bui hydropower reservoir in the Black Volta basin, using general equation of sediment transport and field measurement of discharge and suspended sediment concentrations at Chache for the 2014/2015 hydrological year. The following conclusions were made from the results of the study:

- The discharge rating curve for Chache monitoring station showed much different channel characteristics from what it was in the 1970s when the rating curve still being used by the Hydrological Services Department was developed. The datum correction had increased and this could be as a result of the river cutting into the bed (scouring). The rating curve used by HSD, presently, does not depict the new channel characteristics and therefore may not give accurate discharge values.
- The suspended sediment rating curve for Chache monitoring station was successfully constructed and the rating equation could be useful in predicting future sediment inflows.
- The total annual sediment yield into the Bui Reservoir was estimated to be 1.37×10^6 t/yr. This exceeded the designed rate by 41.5%. This can seriously undermine the power generation capacity of the reservoir, impact negatively on aquatic resources including fishery in the reservoir, and may considerably shorten the useful life of the reservoir.

6.2 Recommendations

The following recommendations were made out of the outcome of the research

- The increase in the sedimentation rate in the reservoir calls for immediate river basin management practices to curb the inflow of suspended sediments. This will ensure the long term sustainability of the Bui reservoir to generate hydropower, irrigation, navigation and other purposes. Activities such as farming close to the river and sand winning in river beds should be halted as well as small scale mining activities in the Black Volta River.
- The sampling programme as equivalent to the one in this study should be extended to cover a longer period of about five continuous years. This will also make it possible to sufficiently define the suspended sediment concentrations and transport regime on the Black Volta River and into the Bui reservoir.
- The rating curves should be updated regularly to conform to the changes that occur in the river channel.
- After a longer period of the operation of the reservoir for generating hydropower, reservoir sampling should also be carried out to determine the actual sedimentation in the reservoir.

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APPENDICES

Appendix A:

Factor C for converting sediment concentration from parts per million to milligrammes per litre. (The factors are based on the assumption that the density of water is 1.000, plus or minus 0.005, the range of temperature is 0°-29°C, the specific gravity of sediment is 2.65, and the dissolved solids concentration is less than 10,000 parts per million).

Ratio	C	Ratio	C	Ratio	C
0-15,900	1.00	234,000-256,000	1.18	417,000-434,000	1.36
16,000-47,000	1.02	257,000-279,000	1.20	435,000-451,000	1.38
47,000-76,000	1.04	280,000-300,000	1.22	452,000-467,000	1.40
77,000-105,000	1.06	301,000-321,000	1.24	468,000-483,000	1.42
106,000-132,000	1.08	322,000-341,000	1.26	484,000-498,000	1.44
133,000-159,000	1.10	342,000-361,000	1.28	499,000-513,000	1.46
160,000-184,000	1.12	362,000-380,000	1.30	514,000-528,000	1.48
185,000-209,000	1.14	381,000-398,000	1.32	529,000-542,000	1.50
210,000-233,000	1.16	399,000-416,000	1.34		

Appendix B:

Monthly Mean Discharge at Chache in cubic meter per second.

	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1998 - 1999	0.53	0.71	33.47	20.94	31.71	223.12	231.84	182.27	40.16	8.52	3.18	2.45
2000 - 2001	4.78	3.61	3.73	31.94	66.54	234.44	440.17	309.28	57.61	19.58	5.92	1.86
2001 - 2002	1.21	1.96	15.79	49.08	84.59	158.20	374.43	131.60	18.36	4.18	NR	0.49
2002 - 2003	1.11	2.93	13.84	22.28	61.27	229.16	284.21	116.15	10.44	2.85	1.65	1.44
2003 - 2004	1.28	2.79	11.95	65.76	152.47	375.71	NR	427.13	53.00	23.38	11.00	4.29
2004 - 2005	3.77	7.92	19.10	19.68	74.80	368.08	452.27	65.81	20.63	5.94	3.67	2.54
2005 - 2006	1.49	2.90	10.28	23.35	59.75	83.64	306.24	145.42	19.97	3.01	1.68	1.36
2006 - 2007	1.41	1.08	6.66	60.00	54.89	92.23	685.15	517.22	53.18	13.32	9.18	5.62
2007 - 2008	4.79	15.59	28.94	6.70	56.91	301.88	929.43	155.21	33.83	15.68	11.46	5.54
2008 -2 009	5.76	3.72	236.274.94	716.46 14.36	1223.45	549.61	1.37	94.75 10.43	26.65			
AVERAGE	**2.61**	**4.32**	**14.87**	**31.42**	**87.92**	**280.28**	**547.47**	**259.97**	**40.19**	**12.31**	**5.46**	**3.60**

NR – NO RECORDS

Data source: Ghana Hydrological Services.

Appendix C: Johnson Method for determination of datum correction, c.

Eliminate coefficients from the power type equation between gauge and discharge. Two points (Q_1 and Q_3) are selected in the lower and upper range of a curve fitting the stage discharge observations, whiles the third point Q_2 is computed from

$$\frac{Q_1}{Q_2} = \frac{Q_2}{Q_3}$$

Such that, $${Q_2}^2 = Q_1 \cdot Q_3$$

With the corresponding gauge heights for the respective discharges read from the plot as h_1, h_2 and h_3 and using the power type, the following expression is made

$$\frac{c(h_1 + a)}{c(h_2 + a)} = \frac{c(h_2 + a)}{c(h_3 + a)}$$

This yields:

$$c = \frac{h_1 h_3 - {h_2}^2}{h_1 + h_3 - 2h_2}$$

Appendix D:

D1: Maximum and Minimum Suspended Sediment concentrations (SSC) obtained in earlier studies in the study area and other rivers in Ghana.

MONITORING STATION	RIVER	MAXIMUM CONC. (mg/l)	MINIMUM CONC. (mg/l)	STUDY
Bui	Black Volta	208.0	4.4	Hydroproject USSR (1964)
Pwalugu	White Volta	218.0	43.0	FAO (1967)
Pwalugu	White Volta	440.0	40.0	Nippon Koei (1967a)
Ekumdipe	Daka	71.0	11.0	FAO (1967)

Source: Amisigo and Akrasi, 1996

D2: Suspended sediment concentration of various rivers at different discharge gauging stations.

STATION	RIVER	MINIMUM CONC. (mg/l)	MAXIMUM CONC. (mg/l)
Bamboi	Black Volta	20.0	568.0
Lawra	Black Volta	34.0	470.0
Pwalugu	White Volta	44.0	668.0
Nawuni	White Volta	31.0	671.0
Saboba	Oti	13.5	486.0
Ekumdipe	Daka	17.4	218.0
Aframso	Afram	15.0	149.0
Pruso	Pru	14.9	96.0
Prang	Pru	13.6	111.2

Source: Amisigo and Akrasi, 1996.

D3: The mean annual suspended sediment load and specific suspended sediment yield for some Ghanaian and other major world river basins.

River	Country	Mean Annual Suspended Sediment Load (x 10^6 tonnes/yr)	Mean Annual Specific Suspended Sediment Yield (tonnes/km^2/yr)
Volta**	Ghana	17	52.25
Black Volta**	Ghana	4	28.05
White Volta**	Ghana	4	32.5
Oti**	Ghana	5	63.26
Pra##	Ghana	0.7	28.39
Ankobra##	Ghana	0.2	28.54
Tano##	Ghana	0.3	15.78
Ochi-Amisa***	Ghana	0.03	24.3
Ochi-Nakwa***	Ghana	0.02	17.8
Congo*	D. R. Congo	65	16.19
Niger*	Nigeria	5	4.49
Nile*	Egypt	111	113.5
Amazon#	Brazil	363	62.84
Ganges*	India	1455	1352.23

*Stocking (1984); #Carvalho (1988); **Akrasi (2005); ##Amisigo & Akrasi (2000); *** (WARM.1998)

Source: (Akrasi, 2008)

D4: Parameters for Suspended Sediment Rating Curve Equations for some rivers in Ghana.

STATION	RIVER	R^2	k	n
Bamboi	Black Volta	0.87	0.484	1.476
Lawra	Black Volta	0.85	3.687	1.191
Pwalugu	White Volta	0.96	7.118	1.139
Nawuni	White Volta	0.90	3.117	1.171
Saboba	Oti	0.94	0.904	1.401
Ekumdipe	Daka	0.97	4.077	1.161
Aframso	Afram	0.54	3.508	1.118
Pruso	Pru	0.94	2.497	0.993

Source: Amisigo and Akrasi 1996.

Appendix E:

Maddock"s classification for estimation of the bedload Maddock

Concentration of suspended load (ppm)	**Type of material forming channel of stream**	**Texture of suspended material**	**% bed load in terms of measured (total) suspended load**
Low: less than 1000	Sand	Similar to bed material	25 - 30
Low: less than 1000	Gravel, rock or consolidated clay	Small amount of sand	5 - 12
Medium: 1000 to 7500	Sand	Similar to bed material	10 - 35
Medium: 1000 to 7500	Gravel, rock or consolidated clay	25% sand or less	5 - 12
High: over 7500	Sand	Similar to bed material	5 - 15
High: over 7500	Gravel, rock or consolidated clay	25% sand or less	2 - 8