KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

ASSESSMENT OF CATCHMENT EROSION, SEDIMENTATION AND NUTRIENT EXPORT INTO SMALL RESERVOIRS FROM THEIR CATCHMENTS IN THE UPPER EAST REGION OF GHANA

A THESIS SUBMITTED TO THE DEPARTMENT OF CROP AND SOIL SCIENCES, COLLEGE OF AGRICULTURE AND NATURAL RESOURCES, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN SOIL SCIENCE (SOIL AND WATER CONSERVATION AND MANAGEMENT OPTION)

BY

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CERTIFICATION

I hereby declare that this submission is my own work and it contains neither any material previously published by another person nor that 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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DEDICATION

To Mum, Miss Edith Sagoe. Thank you for this great investment.

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ABSTRACT

Soil erosion is one of the most important forms of land degradation that threatens continued and sustained agricultural production in Ghana. The most severely affected areas are the three northern savanna regions, particularly the Upper East Region, where large tracts of land have been destroyed by water erosion leading to soil depth reduction, soil fertility decline and siltation of rivers and reservoirs. This study was carried out in the Upper East Region of Ghana to assess the rate of sedimentation and nutrient export into five small reservoirs and their implications. The five reservoirs studied were Dua, Doba, Zebilla, Kumpalgogo and Bugri. The rate of sedimentation was determined by bathymetric survey. The catchment soils and reservoir sediments from the various study sites were sampled and analyzed for their bulk density, particle size and nutrient content. The results, analyzed by Analysis of Variance (ANOVA), showed sediment deposit in the reservoirs, to range from 55,413 to 11480 Mg. The amount of sediment deposit followed the trend of Kumpalgogo> Bugri >Dua>Zebilla>Doba and varied significantly between the reservoirs. The annual rate of siltation (RS) ranged from 1276 to 6157 Mg y^{-1} for the reservoirs. Sediment yield varied significantly among the reservoirs with a range of 1299 to 6302 Mg y^{-1}. The results showed that the reservoirs have lost the dead storage capacity designed to store sediment until their anticipated design life. This could adversely affect the long dry season occupation and the various benefits small reservoirs bring to the local inhabitants.

The area specific sediment yield (ASY), taken as proxy for catchment erosion, ranged from 18.28 to 157.55 Mg $ha^{-1}y^{-1}$ with a mean of 64.74 Mg $ha^{-1}y^{-1}$. The magnitude of ASY was in the order of Kumpalgogo>Dua>Zebilla>Doba>Bugri with considerable variation

among the reservoirs. The ASY in this study was higher than the tolerable soil loss of 2 to 18 Mg ha^{-1} y^{-1} for the tropics but fell within the range of 10 - 200 Mg ha^{-1} y^{-1} typical of savanna ecosystems. ASY increased as catchment area decreased. Although the large catchments may produce more total sediments than the small ones, they also provide a longer travel distance for sediment transport and opportune time for sediment entrapment and storage by surface roughness elements.

Soil loss-induced reduction in soil depth in the various catchments ranged from 1.087 cm to 8.456 cm in the order of Kumpalgogo>Dua>Bugri>Zebilla>Doba and a mean of 3.82 cm. The loss in soil depth decreased the water holding capacity of the top 20 cm depth of the catchment soils by 5.44 to 42.28 percent.

The assessment of nutrient concentrations showed the reservoir sediments to be richer not only in nutrients and organic carbon but clay and silt than the catchment soils with enrichment ratios greater than 1. The total amount of organic carbon (OC) loss ranged from 2383 to 19672 kg ha^{-1} equivalent to 3619 to 33894 kg ha^{-1} organic matter (OM). The magnitude of OC loss was in the order of Kumpalgogo>Dua>Bugri>Zebilla>Doba with a considerable spatial variability. The total amount of nutrient loss in kg ha^{-1} among the reservoirs ranged from 153 to 3048 for N, 3.15 to 42.59 for P, 41 to 290 for K, 17.6 to 184.2 for Na, 432 to 2158 for Ca, and 63 to 483 for Mg.

The N, P, K removed by erosion from the catchment areas and deposition in the reservoir sediments represents a hidden cost to agricultural production. The cost in Ghana cedis per hectare of N, P, K losses expressed as sulphate of ammonia, single superphosphate and muriate of potash ranged from 437.10 to 8708.70, 36.00 to 487.80 and 131.20 to 928.00 GH¢/hectare respectively.

Soil carbon sequestration is an important and immediate sink for removing atmospheric CO_2 and mitigating global warming and climate change. From this study, the total organic carbon sequestered by the five reservoirs was 226.31 Mg y^{-1} with its CO_2 equivalent of 830.56 Mg y^{-1}. This is indicative of the potential of reservoirs as an important sink for OC in the global carbon balance. Nutrient export rates (NE) (in kg $ha^{-1}y^{-1} \times 10^{-3}$) from the reservoir catchments ranged from 755 for OC, 104 for N, 2 for P, 16 for K, 9 for Na, 113 for Ca, 27 for Mg and 1300 for organic matter (OM). These rates were lower than those of other studies probably due to the low content of the nutrients in the catchment soils.

Relationships established between NE and ASY showed NE to be positively correlated with ASY (R^2 = 0.66 – 0.99). ASY therefore accounted for between 66 to 99% of the variations in the calculated NE. The empirical equations can be satisfactorily used to predict the amount of plant nutrients actually lost from the catchments and stored in the reservoir sediments.

The use of sustainable land management practices to forestall erosion in the catchment areas and to reduce sedimentation of the reservoirs for enhanced livelihoods of the communities in the study area is very important.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF ABBREVIATIONS

°C	Degrees Celcius
A	Catchment Area
AGDP	Agricultural Gross Domestic Product
Al	Aluminium
ANOVA	Analysis of Variance
ASY	Area Specific Sediment Yield
Ca	Calcium
cm	Centimeter
CO_2	Carbon Dioxide
CV	Coefficient of Variation
ECEC	Effective Cation Exchange Capacity
EDTA	Ethylene Diamine Tetraacetic Acid
EPA	Environmental Protection Agency
ER	Enrichment Ratio
FAO	Food and Agriculture Organization
FSL	Full Supply Level
g	Gramme
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GLASOD	Global Assessment of Human Induced Soil Degradation
GLOWA	Globaler Wandel des Wasserkreislaufes
GPS	Geographical Positioning System
GSS	Ghana Statistical Service
H	Hydrogen
ha	Hectare
IDA	Irrigation Development Authority
IFAD	International Fund for Agricultural Development
ITCZ	Inter-tropical Convergence Zone
K	Potassium

kg	Kilogram
km	Kilometer
m	Meter
Mg	Magnesium
Mg	Megagram
mm	Millimeter
MoFA	Ministry of Food and Agriculture
N	Nitrogen
N/A	Not Applicable
Na	Sodium
NC	Nutrient Content
NSE-SPRPC	National Soil Erosion – Soil Productivity Research Planning Committee
NTE	Nutrient Trap Efficiency
OC	Organic Carbon
OM	Organic Matter
P	Phosphorus
ppm	Parts Per Million
R	Correlation Coefficient
R^2	Coefficient of Determination
RS	Rate of Siltation
s.e.d	Standard Error Difference
SC	Storage Capacity
ISSER	Institute of Social, Statistical and Economic Research
SM	Sediment Mass
SSA	Sub-Saharan Africa
SV	Sediment Volume
SY	Sediment Yield
TE	Trap Efficiency
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme

UNEP	United Nations Environmental Programme
UNESCO	United Nations Education, Scientific and Cultural Organization
US	United States
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
V	Volume
W	Weight
WHC	Water Holding Capacity
y	Year
ρ_b	Bulk Density

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Water is one of the most important natural resources for sustainable agriculture. In many parts of the world, there exist problems of water scarcity (UNDP, 2007). This has led to recurrent and substantial declines in agricultural production which affect food security. Scarcity of water resources for agricultural production is mainly due to changes in climate and human activities (UNDP, 2007). Strategies to combat the problem of water scarcity must be based on the provision of water particularly through rainfall and its proper conservation. The achievement of this through surface water harvesting underscores the construction of many small reservoirs in the Upper East Region of Ghana within the Sudan savanna agro-ecological zone (IFAD 1991).

Sustainable agricultural production also depends on productive soils, but the land resources of Ghana, particularly the soils, are being degraded as a result of both natural and anthropogenic factors (Adama, 2003). Soil degradation in its several forms is evident in all the agro-ecological zones of Ghana (Asiamah, *et al*., 2000, Quansah *et al.,* 2002) and therefore a major constraint to the attainment of the desired growth rate in the agricultural sector (MoFA, 1998).

The semi-arid climate of the Upper East Region is characterized by 5-6 months unimodal rainy season with a mean annual rainfall of about 986 mm. Rainfall intensities often exceed soil infiltrability with a resultant generation of surface runoff and low replenishment of soil moisture and groundwater (Liebe *et al.*, 2005). To make water available in the dry season and better use of the locally received rainfall, numerous small reservoirs have been constructed with the aim of intercepting runoff during the rainy season.

There are about 200 small reservoirs in the Upper East Region within the White Volta Basin of Ghana used for agricultural production (irrigation, fishing farming, livestock watering), domestic use, construction and recreation. The proximity of these reservoirs to places of demand is an advantage for drought mitigation.

However, the sustainability of these small reservoirs is challenged by problems, which directly affect the livelihoods and the economic development of the people. These include soil erosion and sedimentation which adversely affect the useful life of the reservoirs and water quality. In the dry season, many of these reservoirs dry up completely or reduce to a series of ponds with a consequent reduction in the value of the reservoirs for dry season agricultural production, domestic and other uses. The local perception is that the drying up of these reservoirs is caused by siltation which reduces their storage capacities (Gyasi and Sciffer, 2005).

Soil erosion is the most potent form of land degradation that threatens continued and sustained agricultural production in Ghana (Folly, 1997). Accelerated soil erosion does not only reduce the storage capacity of reservoirs, but also, lead to valuable nutrient loss from the reservoir catchments which are mostly agricultural croplands. The nutrients are lost through runoff water and eroded sediments. The enrichment of the sediments with valuable plant nutrients is mainly due to the selective removal and deposition of the finer particles rich in nutrients and organic matter by erosion. This leads to a decline in soil fertility and soil depth with a consequent loss of productivity of agricultural lands up-slope of the reservoirs (on-site effects) (Pimentel *et al.*, 1995). The ultimate effects of the productivity loss are low crop yields, food insecurity and poverty.

Also, the quality of water in the reservoirs (off-site effects) is reduced due to water pollution with serious health implications. Sediments, with their load of adsorbed agrochemicals and soil nutrients, are pollutants which can lead to eutrophication in water bodies (Steegen *et al.*, 2001). The reduced reservoir capacity by siltation enhances the risk of flooding and shortens the design life of the reservoirs (Verstraeten and Poesen, 1999).

Meeting the future food needs and improved livelihoods of the communities in the Upper East Region would therefore require a goal directed management of the soils and water resources for long term productivity. In order to achieve this, the degradation of soil and water bodies by erosion has to be halted through restorative measures of sustainable soil, water, nutrient and crop management (Quansah, 1996; Syers, 1997). Catchment area protection using vegetative cover would also be required to deal with erosion and the reservoir siltation problem. The design and implementation of erosion control measures would however require studies to establish the magnitude and extent of the erosion and productivity problem. This will facilitate the choice of appropriate sustainable land management technologies and provide the requisite baseline information for monitoring the effectiveness of the implemented technologies.

The assessment of erosion and its off-site effects and impact on nutrient and organic matter losses as they influence the productivity of reservoir catchments has never been studied. So also is the link between nutrient and organic matter losses from the erosion source area and nutrient input in the deposited sediment of the candidate reservoirs in the Upper East Region of Ghana.

This study, was therefore, carried out with the view to contributing to the generation of the requisite data to fill this gap. Most importantly, the focus of the study was on sediment-bound nutrients transported and deposited in the reservoirs.

1.2 Research Objectives

The main objective of this study was to assess sedimentation and nutrient export into some selected small reservoirs in the Upper East Region in the White Volta Basin of Ghana.

The specific objectives were to:

i. assess the rate of sedimentation in selected small reservoirs in the Upper East Region and its consequences on soil productivity.

ii. assess the variability in the nutrient content of the various catchment (erosion source) soils and the deposited sediment in their candidate reservoirs and to understand their relationship and controlling factors;

iii. evaluate the nutrient status of the deposited sediment and its potential use for land reclamation of the surrounding degraded croplands;

iv. assess the cost of fertility erosion;

v. assess and evaluate the rate of nutrient export;

vi. establish a sediment/nutrient export relationship for predicting annual rate of sediment/nutrient loss in similar agro-ecological locations; and

vii. evaluate the potential of the reservoirs for carbon sequestration.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 The Importance of Small Reservoirs

The rural population in the Upper East Region of Ghana is characterized by very high degree of household food insecurity due to the high level of poverty in the region. This condition arises from the dependence of farmers on a single cropping season for their incomes, low and erratic rainfall which limits the range of crops that can be cultivated and high risk of crop failure (IFAD, 1999). The region, however, experiences high rainfall intensities exceeding soil infiltrability resulting in high rates of runoff (Poolman, 2005). To efficiently make good use of the runoff, numerous small reservoirs totalling about 200 constructed in the region by various agencies as well as the Government of Ghana help capture the surface runoff during the rainy season making water available in the dry season. The reservoirs serve many important purposes including the provision of water mainly for irrigation and for livestock watering, construction, aquaculture, domestic use and recreation.

Sixty percent (60%) of the water in these small reservoirs is allocated to livestock, domestic and irrigation where as the remaining 40% is lost to evaporation, dead storage and seepage (Adwubi, 2008). For the useful portion of 60% of the water in the small reservoirs, irrigation constitutes the largest consumer of the water because in the dry season, vegetable gardening is the main activity which serves as a source of income for the people (Adwubi, 2008). Community needs assessment study conducted in the region indicates that farmers benefit more from 0.1ha of land in the dry season compared to 0.8ha of land in the rainy season (Gyasi and Schiffer, 2005).

The reservoirs have a significant effect on downstream flows as they provide a buffer by delaying and diminishing floods because water can be (temporarily) stored (Poolman, 2005). They also recharge the groundwater table, thus increasing the base flow in the downstream part of the catchment area, stabilizing the water supply to wells further downstream and reducing siltation of the Akosombo reservoir by trapping sediment that enters the reservoirs (IFAD, 1999).

However, as these reservoirs trap sediment, their storage capacities and useful life are reduced (Verstraeten and Poesen, 1999) to the detriment of livelihood enhancement of the local communities. Siltation studies in the reservoirs are therefore vital for the design and implementation of catchment management plans.

2.2 Land Degradation

The Agricultural sector is the largest contributor to Gross Domestic Product (GDP) accounting for 39.2% of GDP in 2003 and 46.1% of total foreign revenue in 2003 (ISSER, 2003). Growth in the agricultural sector is dependent on the exploitation of natural resources, particularly soil and water bodies. About 70 percent of Ghana's population depends on agriculture for their livelihoods. Although cultivated land per capita is relatively high, most lands are characterized by poor fertility and are subject to degradation. Studies have shown that agricultural cropland is the most important contributor to soil erosion and sediment loading (USEPA, 2000). In order to sustain high crop production and ensure food security, the soil, nutrient and water resources need to be properly managed and conserved (Quansah 1996).

Land degradation is generally defined as the temporary or permanent decline in the productive capacity of the land (Stocking *et al.,* 2001). Essentially, it is the reduction in the productive potential of the land, including its major resources, its farming systems and value as an economic good that may result from a number of overlapping biophysical and landuse processes (Amikuzuno, 2005).

Land degradation is therefore an issue of worldwide concern as it threatens global food security and environmental quality. It is a major factor for the low agricultural productivity of Sub-Saharan Africa and in Ghana, soil degradation alone is estimated to be responsible for 2.4% loss in GDP (Sarpong *et al.,* 2006).

According to the results of the GLASOD (Global Assessment of Human Induced Soil Degradation) survey, about 69 percent of the land area in Ghana is affected by moderate to very severe degradation (FAO, 2000) and approximately 30 - 40 percent subject to desertification (EPA, 2005).

As many as 1.8 billion people live in areas with some noticeable land and water degradation which reduces livelihood and household food security (Penning de Vries *et al.,* 2002). Global assessment of soil quality in agricultural areas reveal that only about 16% of the agricultural soils are free of significant constraints, such as poor drainage, poor nutrient status, difficult workability, salinity or alkalinity, or shallowness. Of the favoured soils, 60% are in temperate areas, and only 15% lie within the tropics (Wood *et al.,* 2000). Intensive land use without adequate investments in appropriate input for resource conservation only leads to unproductive and unsustainable agriculture (Cofie and Penning de Vries 2002).

2.2.1 Types of land degradation

Of the major types of degradation in Ghana, the degradation of forests and woodlands and soil are considered the most serious. It is estimated that 70 percent of the original 8.2 million ha of closed forest in Ghana have been destroyed leaving the current level of about 1.9 to 2.0 million hectares. Currently the rate of forest depletion is about 2 percent. The main types of soil degradation include water and wind erosion which displaces soil material, soil chemical degradation (depletion of organic matter and nutrients, salinization, acidification and pollution), soil physical degradation (compaction, crusting and sealing) and sedimentation of water bodies, carbon loss, and loss of water holding and buffering capacity of agricultural lands.

Soil erosion is the main form of physical land degradation affecting an estimated 69 per cent of the total land surface of Ghana (Asiamah, 1987; EPA, 2002). The major form is water erosion which is the focus of this study. One important feature of soil erosion by water is the selective removal of the finer and more fertile fraction of the soil. Of the land area subjected to very severe sheet and gully erosion, about 58 percent occurs in the three northern regions within the Sudan and Guinea Savanna zones.

Chemical degradation of the soil is considered the second most severe process of land degradation (Sherr, 1999; in EPA 2002). Annual projected depletion of soil nutrients in 2000 was 35 kg N, 5 kg P and 20 kg K/ha (EPA, 2002).

Sedimentation which is another indirect measure of soil erosion, is one of the major offsite damage caused by accelerated soil erosion. It is the deposition of the most fertile part of the soil transported by surface runoff into rivers, reservoirs, lakes and other water bodies.

Salinity occurs mostly within the Coastal Savanna. The organic matter content in the soils of Ghana is generally low (less than 2% in the topsoil) (MoFA, 1998). The levels of organic carbon, nitrogen and available phosphorus are also generally low (FAO, 2005). The annual burning, removal and grazing of crop residues constrain the build-up of new organic matter.

2.2.2 Causes of land degradation

Land degradation results from a combined effect of physical elements such as climate, soil and topography on one hand and human activities including the use, misuse or overuse of natural resources on the other hand. The causes of land degradation include the cultivation of steep slopes, destruction of vegetation cover, over exposure of cultivated soil to rainsplash at critical periods in the rainy season, intensive land cultivation leading to soil crusting and compaction, inadequate on-farm conservation, shortened bush fallow, inadequate supply of farmyard and mineral fertilizers, inappropriate irrigation, drainage or cultivation practices, destruction of catchment vegetation, overgrazing, land clearing for agriculture and road construction.

2.2.3 Effects of land degradation

The effects of land degradation, although temporarily masked by modern technological advances, are evident in many ways (Amikuzuno, 2005). According to IFAD (1992), the result of land degradation for the people of sub-Saharan Africa is a general reduction in the productivity of the land through erosion, soil nutrient depletion and other processes resulting in undesirable physico-chemical status such as reduced soil depth, loss of soil porosity, permeability and water holding capacity as a result of soil compaction and reduced crop yields which lead to food insecurity and exacerbates the poverty problem. In the livestock sector, land degradation reduces the productivity of grasslands and causes loss of nutrients and palatable shrub and grass species available to livestock (Bezuayehu *et al.*, 2002). Severely degraded farmlands therefore require much more manure, fertilizer and other agro-chemicals to attain their potential yield levels. The more these factor inputs are used, the more the expenditure in the farmers budget.

Land degradation has a negative impact on the environment and natural resources through reduced goods and services provided by land. These include regulation of critical ecosystem functions, loss of vegetation cover and biodiversity, instability in hydrological regimes, a reduction in the land's resilience to climate variability and increased vulnerability to natural hazards, such as droughts, downstream flooding, sedimentation and siltation in rivers and dams.

In the context of Ghana's national economy, the estimated annual cost of land degradation mainly through erosion, ranges from 1.1 to 2.4 percent of the GDP corresponding to 2.9 and 6.3 percent of Agricultural Gross Domestic Product (AGDP) (World Bank *et al.*, 2005) or US $166.4 million. This accords with past estimates of 5% of AGDP for cost of annual production loss through erosion and nutrient depletion (Convery and Tutu, 1990). Drechsel and Gyiele (1999) assessed the cost of productivity loss at around 4 to 5 per cent of the AGDP or US $115.14 million. Using the Replacement Cost Approach, Quansah *et al.* (2000) estimated the seasonal cost of N, P, K lost through erosion per hectare under a maize monocrop grown under excessively tilled land as US $7.1. Akyea (2009) reported the total cost (in GH¢) of replacing lost nutrients by straight fertilizers under various tillage treatments for cassava cultivation as 1304.90, 831.70, 875.90, 210.15 for bare plot, planting on the flat, zero tilled plot and ridging across slope respectively.

Global efforts in assessing degradation by soil erosion often measure degradation in terms of erosion rate rather than by its off-site impacts on agricultural productivity and poverty. Such studies are, however, needed in assessing the socio-economic impacts of degradation on affected communities and in designing the requisite control measures.

2.3 Soil Erosion

Soil erosion is the most serious form of environmental degradation that threatens sustainable agriculture and ecosystems integrity in Africa and other parts of the world (UNEP and UNESCO, 1980; Eswaran *et al.*, 2001). It is the most common form of physical degradation affecting soil productivity in Africa and it involves the removal of soil particles (including nutrients and organic matter) by water or wind. The erosion process consists of detachment and transport of soil particles by an erosive agent and deposition when the energy for transport diminishes.

The processes and impacts of soil erosion are more pronounced in tropical regions due to intensive rainfall, highly weathered erodible soils, poor vegetation cover and greater potential energy of water flow in steep slopes (El-Swaify, 1997; Enters, 1998). The major forms of soil erosion are splash, sheet or interrill, rill, gully and stream bank erosion. The causes of soil erosion are often complex. Cultural, institutional, socioeconomic and environmental factors play varying roles. Major practices leading to erosion include over-cultivation, overgrazing, deforestation, cultivation of steep slopes and unsustainable land use.

2.3.1 Soil erosion in Ghana

Soil erosion is a major problem that threatens continued and sustained agricultural production in Ghana (Folly, 1997). Large tracts of land have been destroyed by water erosion leading to soil and nutrient losses as well as flooding and siltation of river bodies (Quansah, 2001). According to investigations carried out by the Soil Research Institute, 29.5% of the country is subject to slight to moderate sheet erosion, 43.3% to severe sheet and gully erosion and 23% to very severe sheet and gully erosion (Quansah *et al.,* 1989). The northern regions of Ghana are relatively much more affected by erosion than the Southern Regions (Asiamah and Antwi, 1988)

However, soil erosion continues to accelerate as a result of the intensification of agricultural production often considered to be associated with the increased population pressure (Adu and Owusu, 1996). The soil removed is not the only problem.

The eroded sediment often contains higher concentrations of organic matter and plant nutrients in available forms than the soil from which it is eroded (Quansah and BaffoeBonnie, 1981). Smaller erosion losses which may seem unimportant with respect to volume of soil removed may therefore be very important as far as the nutritional depletion and the general decline in the productive capacity of the surface soil is concerned (Asiamah and Antwi, 1988).

2.3.2 Soil erosion in the Upper East Region

The Upper East Region is the poorest Region in Ghana and one of the most seriously affected Regions by soil erosion. Large tracts of land have been destroyed by rill, sheet and gully erosion and though figures on absolute quantities of soil eroded are scanty, the few available studies reveal alarming losses of soil (Quansah, 1990). In the savanna environment of the Upper East Region, Adu (1972) reported a loss of 90 cm of soil by sheet and rill erosion, but in some severely eroded savanna lands, as much as 120 cm of soil has been lost above the unweathered parent rock. While it takes only one year to lose 1 cm of topsoil, it is estimated to take about 12 years to replace it under ideal soil and climatic conditions (Hudson, 1981) and 120 - 400 years under normal conditions (Asiamah and Antwi 1988; Friend, 1992).

Generally, the agricultural soils are light, sandy and non-cohesive, heavier soils being found in valley bottoms. The soils are generally highly susceptible to erosion. Poor cultivation practices enhance erosion of these light soils and cause sedimentation problems when practised in reservoir catchment areas.

2.3.3 Catchment characteristics that influence erosion and sedimentation The major factors affecting rates of soil erosion and sedimentation are soil erodibility, erosivity of the eroding agent (rainfall), topography, vegetation cover. All these factors interact to cause erosion leading to sedimentation.

Soil erodibility

Soil erodibility is defined as the susceptibility of a soil to erosion (Hudson, 1995). It defines the resistance of the soil to both detachment and transport. Erodibility varies with soil texture, aggregate stability, shear strength, infiltrability, organic and chemical content.

Soil texture is important because large particles are resistant to transport and settle faster than smaller particles. Fine particles, on the other hand, are resistant to detachment because of their cohesiveness. Richter and Negendank (1977) showed that soils with 40-60% silt content are most erodible, whilst Evans (1980) observed a soil with 9-30% clay fraction as the most erodible.

Osei-Yeboah (Personal Communication) showed that soil erodibility (in t. ha. h/ (ha.MJ.mm)) range from 0.11 at Dawadawa in the Transition zone on a Gleysol which is low to 0.68 at Jirapa in the Sudan Savanna zone of the Upper West Region on a Lixisol. Very high erodibilities were recorded in the Interior Savanna zone, particularly in the Jirapa (Sudan savanna) and Bole (Guinea savanna) districts. As observed by Folly (1997), Sombroek *et al.* (1980) and Quansah (1990), most of the soils in the savanna region are predominantly sandy, sandy loams or black cracking clays that have a weak structural stability thereby making them more susceptible to erosion.

Clay particles combine with organic matter to form soil aggregates which are more resistant than silts and fine sands to erosion. Aggregate stability largely depends on the type of clay minerals present in the soil. Silicate clay minerals such as illite and smectite exhibit greater shrinkage and swelling on wetting and drying than kaolinite. These properties render the former two clays less stable as soil aggregate components (Hillel, 1998).

The shear strength of the soil is a measure of its cohesiveness and resistance to shearing forces exerted by gravity, moving fluids and mechanical loads. An increase in the moisture content of a soil decreases its shear strength and changes its behaviour. Under inadequate drainage conditions, a saturated soil tends to deform and behave as a plastic material. This leads to soil creep even on a relatively gentle slope. A soil's infiltrability also influences the magnitude of erosion. A reduced infiltrability enhances runoff generation and erosion. Infiltrability is influenced by pore size, pore stability and the form of the soil profile. In a soil profile, the layer with the least infiltrability (e.g. tillage induced compaction) becomes the critical factor that determines the overall infiltrability of the soil.

The organic and chemical constituents of the soil are also important because of their influence on aggregate stability. Soils with less than 3.5% organic matter are considered erodible (Evans, 1980) whilst saline soils with Na^+ as a significant constituent (about 15% of its cation exchange capacity) may exhibit structural collapse.

Rainfall erosivity

Rainfall erosivity is defined as the potential ability of rain to cause erosion (Hudson, 1995; Bergsma *et al.*, 1996). The amount of soil detached and splashed depends on drop size distribution, frequency, intensity of rainfall and falling velocity. Gentle rainfall distributed more evenly throughout the year causes less erosion than heavy rainfall concentrated only to few months. More frequent rainfall causes more erosion than the less frequent one. Rainfall of high intensity causes more erosion than that of low intensity. The most significant characteristic value of rainfall is the kinetic energy of raindrops impacting the soil surface. Erosivity is therefore closely related to intensity and can be evaluated by calculations based on kinetic energy (Morgan, 1995; Hudson, 1995; Lal, 1976). Rainstorms with kinetic energy loads of 70 – 100 $Jm^{-2}mm^{-1}$ are commonly observed in the tropics (Lal, 1981). Hudson (1981) showed that the annual energy load of most rains in the temperate zone is 900 Jm^{-2} compared to 16800 Jm^{-2} for the tropics. In the semi-deciduous zone of southern Ghana, kinetic energy load is very high with annual values ranging from 13638 to 19521 Jm^{-2} (Apraku, 1994). The relationship between rain intensity, kinetic energy and erosive force of rain is of most importance for rain-induced erosion. Low intensity rain is mainly composed of small drops, while high intensity rain has at least some much larger drops. The high intensity of tropical rains is partly attributed to relatively large drop sizes. In Zimbabwe, Hudson (1981) reported that the modal value of drop diameter rose up to about 2.5 mm at an intensity of 80 – 100 mmh^{-1}. Acquaye (1994) also reported that raindrop size ranged between 0.55 and 3.97 for intensities of 2.32 and 78.3 mmh^{-1} in the semi-deciduous forest zone of Ghana.

Osei-Yeboah (Personal Communication) reported moderate to high erosivity for the western half of the Guinea savanna zone, while the eastern and the southern halves were characterized mainly by very high erosivities. In the Sudan savanna, the western half falls within the high erosivity zone whilst the eastern half consists of high erosivity in the south, moderate in the north-east and low in the north. His erosivity value of 400 - 500 MJ. mm/(ha.h.y) covering the Frafra District in the north-east of the Sudan savanna zone where Zuarungu is situated compares with the 477.22 MJ.mm/(ha.h.y) obtained for the same area by Folly (1997).

Topography

Topographic features that influence erosion are slope, size (small or large) and shape (long and narrow or broad and compact) of a watershed and aspect of a mountain. The amount of erosion on an arable land is influenced by the steepness, length and curvature of the slope (convex and concave). The steeper and longer the slope, the more the erosion. Convex curvatures cause more erosion than the concave ones, because there are accelerated flows in convex curvatures than in the concave ones. Larger watersheds cause more erosion than the smaller ones. Furthermore, broad and compact watersheds cause more erosion than long and narrow ones (Tulu, 2002).

Vegetation cover

Vegetation acts as a protective layer or buffer between the atmosphere and the soil. The above-ground components, such as leaves and stems absorb some of the energy of falling raindrops, running water and wind, so that less is directed at the soil, whilst the below ground components, comprising the root system, contribute to the mechanical strength of the soil.

The effectiveness of a plant cover in reducing erosion by raindrop impact depends upon the height and continuity of the canopy, and this depends on the ground cover. The height of the canopy is important because water drops falling from 7 m may attain over 90 per cent of their terminal velocity. Raindrops intercepted by the canopy may also coalesce on the leaves to form larger drops which are more erosive. For a wide range of plant types, Brandt (1987) showed leaf drips to have a mean volume drop diameter between 4.5 and 4.9 mm, which is about twice that of natural raindrops. Tree canopies in the absence of under storey protective litter layer, cause greater rates of detachment as raindrops coalesce to form larger and more erosive raindrops (Mosley, 1982). Lower canopies, especially if grown in rows, may concentrate leaf drip in the inter-row spaces, thereby encouraging greater rates of detachment as compared to an open site. Morgan (1985) found that detachment under 88% canopy cover at a height of 2 m was 14 times greater than that in open ground for a rainfall intensity of 100 mm/h and 2.4 times greater for an intensity of 50 mm.

However, the effectiveness of plant cover in controlling erosion depends among other factors, on the crop and soil management practice adopted. In the semi-deciduous forest zone of Ghana, Quansah *et al.* (1990) reported soil loss values of 11.37, 1.93, 2.35, 3.82 and 4.87 Mg/ha under bare, canavalia, cowpea, groundnut and bambara nut, respectively. The corresponding runoff was 50, 27.10, 30.90 and 31.70 mm.

Plant covers can play an important role in reducing erosion provided they extend over a sufficient proportion of the soil surface. For adequate protection, at least 70% of the ground surface must be covered (Elwell and Stocking, 1976) but reasonable protection can be achieved with 40% cover (Morgan, 1995). The effects of vegetation are, however, not straight forward. Under certain conditions a plant cover can exacerbate erosion.

2.3.4 Impacts of erosion (on-site and off-site)

The rapid erosion by water has been a problem ever since land was first cultivated (Morgan, 1995). The consequences of soil erosion occur both on – and off-site.

On-site impact of erosion

On-site effects of erosion are those that occur at the site where erosion originated. This leads to the redistribution of soil within the field, the loss of soil from a field, the breakdown of soil structure, the decline in soil organic matter and nutrients, reduction in cultivable soil depth and a decline in soil fertility.

Erosion also reduces available soil moisture, resulting in more drought-prone conditions.

The net effect is a loss of land productivity which initially restricts what can be grown and results in increased expenditure on fertilizers to maintain yield, but later threatens food production and leads, ultimately, to land abandonment. The value of the land is therefore reduced as it changes from productive farmland to wasteland.

Soil nutrient depletion

Soil nutrient depletion is more widely found and is of more serious concern to food security in SSA than in any other part of the world (Smaling, 1993). This is the most important form of chemical degradation and is the major limiting factor for raising per capita food production in most African small farms (Mokwunye, 1996; Sanchez *et al.*, 1997).

Nutrient depletion occurs mainly through crop removal in harvested crops and residues, leaching, erosion, burning and nitrogen volatilization. Stoorvogel and Smaling (1990) showed that nutrient losses through these depletion pathways are only partially compensated for by crop residues left on the field, manure and fertilizer application besides atmospheric inputs. For sub–Saharan Africa, Stoorvogel and Smaling (1990) estimate depletion rates for the major nutrients as 22 – 26 kg N, 6 – 7 kg P_2O_5 and 18 – 23 kg K_2O kg per hectare per year between 1983 – 2000. Sanchez (1995) estimated net loss in SSA to average about 700 kg of N, 100 kg of P and 450 kg of K per hectare during the last 30 years over about 100 million hectares of cultivated land. Annual net nutrient depletion exceeds 30 kg/ha of N and 20 kg/ha of K for arable land in Ethiopia, Kenya, Rwanda and Zimbabwe (Smaling 1993; Stoorvogel 1993). Similar losses are estimated for the most important crop production areas in Mali. In Ghana, the estimates for 2000 were 35 kg N, 4 kg P_2O_5 and 20 kg K_2O (Stoorvogel and Smaling, 1990). Allison (1973) reported that one tonne of rich topsoil lost through erosion may contain as much as 4 kg of phosphorus, 10 kg of nitrogen, 66 kg of potassium, and 72 kg of calcium.

The extent of soil nutrient depletion in Ghana is widespread in all agro-ecological zones with nitrogen and phosphorus being the most deficient nutrients. These deficiencies are, however, more pronounced in the Coastal, Guinea and Sudan Savannah zones where the organic matter content is low and the annual burning and removal of crop residues further prevent the build-up of organic matter. It has also been generally observed that eroded sediments contain higher concentrations of organic matter and plant nutrients in available forms than the soil from which these were lost (Quansah *et al.,* 2000). Soil erosion and the loss of soil carbon, among other effects, impact negatively on the potential of the soil to sequester carbon and to mitigate climate change (USGS, 2008). Additionally, soil nutrient decline is almost always associated, among other things, with lowered water infiltration and soil crusting (Greenland *et al.,* 1994). These losses reduce soil productivity, with a consequent decline in food production, food insecurity, reduced farm family incomes and livelihoods, slow economic growth against the background of increasing population and urbanization (Shetty *et al.,* 1995). The maintenance of soil nutrient replenishment could, therefore, contribute significantly to marked increases in crop yield, food security and mitigate the effects of water stress. A practical goal in the maintenance of soil fertility is to return to the soil most of the nutrients removed from it through crop harvests, runoff, erosion and other loss pathways. The available technologies for soil nutrient replenishment include mineral fertilizer application, maintenance of soil organic matter (animal manure, green manuring and cover crops, compost, etc.) and accompanying technologies such as soil conservation and sound agronomic practices.

Reduced available water capacity and rooting depth

Erosion affects the water holding properties of the soil by reducing soil depth and organic matter and the finer soil particles which have a greater ability to retain water. The majority of tropical soils have adaphically inferior subsoil and shallow effective rooting depth. Consequently, crop yield declines drastically as surface soil thickness is reduced (Lal, 1984). The loss of the surface layer cannot be compensated for by additional inputs.

In Malaysia, Hunt (1974) reported that maize yield declined sharply after artificial removal of 15 and 30 cm of soil. In a study on Alfisols in Ibadan, Nigeria, Lal (1976) reported a maize yield for reduction of 23% after removing 2.5% of topsoil. Rehm (1978) reported that in Cameroon the removal of 2.5 cm of topsoil caused a 50% drop in maize yield and that the exposed subsoil became completely unproductive when 7.5 cm of soil was removed.

Mbagwu *et al.* (1983) studied the effects of topsoil removal on maize and cowpea grain yield with variable rates of N and P application on an Ultisol in Southern Nigeria (Onne) and two Alfisols in South-Western Nigeria (Ikenne and Ilora). The data showed that after removal of 5, 10 and 20 cm of soil and at 120 kg ha^{-1} N and 30 kg ha^{-1} P, maize grain yield was reduced by 82, 94 and 100% of the uneroded Ultisol control at Onne; 25, 76 and 86% at Ikenne (Alfisol); and 31, 81 and 97% at Ilora (Alfisol). None of the fertilizer combinations used was an effective substitute for topsoil removal on the Ultisol at Onne. For some Alfisols, however, nitrogen rates of 60 and 120 kg ha^{-1} in combination with 30 kg ha^{-1} P were able to restore productivity on soils from which 5 cm of topsoil had been removed. In contrast, the removal of 5 cm of topsoil caused the following yield reductions in cowpea; 15% for Ultisol at Onne and 15 and 26% for Alfisol at Ikenne and Ilora, respectively.

On an Alfisol in Ibadan, Nigeria, Lal (1987) reported maize grain yields of 2.0, 0.7, 0.2 t ha^{-1} for topsoil removal depth of 0,10 and 20 cm respectively. The respective stover yield was 4.2, 2.6, and 1.9 t ha^{-1}. Lal (1983) compared the effects of natural erosion and desurfacing on maize grain yield. The rate of decline in maize grain yield caused by natural erosion was 0.26 t ha^{-1} mm^{-1} of eroded sediment.

Lal (1987), reported that new soil is formed at the rate of about 2.5 cm in 300 to 1000 years (i.e. 1 mm/12 – 40 years) under normal conditions. Other values show the rate of soil formation on Alfisols to be 0.001 – 0.007 mm $year^{-1}$ and 0.013 – 0.045 mm $year^{-1}$ for Ultisols. Available information suggests that it takes hardly one year to lose 1 cm of topsoil but 1000 years to replace it (Lal, 1984).

Off-site impact of erosion

This occurs outside the area where the erosion originated and relates to the economic and ecological costs of sediment, nutrients, or agricultural chemicals being deposited in reservoirs, streams, rivers, and lakes resulting in water quality degradation. The off-site impacts include sedimentation and pollution. Sedimentation, which is the focus of this study, however results from deposition of sediments downstream which reduces the channel capacity of rivers, reservoirs and drainage ditches, and enhances the risk of flooding, blocks irrigation canals and shortens the design life of reservoirs. Generally, the off-site impacts of soil erosion on water resources are more costly and severe than the on-site impacts on land resources (Phillips, 1989).

Sedimentation and its consequences

Sedimentation is the process whereby detached soil particles transported by runoff are deposited elsewhere on the land or in lakes, reservoirs, streams, and wetlands. Sediment deposition in reservoirs is a reflection of catchment erosion and deposition processes, which are controlled by terrain form, soil, surface cover, drainage networks, and rainfall-related environmental attributes (Renard and Foster, 1983; Walling, 1994). Soil erosion is the first step in the sedimentation processes which consist of detachment, transportation and deposition of soil particles in reservoirs or channels downstream. Sedimentation downstream leads to water quality degradation (sediments may carry pollutants into water systems and cause significant water quality problems), reduces the capacity of rivers and retention ponds, enhances the risk of flooding and muddy floods and shortens the design life of reservoirs (Clark, 1985; Boardman *et al.,* 1994; Verstraeten and Poesen, 1999).

Approaches to siltation/sedimentation assessment

Sustainable land management and water resources development are threatened by soil erosion and sediment-related problems. Sediment yield is the amount of eroded material that moves from a source to a downstream control point, such as a reservoir, per unit time (Chow 1964).

It provides a valuable indicator of the quantity of soil mobilized from the surface of a drainage basin, as well as efficiency of the delivery of that sediment both to, and through, its channel system. Sediment yield estimation is crucial in water resources analysis, modelling and engineering, as sedimentation rates and amounts determine the performance and life of reservoirs (Lane *et al.,* 1997). Understanding the causes and processes of siltation are prerequisites for designing management interventions for reducing the off-site effects of accelerated erosion (Mitas and Mitasova, 1998). Thus, information on the sediment yield of a drainage basin is an important requirement for water resource development, catchment management and soil and water conservation (Akrasi, 2005). A combination of reservoir bottom sediment analysis and catchment monitoring provides a powerful conceptual and methodological framework for improved understanding of drainage basin sediment dynamics (Foster, 1995; Foster *et al.,* 1990).

Different approaches are available for estimating reservoir siltation rates. The use of **distributed physically based models**, that determine catchment erosion and route the soil along channels to ultimately estimate sediment delivery, is becoming increasingly widespread (Ferro *et al.*, 1998; Van Rompaey *et al.*, 2001). However, such models require extensive distributed data for calibration and validation, making their application difficult in data-scarce regions (Morgan, 1995; De Roo, 1998; Stefano *et al.*, 1999).

Other approaches to estimating sediment yield are those based on **sediment rating curves and river sampling** (Dearing and Foster, 1993; Steegen *et al.*, 2000). In Ghana, Akrasi (2005) employed this method in assessing suspended sediment inputs to the Volta Lake. However, these methods require repeated measurements from representative samplings undertaken over frequent periods, which result in high operational costs (Verstraeten and Poesen, 2001b; 2002a). The main problem of such techniques is that measurements that are not based on continuous recordings could give unreliable estimates of sediment yields (Walling and Webb, 1981).

The bathymetric survey is another alternative method used to estimate sediment yield. This approach is based on calculating the differences in the elevation of a reservoir-bed over a period of time during which original measurements were undertaken and the survey time (e.g., Rausch and Heinemann, 1984; Juracek and Mau, 2002; Tamene, 2005). The main problem in the use of this method is "dislocation" or removal of original bench-marks, where the use of slightly different bench-mark locations could lead to huge errors (Butcher et al., 1992).

The use of **sediment cores from reservoir deposits** is another possibility for determining sediment yield (Duck and McManus, 1990; Butcher *et al.,* 1993; Schiffer *et al.,* 2001). The major drawback associated with this method is that errors could be compounded, since several calculations and measurements are needed to derive sediment yield (Duck and McManus, 1990; Verstraeten and Poesen, 2001b; 2002a). Among the aforementioned approaches, the reservoir sedimentation survey (bathymetry and pit-based) seems to be appropriate in terms of cost, speed and applicability.

Considering the above issues, **bathymetric (reservoirs filled with water) survey** was used in this study to estimate sediment deposition in reservoirs. This is because it is simple and requires few field surveys compared to the other approaches. Moreover, since the study involved small reservoirs with no gauging stations, the sediment rating curves and river sampling approaches could not be used.

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter describes the Volta basin, the study area as well as the materials and methods used for the study.

3.1 The Volta River Basin

The Volta River Basin is the 9th largest in sub-Saharan Africa. The Volta basin stretches from approximately latitude 5°45’ N in Ghana to 14°N in Mali. The Volta basin covers over six West African countries with a total drainage area of 104,749 km^2. It lies mainly in Ghana (42%) with a drainage area of 45,804 km^2 and Burkina Faso (43%) with minor parts (15%) in Togo, Cote d´Ivoire, Mali and Benin.

Ghana occupies the downstream part of the basin. It is the largest of the 16 major river basins in Ghana and the White Volta Basin is one of the four major sub-basins of the Volta basin with a total catchment area of 10741.67 km^2. The basin is drained by several major rivers: the Black Volta, the White Volta with the Red Volta as its tributary, the Oti River and the Lower Volta. Agriculture is the dominant economic activity in the Volta basin (Barry *et al.*, 2005).

The basin, in general, has a low relief with altitudes varying between 1 and 920 m. The average mean altitude of the basin is approximately 257 m, with more than half the basin in the range of 200 – 300 m. The global slope index is between 25 – 50 cm/km.

The geology of the main Volta is dominated by the Voltaian system. Other geological formations include the Buem formation, Togo series, Dahomegan formation, and Tertiary-to-Recent formations. The White Volta Basin is composed of the Birimian system and its associated granitic intrusive and isolated patches of Tarkwaian formation. The geology, relief, and climate of locations interact to produce soils of typical characteristics. The soils of the main Volta Basin in the sub-humid Savannah Zones are Lixisols/Luvisols, Plinthosols/Planosols, Vertisols/Gleysols, Solonchaks, Fluvisols, Solonetz, and Cambisols.

The climate of the region is controlled by the North-East and the South-West Trade Winds. The North-East Trade Winds, or the Harmattan, blowing from the interior of the continent, are dry whilst the South-West Trade Winds, or the monsoons, are moist since they blow over the seas. The annual mean temperatures vary from about 27° C to 30° C. Daily temperatures can be as high as 32° C - 44° C. However, night temperatures can be as low as 15° C in some locations within the northern part of the Basin. The humidity varies between 6% and 83%, depending on the season and the location.

There have been some changes in the precipitation patterns of some sub-catchments in the basin, with evidence of runoff reduction since the 1970s (Opoku-Ankomah, 2000). Some areas that used to have bi-modal rainfall regimes have only one mode as the second minor season has become very weak or non-existent. The mean annual precipitation ranges from 800 – 1000 mm per annum. This situation means that rainfed agriculture can only be carried out once instead of twice a year.

3.2 Study Area

This study was conducted in the Upper East Region of Ghana which is the northeasternmost part of Ghana's ten regions and is situated in the centre of the Volta Basin (Figure 3.1). Brief descriptions on the geographical location, population, climate, relief and drainage, vegetation, geology and soils of the region are presented below.

3.2.1 Location and population

The region is located between latitudes 10^o 15' and 11^o 10' North and longitudes 0^o and 1^o40' West. To the west, it borders the Upper West Region and on its southern side the Northern Region. To the north of Upper East Region lies Burkina Faso, whilst Togo is in the east. It has a gross area of 8842 km^2 (IFAD, 1991). There are eight administrative districts namely Bolga, Bongo, Builsa, Kasena-Nankana, Talensi Nabdam, Bawku West, Bawku East and Garu Tempani (Figure 3.2). According to the population and housing census of 2000 (GSS, 2005), the region has a population of 920,089, made up of 442,492 males and 477,597 females with a population growth rate of 3% per annum. The Upper East Region has a comparatively high population density of 104.1 persons per km^2 compared to the national average of 79.3 persons per km^2. The population of the Upper East Region is ethnically diverse with different languages (Birner *et al.*, 2005). The residents' incomes are generated from rainfed and partly irrigated agriculture, livestock rearing and craftwork. The high population density in the region places pressure on the scarce land and water resources.

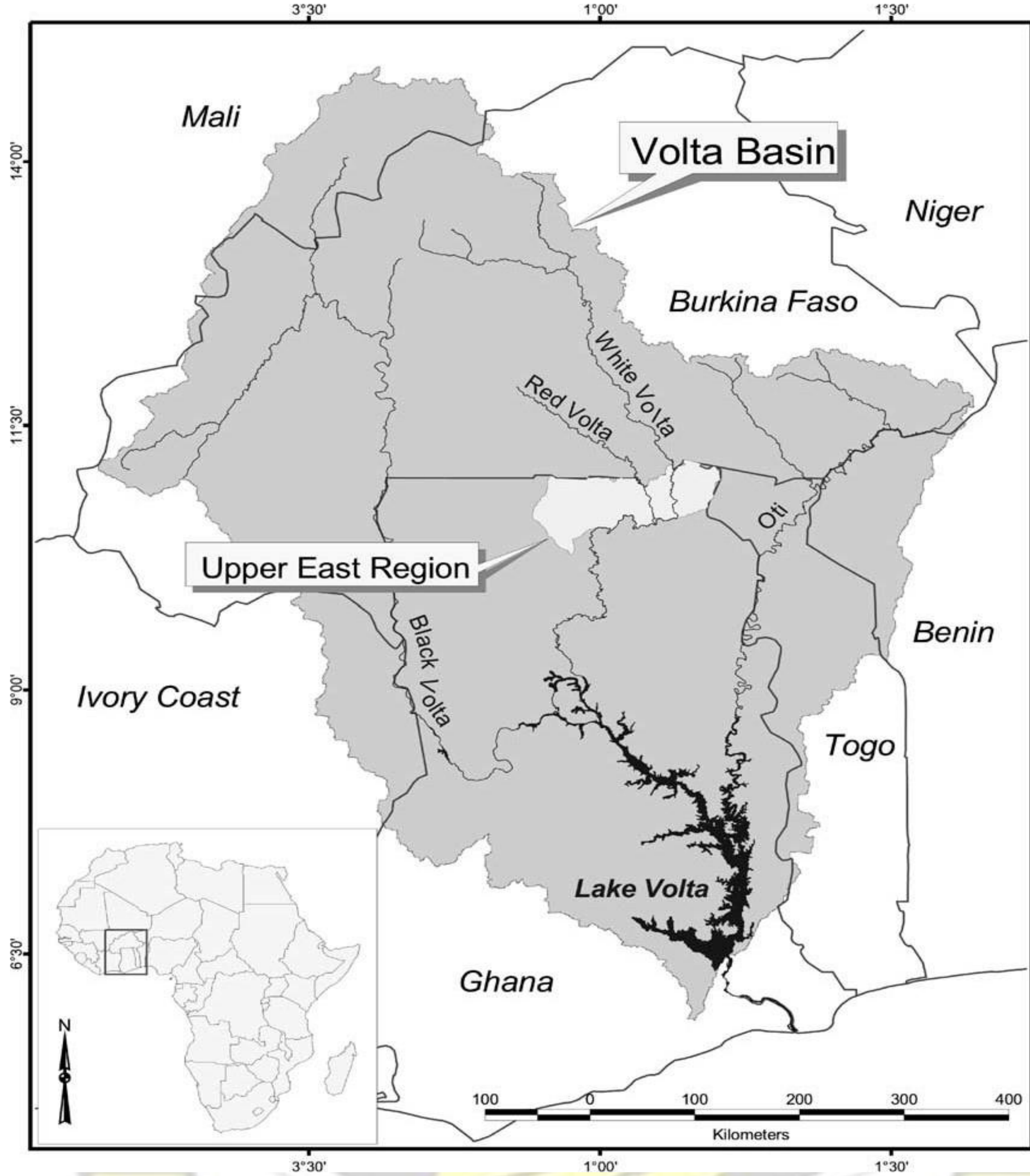

Figure 3.1 The Upper East Region of Ghana within the Volta Basin, West Africa (source: van de Giesen et al., 2002)

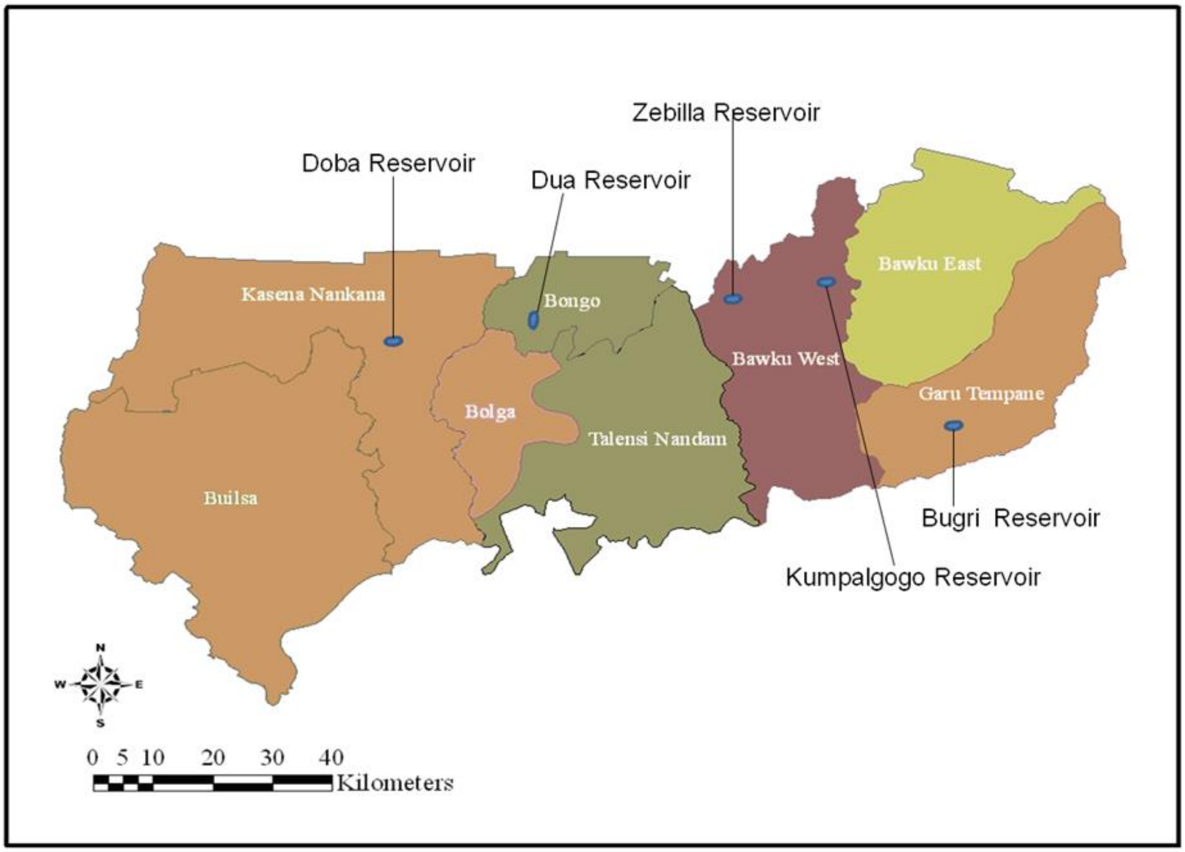

Figure 3.2 Upper East Regional Map showing its Districts and Reservoir Study Sites (Adwubi, 2008)

3.2.2 Climate

The region falls within the Inter-tropical Convergence Zone (ITCZ) whose climatic boundary oscillates annually between the south coast of Ghana and 20^{o} north. As the boundary moves north and south it draws with it the associated weather zones. Rainfall in the region is uni-modal lasting from 5 - 6 months. It has a mean annual of 900 - 1000 mm and a dry period of 6 - 7months. Considerable variations exist between successive rainy seasons with respect to time of onset, duration and amount of rainfall received (Walker, 1962). The average temperature is 28.6°C, which is consistently high. Monthly averages range from 26.4°C at the peak of the rainy season in August to a maximum of

32.1°C in March - April at end of the dry season (Liebe, 2002). Average annual relative humidity is 55%. Relative humidity is highest during the rainy season with values of 65% and may drop to a minimum value of less than 10% during the harmattan period in December and January. Relatively high temperatures and moderately low humidity in the dry season lead to high evapotranspiration (Liebe, 2002), thus contributing to the drying up of a lot of reservoirs in the region during the dry season.

3.2.3 Relief and drainage

The relief of the area is generally flat to gently undulating with slopes ranging from 15% except in a few uplands where slopes may exceed or equal to 10%. These plains are broken in some places by hills or ranges formed from either outcrops of Birimian rocks or granite intrusions. The granite areas are generally low to gently rolling (120 – 255 m above sea level) except the inselberg outcrops near Bongo which rise to about 326 m (Adu, 1969). The area is drained by the White Volta and its major tributaries – Red Volta, Sisili and Tono Rivers.

3.2.4 Vegetation

The vegetation is Sudan savanna consisting of short drought and fire resistant deciduous trees interspersed with open savanna grassland. Grass is very sparse and in most areas the land is bare and severely eroded. Studies on the natural resources and livelihood systems in the region revealed that it is very difficult to find examples of natural vegetation due to the exploitation of the natural resource base for several hundred years (Needham, 1993). The natural vegetation has been modified by human activities, particularly agriculture which is almost entirely in the hands of smallholder farmers, who combine bush farm cultivation of distant fields with permanent cultivation of nearby compound farms. The region has the highest density of cattle, overgrazing being evident in some areas particularly near ponds and dams (IFAD, 1991). Forest reserves also provide an abrupt change in tree population and type over significant areas. Common grasses include *Andropogon gayanus* in the less eroded areas and *Hyperrhenia spp*., *Aristida spp*. and *Heteropogon spp*. in the severely eroded areas. Common trees include *Anogeissus spp*., *Acacia spp*, *Triplochiton spp*, *Parkia biglobosa* (dawadawa) and *Vitelleria paradoxa* (shea butter).

3.2.5 Geology

A large part of the area (82%) is underlain by metamorphic and igneous complexes with gneiss and granodiorite predominating. Where hills rise above the soil surface, they consist of greenstone and schist. In the south-eastern boundary of the region a substantial band of sandstone, grit and conglomerate parallels the boundary and the course of the White Volta. There are small areas of intrusive diorite in the north-west of the region. Laterite has been formed by fluvial processes in the flat lands adjacent to present and past water courses and occurs over large areas. Sand occurs as local deposits and along most of the major river courses.

3.2.6 Soils

Soils in the area are generally formed by weathering of the bedrock although some drift of soil transported by wind and water is also found. The seasonal rainfall and high temperatures experienced in the region provide conditions for rapid oxidation of soil organic matter with subsequent chemical reaction leaving a residue rich in iron and aluminium oxides, providing the lateritic soils commonly found in the region. The soils of the area belong to one or a combination of the following: Luvisols, Cambisols, Gleysols, Regosols, Vertisols, Plinthosols and Fluvisols, developed from granites, Birimian rocks and alluvia of mixed origin (Asiamah, 1992). The soils have predominantly light textured surface horizons with heavy textured soils confined to valley bottoms. There are extensive areas of shallow concretionary and rocky soils which have low water holding capacities and limited suitability for agriculture (Quansah, 2005).

3.3 Site Selection

Due to time and limited financial resources, it was not possible to study all reservoirs with siltation problems in the region. Therefore, it was necessary to select sites representative of the catchments in the region (Figure 3.2). This was done through desk study and reconnaissance survey. Brief descriptions of these methods are presented.

3.3.1 Desk study

Based on existing reservoir database on 150 reservoirs from the Irrigation Development Authority (IDA) office in Bolgatanga, twenty reservoir sites were selected omitting:

a) Dugouts

b) All recently rehabilitated as well as newly constructed dams after 1998

c) Reservoirs without design maps during construction

In consultation with IDA officials in Bolgatanga it was noted that most of the selected reservoirs had been rehabilitated with no design maps for dams constructed earlier than 1990. Together with the IDA officials eighteen reservoirs rehabilitated before 1998 were selected.

3.3.2 Reconnaissance survey

Reconnaissance survey was conducted from 19th July to 23rd July, 2007 to ascertain the state of the eighteen selected reservoirs. It was noted that some of the dams were not functioning because the dam-walls were breached while others were inaccessible. For the functional reservoirs, the following criteria were used for selection:

a) Size of reservoir (small, medium and big)
b) Non-desilted reservoirs
c) Reservoirs with design maps and rehabilitated between 1990 and 1998
d) Location of the reservoir so as to spread the study over the region

Based on the above criteria, five reservoirs were selected for the study (Figure 3.2).

3.4 Field Survey

3.4.1 Bathymetric survey

Bathymetric survey is one of the methods used in quantifying sediment deposition in reservoirs that are filled with water and allow boat-based survey. In bathymetric survey, information on the original capacity of the reservoirs is required as a benchmark against which the present storage capacity can be compared (Rausch and Heinemann, 1984). The initial storage capacities of the reservoirs were acquired from IDA, Bolgatanga.

To derive current storage capacity, bathymetric surveys were conducted from 20th September to 2nd October, 2007 for the selected reservoirs using a boat and Lawrance LMS 480 Fish-Finding Sonar and GPS (Plate 3.1). The equipment measures depth with a transducer fitted on the side of the boat and records the geographic position of the transducer with a GPS receiver. In order to account for the spatial variability of sediment deposition within reservoirs, more than 800 points covering the water surface were collected for each reservoir. The periphery and elevation of the water surface for each reservoir were measured with handheld Garmin GPS 72™ of 3m accuracy and Automatic leveling instruments, respectively.

Plate 3.1 Bathymetric Survey

3.4.2 Reservoir soil sampling for physical and chemical properties determination

Undisturbed wet sediment samples of known volume were, collected using a Beeker sampler (Plate 3.2) from the five reservoirs. The beeker sampler is a piston corer with clear perspex tubes (Ø = 57 mm) of different lengths (600, 1000 and 1500 mm). At the bottom of the piston, an inflatable valve assures no sediment losses when raising the piston corer to the surface. Depending on the sediment distribution, one of the following sampling patterns was used for each reservoir:

a) one sampling point at about 10 m from the ends of reservoir, one point about 5 - 10 m closer to the dam wall and three sampling points in the middle of the reservoir;

This pattern was used to sample sediments from Dua, Kumpalgogo, Bugri reservoirs.

b) one sampling point at about 10 m from the ends of reservoir, one in the middle and the remaining three about 5 - 10 m closer to the dam wall.

This pattern was used to sample sediments from Doba and Zebilla reservoirs.

Plate 3.2 Sampling Undisturbed Submerged Sediments using a Beeker Sampler

In all, ten samples were collected from each reservoir with two samples per sampling point. One sample per sampling point was used for the determination of bulk density and the other for the particle size and soil chemical properties determination.

3.4.3 Catchment soil sampling for physical and chemical properties determination

For the analysis of the nutrient content in the catchment soils, sediment-contributing areas were identified (upper, middle and lower parts of the catchment) and from these contributing areas, soil samples were taken using an auger at depths of 0 – 15 cm. This study, however, focused mainly on those nutrients that have been transported down to the reservoir.

To determine the bulk density for the soils in the catchment, the metal core sampler method (Blake and Harte, 1986) was used. The core sampler was driven into the soil with the aid of a mallet. Soil at both ends of the tubes was trimmed and the end flushed with a straight-edged knife. At each sampling site, disturbed samples to be used for chemical properties and particle size distribution.

3.5 Laboratory Analysis of Physical and Chemical Properties of Catchment Soils and Deposited Sediments

For the analysis of the nutrient content in the deposited sediments, five samples taken from each reservoir using a Beeker sampler was used. The sampled deposited sediments and catchment soils were air-dried and sieved through a 2 mm mesh.

The samples were then analysed for particle size distribution and chemical properties such as: soil pH, Total Nitrogen (N), Available Phosphorus (P), Organic Carbon (OC), basic cations like Potassium (K^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+) and exchangeable acidity parameters of Aluminium (Al^{3+}) and Hydrogen (H^+). Finally a simple average nutrient content of the sediment samples and catchment samples were calculated for each nutrient.

3.5.1 Soil physical properties

The soil physical properties of particle size distribution and bulk density were determined as follows:

Particle size analysis

The hydrometer method (Bouyoucos, 1963) was used for this analysis. This method relies on the differential settling velocities of different particle sizes within a water column. The settling velocity is also a function of liquid temperature, viscosity and specific gravity of the falling particle (Okalebo *et al.*, 1993).

A 51 g soil sample was weighed into a 'milkshake' mix cup. To this 50.0 ml of 10% sodium hexametaphosphate along with 100 ml distilled water were added. The mixture was shaken for 15 minutes after which the suspension was transferred from the cup into a 1000 ml measuring cylinder and distilled water was added to reach the 1000 ml mark. The mixture was inverted several times until all soil particles were in suspension. The cylinder was placed on a flat surface and the time noted. The first hydrometer and temperature readings were taken at 40 seconds. After the first readings the suspension was allowed to stand for 3 hours and the second hydrometer and temperature readings taken. The first reading indicates the percentage of sand and the second reading percentage clay. The percentage of silt was determined by the difference.

Calculations:

$$\% \text{ Sand} = 100 - [H_1 + 0.2\,(T_1 - 20) - 2.0] \times 2 \qquad [3.1]$$

$$\% \text{ Clay} = [H_2 + 0.2\,(T_2 - 20) - 2.0] \times 2 \qquad [3.2]$$

$$\% \text{ Silt} = 100 - (\% \text{ sand} + \text{clay}) \qquad [3.3]$$

Where:

H_1 = Hydrometer reading at 40 seconds

T_1 = Temperature at 40 seconds

H_2 = Hydrometer reading at 3 hours

T_2 = Temperature at 3 hours

0.2 (T – 20) = Temperature correction to be added to hydrometer reading

- 2.0 = Salt correction to be added to hydrometer reading.

Soil bulk density (ρ_b)

Soil bulk density is the ratio of the mass of dry soil to the bulk volume of the soil. The content of the core sampler was dried in the oven at 105^0C for 48 hours, removed, allowed to cool and its mass taken. The mass of the drying container was determined and volume of core sampler determined.

In order to compare the siltation rate of the different reservoirs, it was necessary to convert the measured sediment volume (m^3) to sediment mass (Mg) using representative dry bulk density (ρ_b) (Butcher *et al*., 1993; Verstraeten and Poesen, 2001a). The same procedure was used for sediment samples taken for bulk density. The mean ρ_b of each group of samples was determined and used to calculate sediment mass.

Calculation:

$$\text{Dry bulk density } \rho_b \text{ (Mg m}^{-3}\text{)} = \frac{W_2 - W_1}{V} \qquad [3.4]$$

where:

W_2 = Weight of sample container + oven-dried soil

W_1 = Weight of empty sample container

V = Volume of core cylinder ($\pi r^2 h$), where:

π = 3.142 r = radius of the core cylinder h = height of the core cylinder

3.5.2 Soil chemical properties

The chemical composition of sediments is fundamental in relation to their suitability for agricultural use and potential for polluting water bodies. For soils, it is important to study the nutrients levels and the conditions that enhance their release and availability to plants. According to Twinch and Breen (1982) the nature and levels of chemical elements in the sediments of the reservoirs are related to: (1) mineralogical composition of sources in the drainage basin, (2) weathering processes during material transport to the reservoirs, and (3) dynamic equilibrium between sediments and water.

The following soil chemical properties were analyzed to determine the fertility status of the soil.

Soil pH

The pH of the soil was determined using a Suntex pH (mv) Sp meter (701) for soil: water ratio of 1:2.5 as described by McLean (1982). A 20 g soil sample was weighed into a 100 ml beaker. To this 50 ml distilled water was added and the suspension was stirred continuously for 20 minutes and allowed to stand for 15 minutes. After calibrating the pH meter with buffer solutions of pH 4.0 and 7.0, the pH was read by immersing the electrode into the upper part of the suspension.

Soil organic carbon

Organic carbon was determined by a modified Walkley-Black wet oxidation method (Nelson and Sommers, 1982). Two grams of soil sample was weighed into 500ml erlenmeyer flask. A blank sample was also included. Ten millilitres of 1.0 *N* $K_2Cr_20_7$ solution was added to the soil and the blank flask. To this, 20 ml of concentrated sulphuric acid was added and the mixture allowed to stand for 30 minutes on an asbestos sheet. Distilled water (200 ml) and 10 ml of concentrated orthophosphoric acid were added and allowed to cool. The excess dichromate ion ($Cr_20_7^{-2}$) in the mixture was back titrated with 1.0 *M* ferrous sulphate solution using diphenylamine as indicator.

Calculation:

$$\%\ \text{Organic C} = \frac{(\text{m.e}K_2Cr_20_7 - \text{m.e.}FeS0_4) \times (1.32) \times 0.003 \times 100}{\text{wt.of soil}} \quad [3.5]$$

where:

m.e. = normality of solution x ml of solution used

0.003 = m.e. wt of C in grams (12/4000)

1.32 = correction factor

Organic matter

The organic matter of the soil sample was calculated by multiplying the per cent organic carbon by a Van Bemmelen factor of 1.724.

Total nitrogen

The total Nitrogen content of the soil was determined using the Kjeldahl digestion and distillation procedure as described by Bremner and Mulvaney (1982). A 10 g soil sample was put into a Kjeldahl digestion flask and 10 ml distilled water added to it.

Concentrated sulphuric acid and selenium mixture were added and mixed carefully. The sample was digested on a Kjeldahl apparatus for 3 hours until a clear and colourless digest was obtained. The volume of the solution was made to 100 ml with distilled water. A 10 ml aliquot of the solution was transferred to the reaction chamber and 10 ml of NaOH solution was added followed by distillation. The distillate was collected in boric acid and titrated with 0.1*N* HCl solution with bromocresol green as indicator. Traces of nitrogen in the reagents and water used were taken care of by carrying out a blank distillation and titration.

Calculation:

$$\% \text{ N} = \frac{14 \times (A - B) \times N \times 100}{1000 \times 1} \qquad [3.6]$$

where:

N = concentration of HCl used in titration.

A = ml HCl used in sample titration

B = ml HCl used in blank titration
14 = atomic weight of nitrogen

1 = wt. of soil sample in gram

Available phosphorus

This was determined using the Bray P_1 method (Olsen and Sommers, 1982). The method is based on the production of a blue complex of molybdate and orthophosphate in an acid solution. A standard series of 0, 0.8, 1.6, 2.4, 3.2, and 4.0 μgP/ml were prepared by diluting appropriate volumes of the 10 μgP/ml standard sub-stock solution. These standards were subjected to colour development and their respective transmittances read on a spectrophotometer at a wavelength of 520. A standard curve was constructed using the readings.

A 2.0 g soil sample was weighed into a 50 ml shaking bottle and 20 ml of Bray-1 extracting solution was added. The sample was shaken for one minute and then filtered through No. 42 Whatman filter paper. Ten millilitres of the filtrate was pipetted into a 25 ml volumetric flask and 1 ml each of molybdate reagent and reducing agent were added for colour development. The percent transmission was measured at 520 nm wavelength on a spectrophotometer. The concentration of P in the extract was obtained by comparison of the results with a standard curve.

Calculations:

$$P\ (mgkg^{-1}) = \frac{\text{Graph reading} \times 20 \times 25}{w \times 10} \quad [3.7]$$

where:

w = sample weight in grams

20 = ml extracting solution

25 = ml final sample solution

10 = ml initial sample solution

Exchangeable cations determination

Exchangeable bases (calcium, magnesium, potassium and sodium) content in the soil were determined in 1.0 *M* ammonium acetate (NH_4OAc) extract (Black, 1965) and the exchangeable acidity (hydrogen and aluminum) was determined in 1.0 *M* KCl extract (McLean, 1965).

Extraction of the exchangeable bases

A 10 g soil sample was weighed into an extraction bottle and 100 ml of 1.0 *M* ammonium acetate solution was added. The bottle with its contents was shaken for one hour. At the end of the shaking, the supernatant solution was filtered through No. 42 Whatman filter paper.

Determination of calcium

For the determination of calcium, a 10 ml portion of the extract was transferred into an erlenmeyer flask. To this, 10 ml of potassium hydroxide solution was added followed by

1 ml of triethanolamine. Few drops of potassium cyanide solution and few crystals of cal-red indicator were then added. The mixture was titrated with 0.02*N* EDTA (ethylene diamine tetraacetic acid) solution from a red to a blue end point.

Determination of calcium and magnesium

A 10 ml portion of the extract was transferred to an erlenmeyer flask and 5 ml of ammonium chloride-ammonium hydroxide buffer solution was added followed by 1 ml of triethanolamine. Few drops of potassium cyanide and Eriochrome Black T solutions were then added. The mixture was titrated with 0.02*N* EDTA solution from red to blue end point.

Calculations:

$$Ca^{2+} + Mg^{2+} \text{ (or Ca) (cmol/kg soil)} = \frac{0.02 \times V \times 1000}{W} \quad [3.8]$$

where:

W = weight in grams of soil extracted

V = ml of 0.02 *N* EDTA used in the titration

0.02 = concentration of EDTA used

Determination of exchangeable potassium and sodium

Potassium and sodium in the soil extract were determined by flame photometry. Standard solutions of 0, 2, 4, 6, 8 and 10 ppm K^+ and Na^+ were prepared by diluting appropriate volumes of 100 ppm K^+ and Na^+ solution to 100 ml in volumetric flask using distilled water. Photometer readings for the standard solutions were determined and a standard curve constructed. Potassium and sodium concentrations were read from the standard curve.

Calculations:

$$\text{Exchangeable } K^{+} \text{ (cmol/kg soil)} = \frac{\text{Graph reading} \times 100}{39.1 \times w \times 10} \qquad [3.9]$$

$$\text{Exchangeable } Na^{+} \text{ (cmol/kg soil)} = \frac{\text{Graph reading} \times 100}{23 \times w \times 10} \qquad [3.10]$$

where:

w = air-dried sample weight of soil in grams

39.1 = atomic weight of potassium

23 = atomic weight of sodium

Exchangeable acidity

This consists of aluminium (Al^{3+}) and hydrogen (H^{+}). The soil sample was extracted with 1.0 *M* KCl, and the sum of Al^{3+} + H^{+} was determined by titration (McLean, 1965). Five grams of soil sample was put into a shaking bottle and 100 ml of 1.0 *M* KCl solution added. The mixture was shaken for one hour and then filtered. Fifty millilitres portion of the filtrate was transferred into an erlenmeyer flask and few drops of phenolphthalein indicator solution added. The solution was titrated with 0.05 *N* NaOH until the colour just turned permanently pink. The amount of base used was equivalent to total acidity (H^{+} + Al^{3+}). A few drops of 0.05 *N* HCl were added to the same mixture to bring the solution back to colourless condition and 10 ml of ammonium fluoride (NaF) solution added. The solution was then titrated with 0.05 *N* HCl until the colour disappeared. The milliequivalents of acid used are equal to the amounts of exchangeable Al^{3+} and the amount of H^{+} was determined by difference.

Calculation:

$$\text{Exchangeable } Al^{3+} + H^{+} \text{ or } Al^{3+} \text{ (cmol/kg soil)} = \frac{0.05 \times v \times 200}{w} \quad [3.11]$$

where:

0.05 = normality of NaOH or HCl used for titration

v = ml NaOH or HCl used for titration w = air-dried soil sample weight in grams

Effective cation exchange capacity (ECEC)

Effective cation exchange capacity was determined by the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) and exchangeable acidity (Al^{3+} and H^{+}).

3.6 Data Analysis

3.6.1 Sediment volume determination

The data collected from the bathymetric survey was analyzed using Golden Software Surfer 8 (Golden Software Inc., 2003). The elevation of the current reservoir bed (top of sediment) at each measurement point was defined by subtracting the recorded depth from the water surface level, measured with Automatic levelling instrument. Storage capacity and water surface area of the reservoirs at 1m interval was calculated using Surfer's "Volume" function, based on which the current capacity curves of the reservoirs were constructed. The total volume of sediment deposition was then calculated by subtracting current water storage capacity from the initial water storage capacity.

3.6.2 Estimating sediment trap efficiency of reservoirs

Sediment Trap Efficiency (STE) is the proportion of the incoming sediment that is deposited, or trapped, in the reservoir (Rausch and Heinemann, 1984; Verstraeten and Poesen, 2000).

In order to determine the average sediment yield from the contributing watersheds, the weight of deposited sediment needs to be adjusted for reservoir STE. Equation 3.12 as proposed by Brown (1943) was used in estimating STE of the reservoirs.

$$STE = 100\left[1 - \frac{1}{1 + 0.0021D\frac{SC}{A}}\right] \qquad (3.12)$$

Where SC = reservoir storage capacity (m^3); A = catchment area (km^2). D is a constant with values ranging from 0.046 to 1 and a mean value of 0.1. The value of TE depends on D which also depends on a reservoir's characteristics. Considering the difficulty in objectively defining the value of D, the mean value was used in the estimation.

3.6.3 Calculation of sediment yield to reservoirs

Sediment yield from catchments is an important indicator of the difference in erosional susceptibility between catchments. Measuring sediment yield is important as it reveals the impact of water erosion and delivery processes on the siltation of the reservoir. Thus changes in sediment yield reflect the impact of land use or climate changes on soil erosion by water (Walling, 1997).

The following equations were used to calculate annual sediment yield (SY) and Area- specific sediment yield (ASY).

$$RS = \frac{SV \times \rho_b}{Y} \quad (3.13)$$

$$SY = 100\frac{SV \times \rho_b}{TE \times Y} \quad (3.14)$$

$$ASY = \frac{SY}{A} \quad (3.15)$$

Where *RS* = rate of siltation (Mg y^{-1}); *SY* is sediment yield (Mg y^{-1}); ρ_b = dry-bulk density (Mg m^{-3}); *TE*= trap efficiency (%); *Y* = age of reservoir (years); *SV* = sediment volume calculated (m^3); ASY= Area-specific sediment yield (Mg ha^{-1} y^{-1}); A= catchment area (ha)

3.6.4 Soil depth deduction due to soil loss

The physical loss of soil through erosion reduces the depth of soil needed for the storage of water and nutrient and increased root room. It is expressed as:

$$\rho_b = \frac{Ms}{Vt} = \frac{Ms}{Axh}$$

Therefore: $$h = \frac{Ms}{\rho_b \times A} \qquad (3.16)$$

Where:

h = depth reduction due to soil loss (m)

Ms = weight of dry soil loss (kg)

Vt = total volume of soil loss (m^3)

A = area from which soil is lost (m^2)

ρ_b = bulk density of parent soil from which eroded sediment originates (kg m^{-3})

Example: Dua reservoir

Sediment mass = 3518.3 Mg/ha

ρ_b = 1511.96 kg m^{-3} h =

351830035000mkg2 x 1511

________m.963 kg

= 529186003518300mm32

= 0.06649 m

= 66.49 mm

3.6.5 Reduction in water holding capacity due to loss in soil depth

The reduction of soil depth due to soil loss reduces the water holding capacity of the soil, which in turn, adversely affects soil productivity. In this study, it is assumed that the water holding capacity of the surface (20 cm) sandy loam for Dua, Loamy sand for Doba, Zebilla, Kumpalgogo, Bugri reservoirs respectively, is 100 mm per metre soil depth (Hudson, 1995). Assuming even distribution of water along the metre depth, the top 20 cm depth will hold 200 mm of water (i.e. 0.1 mm)/mm depth). Using the depth loss values (Equation 3.16) the percentage reduction in the water holding capacity of the top 20 cm is calculated as:

% Reduction in water holding capacity (WHC)

$$WHC = \frac{(\text{depth loss (mm)} \times 0.1\text{mm})}{(200\text{mm} \times 0.1\text{mm})} \times 100 \qquad [3.17]$$

3.6.6 Calculation of nutrient enrichment ratios (ER)

Previous studies on fertility erosion indicate that the eroded sediment is often richer in nutrients and colloidal clay than the soil from which the sediment originated. Enrichment ratio (ER) is a measure of the magnitude of richness. The enrichment of sediment occurs because of the selective erosion and deposition processes. The enrichment ratio was quantified as (Wan and El-Swaify, 1998):

$$ER = \frac{\text{The concentration of a constituent such as OC; N and others in the eroded sediment}}{\text{The concentration of the same constituent in the in situ soil}} \quad [3.18]$$

3.6.7 Estimation of cost of nutrients in the eroded sediments using the replacement cost method

The NPK contents of the eroded soil were converted to the forms in which they exist in straight fertilizers, i.e. N, P_2O_5 and K_2O (kg), respectively by multiplying by the following constants:

Kg N = Kg N [3.19]

Kg P × 2.29 = kg P_2O_5 [3.20]

Kg K × 1.2 = kg K_2O [3.21]

The current cost of fertilizers used in this study for estimating the cost fertilizer lost is:

One bag of sulphate of ammonia (50 kg) cost = GH¢ 30.00

Single Superphosphate (50 kg) cost = GH¢ 45.00 and

Muriate of Potash (50 kg) cost = GH¢ 80.00

Calculations on number and cost of bags of fertilizer lost Example:

The Dua catchment

The N, P and K lost from the catchment into the reservoir are:

Nitrogen = 536 kg N/ha

Phosphorus = 35.14 kg P/ha = 80.47 kg P_2O_5/ha

Potassium = 290 kg K /ha = 348 kg K_2O/ha

1 bag of each straight fertilizer = 50 kg

(i) 100 kg of Sulphate of Ammonia contains 21 kg N

Therefore 536 kg N = 100 kg × $\frac{536\ kg}{21\ kg}$ = 2552.38 kg ÷ 50 = 51.05 bags Sulphate of Ammonia

(ii) 100 kg of Single Superphosphate contains 18 kg P_2O_5

Therefore 80.47 kg P_2O_5 = 100 kg × $\frac{80.47kg}{18kg}$ = 447.06 kg ÷ 50 = 8.94 bags Single Superphosphate

(iii) 100 kg of Muriate of Potash contains 60 kg of K_2O

348 kg K_2O = 100 kg × $\frac{348kg}{60kg}$ = 580 kg ÷ 50 = 11.60 bags Muriate of Potash

Therefore the number of bags of fertilizer lost to the candidate reservoirs is 51.05, 8.94 and 11.60 for Sulphate of Ammonia, Single Superphosphate and Muriate of Potash respectively. The number of bags of each straight fertilizer is multiplied by the cost/50kg to give the total cost of fertilizer lost.

3.6.8 Total stock of carbon sequestered and its CO_2 equivalent

The CO_2 equivalents of total stock of carbon sequestered in the candidate reservoirs was calculated by:

Total carbon per annum (in Mg/y) × 3.67 (factor) [3.22]

Factor = Molecular mass of CO_2/Atomic mass of Carbon (C)

$$\text{Factor} = \frac{44}{12} = 3.67$$

3.6.9 Quantification and evaluation of nutrient export rates

The sediment-bound Nutrient Export (NE) value for each catchment draining to the respective reservoirs was calculated by:

$$NE = \frac{SM \times NC}{A \times Y \times NTE \times 10}$$ (Modified after Verstraeten and Poesen, 2002b) [3.23]

$$SM = SV \times \rho_b$$ [3.24]

where, NE represents the nutrient export (kg ha^{-1} y^{-1}), SM is total measured sediment mass (kg); NC is average nutrient content of the sample (mg of nutrient per kg of sediment); A is catchment area (ha); Y is age of the reservoir for a duration of sediment accumulation (y); NTE (=STE) is the nutrient (=sediment) trap efficiency of the reservoirs (per cent); SV is total measured sediment volume (m^3) in the reservoir and dry bulk density (ρ_b; kg m^{-3}).

3.7 Statistical Analysis

Data obtained in this study were analysed by Analysis of Variance (ANOVA) using GENSTAT Statistical Package (GENSTAT, 2007) to determine the variability in bulk density and sediment nutrients. Standard error difference (s.e.d) at 5% was used to compare treatment means. Mean comparison, bi-variate correlation matrixes were used to assess the degree of association between catchment soils and sediment deposits.

Regression analysis was carried out to generate empirical equations to predict the amount of plant nutrients lost from reservoir catchments and deposited in the reservoir sediments.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The characteristics of the reservoirs used for this study are presented in Table 4.1.

Table 4.1 Characteristics of the Selected Reservoirs in the Upper East Region

Description	Dua	Doba	Kumpalgogo	Zebilla	Bugri
District	Bongo	Kasena-Nankana	Bawku East	Bawku West	Garu Tempane
Year of construction	1970	1956	1960	1962	1956
Year rehabilitation started	1996	1997	1997	1997	1992
Year rehabilitation completed	1997	1998	1998	1998	1994
Catchment area (ha)	35	70	40	105	216
Flooded area at FSL (ha)	6.89	12.5	6	22.5	24
Storage capacity (ha-m)	9.96	18.5	12	46	51
Live storage (ha-m)	9.86	18	N/A	45.2	50.89
Dead storage (ha-m)	0.1	0.5	N/A	0.8	0.11
Length of dam wall (m)	530	364	300	500	N/A

Max height of dam wall (m)	4.2	4.6	3.8	7	7.5
Dam crest elevation (m)	229	178	194	227.25	500.75
Spillway elevation (m)	228	177	193	225.8	499.25
Free board (m)	1	1	1	1.45	1.5
Spillway length (m)	10	N/A	20	20	10
Total Irrigable area (ha)	4	7	5	8.5	30

FSL- Full supply level; N/A – Data not available (Source: IDA, Bolgatanga Regional Office)

4.1 Sediment Volume of the Reservoirs Studied

The use of the bathymetric survey allowed the estimation of sediment volumes in the reservoirs. Sediment volume, calculated as the difference between the initial and current capacities of the reservoirs, is presented in Table 4.2.

Table 4.2 Initial and Current Storage Capacities of the Five (5) Reservoirs

Site	Initial Capacity (10^3 m^3)	Current Capacity (10^3 m^3)	SV (10^3 m^3)
Dua	99.6	76.3	23.3
Doba	185.0	178.0	7.00
Zebilla	460.0	434.9	25.1
Kumpalgogo	120.0	80.7	39.3
Bugri	560.0	517.0	43.0

SV= sediment volume

The initial capacity of the reservoirs, provided by the IDA, ranged from 99600 m^3 to 560000 m^3 for the Dua and Bugri reservoirs, respectively. On the other hand, the current capacity, determined by the bathymetric survey, varied between 76300 m^3 and 517000 m^3 for the Dua and the Bugri reservoirs, respectively. The values showed that the original capacities of the reservoirs have been reduced by a range of 7000 m^3 to 43000 m^3 for Doba and Bugri, respectively. The reduction in the original capacity was 23.4, 7.7, 5.5, 3.8 and 3.3 percent for Dua, Bugri, Zebilla, Doba and Kumpalgogo, respectively. The reduction in capacity was due to sediment deposition from the respective catchments.

The reduction in storage capacity due to sediment deposition has serious implications for the dead storage capacity of the reservoirs. The latter capacity is the allowable space for sediment storage for optimum functioning of the reservoirs during the entire 25 year design life. The dead storage capacities were 1000, 5000, 8000 and 11000 m^3 for the Dua, Doba, Zebilla and Bugri reservoirs respectively. The corresponding volumes of sediment deposits were 23300, 7000, 25100 and 43000 m^3.

The implication of these sediment volumes is that, in the context of the dead storage capacity, all the reservoirs have, in their age range of 9 to 13 years, lost more than 100 per cent of their designed dead storage capacity. The optimum functioning of the reservoirs is therefore already compromised by sedimentation within 50 percent of their designed useful life. This will deprive the communities in the study area from deriving maximum benefits from the reservoirs. In this area, water scarcity is a persistent problem, particularly in the dry season. There is therefore the need to conserve and protect water stored in reservoirs to sustain availability both in quantity and quality to meet the demands of the evergrowing population. These demands include domestic, agricultural, industrial as well as for other economic activities and maintaining ecosystem functions.

4.2 Physical Characteristics of Catchment Soils and Reservoir Sediments The results of the bulk densities and the textures of the reservoir sediments and catchment soils are presented in Tables 4.3 and 4.4.

Table 4.3 Sediment Bulk Densities with their Standard Deviations and Particle Sizes of Five (5) Reservoirs in the Upper East Region of Ghana

Reservoirs	ρ_b (Mg/m^3)	Sand (%)	Clay	Silt
Dua	1.35±0.10	28	33.9	38.1
Doba	1.53±0.73	70.7	16.5	12.8
Zebilla	1.29±0.40	30.7	31.9	37.5
Kumpalgogo	1.33±0.24	28.7	39.2	32.1
Bugri	1.17±0.64	22.7	48.5	28.8
Average	**1.33**	**36.16**	**34**	**29.86**
s.e.d	0.43	7.41	5.49	6.19
CV(%)	41.9	25.1	19.8	25.4

Table 4.4 Soil Bulk Densities with their Standard Deviations and Particle Sizes of Five (5) Catchments in the Upper East Region of Ghana

Catchments	ρ_b (Mg/m^3)	Sand (%)	Clay	Silt
Dua	1.52±0.06	88	4.13	7.87
Doba	1.63±0.04	87.73	4.27	8
Zebilla	1.72±0.10	90.4	2.53	7.07
Kumpalgogo	1.60±0.08	83.87	9.07	7.07
Bugri	1.49±0.14	81.07	9.2	9.73

Average	**1.59**	**86.21**	**5.84**	**7.95**
s.e.d	0.08	1.99	1.90	1.7
CV(%)	6.2	2.8	39.8	26.2

4.2.1 Dry bulk density

The mean dry bulk densities of the sediment deposits ranged from 1.17±0.64 to 1.53±0.73 Mg/m^3 with a decreasing trend of Doba>Dua>Kumpalgogo>Zebilla>Bugri (Table 4.3). Doba and Dua recorded significantly higher bulk densities than Zebilla and Bugri. The difference in bulk density between Doba and Zebilla was also significant. The bulk density values are indicative of the degree of compaction of the deposited sediments. Bulk density increases with increasing compaction. There was a considerable variation in the measured bulk densities between the reservoirs studied. The coefficient of variation (CV) was 41.9% (Table 4.3). This falls within the medium variation class according to Warrick's (1998) guidelines for variability of soil properties. The variations, as observed in a similar study by Verstraeten and Poesen (2001b), may be due to different hydrologic conditions of the reservoirs and differences in sediment texture between the reservoir deposits and their interactions. The organic matter content, particularly the nature of organic matter also influences dry bulk density. Deposits with high amounts of litter have unusually low dry bulk density values. Within reservoir variability was also observed in the bulk density samples. In explaining the possible causes of such variability in their study, Verstraeten and Poesen (2001b) indicated that the observed differences may be due to spatially distributed patterns of bulk density within the reservoir, which, in turn, are controlled by the flow distance from the reservoir inlet to the reservoir outlet, and by spatially hydrologic conditions within the reservoir.

On the other hand the catchment bulk densities were 1.52±0.06, 1.63±0.04, 1.72±0.10, 1.6±0.10, 1.49±0.14 Mg/m^3 for Dua, Doba, Zebilla, Kumpalgogo and Bugri respectively (Table 4.4). The mean, s.e.d and CV was 1.59 Mg/m^3, 0.08 and 6.2 per cent respectively. A comparison of the bulk density of the reservoirs and the catchments showed less variability in the latter.

4.2.2 Particle sizes of the reservoir sediments and catchment soils

The textural analysis of sediment samples provide an estimate on the relative fraction sizes of the sediments from their catchment areas where the finer fractions of soil eroded are carried along runoff and deposited in reservoirs. The various particle sizes of all the reservoir catchment soils and sediment deposits are presented in Tables 4.3 and 4.4. The mean particle sizes of the sediment deposits ranged from 22.7 to 70.7, 16.5 to 48.5 and 12.8 to 38.1 percent for sand, clay and silt respectively (Table 4.3). The results showed the sediments deposits to be richer in clay and silt than sand. The differences in the sediment textures observed for the various reservoirs reflect the different soil types, topography, rainfall intensity, crop cover and organic matter content of the soils in the various catchment areas of the reservoirs.

On the other hand, the mean catchment particle sizes ranged from 81.07 to 90.4, 2.53 to 9.2 and 7.07 to 9.73 percent for sand, clay and silt respectively (Table 4.4). The results showed the catchment soils to contain more sand than clay and silt. This therefore confirms the selectivity of the erosion process in removing finer particles of the catchment soils and their resultant deposition in their respective reservoirs.

4.3 Sediment Deposition in the Reservoirs

Sediments produced from the various catchments as a result of detachment of soil by raindrop impact and runoff are mainly transported along the slope by runoff. Deposition of the sediments occurs along the flow path as runoff velocity or energy available for transport diminishes. At any velocity, the larger particles settle first whilst the finer particles end and settle out in the reservoir or river in the valley bottom.

Sediment yield is generally expressed in mass units (Mg), therefore, the sediment volumes obtained in this study were converted into sediment mass using the measured bulk densities. The results are presented in Table 4.5 in addition to the calculated sediment trap efficiencies, rates of siltation and sediment yield.

Table 4.5 Trap Efficiency, Sediment Mass, Sediment Yield and Area-Specific Sediment Yield of Five (5) Reservoirs in the Upper East Region of Ghana

Reservoirs	**TE** (%)	**SM** **(Mg)**	**RS** **(Mg y^{-1})**	**SY** **(Mg y^{-1})**	**ASY** **(Mg ha^{-1} y^{-1})**
Dua	97.86	35,183	3,518.30	3,595.24	102.72
Doba	98.16	11,480	1,275.56	1,299.47	18.56
Zebilla	98.86	24,849	2,761.00	2,792.84	26.60
Kumpalgogo	97.70	55,413	6,157.00	6,301.94	157.55
Bugri	98.03	50,310	3870.00	3,947.77	18.28
Average	**98.12**	**35447**	**3516.37**	**3587.45**	**64.74**
SD	**0.45**	**18071.80**	**1781.14**	**1827.88**	**62.85**

SM=sediment deposit; RS=rate of siltation; SY=sediment yield; ASY=area specific sediment yield;

TE=sediment trap efficiency; SM=Sediment mass

4.3.1 Trap efficiency

Trap efficiency (TE) is the proportion of the incoming sediment that is deposited or trapped, in the reservoir (Rausch and Heinemann, 1984; Verstraeten and Poesen, 2000). The determination of the average sediment yield from the contributing catchments requires the weight of the deposited sediment to be adjusted for sediment trap efficiency. This facilitates adjusting for sediment that may leave the reservoir and avoid possible underestimation of sediment deposition (Rausch and Heinemann, 1984). The results (Table 4.5) showed that all the reservoirs had very high trap efficiency with values ranging from 97.70 to 98.86 percent for Kumpalgogo and Zebilla, respectively and a mean of 98.12 percent.

4.3.2 Sediment deposit

The amount and annual rate of sedimentation in the reservoirs studied are presented in Table 4.5. The sediment deposits, as at the time of the study, ranged from 55,413 to 11480 Mg for the reservoirs respectively. The amount of sediment deposits followed the trend of Kumpalgogo > Bugri >Dua>Zebilla>Doba. The sediment deposits varied significantly between the reservoirs. The differences in the hydrologic conditions of the reservoirs, catchment area and characteristics as well as the duration of sedimentation, which ranged from 9 to 13 years may account for the observed differences. The amount of sediment deposits, shows that, within 9 to 13 years, relative to the 25 year-design life of the reservoirs 4, 6, 10 and 24 percent of the live storage capacity of Doba, Zebilla, Bugri and Dua reservoirs, respectively is already filled. This is at a siltation rate (RS) of 1275.56

and 6157 Mg y^{-1} for the Doba and Bugri reservoirs respectively. The mean siltation rate of the five reservoirs was 3516.37 Mg y^{-1}.

The annual rate of siltation differed significantly among the reservoirs in the order of Kumpalgogo>Bugri>Dua>Zebilla>Doba. The adjustment of the siltation rate by the trap efficiencies of the reservoirs (TE) gave sediment yield (SY) values ranging from 1299.47 to 6301.94 Mg y^{-1} with a mean value of 3587.45 Mg y^{-1}. The magnitude of SY followed the same trend as RS. The SY differed significantly among the reservoirs.

The amount of sediment deposits shows that 47, 19.4, 11, 7.8 percent of the 12.5 years or 50% of the projected live storage of Dua, Bugri, Zebilla and Doba reservoirs, is already filled. The rate of siltation shows that the reservoirs will not be filled by sediments before the design life of 25 years. However the storage capacities of the reservoirs will be considerably reduced to limit their ability to meet the intended use, particularly for dry season irrigated agriculture. This will adversely affect the attainment of food security, creation of jobs for preventing the migration of the youth to the south in search of jobs during the long dry season. Moreover the rapid failure of the service life will also result in a much lower internal rate of return and greater loss of money spent for the construction of the reservoirs. Preventive measures, aimed at effective catchment area protection, erosion control and appropriate water resources management would be required to avert the ongoing degradation of the reservoirs.

4.3.3 Catchment erosion and area-specific sediment yield

The area specific sediment yield (ASY), taken as proxy for catchment erosion, is presented in Table 4.5. The rate of sediment yield from the various catchments into their respective reservoirs ranged between 18.28 to 157.55 Mg ha^{-1} y^{-1} for Doba and Kumpalgogo, respectively. The magnitude of ASY was in the order of Kumpalgogo>Dua>Zebilla>Doba >Bugri with a mean of 64.74 Mg ha^{-1} y^{-1}.

There was a considerable variation in the ASY values, the difference between the maximum and minimum rates being 139.27 Mg ha^{-1} y^{-1}. The observed differences in the ASY values of the reservoirs could be attributed to variations in the bio-physical characteristics of the watersheds as well as anthropogenic activities as similarly reported by Tamene *et al.* (2006) in their studies. Among the bio-physical parameters, the size of the catchment area contributing runoff and sediment to the reservoir appears to be a major determining factor. The results (Table 4.5) showed a tendency of ASY to increase with a decreasing catchment area. This was amply demonstrated in the calculated ASY to catchment area ratios for the reservoirs. The reservoirs that had relative smaller sizes, such as Dua (35 ha) and Kumpalgogo (40 ha) recorded 3:1 and 4:1 respectively. For the larger catchments, such as Bugri (216 ha), Zebilla (105 ha) and Doba (70 ha), the respective ratios were 0.1:1, 0.3:1 and 0.3:1. These ratios imply that a hectare yields 3 – 4 Mg sediments for the 35 – 40 ha catchments and 0.3 Mg for the 70 – 216 ha catchments. Although the large catchments may produce more total sediments than the small ones, they also provide a longer travel distance for sediment transport and opportune time for sediment entrapment and storage by surface roughness elements.

Consequently the catchment sediment output which will be measured in the reservoir at the downslope end of the catchment is significantly reduced.

On the other hand most of the sediments transported by runoff in small catchments reach the reservoir, because of the relatively shorter travel distance and less time for sediment entrapment and storage within the catchment. Other contributing factors to the variations in catchment ASY include slope steepness and length, shape of the catchment, size of marshy buffer zone surrounding the reservoirs, land cover, soils and land use.

A large proportion of the catchments studied had gentle slopes less than 5 per cent. However in the upslope reaches of the catchment, where homesteads and compound farms were located, the slopes could reach 10 per cent. All the reservoirs had patches of marshy land of varying sizes around them. These marshy sites served as sinks for sediment transported from the source areas thereby reducing the amount of sediment reaching the reservoirs. Some of the marshy sites were planted to rice. Land use in the catchments comprised compound farms cultivated to a variety of crops including millet, sorghum and okro. The cultivation practices, including bullock ploughing tended to loosen the soil and made them more erodible. In some cases, vegetables were cultivated very close to the periphery of the reservoirs, as observed at Zebilla. Some of the reservoirs, such as Doba, Dua, Bugri and Kumpalgogo had lines or patches of vetiver along the periphery, the dam wall and the spillway of the reservoirs. The variable entrapment of sediments by the poorly installed vetiver could cause differences in ASY.
The annual area specific sediment yield of 18.28 to 157.55 Mg ha^{-1} y^{-1} observed in this study was found to fall within the range of 10 - 200 Mg ha^{-1} y^{-1} typical of savanna ecosystems (Lal, 1993). Soil loss estimates by Folly (1997) in the Sudan savanna zone of Ghana, where this study was carried out, gave values in Mg ha^{-1} y^{-1} > 1-10 for 28% of the area, >50 - 100 for 4% of the area, and >100 for 1% of the area. In the same study,

potential soil loss on bare soils using the Universal Soil Loss Equation predicted rates in Mg ha^{-1} y^{-1} of <10 for 7.1% of the area, 10-50 for 66% of the area, 50-100 for 16% of the area and >100 for 10% of the area. Osei-Yeboah (Personal Communication) found the mean predicted soil loss on bare soil for the interior savanna zone to be 68.82 Mg ha^{-1} y^{-1} whilst Bonsu and Obeng (1979) reported 2.2 Mg ha^{-1} y^{-1} at Manga in the Sudan savanna zone from runoff plots.

The ASY rates are however generally higher than the tolerable soil loss of 2 to 18 Mg ha^{-1} y^{-1} proposed for tropical soils (Hudson, 1995; Lal, 1984; Hurni, 1985). These high rates of sediment loss in the catchments show the significance of upslope catchment erosion on downstream sedimentation. In the global context, the mean ASY of 65 Mg ha^{-1} y^{-1} puts the Upper East Region of Ghana along with regions of the world experiencing high amounts of sediment yield as classified by Lawrence and Dickinson (1995). The Global and Africa mean values are 15 and 9 Mg ha^{-1} y^{-1}, respectively.

4.3.4 Prediction of ASY

Informed by the calculated ASY : Catchment area ratios, an attempt was made to produce a simple relationship that could facilitate the prediction of ASY as a function of catchment area. The result presented in Figure 4.1 further shows a negative relationship between ASY and catchment area, i.e. the observed ASY decreases with increasing catchment area. The coefficient of determination (R^2) of the predictive equation indicates that catchment area accounts for about 65% of the variations observed in the ASY values from the catchments. The remaining 35% may be due to other contributing factors such as slope steepness and length, shape of the catchment, size of marshy buffer zone surrounding the reservoirs, land cover, soils and land use. This should be noted when interpreting predictive values produced by the equation.

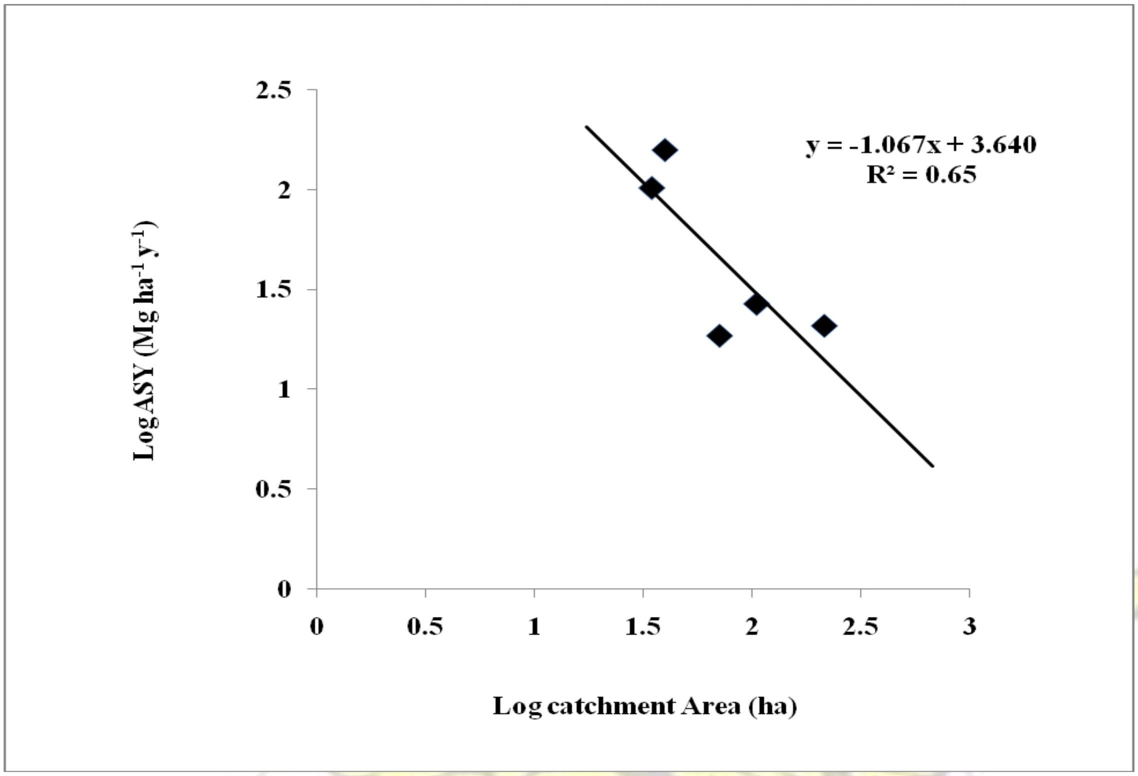

Figure 4.1 Relationship between Area-Specific Sediment Yield and Catchment Area

4.4 The Consequences of Catchment Erosion

4.4.1 On-site effects

On-site damage affects the land where the erosion originates. Soil erosion on a given field destroys soil structure and increases soil erodibility, surface crusting and soil compaction. The loss of soil reduces soil depth, infiltration and water storage capacity of the soil. This result in the shortening of the growing season, plants suffer from more frequent and severe water stress and ultimately crop yields decline. These impacts are commonly observed in the Sudan savanna zone.

In order to assess the on-site effects of catchment erosion, soil-loss induced reduction in soil depth and water holding capacity in the various catchments were determined. The soil depth reduction was calculated from the total sediment deposit of the reservoirs, the area and bulk density of the catchments using equation 3.16 over a period of 9 to 13 years. The reduction in water holding capacity due to depth loss was calculated by equation 3.17. The results are presented in Table 4.6.

Table 4.6 Loss of Depth due to Cumulative Soil Loss

Reservoir	Bulk Density (kg m)	Sediment Mass (Mg)	Depth Loss (mm)
Dua	1511.96	35,183	66.49
Doba	1508.10	11,480	10.87
Zebilla	1640.31	24,849	14.43
Kumpalgogo	1638.35	55,413	84.56
Bugri	1589.93	50,310	14.64 **38.20**
Average	**1577.73**	**3516.37**	

-3

The reduction in soil depth in the various catchments ranged from 1.1 cm to 8.5 cm (Table 4.6) in the order of Kumpalgogo>Dua>Bugri>Zebilla>Doba. The loss in soil depth does not only reduce rooting depth but the storage capacity of the soil for water and nutrients. The results of the study (Table 4.7) showed the percentage reduction in the water holding capacity of the top 20 cm of the catchments to range from 5.44 to 42.28 for Doba and Kumpalgogo respectively. The reduction in water holding capacity followed the same trend as that of soil depth reduction.

Table 4.7 Reduction in Water Holding Capacity (WHC) due to Cumulative Loss in Soil Depth

Reservoir	**Depth Loss (mm)**	**Reduction in WHC (%)**
Dua	66.49	33.25
Doba	10.87	5.44
Zebilla	14.43	7.22
Kumpalgogo	84.56	42.28
Bugri	14.64 **38.20**	7.32
Average		**19.10**

Erosion reduces productivity first and foremost through loss of plant-available soil and water holding capacity (NSE-SPRPC, 1981). Consequently, in a predominantly rainfedagricultural zone, such as the study area, where shallow soils are common and smallholder farmers depend on the relatively nutrient rich 20 cm top soil with its in-situ moisture storage for growing their crops, the reduced soil depth and water holding capacity will cause significant adverse impacts on crop growth and yield and agricultural productivity.

According to Lal (1984) the majority of tropical soils have edaphically inferior subsoil and shallow rooting depth as observed in most soils in the Sudan Savanna zone underlain by petroplinthite. Because of this, crop yield declines drastically as surface thickness is reduced. Research information on the effect of soil depth reduction due to natural erosion is scanty. Most of the evidence is from artificially desurfaced experiments. Lal (1976) reported a maize yield reduction of 23% after removing 2.5 cm of topsoil of an Alfisol in Ibadan, Nigeria. In Cameroon the removal of 2.5 cm topsoil caused a 50% drop in maize yield (Rehm, 1978).

A major factor of significance in the loss of soil depth due to erosion is the length of time it takes to replace the lost soil. Hudson (1995) estimated that, under ideal soil conditions in the tropics the rate of new soil formation was about 2.5 cm in 30 years (i.e 1mm/1.2 years). From other sources quoted by Lal (1987) new soil is formed at the rate of about 2.5 cm in 300 to 1000 years (i.e 1mm/12-40 years) under normal conditions. Available information suggests that it takes hardly one year to lose 1 cm of topsoil but 1000 years to replace it (Lal, 1984). In this study it has taken 9 to 13 years to lose 1.1 to 8.4 cm of topsoil which by the above calculations will take between 1000 to 8000 years to replace. The mismanagement of the catchments of the reservoirs can therefore readily lead to irreversible soil degradation.

Additionally, apart from the physical loss in soil depth and water holding capacity, the sediment lost through erosion is usually the most fertile containing the plant nutrients, humus and any fertilizers that the farmer has applied. The soil that is left becomes increasingly difficult to work and is less productive. Crop yields are further reduced, food becomes scarcer and dearer and malnutrition, more common.

In this situation more fertilizer amendments are needed to maintain crop yields. This increases production cost which many smallholder farmers cannot afford, yet the addition of mineral fertilizers alone cannot compensate for the productivity loss.

The loss of agricultural production in the affected districts and communities means a loss of agricultural revenue and delayed district plans for development. The rural population finds life increasingly hard and seeks a better life in the towns and cities. In this study site, this is exemplified by the seasonal out migration of the youth to the south during the long dry season. These impacts underscore the urgent need for promoting sustainable land management interventions in the catchments of the reservoirs and other water bodies in the Sudan savanna zone. In these developments, it is recommended that the watershed be taken as the planning unit and integrated watershed management effected involving the active participation of the affected communities.

4.4.2 Off-site effects

Off-site effects occur outside the area where the erosion originated, which in this study, comprises the catchments of the reservoirs. According to Quansah (2000), off-site effects may be equally damaging when the sediments are deposited to bury crops growing on lowlands. If the eroded sediments are poor in fertility, the site on which deposition has occurred would be infertile. On the other hand, deposited sediments rich in nutrients may raise the fertility of the site of deposition. The eroded sediments may contain fertilizer residues, pesticides, animal wastes which can pollute streams, rivers, ponds and reservoirs.

In this study, the major off-site effect is the siltation of the candidate reservoirs which has resulted in the following negative impacts:

i. Reduced dead and live storage capacities of the reservoirs which shortens the designed useful life of the reservoirs to meet the water demands for domestic as well as livestock and agricultural production purposes.

ii. Reduced water carrying capacities of the reservoirs. In the event of heavy rains, as occurred in the recent past (2008) in several locations in the Sudan savanna zone of the country, the silted reservoirs would overflow their banks to flood valuable farmlands causing total crop failure, food insecurity and famine. Costly irrigation structures may also be wrecked.

iii. Polluted reservoirs by sediments as a pollutant with their load of adsorbed nutrients which may cause eutrophication and prolific growth of aquatic plants, as observed in some of the reservoirs (e.g. Doba, Zebilla, Kumpalgogo, Bugri). This may result in reduced fish catch and possible increase in waterborne diseases, such as bilharzia and guinea worm infestation.

iv. Increased rate and cost of reservoir rehabilitation through dredging and repair of physical structures. In situations where funds are not available for such work, the reservoir will eventually be abandoned as has happened to most of the reservoirs built before the 1990s. These effects ultimately impact negatively on the socio-economic development and livelihoods of the affected communities.

4.5 Nutrient Losses through Erosion in the various Catchments

Soil erosion and its associated sediment loss are always accompanied by losses of plant nutrients from the parent soil undergoing erosion. This process, termed soil fertility erosion (Ellison, 1950), is selective in that finer soil particles relatively high in plant nutrients and organic matter are the most susceptible to erosion. Consequently, the eroded sediment is usually the most fertile. It contains higher concentrations of organic carbon and plant nutrients in available form than the soil from which it was eroded (Quansah *et al.,* 2000; Adama, 2003).

Most studies on erosion in Ghana (Bonsu and Obeng, 1979; Adu, 1972; Quansah *et al.*, 1989) concentrates on the measurement of runoff and soil loss without much attention to fertility erosion. Consequently, data on nutrient losses through erosion are scarce. To contribute to filling this knowledge gap, particularly for the Upper East Region, the reservoir sediments and the soils of the contributing catchments were analyzed for nutrient concentration and total amounts. The results are presented in Tables 4.8 to 4.13.

4.5.1. Nutrient concentration in the catchment soils and reservoir sediments The pH and concentration of nutrients in the catchment soils and reservoir sediments are presented in Tables 4.8 and 4.9.

pH

The pH of the catchment soils (Table 4.8) ranged between 5.23 and 6.43 for the

Kumpalgogo and Bugri catchments respectively. The pH values, according to Landon (1991), indicate strongly acidic soils in the Kumpalgogo and Zebilla catchments, moderately acidic for Doba and Dua and slightly acid for the Bugri catchments. Since the sediments in the reservoirs were produced from these catchments, it is not surprising that their pH is in the acidic range with values varying from 4.85 to 6.07 (Table 4.9). The sediments of Kumpalgogo and Bugri Reservoirs were very strongly acid, strongly acidi for Doba and Zebilla and moderately acid for Dua. The low organic matter content of the soils and the acidic granitic parent material of most of the soils may account for the observed low soil pH. A comparison of the pH of the catchments and that of their respective reservoirs showed the values to be positively but not significantly correlated (Table 4.10). The poor correlation, as observed by Haregeweyn *et al.* (2008) in a similar study, could be due to the variability in parameters such as moisture content and concentration of basic cations.

Table 4.8 Soil Nutrient Concentration from Five (5) Catchments in the Upper East Region of Ghana

Catchments	pH (1:2.5)	OC (%)	N (%)	P mg/kg	K^+ mg/kg	Na^+ mg/kg	Ca^{2+} mg/kg	Mg^{2+} mg/kg	Al^{3+} mg/kg	H^+ mg/kg	OM (%)	C:N	Ca:Mg	K:Mg	ECEC
Dua	5.76	0.55	0.07	20.2	231	135	969	130.7	80	24.4	0.95	0.94	7.38	1.79	1569
Doba	5.53	1.00	0.08	16	406	91	796	109.3	60	29.8	1.72	12.41	7.29	3.76	1492
Zebilla	5.31	0.91	0.06	23.8	39	59	702	133.3	72	31.1	1.57	16.04	5.45	0.29	1037
Kumpalgogo	5.23	0.48	0.10	15.7	639	201	836	157.3	64	31.1	0.83	4.62	5.27	4.07	1928
Bugri	6.43	0.81	0.09	21.6	1434	200	1142	138.7	60	28.4	1.40	9.72	8.5	9.66	3003
Average	**5.65**	**0.75**	**0.080**	**19.46**	**549.8**	**137.2**	**889**	**133.86**	**67.2**	**28.96**	**1.29**	**8.75**	**6.78**	**3.91**	**1805.8**
s.e.d	0.33	0.17	0.02	3.88	514.1	53.9	261	21.52	10.18	6.55	0.29	1.99	1.65	2.73	500.9
CV(%)	7.1	27.1	23.5	24.4	114.5	48.2	36	19.7	18.6	27.7	27.1	27.8	29.8	85.3	34

Table 4.9 Nutrient Concentration of Sediment Deposits in Five (5) Reservoirs in the Upper East Region of Ghana

Reservoirs	pH	OC	N	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	OM	C:N	Ca:Mg	K:Mg	ECEC
	(1:2.5)	(%)	(%)	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	(%)				
Dua	6.07	0.59	0.05	35	289	183	2147	480	66	17.3	1.02	11.31	4.8	0.657	3182
Doba	5.37	1.45	0.09	24.3	354	107	1573	688	78	32	2.51	16.73	2.41	0.527	2832
Zebilla	5.53	1.39	0.26	29.4	251	131	4173	776	66	16	2.4	6.65	5.37	0.324	5413
Kumpalgogo	4.85	1.42	0.22	30.7	199	103	1093	312	126	22.7	2.45	6.37	3.88	0.703	1856
Bugri	5.24	1.58	0.16	13.5	177	117	1853	272	132	14.7	2.72	9.7	7.81	0.824	2566
Average	**5.41**	**1.29**	**0.16**	**26.58**	**254**	**128.2**	**2167.8**	**505.6**	**93.6**	**20.54**	**2.22**	**10.15**	**4.85**	**0.61**	**3169.8**
s.e.d	0.50	0.24	0.05	4.78	59.6	34.5	327.5	123.9	24.07	5.78	0.42	2.66	1.49	0.27	446.2
CV(%)	11.3	23.1	36.8	22	28.8	32.9	18.5	30	31.5	34.5	23.1	32.1	37.6	54.7	17.2

Table 4.10 Paired Mean Comparison and Correlations of Catchment and Reservoir Samples

Pairs	Mean Comparison: Paired Mean Difference	df	Correlation: R	n
pH_C and pH_R	0.24	4	0.16	5
OC_C and OC_R	-0.54*	4	0.51	5
N_C and N_R	-0.08	4	-0.01	5
P_C and P_R	-7.12	4	-0.15	5
K^+_C and K^+_R	295.80	4	-0.63	5
Na^+_C and Na^+_R	9.00	4	-0.20	5
Ca^{2+}_C and Ca^{2+}_R	0.0013	4	-0.42	5
Mg^{2+}_C and Mg^{2+}_R	-0.037*	4	-0.66	5
Al^{3+}_C and Al^{3+}_R	-26.40	4	-0.66	5
H^+_C and H^+_R	-8.42*	4	-0.29	5

*R=correlation coefficient; df=degree of freedom; n=number of samples; *: significant at 0.05 levels respectively. Underscores 'C'and 'R' stand for catchment and reservoir respectively.*

Organic carbon (OC)

The results of the organic carbon (OC) content of the catchment soils and reservoir sediments are presented in Tables 4.8 and 4.9, respectively. The perent organic carbon of the catchments (Table 4.8) ranged between 0.48 and 1.0 in the order of Doba>Zebilla>Bugri>Dua>Kumpalgogo and a mean of 0.75. The differences in the OC content were significant except that between Doba and Zebilla and Zebilla and Bugri.

The variation between the maximum and minimum OC content was 0.52 and the coefficient of variation (CV) was 27.1 percent. This, according to Warrick (1998) falls within medium variability. The variations in the organic carbon content of the catchment soils may, among several factors, be due to the soil type, the quantity of organic amendments applied by farmers in the catchments and the amount of cowdung littered by cattle on free range grazing.

In the reservoirs, organic carbon varied from 0.59 to 1.58 percent with a mean of 1.29 percent (Table 4.9). The magnitude of the OC content was in the order of Bugri>Doba>Kumpalgogo>Zebilla>Dua. The differences in OC content for the first four reservoirs in the ranking order were not significant. However, they all recorded significantly greater OC than Dua. The variation between the maximum and minimum OC content of the reservoir sediments was 0.98 percent. The variability in OC content, indicated by a CV value of 23.1 percent, was medium.

A comparison of the catchment and reservoir organic carbon content (Tables 4.8 and 4.9) showed the reservoir sediments to be richer in organic carbon. The concentration of organic matter, which is the source of carbon in the surface soil of the catchments, its low density and one of the first soil constituents to be removed through erosion and transported downslope are implicated in the higher concentrations of organic carbon in the sediments deposited in the reservoirs. Additionally, the submergence of the reservoir sediments for most part of the year could facilitate a slower rate of organic matter decomposition than that of the well-drained catchment soils. Consequently, a higher level of organic carbon is maintained in the poorly drained reservoir sediments.

The results of the paired mean comparisons (Table 4.10) showed that the differences in the OC content of the catchment soils and the reservoir sediments were highly significant (P>0.05). The OC content of the catchment soils was positively correlated with that of the reservoir sediments (Table 4.10). The correlation coefficient was however not significant. The implication is that the catchments were not the only source of the organic carbon in the reservoir sediments.

The conversion of organic carbon to organic matter showed the latter to range from 0.83 to 1.72 percent for Kumpalgogo and Doba catchments respectively with a mean value of 1.29 percent (Table 4.8). On the other hand, the reservoir sediments recorded higher organic matter than the catchment soils with values ranging from 1.02 to 2.72 percent with a mean value of 2.22 percent (Table 4.9). The ranking of the catchment and reservoirs in terms of the magnitude of organic matter was similar to that of organic carbon. The importance of OM in sustaining soil fertility and productivity underscores the global concern about its loss through erosion.

Total nitrogen (N)

The mean total nitrogen ranged between 0.06 and 0.10 per cent with a mean of 0.08 percent in the catchment soils (Table 4.8). Total N was in the order of Kumpalgogo>Bugri>Doba>Dua>Zebilla and the differences were significant. The mean total nitrogen in the reservoir sediments, on the other hand varied from 0.05 to 0.26 percent with a mean of 0.16 percent (Table 4.9). The magnitude of total N ranked as Zebilla>Kumpalgogo>Bugri>Doba>Dua. Total nitrogen of the Zebilla reservoir sediments was significantly higher than that of all the other reservoirs. Whilst there were no significant differences in the total N of the Zebilla and Kumpalgogo, the two reservoirs recorded significantly higher total N than the Dua and Doba and Bugri reservoirs which had similar total N.

A comparison of the total N of the reservoir sediments with that of the catchment soils showed the former to be richer in total N and more varied (CV=36.8%) than the catchment soils (CV=23.5%). There was also a negative but not significant correlation (r=-0.01) between the nitrogen of the catchment soils and that of the reservoir sediments. The results further showed that the total N in the sediments deposited in the reservoirs was of organic origin as it is strongly correlated with organic carbon (r=0.61, Table 4.11). A similar observation was made by Ortt *et al.* (2000) and the correlation coefficient (r) was 0.84.

Table 4.11 Pearson's Correlations Matrix for Sediment Nutrients and Textural Classes for the Studied Reservoirs

	OC	N	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	Sand	Clay	Silt
pH	-0.82*	-0.59	0.40	0.50	0.92*	0.43	0.39	-0.78	-0.27	0.04	-0.50	0.57
OC		0.61	0.71	-0.34	-0.93*	-0.06	-0.05	0.56	0.20	0.07	0.48	-0.67
N			-0.09	-0.59	-0.51	0.44	0.07	0.29	-0.31	-0.20	0.04	0.17
P				0.36	0.52	0.17	0.33	-0.60	0.08	0.29	-0.83*	0.70
K^+					0.22	0.05	0.71	-0.77	0.68	0.87*	-0.67	-0.12
Na^+						0.31	0.10	-0.59	-0.46	-0.23	-0.40	0.74
Ca^{2+}							0.68	-0.60	-0.49	-0.001	-0.49	0.61
Mg^{2+}								-0.85*	0.30	0.73	-0.80	0.19
Al^{3+}									-0.13	-0.56	0.89*	-0.49
H^+										0.87*	-0.25	-0.63
sand											-0.63	-0.31
clay												-0.54

*correlation significant at 0.05 level

Available phosphorus (P)

Available phosphorus (P) ranged from 15.7 to 23.8 mg kg^{-1} for Kumpalgogo and Zebilla catchments respectively with a mean of 19.46 mg kg^{-1} in the catchment soils (Table 4.8). The magnitude of P content was in the order of Zebilla>Bugri>Dua>Doba>Kumpalgogo. The Zebilla, Bugri and Dua catchments recorded significantly higher P than Doba and Kumpalgogo catchments. For the reservoir sediments, P ranged from 13.5 to 35.0 mg kg^{-1} with a mean of 26.58 mg kg^{-1} and a ranking of Dua>Kumpalgogo>Zebilla>Doba>Bugri (Table 4.9). The differences in Dua, Kumpalgogo and Zebilla which were not significant were significantly greater than those of Bugri and Doba. The P level of the reservoirs was significantly higher than that of the catchments (Tables 4.8 and 4.9). A negative but not significant correlation (r=-0.15) was recorded for the catchment and reservoir P (Table 4.10). This may be partly explained by the strong positive correlation between available P and silt (r=0.70, Table 4.11) which is the most erodible soil textural fraction from the catchments.

On the other hand, the reservoir P correlated negatively with the clay but positively with sand fractions. The implication is that available P decreases as the clay fraction of the soil increase but decreases as the sand fraction of the soil decreases. In the former case, the clay fraction fixes the phosphate ions (Haregeweyn *et al*., 2008; Ongley, 1982; Sibbesen, 1995) while in the latter, the P is leached. There is also a negative correlation between the reservoir P and Al. Increase in Al, which leads to increased acidity, decreases the amount of available P. At low pH values (<5.5), phosphate ions combine with iron and aluminium to form compounds which are not readily available to plants (Landon, 1991).

The other possible reason for the high level of P in the reservoirs, although the contributions was not quantified in this study, is the addition of manure and urine from cattle, sheep, goats and birds which visit the reservoirs to drink water, especially during the dry season (Plate 4.1). Crop residues transported by runoff and deposited in the reservoirs also constitute another source of P. However, the contribution of these sources of P merits further quantitative study.

Plate 4.1 Cattle, Sheep and Birds Population feeding around and within Reservoirs

Exchangeable potassium (K^+)

The mean exchangeable potassium (K^+) content of the catchment soils and the reservoir sediments are presented in Tables 4.8 and 4.9 respectively. The K^+ content of the catchment soils varied from 39 to 1434 mg kg^{-1} in the order of Bugri>Kumpalgogo>Doba>Dua>Zebilla and a mean of 549.8 mg kg^{-1}. Bugri recorded significantly higher K^+ content than all the other catchments. In spite of the wide variation in the magnitude of K^+ content in the catchment soils (CV=114.5%), the differences in Kumpalgogo, Zebilla, Doba and Dua were not significant.

The reservoir sediments recorded a higher concentration of K^+ than those of Dua and Zebilla catchment soils. The concentrations of K^+ in the other reservoirs were lower than their candidate catchments. The paired mean differences between the catchment and the reservoir sediments were however not significant. The K+ content of the sediments ranged between 177 and 354 mg kg^{-1} with a mean of 254 mg kg^{-1} and a ranking of Doba>Dua>Zebilla>Kumpalgogo>Bugri. The K^+ content of the Doba reservoir was significantly greater than all the other reservoirs. Significant differences were also observed between Dua and Bugri and Kumpalgogo, and Zebilla and Bugri. All other differences were not significant. The catchment K correlated negatively (r=0.63, Table 4.10) with the reservoir K^+. Although the correlation was not significant, it suggests other sources than the catchment for the K^+ in the reservoir sediments. On the other hand, the negative correlation between the K^+ and clay and organic carbon contents of the reservoir sediments could imply that most of the reservoir K^+ was in solution.

Exchangeable sodium (Na^+)

The mean exchangeable sodium (Na^+) content of the catchment soils (Table 4.8) ranged from 59 to 201 mg kg^{-1} with a mean of 137.2 mg kg^{-1} and a rank of Kumpalgogo>Bugri>Dua>Doba>Zebilla. The Bugri and Kumpalgogo catchments recorded significantly higher Na^+ content than all the remaining catchments. The difference in the Na^+ content of Dua and Zebilla was also significant.

The magnitude of the Na^+ content of the catchments and reservoirs varied. The Dua, Doba and Zebilla reservoirs recorded higher concentrations of K^+ while Kumpalgogo and Bugri had lower concentrations than their contributing catchments. The paired mean differences were however not significant (Table 4.10). The Na^+ concentration of the reservoir sediments correlated poorly and negatively with that of the catchments (r=-0.20, Table 4.11).

Exchangeable calcium (Ca^{2+})

The concentration of calcium in the catchment soils ranged from 702 to 1142 mg kg^{-1} with a mean of 889 mg kg^{-1} and a ranking of Bugri>Dua>Kumpalgogo>Doba>Zebilla (Table 4.8). The difference in calcium concentration of the Dua, Doba and Kumpalgogo as well as that of Dua and Bugri was not significant. All other differences were significant. The variation (CV=36%) was rated as medium (Warrick, 1998). The exchangeable calcium of the reservoir sediments varied from 1093 to 4173 mg kg^{-1} with a mean of 2167.8 mg kg^{-1} and a ranking of Zebilla>Dua>Bugri>Doba>Kumpalgogo (Table 4.9). The differences in the reservoir Ca^{2+} was significant. The variation (CV=18.5%) in the Ca^{2+} concentration of the various reservoirs was rated medium. However, the reservoir sediments recorded significantly higher Ca^{2+} concentration than that of the catchment soils (Tables 4.8 and 4.9).

Although the paired mean differences in Ca^{2+} between the catchment and reservoirs were not significant, the exchangeable Ca^{2+} of the catchment soils correlated negatively with that of the reservoir sediments (Table 4.10). This implies other sources of Ca^{2+} in the reservoirs. The implication of the poor correlation between the Ca^{2+} and clay concentrations of the reservoir sediments (Table 4.11) is that runoff is the main transportation agent of calcium from the catchments to the reservoirs as similarly reported in the study of Haregeweyn *et al.* (2008).

Exchangeable magnesium (Mg^{2+})

The exchangeable Mg^{2+} concentration of the catchment soils varied between 109.3 and 157.3 mg kg^{-1} with a mean of 133.9 mg kg^{-1} (Table 4.8). The Doba and Kumpalgogo catchments recorded the lowest and highest Mg^{2+} concentrations respectively and the differences were significant. For the reservoir sediments, magnesium concentration ranged from 272 to 776 mg kg^{-1} with a mean value of 505.6 mg kg^{-1} (Table 4.9) and a ranking of Zebilla>Doba>Dua>Kumpalgogo>Bugri. Significant differences in the Mg^{2+} concentration of the reservoirs was observed and the variation (CV=30%) was medium. The reservoir sediments recorded significantly higher Mg^{2+} concentration than the catchment soils and the two were not significantly correlated (r=-0.66, Table 4.10) as observed in the case of calcium.

Aluminium (Al^{3+})

The mean Al^{3+} concentration in the catchment soils (Table 4.8) ranged from 60 to 80 mg kg^{-1} with a ranking of Dua>Zebilla>Kumpalgogo>Doba=Bugri and a mean of 67.2 mg kg^{-1}. The Dua and Zebilla recorded significantly higher concentrations than the Doba and Bugri catchments. The latter two catchments and Kumpalgogo did not differ significantly in their Al^{3+} concentrations.

The reservoir sediments recorded a range of 66 to 132 mg kg^{-1} Al^{3+} with a mean of 20.54 mg kg^{-1} and an order of Bugri>Kumpalgogo>Doba>Dua=Zebilla (Table 4.9). The Al^{3+} concentration in the reservoir sediments of Bugri, Kumpalgogo and Doba were greater than their contributing catchments although the differences were not significant. The variations in the Al^{3+} concentrations in the reservoir sediments were greater than that of the catchments.

Hydrogen (H^{+})

The mean concentration of H^{+} (Table 4.8) in the catchment soils ranged from 24.4 to 31.1 mg kg^{-1} with a mean of 28.96 mg kg^{-1}. Apart from the differences in the Dua and Zebilla and Kumpalgogo which were significant, the other differences were not significant. The latter catchments recorded the highest concentration of H^{+}.

The H^{+} concentration in the reservoir sediments (Table 4.9) on the other hand, varied from 14.7 to 32 mg kg^{-1} with a mean of 20.54 mg kg^{-1}. Doba recorded a significantly higher concentration of H^{+} than all the reservoirs which had no significant differences in their H^+ content. The variability of H^+ concentration in the reservoir sediments was greater than that of the catchment soils.

Exchangeable cation ratios

The levels of exchangeable cations in a soil are valuable in advisory work on soil fertility since they not only indicate existing nutrient status, but can also be used to access balances amongst cations. For example, many effects on soil structure and nutrient uptake by crops are influenced by the relative concentrations of cations as well as by their absolute levels. The Ca:Mg and K:Mg ratios were therefore calculated to facilitate the assessment of critical values for availability and uptake by crops.

Ca:Mg ratio

The Ca:Mg ratios of the catchment soils ranged from 5.27 to 8.5 with a mean value of 6.8 (Table 4.8). The values for the Bugri, Dua and Doba catchments were significantly greater than those of Zebilla and Kumpalgogo. The reservoir sediments, on the other hand recorded lower values in the range of 2.41 and 7.81 and a mean value of 4.85 (Table 4.9). According to Landon (1991) the approximate optimum range for most crops is 3 to 4. Magnesium becomes increasingly unavailable and at high pH, P availability may be reduced with increasing Ca as the ratio becomes equal to or greater than 5. At ratios less than 3, P uptake may be inhibited and a ratio of 1.0 is considered the lowest acceptable limit at which Ca^{2+} availability may be slightly reduced. These ranges need to be taken into consideration in assessing nutrient deficiency symptoms and in the management of the catchment soils for fertility and productivity given that their Ca:Mg ratios were greater than 5.

The recycling of the nutrient rich sediment which may be dredged from the reservoirs as a soil fertility amendment in the catchments could enhance the productivity of the catchment soils. However, the Ca:Mg and K:Mg ratios and their implications for soil fertility and nutrient uptake by plants need to be assessed and appropriate management practices adopted when the reservoir sediments are used as a soil amendment.

K:Mg ratio

The K:Mg ratios in the catchment soils varied between 0.29 and 9.66 with a mean of 3.91 and a ranking of Bugri>Kumpalgogo>Doba>Dua>Zebilla (Table 4.8). The variability in the ratios among the catchments (CV=85.3%) was very high. The ratios of the reservoir sediments which ranged from 0.32 to 0.82 with a mean of 0.61 were lower than those of the catchment soils (Table 4.9). According to Landon (1991) a ratio greater than 2 may inhibit Mg^{2+} uptake. Recommended values are less than 1.5 and 1.0 for field crops and vegetables respectively.

4.5.2 Nutrient enrichment ratios of the reservoir sediments

The assessment of nutrient concentrations showed the reservoir sediments to be richer not only in nutrients but clay and silt than the catchment soils. This accords with several studies on fertility erosion (Quansah *et al.*, 2000; Adama, 2003). Enrichment ratio (ER), which is the ratio of nutrient concentration in the eroded sediment to that of the original soil, is a measure of the magnitude of richness. It is also an indicator of the selective removal of the finer, more fertile fraction of the soil by erosion. All enrichment ratios greater than unity shows the eroded sediments in the reservoirs to be richer in all the soil fertility constituents except potassium which was richer only in the Zebilla and Dua reservoir (Table 4.12).

Table 4.12 Enrichment Ratio of Nutrients and Soil Texture from Five (5) Catchments in the Upper East Region of Ghana

Reservoirs	OC	N	P	K	Ca	Mg	Sand	Clay	Silt
Dua	1.08	0.73	1.73	1.25	2.22	3.67	0.31	8.21	4.84
Doba	1.45	1.16	1.52	0.87	1.98	6.29	0.81	3.86	1.6
Zebilla	1.53	4.58	1.24	6.44	5.94	5.82	0.34	12.61	5.3
Kumpalgogo	2.96	2.13	1.96	0.31	1.31	1.98	0.34	4.32	4.54
Bugri	1.937	1.83	0.63	0.12	1.62	1.96	0.28	5.27	2.96
Average	**1.79**	**2.09**	**1.42**	**1.80**	**2.61**	**3.94**	**0.42**	**6.85**	**3.85**
SD	**0.72**	**1.50**	**0.51**	**2.63**	**1.89**	**2.05**	**0.22**	**3.63**	**1.53**

+ 2+ 2+

The enrichment ratios ranged from 1.08 to 2.96, 0.73 to 4.58, 0.63 to 1.96, 0.12 to 6.44, 1.31 to 5.94 and 1.96 to 6.29 for OC, N, P, K^{+}, Ca^{2+} and Mg^{2+} respectively. The ratios varied from 3.86 to 12.61 for clay and 1.6 to 4.84 for silt. The enrichment ratios confirm the selectivity of the erosion process in removing finer particles relatively high in plant nutrients and organic matter. As indicated by Menzel (1980), enrichment ratios are important, not only from soil fertility depletion point of view, but also for predicting the effects of soil erosion and erosion control practices on the quality of water. Therefore, any soil management practice in the catchment areas of the reservoirs that reduces soil loss, runoff, nutrient and organic matter loss has the potential to maintain the fertility and productive capacity of the soils for sustainable agricultural production. However, while the promotion of catchment area protection and soil and water conservation is the preferred option in maintaining the catchment ecosystem integrity, the potential of using the rich reservoir sediments for reclaiming degraded land merits further studies. A positive outcome will serve as a great source of motivation for local communities to dredge and use the sediments for the rehabilitation of their land using their own labour, especially where the drying up of the reservoirs makes such activities feasible. Such a practice would decrease the cost of rehabilitation and increase the useful life of the reservoirs.

4.5.3 Total amounts of nutrients and organic matter in the reservoir sediments The total amount of soil lost from the catchments through erosion is not a complete measure of erosion loss. The enrichment ratios of the reservoir sediments have shown that the eroded sediments contain higher concentrations of organic matter and plant nutrients in available form than the original soil. The assessment of nutrients lost from the catchments was therefore necessary to ascertain the magnitude of soil fertility decline. The assessment was facilitated by multiplying the total weight of the reservoir sediments by the concentration of their fertility constituents. The results are presented in Table 4.13

Table 4.13 Organic Matter and Total Nutrients in Eroded Sediment for Five (5) Reservoirs in the Upper East Region of Ghana

Reservoirs	OC	OM	N	P	K	Na	Ca	Mg	Al	H
					kg/ha					
Dua	5964	10287	536	35.14	290	184.2	2158	483	66.3	17.4
Doba	2383	3619	153	3.99	58	17.6	258	113	12.8	5.2
Zebilla	3297	5680	615	6.95	59	31	988	184	15.6	3.8
Kumpalgogo	19672	33894	3048	42.59	276	143.4	1515	432	174.6	31.4
Bugri	3672	6335	380	3.15	41	27.3	432	63	30.7	3.4
Average	**6997.6**	**11963**	**946.4**	**18.36**	**144.8**	**80.7**	**1070.2**	**255**	**60**	**12.24**
s.e.d	2333.6	4134.2	213.3	2.964	36.6	21.43	155.2	84.3	24.25	3.69
CV(%)	40.8	42.3	27.6	19.8	30.9	32.5	17.8	40.5	49.5	36.9

Organic carbon and organic matter (OC & OM)

The total organic carbon and organic matter lost from the catchments and stored in the reservoir sediments are presented in Table 4.13. The total carbon content of the reservoir sediments varied between 2383 and 19672 kg ha^{-1} with a mean value of 6997.6 kg ha^{-1}. These values convert to 3619 to 33894 kg ha^{-1} for OM with a mean of 11963 kg ha^{-1}. The magnitude of organic carbon in the reservoir sediments was in the order of Kumpalgogo>Dua>Bugri>Zebilla>Doba. There was a considerable variability in the organic carbon among the reservoirs as indicated by the CV of 40.8 percent. Kumpalgogo recorded significantly greater organic carbon storage than the remaining reservoirs which had no significant differences in their OC contents.

Total nitrogen (N)

The losses of nitrogen varied from 153 kg ha^{-1} to 3048 kg ha^{-1} for Doba and Kumpalgogo reservoirs respectively. With a mean of 946.4 kg ha^{-1}, the N content ranked as Kumpalgogo>Zebilla>Dua>Bugri>Doba. Except for Doba and Bugri, Bugri and Dua and Dua and Zebilla, all other differences in total nitrogen were significant.

The variability in the total N content of the reservoirs was medium.

Available phosphorus (P)

The total available phosphorus in the reservoir sediments ranged from 3.15 to 42.59 kg ha^{-1} with a mean of 18.36 kg ha^{-1} and a ranking of

Kumpalgogo>Dua>Zebilla>Doba>Bugri. The differences in the available P content among the reservoirs were significant. The magnitude of P content was smaller than all the other nutrients probably due to its low mobility.

Exchangeable potassium (K)

Total potassium losses showed medium variation (CV=31%) among the reservoirs and ranged between 41 and 290 kg ha^{-1} with a mean of 144.8 kg ha^{-1}. The Dua and Kumpalgogo reservoirs recorded significantly greater K content in their sediments than the three other reservoirs which did not differ significantly in their K content.

Exchangeable sodium (Na)

The total content of Na in the reservoir sediments varied from 17.6 to 184.2 kg ha^{-1} with a mean of 80.7 kg ha^{-1} and a ranking of Dua>Kumpalgogo>Zebilla>Bugri>Doba. The difference in the Na content of the latter three reservoirs in the ranking order were not significant.

Exchangeable calcium (Ca)

The results showed that the catchments have lost tremendous amounts of Ca which ranged from 432 to 2158 kg ha^{-1} with a mean of 1070.2 kg ha^{-1}. The Dua reservoir recorded the highest Ca content, followed by Kumpalgogo, Zebilla, Bugri and Doba.

The differences in the Ca content were significant.

Exchangeable magnesium (Mg)

The total magnesium losses varied from 63 kg ha^{-1} to 483 kg ha^{-1} in the order of Dua>Kumpalgogo>Zebilla>Doba>Bugri and a mean of 255 kg ha^{-1}. The Dua and Kumpalgogo reservoirs significantly out-yielded the remaining reservoirs. The variability in Mg content among the reservoirs was rated medium (CV=40.5%). The significant amount of nutrients and organic matter in the reservoir sediments is indicative of the magnitude of soil fertility decline in the contributing catchments and pollution of the reservoir waters.

Aluminium (Al)

The total amount of Al in the reservoir sediments varied from 12.8 to 174.6 kg ha^{-1} in the order of Kumpalgogo>Dua>Bugri>Zebilla>Doba. The former two reservoirs in the ranking order recorded significantly greater amounts of Al than the remaining reservoirs.

Hydrogen (H)

The reservoir sediments recorded a total amount of H in the range of 3.4 to 17.4 kg ha^{-1}. Kumpalgogo and Dua recorded significantly higher H than the remaining reservoirs which had no significant differences in the total amount of H.

As indicated earlier, organic matter is one of the first soil constituents to be removed through erosion, yet it is among the hardest to replace. Organic matter is the main source of nitrogen, phosphorus and sulphur for crops in no-fertilizer smallholder agriculture (Acquaye, 1990). It is estimated that in tropical soils, the humus content accounts for 80 per cent of the cation exchange capacity under savanna conditions. The ability of the soil to hold nutrients and water is significantly influenced by organic matter. The loss of organic matter of the soil does not only result in the depletion of one of its valuable components, but significant quantities of nutrients, such as nitrogen and phosphorus are removed with organic matter.

The high losses of organic matter are of particular concern because mineral fertilizers are far less effective in supplying nutrients on soils which are low in organic matter than those which contain adequate amounts of it (Swift, 1997). The implication is that if the losses of N, P and K from the catchments were to be replenished by mineral fertilizers, the desired effect on crop yield would hardly be attained because of the low soil organic matter. Soil fertility replenishment in the catchments should therefore aim at integrated nutrient management. This involves the combined use of organic and inorganic inputs for sustaining soil fertility and crop yield (Swift, 1997; Sanchez *et al.*, 1997; Quansah, 1997).

Nitrogen and phosphorus losses also present a major concern considering that they are the most deficient nutrients in savanna soils. Soluble forms of nitrogen (nitrate and ammonium) constitute a major source of pollutants in rivers, lakes, reservoirs and groundwaters.

The contribution of the other nutrients, such as potassium, magnesium and calcium in sustaining crop growth and yield is no less important. The huge amounts of nutrient losses from the catchments, stored in the reservoir sediments, have cost implications for nutrient replenishment in the catchments for sustainable agricultural production. The practice of integrated soil, water and nutrient management and conservation would be required to sustain the fertility and productivity of the catchments and avert the pollution of the reservoirs by nutrients and sediments exported from the catchments through erosion.

4.5.4 Estimating cost of nutrients in the eroded sediments

Eroded sediments contain higher concentrations of organic matter and plant nutrients in available form than the soil from which it was eroded and any fertilizers the farmer has applied (Massey and Jackson. 1952). While it is useful to know the magnitude of soil nutrient losses, their on-site costs are equally important. Unfortunately, these aspects have received very little research attention because nutrient depletion is invisible (FAO, 1990; Gachene *et al.*, 1997). In Ghana apart from the work of Convery and Tutu (1990), Quansah *et al.* (2000) and Akyea (2009), there is no explicit study on the cost of fertility erosion especially in reservoir catchment areas. Yet, the quantification of fertility erosion and the associated costs can significantly contribute to the economic assessment of soil degradation due to erosion, and also enhance the creation of awareness of erosion problems and the need to seriously address them at the policy, institutional and farmer levels (Quansah, 2000).

For countries whose economies depend heavily on the agricultural sector, the loss of agricultural productivity implies loss of agricultural revenue for the socio-economic development of the country (Bonsu and Quansah, 1992).

In this study, the replacement cost method was used to estimate the cost of fertility erosion. This involved converting nutrient loss to existing fertilizer forms, number of bags of fertilizer lost and the cost of nutrients in the eroded sediments per hectare for all the reservoirs. The results are presented in Tables 4.14 to 4.16.

Table 4.14. Total Nutrients in Reservoir Sediments and their Equivalent forms in Fertilizers

Reservoir	Total N	P	P_2O_5	K	K_2O
		kg/ha			
Dua	536	35.14	80.47	290	348
Doba	153	3.99	9.14	58	69.60
Zebilla	615	6.95	15.92	59	70.80
Kumpalgogo	3048	42.59	97.53	276	331.20
Bugri	380	3.15	7.21	41	49.20

Table 4.15. Bags of Fertilizer Lost per Hectare

Reservoir	Sulphate of Ammonia	Single Superphosphate	Muriate of Potash
	Bags/ha		
Dua	51.04	8.94	11.60
Doba	14.57	1.02	2.32
Zebilla	58.57	1.77	2.36
Kumpalgogo	290.29	10.84	11.04
Bugri	36.19	0.80	1.64

Table 4.16. Cost of Fertilizers Lost per Hectare

Reservoir	Sulphate of Ammonia	Single Superphosphate	Muriate of Potash	Total Cost

		GH¢/ha		
Dua	1531.20	402.30	928.00	2861.50
Doba	437.10	45.90	185.60	668.60
Zebilla	1757.10	79.65	188.80	2025.55
Kumpalgogo	8708.70	487.80	883.20	10079.70
Bugri	1085.70	36.00	131.20	1252.90

The nutrient losses ranged from 153 to 3048, 7.21 to 97.53 and 49.20 to 331.20 kg ha^{-1} (Table 4.14) for Nitrogen, phosphorus (P_2O_5) and potassium (K_2O). The conversion of the nutrient loss in existing fertilizer forms to bags of fertilizer per hectare showed the latter to range from 14.57 to 290.29, 0.80 to 10.84 and 1.64 to 11.60 bags per hectare (Table 4.15) for sulphate of ammonia, single superphosphate and muriate of potash respectively.

The results showed the cost of fertilizers lost to range from 437.10 to 8708.70, 36.00 to 487.80 and 131.20 to 928.00 GH¢/hectare (Table 4.16) for sulphate of ammonia, single superphosphate and muriate of potash respectively. The total cost (in GH¢) of these fertilizers was 2861.50 for Dua, 668.60 for Doba, 2025.55 for Zebilla, 10079.70 for Kumpalgogo and 1252.90 for Bugri. The values represent a hidden cost to agricultural production in the respective reservoir catchment areas. This implies that if straight fertilizers were to be bought to compensate for the losses of N, P, K from the respective catchment areas of the reservoirs, the above costs will be incurred. These cost figures, represent only the cost of the mineral fertilizers required to replace the lost N, P and K neither account for the losses of other nutrient elements including micronutrients nor the cost of transporting the fertilizers to the catchment areas as well as their application.

Therefore, the interpretation of the results of the replacement cost approach for assessing the cost of erosion as it affects productivity should, recognize the following limitations (Enters, 1998):

a. Soil erosion does not only affect the nutrient status of the soil, but also its organic matter content and its physical structure.

b. Soil nutrients may not be the most limiting factor in crop production.

c. Fertilizer applications are not necessarily the most cost effective options available to farmers for maintaining yields; in extreme cases, e.g. on deep and fertile soils, farmers may not even experience any yield decline with nutrient losses (Stocking, 1996).

d. It is only a proxy for actual productivity loss.

e. Mineral fertilizers supply nutrients in plant available forms, whereas erosion also removes fixed elements.

4.5.5 Implications of organic carbon loss for carbon sequestration and climate change

The term "carbon sequestration" is used to describe both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in marine – and ocean – based sinks, reservoirs and terrestrial environments (vegetation, soils, and sediments), and geologic formations (USGS, 2008). Apart from the contribution to green house gases by the rapid rise in industrialization, the degradation of land through unsustainable agricultural practices results in emissions of Greenhouse

Gases (GHGs), particularly carbon dioxide, which engenders global warming and climate change. Soil carbon sequestration is an important and immediate sink for removing atmospheric CO_2 and mitigating global warming and climate change. Yet, little recognized is the fact that the world's soils hold more organic carbon (about 1500 Pg) than that held by the atmosphere as CO_2 and vegetation combined (about 1080 Pg) (UNCCD, 2008).

The high losses of organic carbon from the catchments through erosion adversely affect the capability of the catchment soils in sequestering carbon for the benefits of mitigating climate change among the vulnerable communities in the Sudan savanna zone. The restoration of the degraded catchments will therefore demand an increase in soil carbon. This can be achieved by applying soil amendments, both organic or inorganic materials on the soil surface in the form of mulch or by incorporation. Alternative agricultural practices such as silvo-pastoralism, use of cover and nitrogenfixing crops and crop rotation enhance soil carbon sequestration. Soil carbon emissions can be minimized by controlling erosion through sustainable land management and conservation practices such as reducing forage take-off, leaving crop residues on the soil and practising no-tillage and conservation farming.

However, the amounts of organic carbon lost from the catchments were sequestered in the reservoir sediments. Realizing that the potential of reservoirs in sequestering carbon has not received much research attention in Ghana and particularly in the Sudan savanna zone, an estimate of the potential contribution of the reservoirs to carbon sequestration was made. The results are presented in Table 4.17.

Table 4.17 Total Carbon Sequestered in the Five (5) Reservoirs and their CO_2 Equivalents

Reservoir	Age (y)	OC Sequestered (Mg)	OC Sequestered per year (Mg y^{-1})	OC Sequestered per year (Pg y^{-1} × 10^{-8})	CO_2 Equivalent (Mg y^{-1})	CO_2 Equivalent (Pg y^{-1}× 10^{-8})
Dua	10	208.74	20.87	2.09	76.59	7.67
Doba	9	166.81	18.53	1.85	68.01	6.79
Zebilla	9	346.19	38.47	3.85	141.18	14.13
Kumpalgogo	9	786.88	87.43	8.74	320.87	32.08
Bugri	13	793.15	61.01	6.10	223.91	22.39
Total		**2301.77**	**226.31**	**22.63**	**830.56**	**83.06**
Average		**460.35**	**45.26**	**4.53**	**166.11**	**16.61**

The total organic carbon sequestered based on the age of the reservoir, varied from 166.81 to 793.15 Mg. The total organic carbon stock of the five reservoirs was 2301.77 and 226.31 Mg y^{-1} (i.e. 4.94 Mg ha^{-1} y^{-1}) with an average OC stock of 45.26 Mg y^{-1} (i.e. 0.49 Mg ha^{-1} y^{-1}) or 1.78 Mg CO_2 ha^{-1} y^{-1}. The average value of 1.78 Mg CO_2 ha^{-1} y^{-1} compares with the mitigation potential of 0.29, 0.33. 1.14, 1.61, 1.54 Mg CO_2 ha^{-1} y^{-1} of agronomic practices, tillage and residue management, water management, set aside (fallow) and manure application respectively (Smith and Martino, 2007). Stallard (1998) reported that erosion-sedimentation leads to a global net OC sequestration of 0.6 – 1.5 Pg OC y^{-1} with a mean of 1.05 Pg OC y^{-1}. From this study, the contribution of the five reservoirs towards the mean global net carbon sequestration value calculated by Stallard (1998) is estimated as 0.000022 percent. From 64 reservoirs with a total drainage area of 642 km^2 in Tigray, Ethiopia, Haregeweyn *et al.* (2008) estimated the contribution to the above global net carbon sequestration of 0.0005 to 0.001 percent taking the assumption of Stallard (1998) that the eroded organic carbon replacement ranges from 50 to 100 percent. The amount of OC stock in this study is an indication of the potential of reservoirs as an important store for OC in the global carbon balance.

However, it should be noted that in some cases, reservoirs will only be temporary sinks for carbon due to measures to mitigate reservoir sedimentation and dam decommissioning. Where reservoirs are permanent sinks, their ability to sequester carbon will end once their storage capacity is filled with sediments. According to Parekh (2004), the carbon sequestration capacity of reservoirs has a limited life span. More studies are therefore needed to quantify the impact of reservoirs on climate change.

4.5.6 Nutrient export from the reservoir catchments

The nutrients exported from the catchments are those which are sediment-bound in contrast to those in solution. All indications are that these nutrients are mainly transported into the candidate reservoirs by runoff generated from the catchments. The calculated nutrient export (NE) rates are presented in Table 4.18.

Table 4.18 Nutrients Export Rates for Five (5) Catchments in the Upper East Region of Ghana

	OC	N	P	K	Na	Ca	Mg	OM
Reservoirs	**kg/ha/y × 10^{-3}**							
Dua	609	55	3.57	29.60	18.80	220.50	49.30	1050
Doba	270	17.30	0.43	6.60	1.97	29.20	12.80	460
Zebilla	371	69.20	0.77	6.70	3.47	111.10	20.60	640
Kumpalgogo	2237	346.60	4.83	31.30	16.30	172.30	49.20	3850

Bugri	288	29.90	0.24	3.20	2.13	33.90	5	500
Average	**755**	**104**	**2**	**16**	**9**	**113**	**27**	**1300**
s.e.d	264.40	24.50	0.30	3.81	2.43	16.97	9.30	456
CV(%)	42.9	29	20.3	30.2	34.8	18.3	41.70	42.9

The average export rates (in kg ha^{-1} y^{-1}×10^{-3}) were: 755 for OC, 104 for N, 2 for P, 16 for K, 9 for Na, 113 for Ca, 27 for Mg and 1300 for organic matter (OM).

In Ghana and other parts of sub-saharan Africa, data on OC and nutrient export rates are limited. Yet, the extent of nutrient depletion in Ghana through erosion is widespread in all agro-ecological zones with N and P being the most deficient nutrients. Stoorvogel and Smaling (1990) estimated the annual nutrient depletion rate in Ghana through erosion and other loss pathways to be 30 kg N, 3 kg P and 17 kg K per hectare in 1982-84. The projected figures for year 2000 were 35 kg N, 4 kg P and 20 kg K per hectare. Available data from bare runoff plot in the Sudan savanna zone (Bonsu and Obeng, 1979) where this study was carried out, showed sediment-bound nutrient export rates (in kg ha^{-1} y^{-1}) to be 1.79, 19.87, 34.26, 197 and 532 for N, OC, OM, Available P and K respectively. However the authors showed that the type of tillage system and cropping system significantly impacted on the magnitude of nutrient export. For a range of cultivation practices, intercropping and manuring with farmyard manure, the NE rates (in kg ha^{-1} y^{-1}) ranged from 0.069 to 2.26 for N, 1.38 to 43.71 for OM, 0.80 to 25.35 for OC, 136 to 162 for available P and 218 to 818 for available K.

These values are several orders of magnitude higher than those reported in this study for the various catchments. The relatively small runoff plot size from which these calculation were made vis à vis the large catchments in this study with varying land cover, topography, hydrology, landuse, among others, may account for the observed variations. The low levels of nutrients in the catchment soils of this study may also partially account for the low nutrient export rates recorded. It must be pointed out that apart from erosion being responsible for nutrient depletion, other factors, including harvested products, crop residues, leaching, gaseous losses, result in nutrient depletion.

4.6 Association of Nutrient Export (NE) with Area-Specific Sediment Yield (ASY)

The nutrient export rates of the sediment nutrients were correlated with area specific sediment yield for the five (5) catchments and the results presented in Figures 4.2a to 4.2h. From the results, there was a significant correlation for all cases with R^2 of 0.82, 0.73, 0.92, 0.99, 0.83, 0.66 and 0.86 for OC/OM, N, K, P, Na, Ca and Mg, respectively.

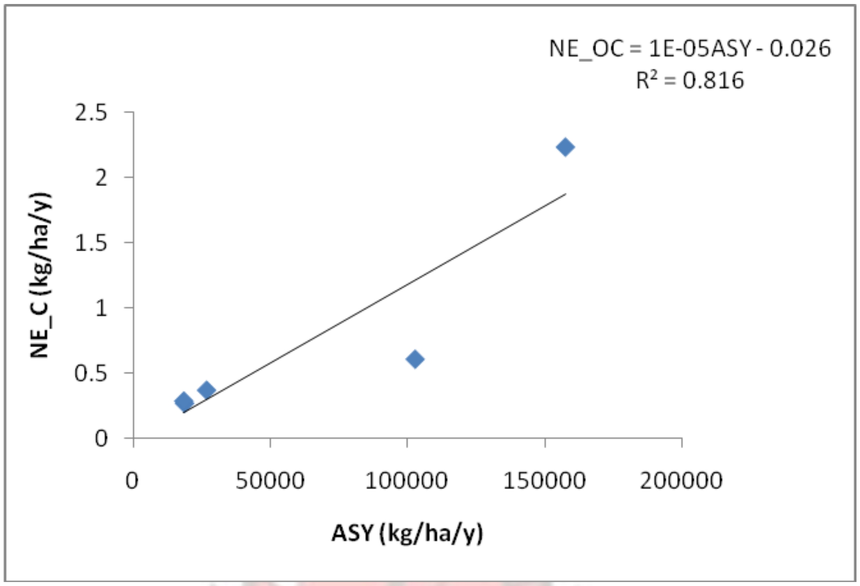

Figure 4.2a: Relationship between NE for OC and ASY

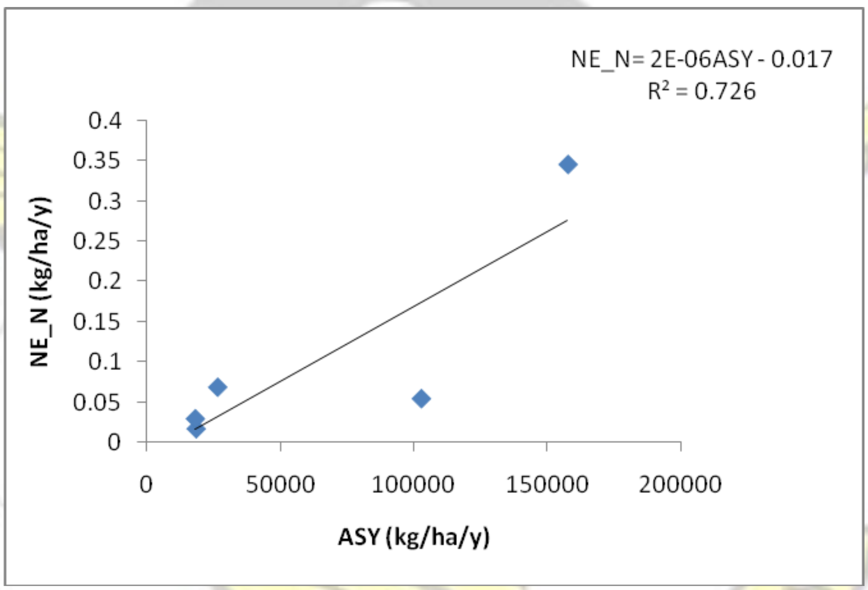

Figure 4.2b: Relationship between NE for N and ASY

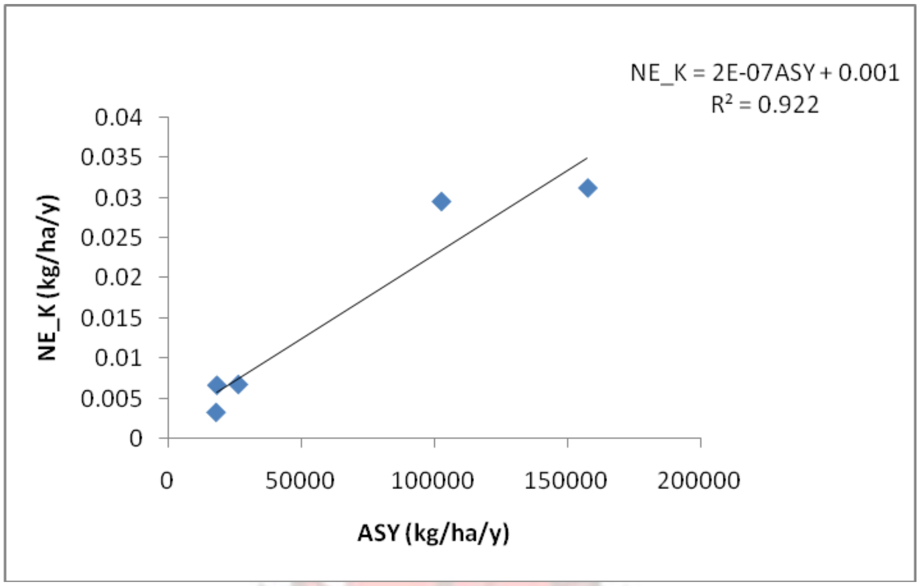

Figure 4.2c: Relationship between NE for K and ASY

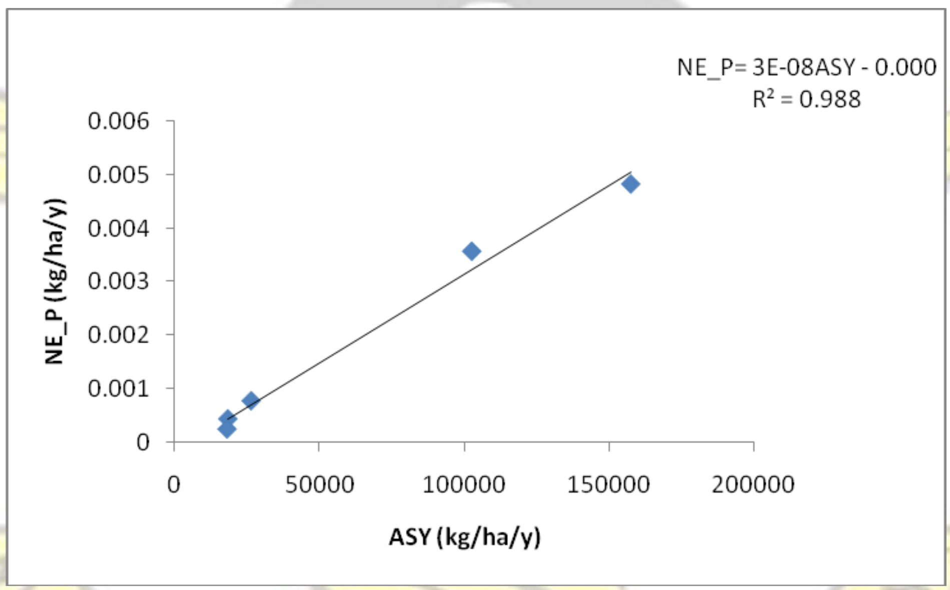

Figure 4.2d: Relationship between NE for P and ASY

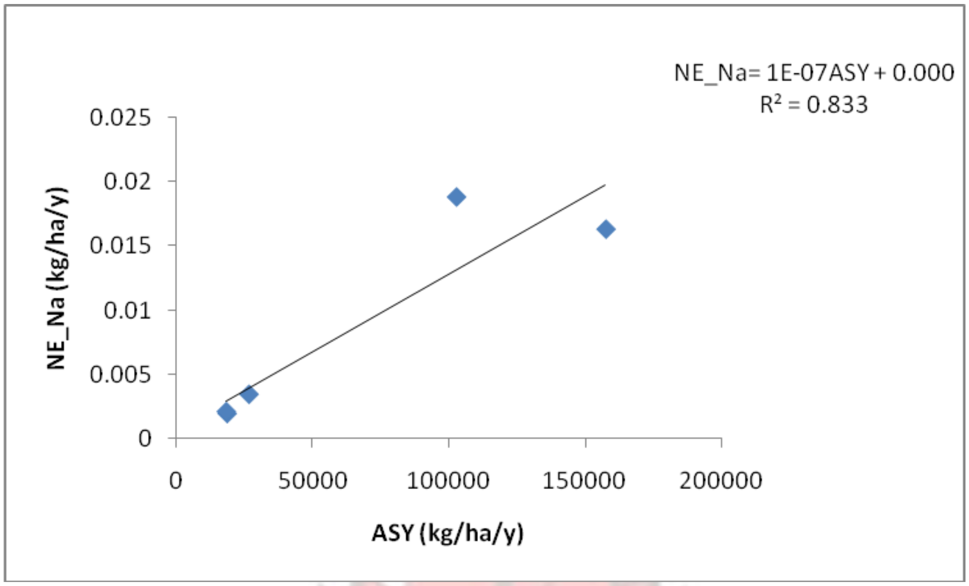

Figure 4.2e: Relationship between NE for Na and ASY

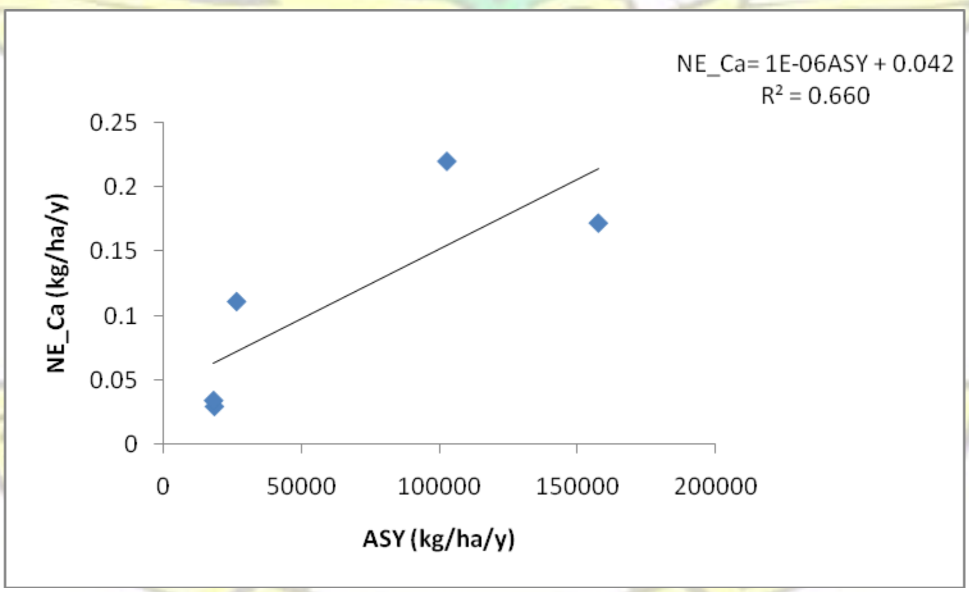

Figure 4.2f: Relationship between NE for Ca and ASY

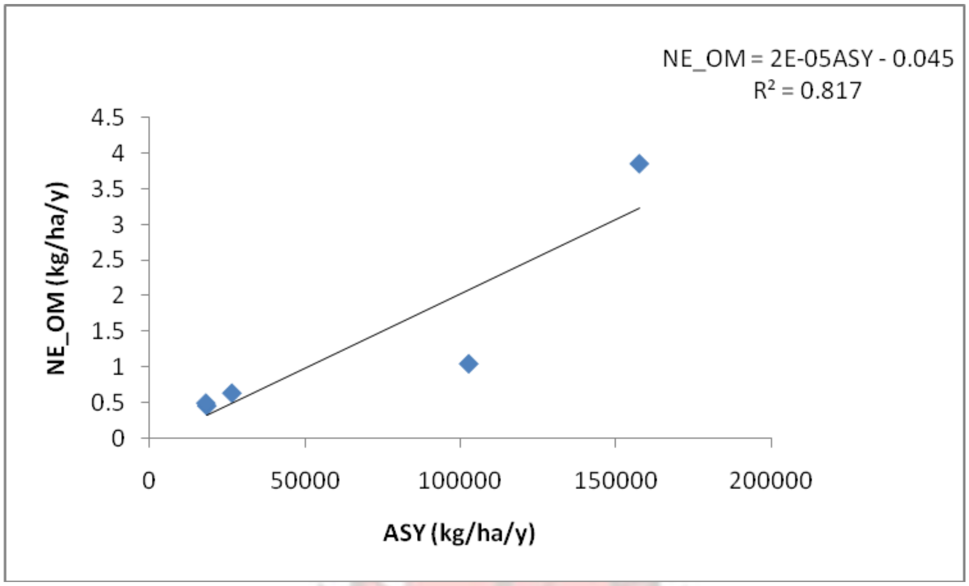

Figure 4.2g: Relationship between NE for OM and ASY

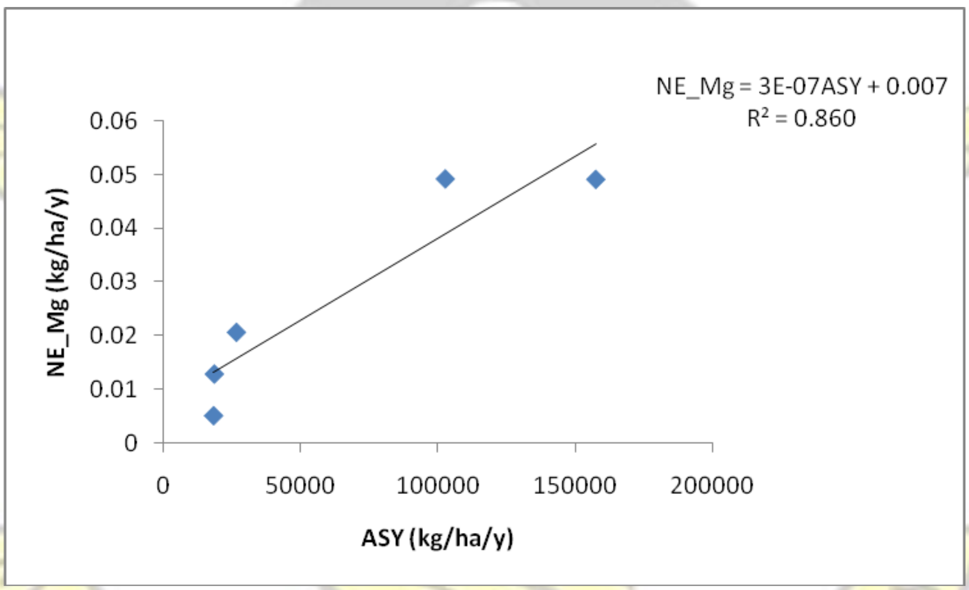

Figure 4.2h: Relationship between NE for Mg and ASY

From the various relationships established, nutrient export and area specific sediment yield have a positive relationship, i.e. an increase in ASY leads to an increase in NE. These relationships also show that soil erosion and sediment transport are very important processes and pathways that control the amounts of nutrients that are delivered to the reservoirs as similarly reported by Garbrecht and Sharpley, 1993; and Sharpley *et al.*, 2000.

The relationships between ASY and the corresponding NE can be useful predictive tools in terms of estimating the amount of plant nutrients actually lost from the catchments and stored in the reservoir sediments.

NE_OC = 1E-05ASY - 0.026 $R^2 = 0.82$ (4.1)

NE_N = 2E-06ASY – 0.017 $R^2 = 0.73$ (4.2)

NE_K = 2E-07ASY + 0.001 $R^2 = 0.92$ (4.3)

NE_P = 3E-08ASY – 0.00 $R^2 = 0.99$ (4.4)

NE_Na = 1E-07ASY + 0.00 $R^2 = 0.83$ (4.5)

NE_Ca = 1E-06ASY + 0.042 $R^2 = 0.66$ (4.6)

NE_OM = 2E-05ASY – 0.045 $R^2 = 0.82$ (4.7)

NE_Mg = 3E-07ASY + 0.007 $R^2 = 0.86$ (4.8)

The coefficient of determination (R^2) obtained for NE relating to ASY is high ranging from 0.66 to 0.99. The implication is that ASY accounts for between 66 to 99% of the variations in the calculated NE. Other factors such as land use patterns and nature of slopes may account for the remaining variations.

The above equations can therefore be satisfactorily used to predict NE from the catchments if the ASY is known. It must be pointed out that since the equations are empirical, they are, in the main, valid for the conditions under which this study was carried out.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The reservoir bathymetric survey showed sediment deposit and sediment yield to be high and vary significantly between the reservoirs. This has therefore led to the loss of the dead storage capacities and useful lives of the reservoirs studied. This confirms soil erosion and sediment transport in the various reservoir catchments.

Soil loss through erosion has reduced top soil depth, nutrient stocks and the water holding capacity of catchment soils. After several years of erosion, the current nutrient concentration of the catchment soils has been established to serve as basis for not only monitoring future trends in soil fertility decline but for selecting appropriate soil amendments for improved productivity. Differences in soil type, topography, rainfall-runoff characteristics, crop cover, organic matter content of soils and soil management practices, among others, cause considerable variability in the nutrient content of the various catchment soils and reservoir sediments.

The assessment of nutrient concentrations showed the reservoir sediments to be richer not only in nutrients and organic carbon but also clay and silt content than the catchment soils with enrichment ratios greater than 1. This therefore confirms the selective nature of the erosion process and the enrichment of the eroded sediments at the expense of the fertility of the parent soil from which erosion originated. The cost incurred as a result of fertility erosion represents a hidden cost to agricultural production.

There is a strong positive correlation between nutrient export (NE) and area specific sediment yield (ASY). An increase in ASY, therefore results in an increase in NE. Sediment transport through erosion, accounts for about high percentage of the variations in nutrient export to reservoirs.

Reservoirs are important sinks for sequestering carbon. The total amount of carbon sequestered in the studied reservoirs per annum and their CO_2 equivalents indicate the potential of small reservoirs in mitigating climate change.

Sediments, organic materials, and nutrients transported from watersheds to reservoirs are a primary cause of water quality degradation. These pollutants pose a potential threat to human and livestock health, decreased reservoir volume due to sedimentation and lost user benefits.

5.2 Recommendations

The potential of small reservoirs for carbon sequestration and mitigating climate change and global warming requires detailed research study. Catchment area protection is needed to control erosion from the catchments and reduce both on-site (fertility and productivity loss) and off-site (sedimentation, pollution) impacts of erosion. These include afforestation, improved cover using recommended cover and forage species, sustainable land management practices such as vetiver vegetative barriers around the reservoirs.

Desilted nutrient-rich sediments could be used as a soil amendment to improve the productivity of catchment soils for vegetable production. This will require field experimentation to ascertain the benefits of these sediments in enhancing crop yields and biomass production.

REFERENCES

Acquaye, D. F. (1994). Raindrop-size distribution of rainstorms in semi-deciduous forest zone of Ghana. BSc. thesis. Kwame Nkrumah University of Science and Technology. Kumasi, Ghana.

Acquaye, D. K. (1990). Towards Development of Sustainable Agriculture in Africa: Reflections of a Soil Scientists. In Zobisch M. A. (ed). Proceedings of the 11^{th} Annual General Meeting of the Soil Society of Ghana, 19 – 28.

Adama, A.I. (2003). The Effect of Different Tillage Practices on Soil Erosion, Water Conservation and Yield of Maize in the Semi-Deciduous Forest Zone of Ghana. Unpublished M.Sc. Thesis. Department of Crop and Soil Sciences, KNUST, Kumasi, Ghana.

Adu S.V. (1972). Eroded savanna soils of the Navrongo – Bawku area. Northern Ghana. *Ghana Jnl agric. Sci.* 5: 3–12.

Adu, S. V. (1969). Soil of Navrongo-Bawku Area upper Region, Ghana. Memoir No 5. Soil Research institute, Kumasi, Ghana.

Adu, S.V. and Owusu, J.G.K. (1996). Natural resources degradation in Ghana: causes, trends and consequences. Paper prepared for National Workshop on soil fertility management action plan for Ghana, Sasakawa Centre, University of Cape Coast, 2-5^{th} July 1996, Cape Coast, Ghana. 12 pages.

Adwubi, A. (2008). Siltation assessment in selected reservoirs in the Upper East Region using bathymetry and models. MSc. Thesis in Water Resources Engineering and Management, Faculty of Civil and Geomatic Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi.

Akrasi, S. A. (2005). The assessment of suspended sediment inputs to Volta Lake. *Lake & Reservoirs. Research and Management*, 10:179 – 186.

Akyea, A.O. (2009). Effect of Different Land Preparation Methods on Erosion, Growth and Yield of Cassava. Unpublished M.Sc. Thesis. Department of Crop and Soil Sciences, KNUST, Kumasi, Ghana.

Allison, F.E. (1973). Soil Organic Matter and Its Role in Crop Production, Elsevier, New York, 1978.

Amikuzuno, J. (2005). The Causes and Effects of Land Degradation in the TolonKumbungu District of the Northern Region of Ghana: A Participatory Analysis. A NARMSAP-UDS Research Project Report.

Andah, W.E.I., Van de Giesen, N., Biney, C.A. (2003). Water, Climate, Food, and Environment in the Volta Basin. Contribution to the project ADAPT. Adaptation strategies to changing environments.

Apraku, T. (1994). Estimation of rainfall erosivity from autographic rain gauge records. BSc. thesis. Kwame Nkrumah University of Science and Technology. Kumasi, Ghana.

Asiamah, R.D. (1987). Soil Resources and their Agricultural Utilization in Ghana. Proceedings of the national Conference on Resource Conservation for Ghana's Sustainable Development. EPA, Accra

Asiamah, R. D. (1992). Soils and soil degradation of the Upper East Region of Ghana. Soil Research Institute, Kwadaso-Kumasi, Ghana.

Asiamah, R. D. and Antwi, B. O. (1988). Soil and water conservation in Ghana- past, present and future activities. Report sur les resources en sols du Monde, 63 FAO, Rome, pp 126-138.

Asiamah, R. D., Quansah, C. and Dedzoe, C. D. (2000). Soil Degradation: Management and Rehabilitation in Ghana – An Overview Report, In: Proceedings of the FAO/ISCW Expert Consultation on Management of Degraded Soils in Southern and East Africa (MADS – SEA). Pretoria, South Africa. Pp. 89 – 100

Barry, B., Obuobie, E., Andreini, M., Andah, W., Pluquet, M. (2005). The Volta River Basin: Comprehensive Assessment of Water Management in Agriculture. Comparative study of river basin development and management. Draft report.

Benzuayehu, T., Gezahegu, A., Yigezu, A., Jabbar, M.A. and Dubale, P. (2002). "Nature and Causes of Land Degradation in the Oremiya Region" in Review Socio-economic and Policy Research Working Paper 36. ILRI, Nairobi, Kenya. pp 30-36.

Bergsma, E., Charman, P., Gibbonsm, F., Hurni, H., Moldenhauer, W.C. and Panichapang, S. (1996). Terminology for Soil erosion and conservation. ISSS, 1996.

Birner, R., Schiffer, E., Asante, F., Gyasi, O. and McCarthy, N. (2005). Analysis of Governance Structures for Water Resources Management in the White Volta Basin Ghana. Report.

Black, C.A. (1965). Methods of soil analysis. Part 2. Chemical and microbialogical properties. First edition. American Society of Agronomy and Soil Science Society of America. Madison, Wisconsin, USA.

Blake, G.R. and Hartge, K.H. (1986). Bulk density. In: Klute, A. (ed.). *Methods of soil analysis. Part 1. Physical and mineralogical methods. Second edition.* American Society of Agronomy and Soil Science Society of America. Madison, Wisconsin USA. pp. 363 – 375.

Boardman, J., Ligneau, L., De Roo, A. and Vandaele, K. (1994). Flooding of property by runoff from agricultural land in north-western Europe. *Geomorphology*, 10: 183-196.

Bonsu, M. and Obeng, H. B. (1979a). Effect of Different Cultural Practices on Soil Degradation in the Sudan-Savanna Ecological Zone of Ghana. Final Report – CSIR/USAID, Accra, Ghana.

Bonsu, M. and Quansah, C. (1992). The importance of soil conservation for agricultural and economic development of Ghana. In: Proceedings of the 12th and 13th Annual General Meetings of the Soil Science Society of Ghana, Accra, Ghana. pp. 77-80.

Bouyoucos, G.J. (1963). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal* 53:464 – 465.

Brandt, J. (1987). The effect of different types of forest management on the transformation of rainfall energy by the canopy in relation to soil erosion. *Forest Hydrology and Watershed Management* (Proceedings of the Vancouver symposium, August 1987) Publ. no. 167.

Bremner, J.M. and Mulvaney, C.S. (1982). Total nitrogen. In: Page, A. L., Miller, R.H. and Keeney, D.R. (eds.). *Methods of soil analysis. Part 2. Chemical and microbiological properties.* American Society of Agronomy and Soil Science Society of America, Madison Wisconsin Inc. pp. 593 – 624.

Brown, C. B. (1943). Discussion of "Sedimentation in reservoirs, by J. Witzig". Proceedings of the *American Society of Civil Engineers* 69(6):1493–1500.

Butcher, D.P., Labadz, J.C., Potter, A.W.R. and White, P. (1992). Assessment of catchment erosion in the southern Pennines, United Kingdom, using reservoir sedimentation monitoring. In: Bogen J, Walling DE, and Day TJ (Eds.) *Erosion and sediment transport monitoring programs in river basins*. Proceedings of the Oslo Symposium, August 1992, IAHS Publication 210: 443-54.

Butcher, D.P., Labadz, J.C., Potter, A.W.R. and White, P. (1993). Reservoir Sedimentation Rates in the Southern Pennine Region, UK. In: McManus, J. and Duck, R.W. (Eds.) *Geomorphology and Sedimentology of lakes and reservoirs*. Chichester,Wiley, pp. 73-92.

Chow, V.T., ed. (1964). Handbook of Applied Hydrology. McGraw Hill, New York.

Clark, E. H. (1985). The off-site costs of soil erosion. *Journal of soil and water conservation*, 40(1): 19-22.

Cofie Olufunke, O. and Penning de Vries Frits W.T. (2002) Degradation and rehabilitation of land and Water Resources; Examples from Africa. International Water Management Institute Sri Lanka symposium no 46.

Convery, F. and Tutu, K. (1990). Evaluating the Costs of Environmental Degradation: Ghana Applications of Economics in the Environmental Planning Process in Africa. University College of Dublin, Environmental Institute, Dublin.

De Roo, A.P.J. (1998). Modelling runoff and sediment transport in catchments using GIS. *Hydrological Processes* 12: 905-922.

Dearing, J.A. and Foster, D.L. (1993). Lake Sediments and Geomorphological processes: Some Thoughts. In: McManus J and Duck RW (Eds.) *Geomorphology and sedimentology of lakes and reservoirs,* Chichester: Wiley, 73-92.

Drechsel, P. and Gyiele, L.A. (1999). The economic assessment of soil nutrient depletion. Analytical issues for framework development. IBSRAM/SWNM. Issues in Sustainable Land Management 7, IBSRAM: Bangkok, 80p.

Duck, R.W. and McManus, J. (1990). Relationships between Catchment Characteristics, Land Use and Sediment Yield in the Midland Valley of Scotland. In: Boardman J, Foster IDL, and Dearing JA. (Eds.) *Soil Erosion on Agricultural Land*, Wiley pp. 285-299.

Ellison, W. D., (1950). Fertility Erosion. The Land, 9: 487.

El-Swaify, S.A. (1997) Factors affecting soil erosion hazards and conservation needs for tropical steeplands. *Soil Technology* 11, 3-6.

Elwell, H.A. and Stocking, M.A. (1975). Parameters for estimating annual runoff and soil loss from agricultural land in Rhodesia. *Water Resources Research* 11(4): 601-605.

Enters, T. (1998) A Framework for Economic Assessment of Soil Erosion and Soil Conservation. In: Penning de Vries FWT, Agus F, and Kerr J (Eds.) *Soil Erosion at multiple scales. Principles and Methods for Assessing Causes and Impacts.* CAB Publishing, Wallingford, UK in association with the International Board for Soil Research and Management pp. 317–342.

EPA (2002). National Action Programme to Combat Drought and Desertification, EPA, Accra

EPA (2005). Ghana. State of Environment Report 2004. Environmental Protection Agency, Accra, Ghana.

Eswaran, H., Lal, R., Reich, P.F. (2001). Land degradation: An overview. In: *Response to Land Degradation,* Bridges, E.M, Hannam, I.D., Oldeman, L.R., Penning de Vries F.W.T., Scherr, J.S., Sombatpanit, S. (eds). Science Publisher, Inc.: Enfield, NH; 20–35.

Evans, J. E. (1980). ^{210}Pb geochronology in lake superior sediments: Sedimentary environments and post-depositional processes. MSc. Thesis, Univ. Minnisota, Minneapolis. 130p

FAO (1990). The conservation and rehabilitation of African lands. ARC/90/4. Rome: FAO.

FAO (2000). Food and Agricultural Organization of the United Nations. http://www.fao.org/livestock/agap/frg/oldafris/data/314.htm. Accessed on 28/03/09.

FAO (2005). Ghana. State of Environment Report 2004. Environmental Protection Agency, Accra.

Ferro, V., Porto, P. and Tusa, G. (1998). Testing a distributed approach for modelling sediment delivery. *Hydrological Sciences Journal* 43(3): 425-442.

Folly, A. (1997). Land Use Planning to Minimize Soil Erosion – A Case Study from the Upper East Region in Ghana. Ph.D thesis, Institute of Geography, University of Copenhagen.

Foster, I.D.L. (1995). Lake and Reservoir Bottom Sediments as Sources of Soil Erosion and Sediment Transport Data in the UK. In: Foster IDL, Gurnell MM, and Webb B (Eds.) *Sediment and Water Quality in River Catchments.* Wiley, Chichester 265-283.

Foster, I.D.L., Dearing, J.A., Grew, R. and Orend, K. (1990). The sedimentary database: an appraisal of lake and reservoir sediment based studies of sediment yield. In: *Erosion, Transport and Deposition Processes* (Proceedings of the Jerusalem Workshop), *IAHS Publication* no. 189: 19-44.

Friend, J.A. (1992). Achieving soil sustainability. *Journal of soil and water conservation*, vol. 47(29), pp 156-157.

Gachene, C.K.K., Jarvis, N.J. and Mbuvi, J.P. (1997). Soil effects on soil properties in a highland area of Central Kenya. *Soil Sci. Soc. Am. J.* 61, 559564.

Garbrecht, J., and A.N. Sharpley. (1993). Sediment–phosphorus relationships in watersheds. p. 54–63. In: P. Larsen and N. Eisenhauer (ed.) *Workshop, Sediment Quality*. Proc. of the 5th Int. Symp. on River Sedimentation, Karlsruhe, Germany. United Nations Educational, Scientific and Cultural Organization, Paris.

GENSTAT (2007). GENSTAT Discovery Edition 3. VSN International, U.K.

Golden Software Inc (2003). Surfer Version 8.0. Surface Mapping System. Golden, Co.

Greenland, D.J., Bowen,G. Eswaran, H., Roades, R. and Valentin, C. (1994). Soil Water and Nutrient Management Research. A New Agenda. IBSRAM Position Paper, IBSRAM, Bangkok, Thailand.

GSS (2005). 2000 Population and housing census of Ghana. Ghana Statistical Service, Accra

Gyasi, O. and Schiffer, E. (2005). Community needs assessment and local water governance appraisal in the Upper East Region, Ghana. Final Report.

Haregeweyn, N., Poesen, J., Deckers, J., Nyssen, J., Haile, M., Govers, G., Verstraeten, G. and Moeyersons, J. (2008). Sediment-bound nutrient export from micro-dam catchments in northern Ethiopia. *Land Degrad. Develop.* 19:136-152.

Hillel, D. (1998). Environmental Soil Physics Academic Press, San Diego, USA.

Hudson, N. W. (1981). Soil Conservation. Batsford, England.

Hudson, N.W. (1995). Soil Conservation. Third Edition, BT Batsford Ltd., London.

Hunt, J. E. (1974). Effects of Simulated Erosion on Performance of Maize Grown on Sardan Alluvium. Soil Conservation and Reclamation Report No. 1, Ministry of Agriculture, Fish., Kuala Lumpur, Malaysia.

Hurni, H. (1985). Erosion - Productivity - Conservation Systems in Ethiopia. Proceedings of 4th International Conference on Soil Conservation, Maracay, Venezuela 654-674.

IFAD (1991). Water resources development, Upper East Region land conservation and smallholder rehabilitation project. Working paper 6.

IFAD (1992). "Soil and Water Conservation in sub-saharan Africa. Towards Sustainable Production by the Rural Poor". A Report prepared for IFAD by the Centre for Development Co-operation Services, Free University, Amsterdam. pp 16.

IFAD, (1999). Upper-East Region Land Conservation and Smallholder Rehabilitation Project - Phase II. Report and Recommendation EB 99/66/R.14

Institute of Social, Statistical and Economic Research (ISSER) (2003). State of the Ghanaian Economy in 2003. Institute of Social, Statistical and Economic research, University of Ghana Legon.

Juracek, K.E. and Mau, D.P. (2002). Sediment Deposition and Occurrence of Selected Nutrients and Other Chemical Constituents in Bottom sediment, Tuttle Creek Lake, Northeast Kansas. Water-Resources Investigations Report 02-4048. USGS.

Lal, R. (1976). Soil Erosion Problems on an Alfisol in Western Nigeria and Their Control. IITA Monograph No. 1, 208 pp.

Lal, R. (1981) Analyses of different processes governing soil erosion by water in the tropics. In: *Erosion and Sediment Transport Measurement* (Proc. Florence Symp., June 1981), 351-364. IAHS Publ. no. 133.

Lal, R. (1983). Soil Erosion and Crop Productivity Relationship for a Tropical Soil. Paper Presented at Malama, Aina 83, Honolulu, Hawaii.

Lal, R. (1984). Soil Erosion From Tropical Arable Lands and Its Control. *Advances in Agronomy* 37: 183 – 248.

Lal, R. (1987). Research Achievements Towards Soil and Water Conservation in the Tropics: Potential and Prioritization. In: I Pla Sentis (ed.). *Soil Conservation and Productivity.* Maracay, Sociedal Venezolana de la Ciencia del Svelo: 755 – 87.

Lal, R. (1993). Soil Erosion and Conservation in West Africa. In: Pimental, D (ed). *World Soil Erosion and Conservation.* Cambridge University Press. pp. 7-25.

Landon, J.R. (1991). Booker Tropical Soil Manual. A handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics.

Lane, L.J., Renard, K.G., Foster, G.R. and Laflen, J.M. (1997). Development and application of modern soil erosion prediction technology: The USDA experience. *Eurasian soil science* 30 (5): 531-540.

Lawrence, P. and Dickinson, A. (1995) Soil erosion and sediment yield: a review of sediment data from rivers and reservoirs (Report prepared under FAO writers' contract). Overseas Development Unit, HR Wallingford Ltd, England.

Liebe, J. (2002). Estimation of water storage capacity and evaporation losses of small reservoirs in the Upper East Region of Ghana. Diploma thesis, University of Bonn.

Liebe, J., Van de Giesen, N. and Andreini, M. (2005). Estimation of small reservoir storage capacities in a semi-arid environment: A case study in the Upper East Region of Ghana. *Physic and Chemistry of the Earth* 30, 448-454. Longman group: UK.

Massey, R.G. and Jackson, M. L. (1952). Selective erosion of soil fertility constituents. *Soil Sci. Soc. Am. Proc.* 16. 353-356.

Mbagwu, J.S.C., Lal, R. and Scott, T. W. (1983). Physical Properties of Three Southern Nigeria. *Soil Science* 136: 48 – 55.

McLean, E.O. (1965). Aluminium. In: Black, C.A. (ed.). *Methods of soil analysis. Part 2. Chemical and microbiological properties. First edition* American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin USA. pp. 978 – 998.

McLean, E.O. (1982). Soil pH and lime requirement. In: Page, A.L., Miller, R.H and Keeney, D.R. (eds.). *Methods of soil analysis. Part 2. Chemical and microbiological properties. Second edition.* American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin USA. pp.199-223.

Menzel, R.G. (1980). Enrichment ratios for water quality modelling. CREAMS. pp 486 – 492

Ministry of Food and Agriculture (MoFA) (1998). National Soil Fertility Management Action Plan. Directorate of Crop Services, Accra, Ghana.

Mitas, L. and Mitasova, H. (1998). Distributed soil erosion simulation for effective erosion prevention. Water Resources Research. 34, 505-516.

Mokwunye, U. (1996). Nutrient depletion: SubSaharan Africa's greatest threat to economic development. Paper presented at the STAP Expert Workshop on land Degradation, Dakar, Senegal.

Morgan, R. P. C. (1985). Establishment of plant cover parameters for modelling splash detachment. In: El-Swaify, S. A., Moldenhauer W. C. and Lo, A. (eds) *Soil Erosion and Conservation*. Soil Conservation Society of America, Iowa, 377-383.

Morgan, R. P. C. (1995). Soil Erosion and Conservation. Second Edition. Longman, England.

Mosley, M. P. (1982). The effect of a New Zealand beech forest canopy on the kinetic energy of water drops and on surface erosion. *Earth Surface. Processes and Landforms* 7:103-107

National Soil Erosion – Soil Productivity Research Planning Committee (NSESPRPC) (1981). Soil Erosion Effects on Soil Productivity. A Research Perspective. *J. Soil, Water Conservation* 36 (2): 82 – 90.

Needham, R. (1993). Natural Resources and Livelihood Systems: The Upper East Region of Ghana. Ph.D. thesis, Sussex University, England.

Nelson, D. W. and Sommers, L.W. (1982). Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H and Keeney, D.R. (eds.). *Methods of soil analysis. Part 2. Second edition. Chemical and microbiological properties.* American Society of Agronomy and Soil Science Society of America. Madison, Wisconsin USA. pp.301-312.

Okalebo, J.R., Gathua, K.W. and Woomer, P.L. (1993). Laboratory methods of soil and plant analysis: A working manual. Tropical Soil Biology and Fertility. Soil Science Society of East Africa. Technical Publication No. 1. Nairobi, Kenya. 88pp.

Olsen, S.R. and Sommers, L.E. (1982). Phosphorus. In: Page, A.L., Miller, R.H. and Keeney, D.R. (eds.). *Methods of soil analysis. Part 2. Chemical and microbiological properties. Second edition*. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin USA. pp. 403-430.

Ongley, E.D. (1982). Influence of season, source and distance on physical and chemical properties of suspended sediment. In: D.E. Walling (ed.) *Recent developments in the explanation and prediction of erosion and sediment yield.* Proc. of the Exeter Symp. July 1982. IAHS Publ. 137. Int. Assoc. of Hydrol. Sci., Wallingford, UK. p. 371–383.

Opoku-Ankomah, Y. (2000). Impacts of Potential Climate Change on River Discharge in Climate Change Vulnerability and Adaptation Assessment on Water Resources of Ghana. Water Research Institute (CSIR), Accra. Ghana.

Ortt, R. A. Jr., Kerhin, R.T, Wells, D. and Cornwell, J. (2000). Bathymetric survey and sedimentation analysis of loch raven and prettyboy reservoirs. Maryland Department of the Environment and the City of Baltimore. Coastal and estuarine geology, File report no. 99-4

Osei-Yeboah, S. (Personal Communication). Soil erosion susceptibility assessment and mapping for landuse planning in Ghana. Ph.D Thesis in preparation to be submitted to the Department of Crop Sciences, KNUST, Kumasi.

Parekh, P. (2004). A Preliminary Review of the Impact of Dam Reservoirs on carbon Cycling. International Rivers Network (IRN), USA. pp 1-8.

Penning de Vries, F.W.T, Molden, D. and Schen, S.J. (2002). Implications of land and water degradation for food security contribution to the briefing document for a GEF Roundtable in Dakar, Feb.

Phillips J.D. (1989) Hillslope and channel sediment delivery and impacts of soil erosion on water resources. In: Hadley RF and Ongley EO (Eds.) *Sediment and the Environment. IAHS Publ.* 184: 183-190.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267(5201): 1117-1123.

Poolman, M. I. 2005. Developing small reservoirs; a participatory approach can help. MSc. Thesis Technical University of Delft

Quansah, C. (1990). Soil erosion and Conservation in the Northern and Upper Regions of Ghana. *Topics in Applied Resources Management* 2: 135 - 157.

Quansah, C. (1996) Soil, water and nutrient management needs for sustainable crop production. Proceedings of DSE International Seminar on Tools for Analysis and Evaluation for sustainable Land use in Rural Development. DSE, Zscortan, Germany. pp 38-46

Quansah, C. (1997). Approaches To Replenishing Soil Fertility Depletion In Ghana. Poster Abstracts For The International Seminar On Approaches To Replenishing Soil Fertility In Africa: NGO Perspective, ICRAF, Nairobi, Kenya.

Quansah, C. (2000). Country Case Studies: Ghana. In: FAO (ed.), *Integrated Soil Management for Sustainable Agriculture and Food Security- Case Studies from 4 Countries in West Africa (Burkina Faso, Ghana, Nigeria, Senegal)*. FAO Regional Office for Africa, Accra, Ghana.

Quansah, C. (2001). Integrated soil management for sustainable agriculture and food security. Country case study: Ghana. FAO. Accra. 33-75

Quansah, C. (2005). Oncho Transborder Project. Burkina Faso and Ghana. Natural Resources use and management report.

Quansah, C. and Baffoe-Bonnie, E. (1981). The effects of soil management systems on soil loss, runoff and fertility erosion in Ghana. In: Tingsanchali, T. and Egger, H. (eds). *South-East Asia Regional Symposium on problems of soil erosion and sedimentation.* Asia Institute of Technology, Bangkok, Thailand.

Quansah, C., Baffoe-Bonnie E. and Asiamah R. D. (1989). Soil erosion in Ghana and strategies for conservation. A paper presented at the African Ministerial Conference on the environment (RCU/SOFERNET) and soil conservation strategy for Africa. Accra, Ghana. 28 – 30 August, 1989.

Quansah, C., Safo, E.Y., Ampontuah, E.O. and Amankwaah, A.S. (2000). Soil Fertility erosion and the associated cost of NPK removal under different soil and residue management in Ghana. *Ghana Journal of Agriculture Science.* Vol. 33 (1) 33-42.

Quansah, C., Agodzo, S. K., Gyawu, Bonsu, M. and Dittoh, J. S. (2002). National Action programme to Combat Desertification in Ghana.
Environmental Protection Agency, Accra, Ghana.

Rausch, D.L. and Heinemann, H.G. (1984). Measurement of reservoir sedimentation. In: Hadley, RF and Walling DE. (Eds.) *Erosion and Sediment yield Yields: Some Methods of Measurement and Modelling.* Geo Books, Nowwich, pp. 179-200.

Rehm, S. (1978) cited in Lal, R. (1984). Soil Erosion from Tropical Arable Lands and Its Control. *Advances in Agronomy* 37: 183 – 248.

Renard, K.G. and Foster, G.R. (1983). Soil conservation: principles of erosion by water. In: Degne HE and Willis WO (Eds.) *Dryland Agriculture*, *Agronomy Monogr*. 23, Am. Soc., Crop Sci. Soc. Am., and Soil Sci. Am. Madison, Wisconsin, pp. 156-176.

Richter, G. and Negendank, J. (1977). Soil erosion processes and measurement in the German Area of the Moselle River. *Earth Surface Processes* 2: 185-190

Sanchez, P. A. Buresh, A. J., Kwesiga, F. R., Mokwunge, A. U., Ndiritu, C. G., Shepherd, K. D., Soule, M. J. and Woomer, P. L. (1997). Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital.

Proceedings of International Seminar on Fertility in Africa – NGO Perspectives ICRAF, Nairobi, Kenya.

Sarpong, D.B., Quansah, C., Björklund, G., Stockholm G.K. (2006). Draft Report on Cost-Benefit Framework to Support Pro-SLM Decision Making in Ghana.

Sharpley, A., B. Foy, and P. Withers. (2000). Practical and innovative measures for the control of agricultural phosphorus losses to water: An overview. *J. Environ. Qual.* 29:1–9.

Sherr, S.J. (1999). Soil Degradaion: A Threat to Developing Country Food Security by 2020? Food and Agriculture and the Environment Discussion Paper 27. International Food Policy Research Institute, Washington, D.C. USA

Shetty, S. V. R., Debrah S. K. and Renard C. (1995). Technology development, testing and transfer: An overview of ICRISAT's Experience in semi-arid Africa. In: *Proc. of Workshop on Moist Savannas of Africa: Potentials and constraints for crop production. Cotonou, Benin. Sept 19–23, 1994.*

Sibbesen, E. (1995). Phosphorus, nitrogen and carbon in particle-size fractions of soils and sediments. In: A. Correl (ed.) *Surface runoff, erosion and loss of phosphorus at two agricultural soils in Denmark, plot studies 1989–92*. SP-Rep. 14. Danish Inst. of Plant and Soil Sci., Tjele, Denmark. pp. 135–148.

Smaling, E.M.A. (1993). Soil Nutrient Depletion in sub-Saharan Africa. In: *The role of plant nutrients for sustainable food crop production in subSaharan Africa.* H. Van Reuler and W.H. Prims (Eds.). The Netherlands: VK pp. 53-67.

Smith, P. and Martino, D. (2007). Agriculture, in Climate Change 2007, Fourth IPCC Assessment Report, IPCC, Geneva, Switzerland.

Sombroek, W.G., Brain, H.M. H. and Van der Pouw, B.J.A. (1980). The explanatory soil map and agro-climatic zone map of Kenya. Report N.E.I., Kenya Soil Survey, Nairobi.

Stallard, R.F. (1998). Terrestrial sedimentation and carbon cycle: Coupling weathering and erosion in the carbon burial. *Global Biogeochemical Cycles* 12: 231–257.

Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Beuselinck, L. and Poesen, J. (2000). Sediment export by water from an agricultural catchment in the Loam Belt of Central Belgium. *Geomorphology* 33: 25-36.

Steegen, A., Govers, G., Takken, I., Nachtergaele, J., Poesen, J. and Merckx, R., (2001). Factors controlling sediment and phosphorus export from two Belgian agricultural catchments. *Journal of Environmental Quality*, 30(4): 1249-1258.

Stefano, C.D., Ferro, V. and Porto, P. (1999). Linking Sediment Yield and Caesium137 Spatial Distribution at Basin Scale. *Journal of Agricultural Engineering Research* 74: 41-62.

Stocking, M. (1996). Soil erosion: Breaking new ground. In: *Land degradation and societies* (ed. P. Blaikie and H. Brookfield), pp. 49-63. London: Viliers Publication.

Stocking, M. and Murnaghan, N. (2001). Handbook for the field assessment of land degradation. Earthscan Publications Ltd, UK/USA. pp 1-35.

Stoorvogel, J. J. and Smaling, E. M. A. (1990). Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983-2000. Winand Staring Centre. Report 28, Wageningen. 137p.

Swift, M., (1997). Biological Management of Soil Fertility: An Integrated Approach to Soil Nutrient Replenishment. Proceedings of International Seminar on Approaches to Replenishing Soil Fertility in Africa – NGO Perspectives. ICRAF, Nairobi, Kenya.

Syers, J. K. (1997). Managing Soils for Long-Term Productivity. *Phil. Trans R. Soc. Land B*: 352, 1011 – 1021.

Tamene L., Park S. J., Diakau R. & Vlek P. L. G. (2006). Analysis of factors determining sediment yield variability in the highlands of north Ethiopia. *Geomorphology:* 76, 76–91.

Tamene, L.D. (2005). Reservoir siltation in Ethiopia: causes, source areas and management options, In: Denich, M., Martius, C., Rodgers, C. and van de Giesen N (eds) *Ecology and Development Series No. 30*

.

Thames, D. J. and Cassell, D. K. (1979). Land Farming Atlantic Coastal Plains Soils: Crop yield Relationships to Soil Physical and Chemical Properties. *J. Soil Wat. Conserv*. 30 (1): 20 – 24.

Tulu, T. (2002). Soil and water conservation for sustainable agriculture. Mega publishing enterprise. Addis Ababa, Ethiopia.

Twinch, A. J. and Breen, C. M., (1982). Vertical Stratification in sediments from a young oligotrophic South African impoundment: Implications in phosphorus cycling: Hydrobiologia 92. Dr W. Junk Publishers, The Hague, pp. 395-404.

UNCCD (2008). Climate Change and Desertification. UNCCD Thematic Fact Sheet Series №1. Bonn, Germany.

UNDP (2007). Fighting climate change: Human solidarity in a divided world. Human development report 2007/2008. Available at http:// www.undp.org Date of access: 16/01/2008

UNEP and UNESCO (1980). Provision map of Present Land Degradation Rate and Present State of Soil. FAO: Rome.

U.S. Environmental Protection Agency (USEPA) 2000. Water Quality Conditions in the United States – A profile from the 1998 National Water Quality Inventory Report to Congress. EPA841-F-00-006. Office of Water, Washington, D.C.

USGS (2008). Carbon sequestration to mitigate climate change, Fact Sheet 2008 – 3097. United States Geological Survey, USA.

Van de Giesen, N., Kunstmann, H., Jung, G., Liebe, J., Andreini, M., Vlek, P.L.G. (2002). The GLOWA-Volta project: integrated assessment of feedback mechanisms between climate, landuse, and hydrology. *Adv. Global Change Res*. 10, 151–170.

Van Rompaey, A., Verstraeten, G., Van Oost, K., Govers, G. and Poesen, J. (2001). Modelling Mean Annual Sediment Yield Using a Distributed Approach. *Earth Surface Processes and Landforms* 26: 1221-1236.

Verstraeten, G. and Poesen, J. (1999). The nature of small-scale flooding, muddy floods and retention pond sedimentation in central Belgium. *Geomorphology*, 29(3-4): 275-292.

Verstraeten, G. and Poesen, J. (2000) Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. *Progress in Physical Geography* 24: 219-251.

Verstraeten, G. and Poesen, J. (2001a). Factors controlling sediment yield from small intensity cultivated catchments in a temperate humid climate. *Geomorphology* 40: 123-144.

Verstraeten, G. and Poesen, J. (2001b). Variability of dry sediment bulk density between and within retention ponds and its impact on the calculation of sediment yields. *Earth Surface Processes and Landforms* 26: 375-394.

Verstraeten, G. and Poesen, J. (2002a). Using sediment deposit in small ponds to quantify sediment yield from small catchments: possibilities and limitations. *Earth Surface Processes and Landforms* 27: 1425-1439.

Verstraeten, G., Poesen, J. (2002b). Regional scale variability in sediment and nutrient delivery from small agricultural catchments. *Journal of Environmental Quality* 31: 870–879.

Walker, H. O. (1962). Weather and climate. In: J.B. Wills (ed). *Agriculture and land use in Ghana*. Oxford University Press, England, pp 7-28.

Walling, D.E. (1994) Measuring sediment yield from river basins. In: Lal R (Ed.) *Soil Erosion Research Methods.* 2nd edition, Soil and Water Conservation Society: Ankeny, Iowa; pp. 39-80.

Walling, D.E. (1997). The response of sediment yields to environmental change. In: *Human Impact on Erosion and Sedimentation* (Proceedings of the Rabat Symposium S6, April 1997). IAHS Publication No. 245: 77– 89.

Walling, D.E. and Webb, D.W. (1981). The reliability of suspended sediment load data: Erosion and sediment transport measurement, Proceedings of the Florence Symposium, Florence: IAHS, 177-194.

Wan, Y., El-Swaify, S.A. (1998). Sediment enrichment mechanisms of organic carbon and phosphorus in a well-aggregated Oxisol. *Journal of Environmental Quality* 27: 132–138.

Warrick, A.W. (1998). Spatial Variability. In: Daniel Hillel (Ed.) *Environmental Soil Physics.* Academic Press, USA. pp 655-675.

Wood, S., Sebastian, K. and Scherr, S.J. (2000). Pilot analysis of global ecosystems: Agroecosystems. International Food Policy Research Institute, and World Resources Institute. Washington, DC, USA. pp 110.

World Bank, ISSER, DFID. (2005). Natural Resource Management and Growth Sustainability. Africa Region. Washington D.C: World bank