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TEMPORAL VARIABILITY IN SEDIMENTATION, NITROGEN AND PHOSPHORUS LOADING IN SURFACE RUNOFF IN SONDU-MIRIU BASIN

KENNEDY OCHIENG OUMA

A Thesis Submitted to the Graduate School in Partial Fulfilment for the Requirements of the Award of Master of Science Degree in Limnology of Egerton University

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ABSTRACT

Integrated resource management in river and lake basins is one cost-effective approach that ensures sustainable utilisation of land and water resources. It is therefore crucial to determine the status of these resources as a basis for implementing effective management strategies of basins. This study was conducted at Kabianga (upper basin) and Sondu (mid-basin) in Sondu-Miriu basin from November 2010 to May 2011. The study aimed to determine the temporal variability in sedimentation and nutrient loading in surface runoff from different land uses (natural vegetation, weedy-fallow and cropped), as part of decision support tools for management. Sampling was done monthly during short rains (November-December 2010) and dry season (January-March, 2011), and bi-monthly in the long rains (April-May, 2011) from experimental plots and River Sondu-Miriu respectively. Lower sediment, nutrient and surface runoff values were observed in land under natural vegetation but higher in the cropped and weedy-fallow lands during the long-rains season. Principal Components Analysis (PCA) correlated sedimentation to temporal variability in land uses as influenced by seasonal variability. Solids and organic matter were significantly higher in surface runoff during the short rains ($p < 0.05$). At Kabianga, there were significantly low nitrate-N concentrations during the two rainy seasons but high soluble reactive-P levels during the long-rains season ($p < 0.05$). In Sondu, there were significantly low ammonium-N concentrations during short-rains while nitrate-N levels significantly varied across the 3 seasons ($p < 0.05$). The soluble reactive-P varied significantly between the dry and long-rains season ($p < 0.05$). PCA associated the levels of nutrient pollution in surface runoff to the influence of seasonality on land use/land cover (LULC) activities. A GIS-based LULC analysis isolated significant percentage changes in spatial coverage between 1985 and 2013 ($p < 0.05$). There was 17% increase in urban settlements, 1% loss in bushland and 0.7% increase in small-scale farmed lands annually. ArcSWAT projections indicated increased sedimentation by 4%, runoff discharge by 6%, and soluble nutrient (nitrates, ammonium and soluble reactive phosphorus) loads in surface waters by 6% from land uses between 2013 and 2020. Temporal variability in seasonal hydrological patterns significantly influenced sediment and nutrient loads in surface runoff. Generally, sediment and nutrient loads increased during the rainy season. The levels also varied with land use activities. Intensification of land-use activities that reduce land cover or increase nutrient levels in surface runoff, will significantly contribute to surface water pollution in Sondu-Miriu Basin in the next decade.

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LIST OF ABBREVIATIONS AND ACRONYMS

APHA	American Public Health Association
DEM	Digital Elevation Model
FAO	Food and Agricultural Organization
GIS	Geographical Information Systems
GPS	Global Positioning System
HRU	Hydrologic Response Unit
LANDSAT	Land Remote-Sensing Satellite
LULC	Land Use and Land Cover
LVB	Lake Victoria Basin
LVEMP	Lake Victoria Environmental Management Programme
MWI	Ministry of Water and Irrigation
NBI	Nile Basin Initiative
NEMA	National Environmental Management Authority
RSM	River Sondu-Miriu
SMB	Sondu-Miriu Basin
SRP	Soluble Reactive Phosphorus
SWAT	Soil and Water Analysis Toolkit
UNEP	United Nations Environmental Programme
USGS	United States Geological Survey
VicRes	Lake Victoria Research Initiative
WHO	World Health Organisation
WRMA	Water Resources Management Authority

CHAPTER ONE

1. INTRODUCTION

1.1. Background Information

Agricultural activities influence aquatic ecosystems by increasing nutrient inputs, which could result in changes to both ecosystem structure and functions (Tilman *et al.*, 2003). In-stream concentrations and catchment export of nitrogen (N) and phosphorus (P), tend to increase with increasing agricultural land use in a catchment (Baker and Richards, 2003; Nord and Lanyon, 2003). Accelerated soil erosion together with the associated nutrients into surface waters through runoff from arable land and natural processes may degrade stream and lake water quality. Since surface drainage outflow may be identified as the leading source of water quality deterioration (Bernot *et al.*, 2006), reduction of nutrient and sediment transport through runoff is of great importance (WAC, 2006). The effects of increased nutrients on freshwater and marine ecosystems include eutrophication (Downing *et al.*, 1999), hypoxia (Rabalais *et. al.*, 2002) and decreased biodiversity (Vitousek *et al.*, 1997). Additionally, elevated nitrate (NO_3-N) concentrations in drinking water have been associated with human health risks, such as methylhemoglobinemia and non-Hodgkin's lymphoma (Townsend *et al.*, 2003).

Recent changes in the ecology of Lake Victoria are associated with natural processes as well as anthropogenic activities within the Lake Victoria Basin (LVB) (Lung'ayia *et al.*, 2001). Odada *et al.* (2004) argued that waters within the LVB are under considerable pressure from a variety of interlinked human activities. The growing population, with an average annual growth rate of 3% and an average population density of about 165 persons per km^2, is exerting increasingly greater pressures on the basin's natural resources (Odada *et al.*, 2009). The utilization of these resources is heavily driven by livelihood needs and demands of the inhabitants within the basin, resulting to far-reaching ecosystem changes. Land use demand has intensified, human and livestock populations have increased within the riparian communities in LVB. Kayombo and Jorgensen (2006) observed that over 70% of the population in the LVB are engaged in agricultural production mainly as small-scale farmers, for crops such as sugarcane, tea, coffee, maize, cotton, horticultural products, and livestock keeping.

The lake Victoria Basin on the Kenyan side covers nearly 47,074 km^2 and is topographically subdivided into the North and South sub-basins (Figure 1-1). The Lake Victoria South Basin

of approximately 27,459 km^2, is drained by several rivers mainly Nyando, Sondu-Miriu, Gucha-Migori, South Awach and Mara (MWI, 2004). River Sondu-Miriu (RSM), the third largest river in the LVB, drains a surface area of approximately 3,508 km^2 in the Sondu-Miriu Basin (SMB). The River originates from the western slopes of the Mau Escarpment and inflows through a narrow gorge, penetrating the Odino Falls before entering the flood plains of Nyakwere, where it drains into the Winam Gulf of the Lake Victoria.

Human activities in the SMB are mainly agricultural production, mostly as small-scale farming and livestock keeping (Vuai *et al.*, 2012). River Sondu-Miriu water provides hydroelectric power (KenGen Sondu-Miriu hydroelectric power project), supports small-scale irrigation and provides water for livestock and for domestic purposes. It also acts as a means of transportation of point and non-point source pollutants and waste materials generated from the basin's socioeconomic activities and urbanisation (NBI, 2005). This implies that the environmental and socio-economic impact of nutrient loss and sediment loading from the basin's terrestrial-aquatic systems into Lake Victoria could be significant. Since RSM integrates the effects of a multitude of stressors arising from agricultural, other anthropogenic and natural processes in the basin, the river is important as an indicator of the ecological effects of anthropogenic and natural lotic ecosystem stressors in SMB.

This study evaluated the impact of different agricultural land use activities in SMB on loading rates of sediments and nutrients into RSM and assessed the underlying factors for temporal variability in surface water quality. Sediments and nutrient loading into RSM reflects both natural and anthropogenic activities occurring in the basin. The nutrient and sedimentation load could also be influenced by basin characteristics such as topography, geology and soil characteristics, rainfall and sediment transportation index (Odada *et al.*, 2004). These factors enhance nutrients loss and transportation both in dissolved and particulate form, attached to particulate matter and soil sediments. Sediments are known to provide a long-term point source of nutrients and pollutants through dissolution under appropriate conditions (Kitaka *et al.*, 2002). Therefore, understanding trends of sedimentation and nutrient loading within SMB will act as a guide to gauge the efficacy of existing environmental laws/policies and programs on reducing aquatic pollution to enhance sustainable management of Lake Victoria.

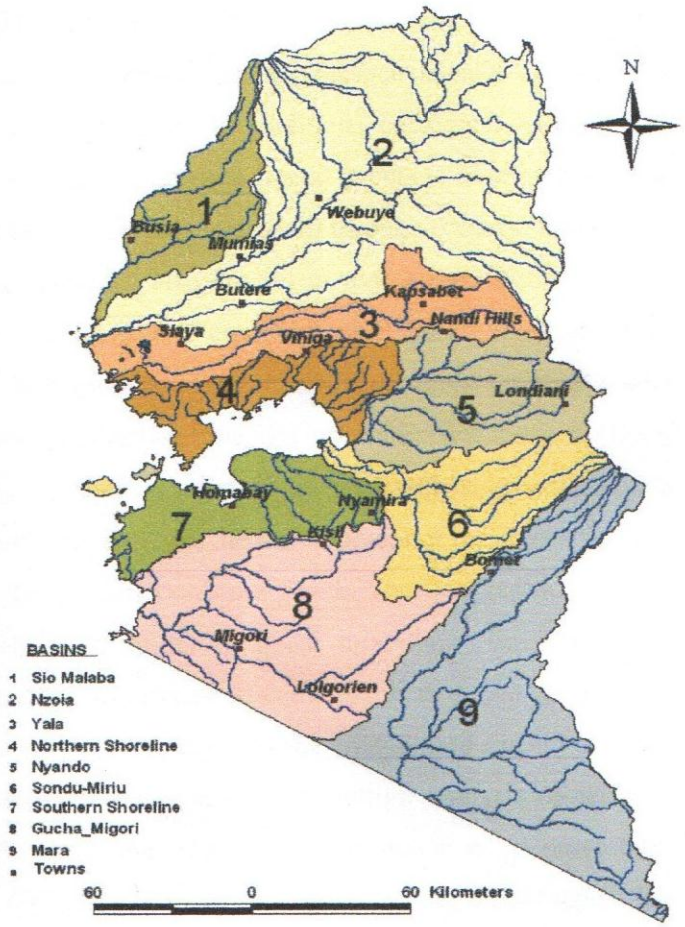


Figure 1-1: Lake Victoria Basin in Kenya indicating the major River Basins (NBI, 2005)

Environmental data acquired by investigating the dynamics of water quality may present complex patterns and variability that depend on a number of unpredictable factors. These factors may be geogenic or lithological, hydrological, meteorological and anthropogenic (Shrestha and Kazama, 2007; Bu *et al.*, 2010). The non-linear nature of environmental data makes temporal and spatial variability of surface water quality often difficult to interpret. This creates a critical need to provide a representative and reliable estimation of the quality of surface waters. Consequently, the application of different multivariate statistical techniques such as Principal Component Analysis (McCarthy *et al.*, 2007) and environmental modelling (Lee *et al.*, 2001; Wunderlin *et al.*, 2001; Reghunath *et al.*, 2002) have been developed for the interpretation of complex data matrices and better understanding of the water quality variability.

In recent years, ecological modelling has rapidly emerged as an indispensable tool for the understanding of the natural processes occurring at the catchment scale. As anthropogenic activities progressively modify these natural processes, application of integrated modelling to

account for the interaction of human activities such as agricultural resources management, water and nutrient removal from land into surface and ground water, release of rainwater and wastewater into surface and sub-surface aquatic systems, urbanisation among others has become very essential. In addition, ecological modelling integrates the anthropogenic activities and natural environmental events to identify the drivers, pressure, state, impact and response factors (DPSIR approach) through scenario analysis of complex systems. Ecological modelling tools are also crucial to assess the effect of alternative management options in varying ecosystems and environmental conditions under different scenarios and forecasts. For this, computer-based environmental simulation models like the Soil and Water Analysis Tool (SWAT) offers an attractive option in river basin studies (Koskiaho *et. al.*, 2007). Since hydrologic systems are heterogeneous, with substantial spatial variability in model inputs such as soil and land use, the development of input files for such models particularly for large watersheds is a time-consuming task. The Geographical Information System (GIS) has been extensively used in hydrological modelling (Castillo *et al.*, 2003). Whereas GIS is a combination of an organized computer system and geographical data designed to efficiently capture, store, update, manipulate, analyse and display all forms of geo-referenced data, the system supports the entering and multiple analysis of geo-referenced data (Nurmohamed *et al.*, 2006). Such analyses lead to production of presentations either in graphical or tabular manner. GIS plays a major role in developing model inputs from digital geospatial databases through model-GIS interfaces.

Hydrological modelling demands huge amounts of spatial data management and thus an efficient system to handle voluminous data is vital. The GIS interface provides alternatives for competent management of complex and large databases. GIS technology has been used to develop Digital Elevation Models (DEM) for hydrological studies at varying scales (USGS, 2012). The SWAT model and GIS interfaces aid water resources professionals in basin-scale studies of water availability and quality. SWAT significantly helps reduce the time and cost necessary to conduct such studies significantly several-fold compared to other distributed-parameter type of models (Jayakrishnan *et. al.*, 2005). The SWAT model has a good potential for application in water quality studies worldwide as well as in developing time and cost-efficient management and decision-making options for analyses of basin water resources.

Within the LVB, researchers have applied SWAT to estimate the impacts of land use and land cover changes on catchment hydrology and surface water quality. Kimwaga *et al.* (2011)

modelled the influence of non-point source pollution in the Simiyu catchment draining into Lake Victoria, Tanzania using SWAT. Githui *et al.* (2009a; 2009b) studied the impacts of changes in land use on surface runoff in Nzoia catchment, and the variability in streamflow in response to climate change in western Kenya basins. Swallow *et al.*, (2008) incorporated the influence of hydrology and sedimentation as integrators of provisioning and regulatory ecosystem services in Yala and Nyando river basins of Lake Victoria. Jayakrishman *et al.* (2005) applied the SWAT model to determine the impact of land use change patterns due to the modernisation of small-scale dairy industry in Sondu-Miriu Basin. SWAT has also been used in the Tana River basin, Kenya, for ecosystem assessment to enhance mitigation of economic losses emanating from environmental degradation (Jacobs *et al.*, 2007).

Field runoff plots have been used to estimate hydrological and water quality parameters within catchments. However, extrapolation of outputs from the field experimental plots only for the entire catchment may lead to unreliable results due to the heterogeneous nature of large catchments (Mutua and Klik, 2006) and hence the need for ecological modelling, which incorporates additional environmental and human variables. In this study, the aim was to use field data from the experimental runoff plots was used in validation of the ArcGIS-SWAT model to eliminate errors in extrapolation of output from runoff plots. The simulated SWAT model outputs were used in further analyses and simulation of the temporal aspects of surface runoff, sedimentation and nutrient trends in surface water from different land uses in SMB.

1.2. Statement of the Problem

In river and lake basins worldwide, expansion and intensification of agriculture, and increasing human population has resulted in reduced water quality, loss of species and their habitats, and changes to ecosystem functioning. The Lake Victoria and its basins is no exception. Current changes in the ecology of Lake Victoria are associated with natural processes and anthropogenic activities within LVB. Aquatic ecosystems in the basin are also under considerable pressure from a variety of interlinked human activities. The growing human population at approximately 3% annually, and an average population density of about 165 persons per km^2, is exerting increasing pressures on the basin's natural resources. The utilization of these resources is heavily driven by socioeconomic livelihood needs and demands of communities within the basin, resulting to far-reaching ecosystem changes. Land use demand has intensified, human and livestock populations have increased within the riparian communities in LVB. More than 70% of the population in the lake's basin are

engaged in agricultural production mainly as small-scale livestock and crop production. Lately, there has been a marked increase in large-scale commercial farming and expansion in urban settlements. The overall impact of the intensification of these activities will likely cause a deterioration on the ecosystems. This is particularly through increased pollution of aquatic systems which receive particulate and dissolved pollutants from terrestrial ecosystems. Different land use activities generate sediment from soil erosion and nutrient loss from fertiliser and organic wastes from farm by-products. Since this scenario is prevalent in the basin, research to establish sedimentation rate and nutrient pollutant loading is essential. The findings will form a basis for effective monitoring, development and implementation of surface water pollution strategies. The SMB, with intensive agricultural and other socio-economic land use activities, coupled with natural environmental pressures, was selected for this study. The study aimed to determine the effect of different land uses in SMB with respect to sedimentation and nutrient loads transported via surface runoff into River Sondu-Miriu, and the ecological impacts on the river system and Lake Victoria.

1.3. Objectives

1.3.1. General Objective

To determine the temporal variability in sedimentation, nitrogen and phosphorus loads in surface runoff from different land uses in Sondu-Miriu Basin.

1.3.2. Specific Objectives

1. To determine the temporal variability in sediment loads in surface runoff from different land uses in Sondu-Miriu Basin.
2. To determine the temporal variability in loads of nitrate-N, ammonium-N and soluble reactive phosphorus in surface runoff from different land uses in Sondu-Miriu Basin.
3. To determine the temporal variability in predicted sediment, nitrate-N, ammonium-N and soluble reactive phosphorus loads in surface runoff from different land uses in Sondu-Miriu Basin using ArcSWAT.

1.4. Hypotheses

1. There is no temporal variability in sediment loads in surface runoff from different land uses in Sondu-Miriu Basin.

2. There is no temporal variability in loads of nitrate-N, ammonium-N and soluble reactive phosphorus in surface runoff from different land uses in Sondu-Miriu Basin.
3. There is no temporal variability in predicted sediment, nitrate-N, ammonium-N and soluble reactive phosphorus loads in surface runoff from different land uses in Sondu-Miriu Basin using ArcSWAT.

1.5. Justification

Rapid growth of anthropogenic activities such as urbanization, industrial development and agriculture has created numerous sediment and nutrient pollution sources to the water bodies in SMB. Studies linking the impact of land use and/or land cover, on surface and river water quality within SMB are scarce. Most of the studies on LVB of Kenya have been conducted on the larger Nzoia and Nyando River basins. Only recently has SMB attracted increased interests in environmental research and management issues with the onset of the KenGen River Sondu-Miriu Hydroelectric Power project. There is need to study the effect of different land use activities in SMB to understand the linkage and/or contribution of these activities to surface water quality and availability in the basin. While different in-stream water quality monitoring methods have been used in SMB, field experimental approaches have not been extensively applied. In this study, the use of experimental runoff plots was adopted to determine sedimentation and nutrient dynamics. The study of the temporal variability in sedimentation and nutrient loading from the basin into river Sondu-Miriu, from a catchment scale provided an alternative scientific approach of investigating basin health in aquatic ecosystem studies within the basin. The application of a GIS-based environmental modelling tool, ArcSWAT, enhanced a whole catchment scale approach of investigating aquatic health in SMB. The ecological model incorporated a pro-active management approach through prediction and scenario analysis of the status of the basin's land and water resources. The outcome of this study provides information on the current ecological status and predicted environmental impacts of anthropogenic activities through different land uses in SMB. Such information is very crucial in the implementation of basin-scale integrated environmental management policies for river basins draining into Lake Victoria. This study will therefore contribute towards the improvement of integrated management of land and water resources in SMB.

1.6. Scope of the Thesis and Limitations

1.6.1. Scope

The main research themes investigated are presented as objectives in separate chapters. However, cross-referencing of different chapters will facilitate understanding of the overall objective.

Chapter One: Introduction

Chapter one provides background information on demographic, socioeconomic and ecological aspects of Lake Victoria basin on the Kenya side. The statement of the problem and study objectives are stated. The hypotheses and justification of the research are also given.

Chapter Two: Literature Review

This chapter reviews literature on sediment and nutrients distribution in river catchments and adjacent aquatic ecosystems. The influence of sediment and nutrient pollutant cycles in aquatic ecosystems is elaborated. The impact of various anthropogenic activities, particularly agricultural land uses, on dynamics of sediments and nutrients within Lake Victoria basin is discussed. The application of ecological models for determination of catchment sediment and nutrient pollution loads using the GIS-based ArcSWAT is also discussed.

Chapter Three: Temporal Variability of Sedimentation in Surface Runoff from different Land Uses in Sondu-Miriu Basin

This chapter compares the effect of different land uses in the basin on sediment loads from surface runoff during the short-rains, dry and long-rains season. A link between the land uses and their relevance to surface water sediment pollution levels in SMB is also established. The environmental effect of sediment loading via surface runoff from the different land uses in SMB on River Sondu-Miriu is also examined.

Chapter Four: Temporal Variability of Nitrogen and Phosphorus Loads in Surface Runoff from different Land Uses in Sondu-Miriu Basin

Nutrient loss from the different land uses in SMB are routinely monitored across three hydrological periods. This chapter presents nitrogen and phosphorus loading on a temporal scale, and the impact of land management on nutrient pollution of surface runoff and surface waters. The loads of these nutrients from different land uses is estimated within the basin.

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Chapter Five: Estimation of Sediment and Nutrient Loading from different Land Uses in Sondu-Miriu Basin using ArcSWAT

This chapter involves ecological modelling which utilises the output of sediment and nutrient components in chapter 3 and 4, GIS digital elevation models and secondary data. Data is processed and validated using an ArcGIS-integrated Soil and Water Analysis Toolkit (ArcSWAT). Prediction of the eight-year temporal variability of sediment and nutrient loads is applied at catchment scale to model the temporal variability of sedimentation and nutrients in SMB.

Chapter Six: Summary, Conclusions and Recommendations

This final chapter summarises the main findings, chapter-by-chapter conclusions and suggests possible catchment-based management approaches to control surface water pollution from different land uses in Sondu-Miriu basin.

1.6.2. Limitations

The following aspects limited the achievement of some of the objectives in this study:

1. Financial constrains limited the study to two sites in the whole basin. Hence some components were not adequately captured to represent the entire basin.
2. Some secondary datasets required for adequate modelling was limited and in some cases unavailable. There were also gaps in a few of the datasets obtained. These were estimated by the model and are known to reduce the model reliability in extreme situations.

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CHAPTER TWO

2. LITERATURE REVIEW

2.1. Sediments and Nutrient Transport in Surface Runoff

Sediments, accompanied with nutrients and other pollutants in surface run-off has increased in many areas of the world, largely because of anthropogenic land use change (UNEP, 2006). Sedimentation processes of catchments are complex and associated with variability in surface runoff, spatial sediment yield and spatial soil erosion (Trahan, 2005; Palmer *et al.*, 2005). This complexity attributes to variability in surface runoff, interflows, erosion rates and subsurface flow as influenced by alteration in site specific land use and land cover systems within catchments (Saenyi, 2002; Kandrika and Venkataratnam, 2005).

Globally, approximately 1903 M ha of the land is susceptible to water erosion (UNEP, 2006). Water erosion within any catchment begins due to surface runoff (Das, 2002) occurring mainly in the inter-rill areas as water dislodge soil particles. As the runoff intensifies, sheet, rill and gulley erosions develop from the runoff (Liu *et al.*, 2005; FAO, 2005; Raude, 2006). Surface runoff transports the detached soil particles down slope and are deposited at various sediment sinks (Trahan, 2005) resulting to degradation of land and water resources. Normally, anthropogenic activities contribute to the degradation of water resources through unsustainable exploitation of land resources (Jones *et al.*, 2001) within its catchment. This does not deter usage of natural resources, but the utilization of the resources should be sustainable through integrated management, hence systems protection particularly in agricultural catchments (Lal, 2004).

Antikainen *et al.* (2008) reported that sediments produced by erosion from the land surface by rain and other human activities into the stream channels are the major agents for pollutants in the surface and subsurface water resources. When runoff occurs, less water infiltrates the ground, thus reducing crop productivity, coupled with increasing sedimentation and nutrients inputs into streams and lakes. High sediment yield in streams and rivers enhances water turbidity, hence impacting negatively on water supplies for domestic and industrial use. Sediment also provides an important transporting medium for a wide range of chemical pollutants and nutrients that readily adsorb on its surfaces. Increased turbidity of surface waters due to sediment load may adversely affect organisms directly or their habitat; such as benthic algae and fish. Biogenic substances (e.g. nitrogen and phosphorus) certainly appear

as the prior pollutants in many river basins (Heiskanen *et al.*, 2004) including Sondu-Miriu basin.

2.2. Sedimentation in Streams

Sediment sinks are some of the points within the catchment in the sediment flow paths, vegetated land surface barriers and water bodies such as streams, rivers, lakes and dams (Saenyi, 2002) where sediment is deposited from surface runoff. Due to the deposition of sediments in these paths, not all particles dislocated upstream reach the outlet of a catchment. The total sediment outflow resulting from erosion processes in a catchment passing through a control station at the outlet of that catchment area in a given period is the sediment yield (Boiten, 2003; Phillips *et al.*, 2006; Raghuwanshi, *et al.*, 2006). Sediment yield is determined by multiplying the sediment concentration by runoff volume or stream discharge (Water Encyclopaedia, 2010) usually expressed in tons yr^{-1}, or in $m^3\ km^{-2}\ yr^{-1}$. The rate of suspended sediment yields is attributed to a catchment's geology, gradient, precipitation patterns, and land use patterns. These factors determine the soil erosion and transportation rate. Permeable soils and low gradients generally help to limit the availability of eroded material within a watershed. Conversely, relatively impermeable soils and steep topography yield high erosion rates and therefore greater sediment yield.

In the context of stream hydrology, sediment is the inorganic and organic material transported, suspended, or deposited in the streams. Sediment load, the quantity of sediment transported by a stream, is a function of stream discharge, soil and land-cover features, weather conditions, land-use activities and catchment geology. Sediment load carried by streams and rivers can be composed either of fine materials, mostly silts and clays, or larger materials such as sand (Troeh *et al.*, 2000). Solid sediment load can be divided into two components based on the mode of sediment transport (Figure 2-1): suspended sediment, and bedload sediment, each of which is produced by mechanical weathering processes. Suspended sediment consists of silt-sized and clay-sized particles held in suspension by turbulence in flowing water. Bedload sediment consists of larger particles, which slide, roll, or bounce along the streambed by the force of moving water. Dissolved load consists of inconspicuous material in solution produced by chemical weathering processes, moving downstream and does not settle out of water.

Changes in land use, stream flow characteristics, and drainage patterns can alter the natural sedimentation rate in streams and rivers. Historically, agriculture has been a main source of human-enhanced sediments in water bodies. Swallow (2006) noted that conversion of forest

to grass and cropland over the last century in LVB has been a major factor contributing to decline in soil fertility, deterioration of soil physical condition and increased soil erosion. The findings also concluded that areas dominated by grass and crops are 16 times more likely to be affected by severe erosion compared to forest and bushland.

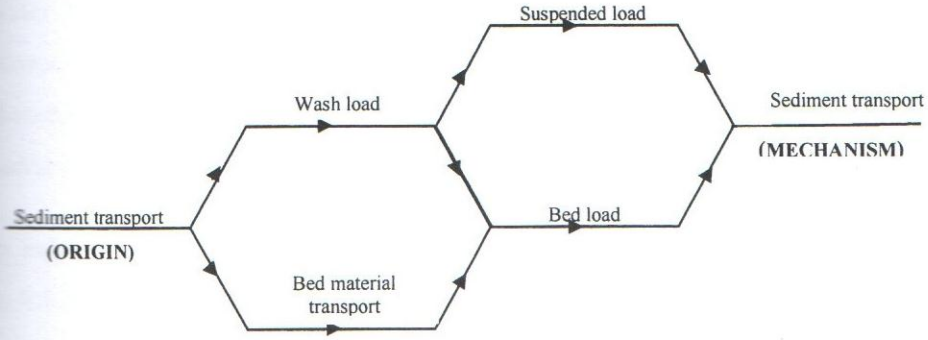


Figure 2-1: Classification of sediment transport in streams (Boiten, 2003).

The conversion of wetlands or woodlands to cropland can increase soil erosion and the associated sedimentation in streams, particularly when bare soil is exposed. The overall effect of deforestation/change of plant species because of population pressures has increased sediment loading to rivers and lakes in Lake Victoria Basin (Swallow *et al.* 2002). The sediment loads from such areas are normally high in nutrients and organic matter. Windblown particles from bare soils also contribute to sedimentation problems. Activities such as dredging and channelization that increase stream slope and velocity can increase the stream's erosive capacity and sediment-transport capability. Construction projects within or adjacent to streams can contribute to sedimentation problems as they dislodge or expose soils and sediments to loss and transportation processes.

2.3. Catchment Contribution of Nitrogen and Phosphorus to Aquatic Ecosystems

Nitrogen (N) and phosphorus (P) are among the three (NPK) essential macronutrients for all biota in a healthy ecosystem and occur naturally in the environment (Wetzel, 2001). N and P are absolutely scarce in available forms on the Earth's surface and so the idea of them restricting the growth of both autotrophs and heterotrophs can be supported (Elser *et al.*, 2007). The relative availability of N and P affects the community structure and function of aquatic ecosystems particularly the biota, including macroinvertebrates, planktonic and fish community assemblages. Indeed, N and P are part of the serious problem of eutrophication greatly experienced in most of freshwater systems especially in developing countries. However, anthropogenic activities contribute new sources of these nutrients to near lethal

levels in aquatic systems. For instance, an increase in the rate of loss of nutrients from the landscape due to poor agricultural practices and improper agricultural waste management, degrades water quality and contribute to eutrophication. Agricultural operations along the river and streams, and lake basins are increasingly contributing to nutrient enrichment of water bodies (Brodie and Mitchell, 2004) via runoff from fertilized land. Other possible sources of these nutrients include atmospheric fall-out and organic matter mineralization (Machiwa, 2001), domestic sewage, river/ lake laundry and vehicle washing, as well as soil surface run off (Tamatamah, 2002).

In nature, the concentrations of nitrates and phosphates seldom exceed 0.1 mg L^{-1} and 0.005 to 0.020 mg L^{-1} respectively in freshwater aquatic ecosystems (Welch and Jacoby, 2004). In rural and suburban areas, the use of inorganic fertilizers plays a significant role as a source of nitrates and phosphates in surface runoff. For example, influence by human activities and different land use systems cause surface waters to have nitrate and phosphorous concentrations up to 5 mg L^{-1} and 200 mg L^{-1} respectively. According to Welch and Jacoby (2004), concentrations in excess of 5 mg L^{-1} NO_3-N usually indicate pollution by human or animal waste, or fertilizer in run-off. The LVB scenario in Kenya on the input of nitrogen and phosphorus loads from rivers draining the basin is summarised in table 2-1. River basins within LVB contribute the second highest N (49,509 t) and third highest P loads (5,693 t) annually (LVEMP, 2003). This points out the significance of anthropogenic land use activities on nutrient loading into Lake Victoria. Therefore, effective monitoring and sustainable management of river basins within LVB should be of high priority.

Table 2-1: Annual external nutrient loading to Lake Victoria from catchments in Kenya LVEMP (2003).

	Loading to Lake Victoria (t yr^{-1})	
Pollution Source	**Nitrogen**	**Phosphorus**
River basins	49,509 (23.78%)	5,693 (14.86%)
Runoff (non-cultivated land)	22,966 (11.03%)	2,297 (6.00%)
Runoff (cultivated land)	29,615 (14.23%)	3,949 (10.31%)
Domestic Waste (including urban runoff)	3,505 (1.68%)	1,624 (4.24%)
Industrial Discharge	414 (0.21%)	342 (0.89%)
Atmospheric Wet Deposition	62,601 (30.08%)	11,831 (30.89%)
Atmospheric Dry Deposition	39,550 (18.99%)	12,567 (32.81%)
Total	**208,160 (100%)**	**38,303 (100%)**

2.3.1. The Nitrogen Cycle and Flows in River Basins

Nitrogen is an important macronutrient fundamental to all biota for growth, maintenance, and biological activity. A molecule of N can occupy many different oxidative/reductive states and thus can exist in different inorganic and organic forms (Fenchel *et al.*, 1998; Megonigal, *et al.*, 2004.). As a result, there are numerous processes, both assimilatory and dissimilatory, that transform the different forms of N (Figure 2-2). The largest pool of N is found in the atmosphere as relatively unreactive nitrogen gas (N_2) that becomes biologically available through the process of N fixation, which converts N_2 into ammonium (NH_4^+) for assimilation into biomass as organic N. This organic N is released from organisms via ammonification into NH_4^+, which can then be used metabolically or cycled back to N_2 through a series of dissimilatory processes. The primary dissimilatory N processes are microbially-mediated nitrification and denitrification. Nitrification is the chemoautotrophic two-step transformation of NH_4^+ to nitrite (NO_2^-) and then to nitrate (NO_3^-). Nitrate and ammonium are available for uptake by algae and plants and are converted back to amino groups in amino acids and proteins (Megonigal, *et al.*, 2004; Moss, 2010) and ultimately recycled through the steps already described. Both are very soluble and readily transferred in water from catchment to river and lake. Nitrate is, however, vulnerable to further bacterial activity. It is a powerful oxidizing agent and if free oxygen is scarce, denitrifying bacteria can use nitrate to oxidize organic matter, converting the nitrate to nitrogen gas and sometimes oxides of nitrogen, such as N_2O in the process. This activity is inevitably greatest in low-oxygen habitats and particularly so in wetlands with organic soils, but it occurs even in open waters. Denitrification closes the N cycle and is the only process that permanently removes N from terrestrial or aquatic ecosystems back to the atmosphere.

Nitrogen occurs in freshwater ecosystems in many chemical states. Dissolved inorganic nitrogen (DIN) includes NH_4^+, NO_3^- and NO_2^-. Dissolved organic nitrogen (DON) consists of amino nitrogen compounds and other organic molecules, and most particulate organic nitrogen (PON) occurs as bacteria and detritus (Allan and Castillo, 2009). In natural lotic systems with little anthropogenic influence, concentrations of DIN are low, around 0.12 mg L^{-1} and include about 0.1 mg L^{-1} NO_3-N, 0.001 mg L^{-1} NO_2-N, and 0.015 mg L^{-1} NH_4-N. Nitrogen concentrations are influenced strongly by land use in settled areas, and especially by agriculture. In unpolluted tropical rivers, present-day concentrations likely represent natural values, for which total N were reported to range between 0.27 and 1.05 mg L^{-1} (Lewis *et al.*, 1999; Perakis and Hedin, 2002).

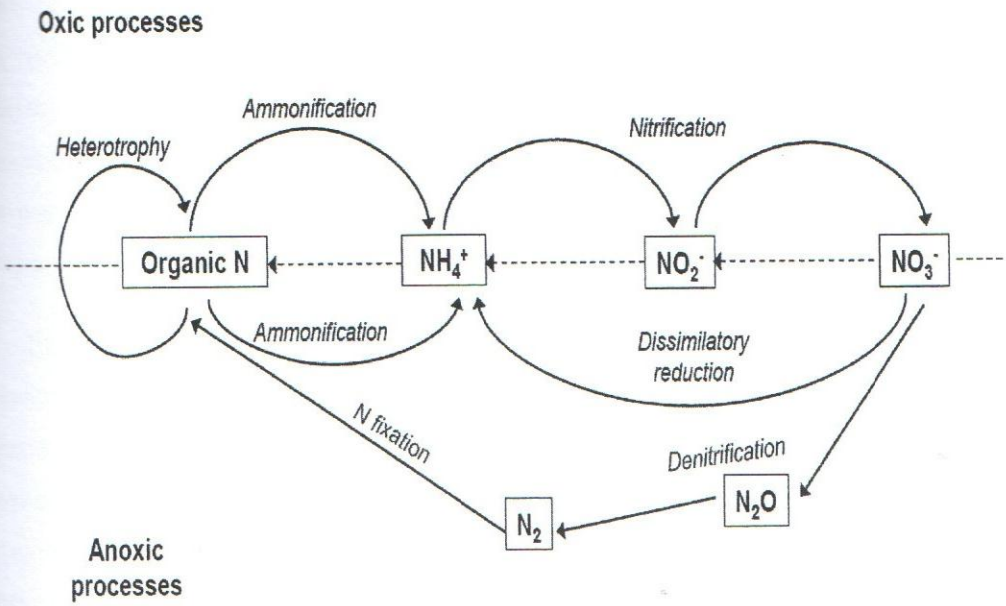


Figure 2-2: Transformations between different forms of nitrogen in terms of the redox conditions required for each process in the nitrogen cycle (Dodds, 2002).

Sources of various forms of N in rivers and streams include atmospheric deposition, N-fixation, and terrestrial inputs (human and animal waste) in runoff and groundwater (Boyer *et al.*, 2002). Atmospheric deposition as precipitation and dry fallout occurs primarily in the form of ammonium and nitrate, although organic forms can also be important (Neff *et al.*, 2002). Nitrogen gas is abundant in the atmosphere and soluble in water, where it can be transformed by free-living N-fixing bacteria, principally cyanobacteria (e.g. *Anabaena* and *Calothrix*), into forms that can be utilised by other aquatic organisms. On land N-fixation is by symbiotic bacteria in the roots of certain plants (e.g. *Rhizobium*, in the root nodules of some legumes). These diazotrophs are able to reduce N_2 to NH_4. Although representing a small proportion of the global annual flux of nitrogen, nitrogen fixation is the ultimate source in both aquatic and terrestrial habitats. Nitrogen in this form (NH_4^+), is only utilized to a limited extent by plants but is most readily accumulated as nitrate. As a result, the productivity of both terrestrial and aquatic systems is frequently limited by the availability of nitrate (Wetzel, 2001). Nitrogen inputs in lotic ecosystems often vary seasonally due to the effects of the crop growing season and hydrology. Nitrogen from the land enters streams as surface runoff and in groundwater, depending on hydrologic flowpaths (Hagedorn *et al.*, 2000). During baseflow, most inputs are from sub-soil leaching. Inputs from throughfall can be significant at the start of a rain event; subsequently, inputs via shallow flowpaths from

topsoils rich in DON are more important. In aquatic systems, autotrophs leak labile DON during periods of high primary production as well as from grazing and cell senescence (Bertilsson and Jones, 2003). Due to uptake of N by terrestrial vegetation, streamwater concentrations tend to be lower during plant growing seasons. Spatial variability in streamwater NO_3^- concentrations is influenced by nitrification in upland soils, which affects the extent to which basins retain or export NO_3^- via streamflow (Bernhardt *et al.*, 2005).

2.3.2. Phosphorus Cycle and Sources in River Basin Ecosystems

Landscape features such as geology, topography, soil, and vegetation types along with human influences control the amounts and forms of phosphorus reaching streams (Jones and Mulholland, 2000). Physical, chemical, and biological processes influence P in streams. The principal biological processes are autotrophic and heterotrophic uptake of dissolved inorganic phosphorus (DIP) and its assimilation into cellular constituents, transfer of organic phosphorus through the food chain, and its eventual release and mineralization by excretion and the decomposition of egested material (Sharpley *et al.*, 2000). Algae and microbes in biofilms likely obtain the majority of their phosphorus from the water column, but rooted macrophytes and benthic algae can remove phosphorus from sediments as well. In stream ecosystems, P may be excreted by aquatic biota or released directly following cell lysis as DIP. Phosphorus released in dissolved organic form (DOP) is subsequently mineralised to orthophosphate by bacterial activity (Figure 2-3). Decomposition of organic matter including faeces, dead organisms, and leaf litter also releases phosphorus into the water column and sediment pore water (Mainstone and Parr, 2002). Phosphorus availability is also dependent on the physical-chemical transformations in water. Adsorption of PO^{3-}_4 onto charged clay particles occurs at relatively high phosphorus concentrations, while desorption is favoured by low phosphorus levels. Adsorption-desorption reactions thus act as a buffer on dissolved phosphorus concentrations. In addition, under aerobic conditions, DIP and DOP both may complex with metal oxides and hydroxides (such as $Fe(OH)_3$) to form insoluble precipitates. Thus, phosphorus is released under anaerobic conditions, and since the extent of the anaerobic zone tends to vary seasonally with organic matter loading, the availability of dissolved phosphorus varies accordingly (Allan and Castillo, 2009).

The principal reservoir for P is rocks and sediments, slowly released by weathering, and in unpolluted waters, often is in short supply relative to metabolic demand. P can exist in a variety of forms: as mineral (generally apatite) phosphorus; non-apatite inorganic-P (NAIP);

organic-P (OP) bound up with carbon and oxygen in organic matter; and as dissolved soluble reactive ortho-P (SRP) (FAO, 2011). Phosphorus levels are generally higher in regions dominated by sedimentary rock deposits, and low in regions of crystalline bedrock. The release of phosphorus from apatite dissolution is a key control on ecosystem productivity (Dodds, 2002). The primary mineral with significant phosphorus content, apatite [$Ca_5(PO_4)_3OH$] undergoes weathering releasing phosphorus contained in different forms (Filippelli, 2002).

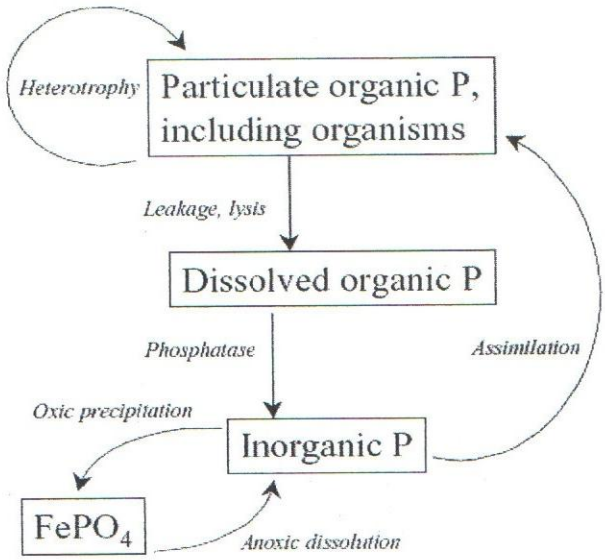


Figure 2-3: Phosphorus cycle in stream ecosystems showing transformations between particulate, dissolved and inorganic phosphorus (Dodds, 2002).

Atmospheric inputs, although small, can be significant in areas where phosphorus is scarce (Neal *et al.*, 2003). Overall, however, phosphorus inputs from the atmosphere depend on the surface area of the recipient water body. Terrestrial ectomycorrhizal fungi (EMF) associated with tree roots can mobilize P and other minerals from solid mineral substrates through organic acid secretion. The soluble P then becomes available to host plants via the fungal mycelium (Landeweert *et al.*, 2001). Phosphorus generated from plant breakdown and stored in soil organic layer is an important input, entering streams by surface runoff and subsurface pathways (McDowell *et al.*, 2001). Since orthophosphate (PO^{3-}_4) is readily adsorbed to charged clay particles, it is transported with sediment eroded during storms especially where slopes are steep and vegetation cover is minimal. Clay particles in soils also tend to bind P and although the enzymes associated with plant roots can loosen it easily, P is resistant to simple leaching by water. Its ionic charge to radius ratio also tends to reduce its solubility

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(Moss, 2010). In studies of P movements from agricultural lands, the largest amount is sorbed onto clay materials and transported as erosion products. Further, sediments are known to play a vital role in transfer of particulate phosphorus (Kitaka *et al.*, 2002; FAO, 2011). Phosphorus concentrations in surface runoff vary with the amount of phosphorus in surface soils (Weld *et al.*, 2001) and the proximity of phosphorus-rich soils to the stream channel. However, uptake of phosphorus by plant roots and immobilization by soil microbes can reduce concentrations in mineral soil water (Kaiser *et al.*, 2000; Goller *et al.*, 2006). Anthropogenic sources include municipal and industrial point wastewater discharges; and fertilizers and manure from agricultural farm fields via diffuse surface and subsurface runoff (Edwards *et al.*, 2000; Branom and Sarkar, 2004; Goller *et al.*, 2006). Point sources discharge phosphorus in dissolved forms while NPS inputs of phosphorus commonly are in particulate form in association with sediments, particularly where erosion is high, although phosphorus originating from fertilizer and manure also can be transported in dissolved forms (Vanni *et al.*, 2001). This can change temporarily because of human activities and hydrology. Since much of the diffuse phosphorus supply is associated with sediments (Kitaka *et al.*, 2002) and storms, often during the non-growing season, there is a high likelihood that these inputs will be exported downstream (Mainstone and Parr, 2002).

2.4. Anthropogenic land use impacts on sediments and nutrients in LVB, Kenya

Changes of land use patterns certainly provide many social and economic benefits. However, they also come at a cost to the natural environment. One of the major direct environmental impacts of development is the degradation of water resources and water quality (USEPA, 2001). Human activities such as logging, mining, agriculture, and urbanization have influenced stream ecosystems in numerous ways and the presence of truly "pristine" streams in the landscape is now rare. Agricultural activities generally lead to increased inorganic nutrient concentrations in receiving waters, especially NO_3^- (Kemp and Dodds, 2001; Royer *et al.*, 2004). Anthropogenic N can saturate stream nutrient demand and has been linked to eutrophication and seasonal hypoxia at the mouths of numerous major river systems draining developed land (Rabalais *et al.*, 2002, Scavia and Bricker, 2006). Many agricultural streams have also been channelized and cleared of riparian vegetation, enhancing erosion and sedimentation (Allan, 2004). Urbanization has a disproportionate influence on stream ecosystems; even small areas of urban land cover can lead to significant ecosystem degradation (Walsh *et al.*, 2005). Typically, urbanized streams contain elevated concentrations of organic contaminants, metals, and nutrients compared to relatively pristine

streams. These chemicals can originate from both point (wastewater effluent) and non-point sources (Paul and Meyer, 2001). Additionally, urbanization leads to increased impervious surface cover that prevents water infiltration into the soil and eliminates groundwater recharge. Surface runoff from impervious surfaces is generally the dominant route for water entering urban streams, resulting in more variable temperatures and greater incidence of flooding. Similar to agricultural activities, urbanization commonly results in stream channelization and riparian clearing (Walsh *et al.* 2005). The influence of agricultural and urban land use generally has an indirect impact on processing and availability of N and P in streams (Glibert *et al.*, 2006). Agricultural and urban activities tend to alter hydrologic flowpaths to streams through channelization, tile drainage, and impervious surfaces (Paul and Meyer 2001; Allan, 2004), which may alter concentrations (Mulholland, 2003) and composition (Findlay *et al.*, 2001) of N and P in lotic ecosystems.

The major rivers in sub-basins draining into Lake Victoria carry and deposit a large quantity of silt and organic matter in the floodplain and deltaic wetlands. Swallow *et al.* (2002) reported a series of studies that have monitored sediment load from four main rivers (Nyando, Sondu, Yala and Nzoia) to quantify and trace the sources of soil carried in these rivers. In particular, the research showed that the Nyando basin is a major source of sediment into Lake Victoria with 61% of the basin of 3,500 km^{-2} constituting a source area with average erosion rates above 40 t ha^{-1} yr^{-1}. Since 1963, the total soil loss to the lake has averaged 3.2 million metric tons per year. Disproportionately high sediment losses have occurred during years with high annual rainfall (Swallow, 2006).

Handa *et al.*, (2002) noted high N and P levels in Nyando, Nzoia and Yala rivers during the April-July rainy season. However, P concentrations in River Sondu-Miriu were lower than those Lake Victoria. Also, P concentrations in River Nyando were five times higher than those of River Sondu. Since the soils in the basin of Nyando, Nzoia and Yala are inherently low in phosphorus due to the basins' dominant geological and soil characteristics, the source of high level of phosphorus in these rivers should be mainly from agricultural activities, farm application of soil chemical fertilizers and livestock waste (LVEMP, 2003). Continued addition of water with such a high concentration of N and P into the Winam Gulf has seriously affect aquatic systems and water quality in the wetlands and in the Lake itself. Gichuki (2003) observed that eutrophication levels in the floodplain wetlands, in the bays and

inlets of Lake Victoria were on an upward trend and may lead to frequent fish kills and water shortage for domestic use in future.

The LVEMP (2001) estimated the nutrients input into the lake with atmospheric deposition contributing 102,000 t yr^{-1} of Total-N and 24,000 t yr^{-1} of Total-P. These values indicated that the atmospheric deposition is by far the most significant contributor to the overall nutrient budget of the lake. Based on these results, the total atmospheric deposition (wet and dry deposition) contributes about 45% and 64% total nitrogen and total phosphorus loading, respectively (LVEMP, 2002). However, municipal and industrial wastewater treatment plants (WWTPs) are also known to be the major point sources of phosphorus in urban areas (Smith *et al.*, 1999). Waste disposal sites, construction sites, fertilizers (Hooda *et al.*, 2000) and farmlands also make substantial contribution to the total phosphorus load (Morgan *et al.*, 2000; Tunney *et al.*, 2000).

2.5. Estimation of sedimentation and nutrient load in ArcSWAT

Environmental analysis of large river basins draining thousands of square kilometres is usually a resource and time-demanding process. Regional and national-scale water resources management strategies and decision-making for sustainable domestic, agricultural and industrial water supply, as well as protection of the environment from the negative impacts of developmental activities, depend on such large-scale analyses. The ArcGIS-based Soil and Water Analysis Tool (ArcSWAT) is a dynamic time, process-based model that operates across a range of timescales, (i.e. hourly, daily, monthly and annual time step) and at different spatial scales (Neitsch *et al.*, 2001).

ArcSWAT is a comprehensive computer-aided simulation tool that can be used to simulate the effect of point and non-point source pollution from catchments, in streams, and rivers. The model is integrated with several readily available databases and Geographic Information Systems (GIS). Due to its versatility, ArcSWAT has been utilised to study diverse environmental phenomena including agricultural management, sediment modelling, climate change, integrated modelling, hydrological processes, and ecological and water quality processes. This tool can be applied in simulating water and nutrient cycles in agriculturally-dominated landscapes (Koskiaho *et. al.*, 2007). The catchment is primarily partitioned into sub-basins where the least unit is a unique combination of soil and land use overlay known as Hydrologic Response Unit (HRU). The model has successfully predicted soil and nutrient losses from different HRUs that caused significant catchment and river sediment yields

(Panagopoulos *et. al.*, 2007) including consequences of non-structural mitigation measures soil erosion in catchments. ArcSWAT has been expansively used but also further developed (Eckhardt *et. al.*, 2002). Further, it has already been found to be potential capable of future predictive requirements in sediment and nutrient management in many catchments worldwide (Dilks *et. al.*, 2003; Barlund *et. al.*, 2007). In addition to loading estimates, ArcSWAT also provides a platform for various land management practices like fertilisation, tillage practices, cropping options, buffer strips, establishment of sedimentation ponds and constructed wetlands in the model set-up (Koskiaho *et. al.*, 2007).

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CHAPTER THREE

3. TEMPORAL VARIABILITY IN SEDIMENTATION IN SURFACE RUNOFF FROM DIFFERENT LAND USES IN SONDU-MIRIU BASIN

3.1. Abstract

A combination of natural and anthropogenic factors influence surface water quality and sedimentation in drainage basins, the relative effects which change over temporal scales. A study was conducted at the upper (Kabianga) and mid (Sondu) Sondu-Miriu basin between November 2010 and May 2011 using runoff plots. This was to determine the temporal variability of sediments in surface runoff from different land uses (natural vegetation, weedy-fallow and cropped). Sediment concentrations ranged between 517 and 1174 mg L^{-1} with maximum values occurring during the long-rains. Runoff was highest in the same period particularly in the weedy-fallow land peaking at 13.5 L. Generally, there were significantly higher sediment concentrations and runoff volumes during this period ($p < 0.05$). Cropped land was the largest contributor to sediment loss via surface runoff while land under natural vegetation least contributed.

However, in river Sondu-Miriu, sediment concentrations were generally lower compared to the land uses, ranging from 15 to 586 mg L^{-1}, peaking during short-rains. Sediment levels were significantly lower during the long-rains season along river Sondu-Miriu ($p < 0.05$). Principal Components Analysis (PCA) for the land uses correlated surface runoff and erosion to seasonal variability in land-use activities, particularly during wet seasons ($0.77 < r < 0.99$, $p < 0.05$). This also influenced sediment content in surface runoff from the land uses. PCA for River Sondu-Miriu suggested ionic pollution by dissolved substances and sediment load introduced via surface runoff during wet seasons ($-0.75 < r < -0.99$, $p < 0.05$). The study established that sediment loads in surface runoff in different land uses is influenced by temporal changes in seasonality, particularly rainfall variability, in Sondu-Miriu basin.

3.2. Introduction

There is increasing awareness of the need to protect our natural resources in order to meet present and future needs. Since economies and environments are dependent on healthy soil and water, it is essential to ensure the sustainable use of these resources in the face of growing demand. Excessive or enhanced soil erosion due to poor land management can result in both on and off-site effects detrimental to a wide range of receptors. Soil erosion depletes

the soil resource when the rate of erosion exceeds that of natural soil formation. This loss often affects the most agriculturally important topsoil and any fertilizer or pesticide application, causing subsequent reductions in agricultural productivity. Soil erosion is a 'hazard' traditionally associated with agriculture, and often occurs in tropical and semiarid areas (Collins and Owens, 2006).

Recent interest in soil erosion has increased awareness of the off-site effects. The effects are predominantly associated with the movement of eroded soil and sediment particles, and changes in surface and sub-surface water flows. Off-site problems are often more evident, and include the loading and sedimentation of watercourses and reservoirs, and increases in-stream turbidity. All these can disturb aquatic ecosystems and disrupt the geomorphological functions of river systems (Owens *et al.*, 2005). Surface water pollution from organic and inorganic sediments generated from agricultural catchments is a serious threat to aquatic ecosystems and public health in many regions. If eroded soil carries nutrients, contaminants and pathogens, it can present serious problems of surface and groundwater pollution and eutrophication, threatening habitat and human health (Owens *et al.*, 2005). Hence, there is need for proactive management of aquatic water quality in agricultural catchments. Most research efforts however, target routine monitoring of water quality (Yillia, 2009) rather than tracking and managing the sources of pollution. Information on pollution levels and nature of pollutants is frequently required to identify the major contributing sources and pathways (Venter *et. al.*, 1997), to draw attention to the intrinsic value of soil as a resource, and the need to prevent soil erosion and sediment transfer for soil and surface water protection (Van-Camp *et al.*, 2004).

Many studies have pointed out that the land-use pattern in a drainage basin affects the quality of the river water (Sliva and Williams, 2001; Tufford *et al.* 2003; Woli *et al.* 2004). The land use–water quality relationship is complex and is likely to be site- or region-specific (Baker 2003). There have been relatively few studies on the relationship between river water quality (in terms of sedimentation) and runoff from agricultural land use (gauged using dominant land uses) in river catchments. The objective of this study was to determine the temporal variability of sedimentation from surface runoff generated from different land use activities in SMB. The levels of sediments in adjacent River Sondu-Miriu were also determined across three seasons, November-December, 2010 (short-rains), January-March, 2011 (dry) and April-May, 2011 (long-rains).

3.3. Materials and methods

3.3.1. Study Area

There are about 10 major rivers flowing into Lake Victoria from the Kenyan side representing multiple sub-basins. River Sondu-Miriu (RSM) is the third largest river in LVB, Kenya, and drains about 3,508 km^2 in the Sondu-Miriu sub-basin. The Sondu-Miriu basin (SMB) lies between Nyando Basin in the northern side and Gucha-Migori basin on the southern part (NBI, 2005). The elevation of SMB ranges from 1000 m to 2000 m a.s.l. and extends between 35° 45'- 34° 45' longitude and 0°15' - 1°00' latitude. The basin is divided into three major climatic regions: humid, sub-humid and semi-humid. The long rainy season is between April and June. Short rains fall around October, November and December. However, this seasonality is much clearer in the lower regions. The highlands receive a cumulative annual rainfall of approximately 1,835 mm, which decreases to about 1,500 mm towards the lowlands. The lowlands have an average annual temperature of 26° C. The mean annual temperature ranges from about 18° C to 30° C. Relative humidity lies around 62 % for most of the year. RSM is an important trans-boundary lotic system partly due to its volumetric water contribution into Lake Victoria and partly as a conduit for carrying pollutants into the Lake Victoria. Nationally, the river contributes to both domestic and industrial water supplies and recently in hydroelectric power production (KenGen Sondu-Miriu HEP project). It is also a source of water for agriculture activities and livestock. Hence, RSM is exposed to both non-point and point sources of pollution (NBI, 2005).

Figure 3-1 shows the location of Kabianga and Sondu. Sampling at Kabianga was done from River Ainapkoi (S 00° 26', E 035° 08', 1712 m a.s.l) in Kabianga. River Ainapkoi, a first order stream, is a tributary of RSM, which traverses Kabianga from western slopes of Mau Escarpment. The river, collectively with rivers Dionsoyet and Kimugu from Kericho, and Kipsonoi draining from Sotik, all originating from the Mau Escarpment, join the main RSM at Sondu. Runoff plots in the upper basin were established at Kabianga High School farm (S 00° 26', E 035° 08', 1760 m a.s.l) next to Kabianga University, approximately 8 km off Kericho-Kisii highway. In Sondu, runoff plots were set up at Nyakach Water Treatment Plant site (S 00° 22', E 035° 00', 1517 m a.s.l), about 1.5 km from Sondu town. River water samples were collected next to Nyakach Water treatment plant intake (S 00° 23', E 035° 00', 1507 m a.s.l).

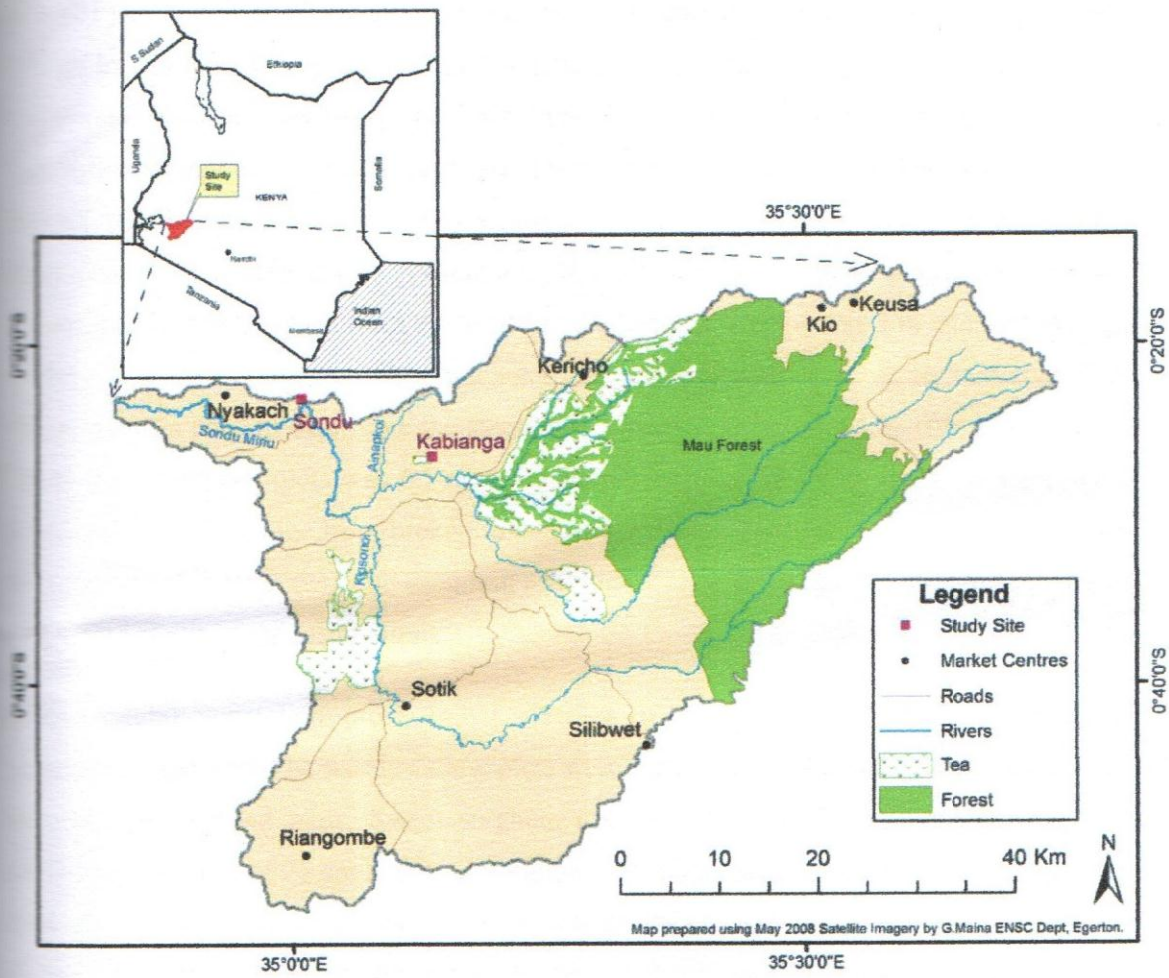


Figure 3-1: Sondu-Miriu Basin showing River Sondu-Miriu network and the study sites.

3.3.2. Design and Layout of Experimental Plots

From the three land uses (natural vegetation, weedy-fallow and cropped), a two-way classification, randomised complete block design, with three replications was established on each site. From each block, the natural vegetation was left undisturbed while the other two treatments were cultivated or cropped accordingly. Each block had three randomised treatments: natural vegetation, weedy-fallow and cropped plots. The natural vegetation at Kabianga is dominated by grassland (Kikuyu grass - *Pennisetum clandestinum* and foxtail grass - *Setaria viridis*). Sondu's natural vegetation is typically *P. clandestinum*, Thatch grass (*Hyparrhenia rufa*), and Red Oat grass (*Themeda triandra*) interspersed with shrubs.

Figure 3-2 illustrates the field layout (not to scale) for 2 m x 2 m unbound plots (UP) and 2 m x 5 m bound plots (BP). The unbound plots are not enclosed on any sides and each is fitted with a modified Gerlach trough at the sloping end to collect runoff (Figure 3-3a and 3-3c). A Gerlach trough as developed by Gerlach (1967) is a simple metallic gutter, 0.5 m long x 0.1

m wide. The trough is enclosed at the sides and opens at the end facing the plots. The bound plots (BP) consist of an all-round polythene sheet boundary inserted deep enough to minimise leakage into or out of the plots. The plastic lining was held firm using wooden pegs attached to a wooden boundary enclosing each plot. Runoff from the plots collects through a drainage pipe at the sloping end of each plots into tanks (Figure 3-4b and 3-4d). The boundaries are inserted deep and high enough to prevent overtopping. A 30-cm deep trench was dug on the upper end of each land use to prevent runoff from outside the plots interfering with the measurements. The distance from the trench to the Gerlach troughs was 2 m and long enough to allow the development of rills and interrills, which could cause significant runoff. A clinometer was used to determine the slope, which ranged between 2 and 10% in both sites. The distance between plots was 0.5 m while the replicates were 1 m apart. Over time, there was possibility of leakage from broken lining, damaged boundary or even the collecting pipe due to different management and sampling activities. This was however minimised by regular checks and repair of the installations.

In the natural vegetation plots, initial clearing of vegetation was done and time for regeneration allowed. The weedy-fallow plots were cultivated during the set-up stage and left bare. On the cropped plots, Sweet sorghum (*Sorghum bicolor* (L.), Serena variety, was planted at a spacing of 75 cm x 20 cm. Sorghum was considered suitable for both sites in the short and long-rain growing season, and short maturity period (11-14 days germination; 55-55 days maturity) appropriate for this study. Phosphate fertilizer was applied at 96 kg P ha^{-1} as Triple Super Phosphate (TSP) at planting. Two weeks from emergence, after the initial weeding, the crop was top-dressed with nitrogen fertiliser at 84 kg N ha^{-1} as Calcium Ammonium Nitrate (CAN).

This study tested land use at three levels and runoff assessment method at two levels each replicated three times in two sites, Kabianga and Sondu. The spatial variability of sediment and nutrient loads was also evaluated but only limited to two sites. The sites were selected based on previous work by Mungai *et al.* (2011) that sub-divided SMB based on the dominant soil types. Vertisols and phaeozems as dominated the lower basin (Nyakwere), regosols characterise the mid-basin (Kabianga) while nitisols occupied most of the upper SMB (Kabianga).

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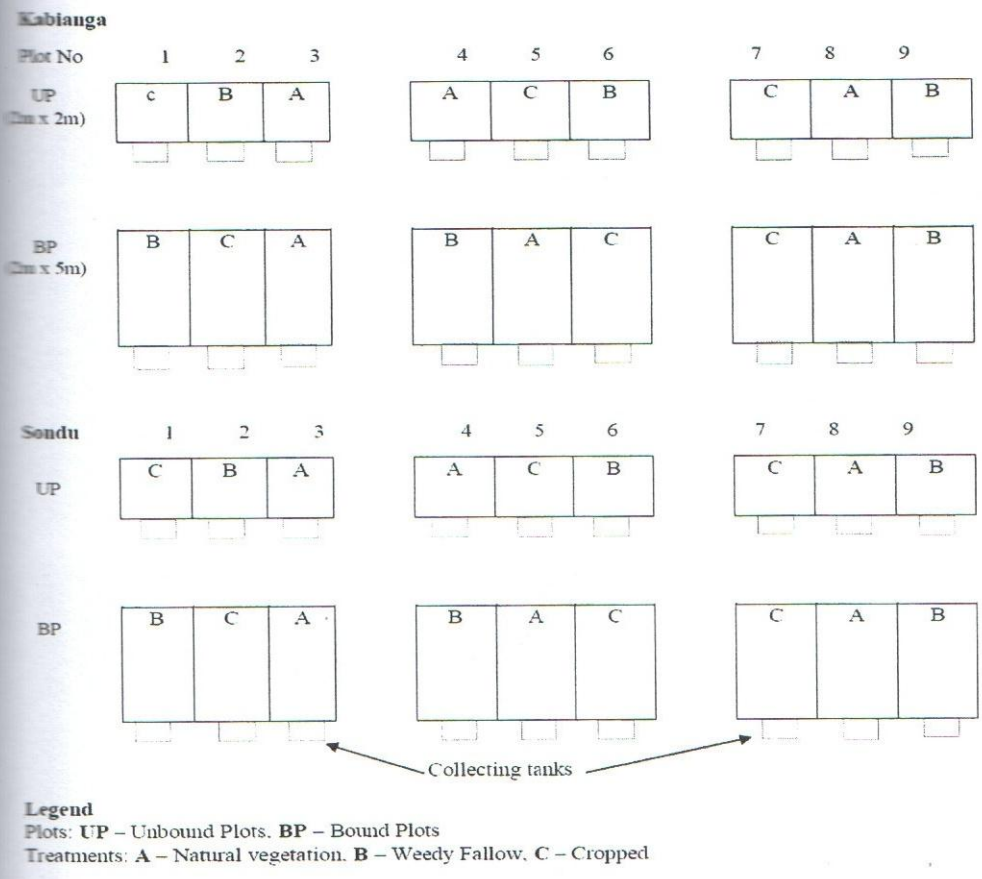


Figure 3-2: Field layout of the experimental runoff plots at Kabianga and Sondu in SMB

3.3.3. Sampling and site measurements

Sampling was conducted from November 2010 to May 2011 to capture temporal variability. Data was collected from runoff plots and RSM bi-monthly in the during the long-rains season long rains (R-S 2011), and once a month during dry season dry (D-S 2011) and short rains short rains (S-R 2010) seasons. (Figure 3-3 & 3-4). Geographic location of the sampling sites was captured using a 'GARMIN®' (*Etrex-legend*) hand-held GPS receiver. Physical water parameters for the runoff plots were measured *in-situ* including dissolved oxygen (DO), temperature, electrical conductivity (EC), total dissolved solids (TDS) and pH using 'HACH' (Eco 40d) multi-probe meters.

Water samples were taken after every rainfall event causing significant runoff (≈25 mm hr^{-1}) into the tanks. In the 10-L tanks, the contents were weighed to determine runoff volumes (V_R), for each rainfall event as follows:

$$V_R = W_{TB} - W_{TA} \quad \text{..... (3-1)}$$

where, W_{TB} = weight of tank plus runoff, and W_{TA} = weight of empty tank



Figure 3-3: Layout of experimental plots showing the installation of (a) Gerlach troughs in the unbounded 2 m by 2 m and (b) all-round boundaries of the 2 m by 5 m plots. Figures (c) and (d) display single plots of unbound and bound plots respectively.

In the 100-L tanks, a calibrated dip-stick indicator was used to measure the height (h) of runoff collected, which was then converted to volume ($\pi r^2 h$). The runoff collected was stirred gently and from each tank, a 500-ml sample was collected in plastic sample bottles for determination of total solids (TS), total suspended solids (TSS) and organic matter (OM) content. Rainfall and temperature data were recorded from the Kenya Meteorological Department station at Kericho. Three replicate water samples were collected from sampling points in the river in 500 ml acid-washed plastic bottles a few centimetres below the water surface in the middle of the river channel (where possible), stored and transported in a cool box for laboratory analysis at Egerton University.

Composite soil samples from each site were collected in labelled polythene bags with a soil auger to 20-cm depth from random points within the runoff plots. The samples were

processed to determine physicochemical (pH, cation-exchange capacity and electrical conductivity) and nutrient (% carbon, % nitrogen and extractable-P) properties. Composite soil samples were taken for nutrient content analysis at the Crop Nutrition and Laboratory Services, Nairobi and MEA Fertilizers Ltd laboratory, Nakuru. Soil texture analyses were conducted at Egerton University Soil Science laboratories based on the Hydrometer method (Okalebo *et al.*, 2002).



Figure 3-4: Field activities and sampling sessions from the experimental plots.

3.3.4. Laboratory analysis

APHA (2005) standard water quality analytical procedures were followed in the analyses. Samples were filtered through pre-dried and pre-weighed Whatman GF/C-grade glass micro-fibre filters (0.6-0.7 µm pore-size and 47 mm diameter) for gravimetric determination of TSS and OM. To estimate TSS, a known volume of water sample was filtered using pre-weighed and dried filters, which were then dried again at 95°C to a constant weight over 24 hours. The weight of suspended solids was estimated using the relationship:

$$\mathbf{TSS\ (mg\ L^{-1})} = \frac{W_c - W_f}{V} \times 10^6 \quad \text{.....(3-2)}$$

where,

TSS = total suspended solids,

W_f = weight of pre-combusted filter, g

W_c = constant weight of filter + residue, g

V = volume filtered, ml

To determine gravimetrically the OM content in the samples, oven-dried and weighed TSS residue in the filters were ignited to a constant weight in a muffle furnace at 500-550 °C for 1-2 hours. The organic content was determined as follows:

$$\mathbf{OM\ (mg\ L^{-1}) = TSS - AFDW} \qquad (3\text{-}3)$$

where,

OM = organic matter content,

TSS = total suspended solids, mg L^{-1}

AFDW = ash-free dry weight, mg L^{-1}

Total solids content (TS) was estimated by evaporating duplicates of a well-mixed 50 ml sample in a weighed dish and drying to a constant weight in an oven at 103-105°C. The increase in weight over that of the empty dish represented the total solids calculated using the formula:

$$\mathbf{TS\ (mg\ L^{-1}) = \frac{[(A-B)x\ 10^3]}{V_s}} \qquad (3\text{-}4)$$

where,

A = weight of dried residue + dish, mg

B = weight of dish, mg

V_s = sample volume, ml

3.3.5. Data Analysis

GenStat® (version 14.2) statistical software was used to analyse data at 5% level of significance. Prior to statistical analyses, data was tested for normality (Shapiro-Wilk test) and equal variance, and where applicable $\log_{10}(x+1)$ transformed. Parameters with significant temporal variability were further separated using *post-hoc* Tukey HSD or Dunn's test as appropriate.

Principal Components Analysis (PCA) was conducted to determine related factor complexes from standardized data (correlation coefficients matrix). The extracted components with an Eigen value ≥ 1 were retained to explain associations among indicator parameters. Factors

assorted by each PC were analysed individually and collectively to determine the temporal trends in their variability. The rotated factors with loadings (correlations coefficients) > 0.6 were considered for interpretation. Communalities (percentages of total variance) for all variables were worked to a minimum 0.7 value to allow all retained components to be described to an acceptable level. Significant associations were confirmed at 5% significance level using Spearman rank correlation test.

3.4. Results

3.4.1. Site soil characterisation

From Table 3-1, the soils had moderately acidic pH of 5.8 at Kabianga and 6.0 in Sondu. The soil cation exchange capacity (CEC) at Kabianga and Sondu was optimal at 27.5 and 22.0 cMol kg^{-1} soil respectively. The soil EC in both sites was low at 200 μScm^{-1} Kabianga and 127 μScm^{-1}. Generally, phosphorus is deficient while nitrogen and carbon content in the soils at both sites is low.

Kabianga soils are predominantly dark reddish brown both when dry and wet. The 20-cm depth soil textural composition at Kabianga is 76% sand, 20% silt, and 4% clay characteristic of loamy-sand soil. Soils from Sondu are sticky and plastic when wet, and dark brown when wet but brown when dry (Plasticity of a soil is its ability to undergo deformation without cracking). The soil is sandy-loam comprising 56% sand, 34% silt, and 10% clay. The soils at Sondu also contain rotten rocks indicative of very shallow soils.

Table 3-1: Surface (0-20 cm) soil characteristics at Kabianga and Sondu.

Parameter	Unit	Kabianga	Sondu	Range
pH		5.8	6.0	6.0 – 6.8
Extr-P	mg kg^{-1}	7.0	3.0	20 – 60
CEC	cMol kg^{-1}	27.5	22.0	15 – 30
EC	μScm^{-1}	200.0	127.0	>800.0
Nitrogen	%	0.30	0.27	0.2 – 0.8
Org-C	%	2.7	2.7	2 – 5

3.4.2. Physicochemical parameters

Dissolved oxygen (DO) and temperature displayed normal distribution. Significant one-way ANOVA for these parameters were separated using a *post-hoc* Tukey HSD test. Electrical conductivity (EC), pH, total dissolved solids (TDS), total solids (TS), organic matter (OM) and runoff were analysed using Kruskal-Wallis One-Way non-parametric ANOVA on Ranks. Periods with significant variability were further separated using a *post-hoc* Dunn's test.

Land Uses

At Kabianga, the pH, EC, TDS and temperature were generally low during the long-rains season and high in the dry season (Table 3-2). The pH varied from acidic (5.5) in weedy-fallow plots to alkaline (8.5) in the natural vegetation. EC ranged from 3.1 to 260 µS cm^{-1} in the weedy-fallow plots while TDS was highest in the natural vegetation (397 mg L^{-1}) and lowest (2 mg L^{-1}) in cropped plots. Temperature generally ranged from 18.5° C in the natural vegetation, to 28.5° C in the weedy-fallow plots. DO was below 0.1 mg L^{-1} during short-rains and dry season in the weedy-fallow plots. The highest DO concentration of 7.3 mg L^{-1} recorded from runoff in the cropped plots in the dry and long-rains seasons. There were significantly lower seasonal pH and TDS values during the long-rains. EC levels also varied significantly across the three periods (ANOVA, df = 2, $p < 0.05$; Dunn's test). Temperature varied significantly during the long-rains (ANOVA, $F_{2,54} = 3.29$, $p < 0.05$; Tukey HSD test).

In the dry season, the pH ranged from 5.0 (cropped) to 7.9 (weedy-fallow) in Sondu. There was a wide range for EC (2.2 to 244 µS cm^{-1}) and TDS (1.4 to 146.8 mg L^{-1}) values in the weedy-fallow plots across the sampling periods. Temperature ranged between 23.3 and 36.7 °C during short-rains in cropped plots. DO concentration was lowest in the dry season (0.2 mg L^{-1}) in weedy-fallow plots and highest in cropped plots (7.8 mg L^{-1}) during short-rains (Table 3-3). There were significantly lower values for pH, EC and TDS during the long-rains season (ANOVA, df = 2, $p < 0.05$; Dunn's test). Temperature varied significantly across the sampling periods ($F_{2, 46} = 15.27$, $p < 0.05$; Tukey HSD test). DO concentration was significantly higher during short-rains (ANOVA, df = 2, $p < 0.05$; Tukey HSD test).

River Sondu-Miriu

The pH at Kabianga and Sondu stations ranged from 6.1-7.7 and 6.5-7.7 respectively. Conductivity ranged between 5.5 and 51.7 µS cm^{-1} while TDS varied from 3.5 to 38.2 mg L^{-1}). The lowest and maximum levels for EC and TDS were reported in long-rains and dry season respectively. In Sondu EC ranged from 5.6 to 45.9 µS cm^{-1} and TDS was between 3.6 and 29.5 mg L^{-1} for similar seasons. Temperature was highest during the long-rains season at both stations although Kabianga displayed a wider range (15.5-22.7 °C) compared to Sondu (20.4-24.4 °C). The lowest temperature at Kabianga and Sondu was observed in the dry and short-rains season respectively. DO concentration ranged from 5.9 to 6.8 mg L^{-1} and 6.9 to 8.2 mg L^{-1} at Kabianga and Sondu respectively. The maximum DO levels were recorded over

the dry season at Kabianga and during the long-rains in Sondu. The DO concentration at Kabianga was generally below 7.0 mg L^{-1} but above this value in Sondu (Table 3-4).

Kabianga station displayed significantly higher pH and EC values with particular variability between the dry and long-rains season (ANOVA, df = 2, $p < 0.05$; Dunn's test). Temperature was significantly higher in the dry season (ANOVA, $F_{2,18} = 3.98$, $p < 0.05$; Tukey HSD test). DO showed significant temporal differences during the short-rains period (ANOVA, $F_{2,18} = 7.26$, $p < 0.05$; Tukey HSD test). TDS was significantly lower during the long-rains season (ANOVA, $p < 0.05$; Dunn's test).

At the Sondu station, there was a significant temporal variability in pH between the dry and short-rains period (ANOVA, $F_{2,15} = 5.33$, $p < 0.05$; Tukey HSD test). EC significantly varied during the long-rains (ANOVA, df = 2, $p \leq 0.05$; Dunn's test). Significant temperature differences were observed in the dry and long-rains seasons (ANOVA, $F_{2,15} = 25.99$, $p < 0.05$; Tukey HSD test). Significant temporal variability was also noted for DO between dry season and short rains while TDS recorded a significant difference during the long-rains season (ANOVA, df = 2, $p < 0.05$; Dunn's test).

3.4.3. Solids, Organic Matter and Surface Runoff

Land Uses

The TSS, OM and TS displayed wide ranges; 0.5-336, 1-148 and 2-517 mg L^{-1} respectively. The highest surface runoff collected was 13.5 L in the weedy-fallow plots during the long-rains season at Kabianga (Figure 3-5). In Sondu, wider ranges were observed for TSS (4-850 mg L^{-1}), OM (9-545 mg L^{-1}) and TS (7-1174 mg L^{-1}) compared to Kabianga. Also, sediments generally displayed lower concentrations in the natural vegetation although maximum levels for these solids occurred in the short-rains period in Sondu. Surface runoff volume was higher in the dry season in the natural vegetation but lowest in cropped land during the long rains. (Figure 3-6).

At Kabianga, the TSS and TS concentrations were significantly lower while surface runoff volume was significantly higher in the long-rains season. Also, OM content was significantly lower in the same period (ANOVA, df = 2, $p < 0.05$; Dunn's test). In Sondu, TSS, OM and TS concentrations were significantly higher during short-rains (ANOVA, df = 2, $p < 0.05$; Dunn's test).

River Sondu-Miriu

The lowest TSS concentration (8 mg L^{-1}) was observed in the dry season. Minimum values for OM (2 mg L^{-1}) and TS (15 mg L^{-1}) respectively occurred during the long-rains season at Kabianga station along RSM (Figure 3-7). Maximum concentration for the solids (TSS 42 mg L^{-1}, OM 21 mg L^{-1} and TS 148 mg L^{-1}) were recorded also during the long-rains. There was significant seasonal variability for OM between the short and long-rains season (ANOVA, $F_{2,18} = 4.01$, $p < 0.05$; Tukey HSD test).

In Sondu, TSS, OM and TS values ranged from 4 to 360, 8 to 320 and 87 to 586 mg L^{-1} respectively. The maximum concentration for TSS, OM and TS occurred during the short-rains. Significantly lower TSS concentrations in Sondu were noted during short-rains and dry season. OM content was significantly higher during short-rains while TS concentration was significantly lower during the long-rains season (ANOVA, df = 2, $p < 0.05$; Dunn's test).

3.4.4. Principal Components Analysis (PCA)

Land Uses

The principal components (PCs) for water quality parameters in different land uses at Kabianga and Sondu were defined (Table 3-5). The PCA was complemented by factor analysis of the retained components and comparison of the first two PCs (Figure 3-6; 3-7).

At Kabianga, PC1 explained 31.7% of total variance in water quality and had strong positive loadings on TSS, TS and OM (Figure 3-6). This factor group is contributed to by the variables related to surface runoff and erosion. PC1 describes the influence of seasonality and hydrology on the quality of surface runoff from the land uses. The high contribution of TSS ($r = 0.94$), TS ($r = 0.88$) and OM ($r = 0.72$) indicates loading from land particularly during wet periods. This is corroborated by significant correlations between runoff and the three variables (TSS, $r_s = -0.47$; TS, $r_s = -0.42$; OM, $r_s = -0.41$; $p < 0.01$) (Table 3-6). PC2 had strong loadings of EC, TDS and temperature. This component explained 22.9% of total variance depicting the influence of hydrology on ionic pollution of surface runoff. EC and TDS were significantly correlated ($r_s = 0.64$, $p < 0.05$). EC and TDS also correlated significantly with surface runoff volume (EC, $r_s = -0.53$; TDS, $r_s = -0.56$, $p < 0.05$). PC3 had strong loadings on DO ($r = 0.94$) and pH ($r = -0.72$) respectively. The two variables explained 18.2% of the total variance in surface runoff quality and significantly correlated ($r_s = -0.26$, $p < 0.05$). PC4 had strong loading on surface runoff ($r = 0.92$) and accounted for 12.4% of the total variance. This component was attributed to seasonal variability. Surface runoff volume

also correlated significantly with water quality parameters (pH, EC and TDS) and solids (TSS, TS and OM) ($p < 0.05$).

In Sondu, PC1 accounted for 32.5% variance of overall surface runoff quality. PC1 is characterised by the strong factor loading of TSS ($r = 0.94$), TS ($r = 0.97$) and OM ($r = 0.93$). This component is attributed to temporal changes in surface runoff loads from the catchment as determined by seasonal variability. The three indicators show very strong correlations and significant relationships ($0.91 \leq r_s \leq 0.94$, $p < 0.05$). PC2 was linked to ionic pollution indicators pH, EC and TDS with moderate to high factor loadings ($0.61 \leq r \leq 0.92$) representing 29.1% of the total variance (Figure 3-7). EC directly and significantly related to TDS ($r_s = 1.0$, $p < 0.05$) which also correlated significantly to pH ($r_s = 0.47$, $p < 0.05$). All the indicators in PC2, except pH, significantly correlated with indicators in PC1 (Table 3-6). PC3 accounting for 13.0% of the overall variability was associated with surface runoff ($r = -0.92$). PC4 contributed 11.9% to the total variance and loaded highly and positively on DO ($r = 0.85$). DO correlated significantly with temperature ($r_s = -0.37$, $p < 0.05$) (Table 3-6).

River Sondu-Miriu

At Kabianga, the first three PCs explained 39-73% of the total variance (Table 3-7). The first two PCs were also compared to discern the major contributing parameters (Figure 3-8). PC1 accounted for 39% of the overall variability and suggested ionic pollution contributed by dissolved substances given the high factor loadings on pH ($r = -0.95$), EC ($r = -0.96$) and TDS ($r = -0.97$) which displayed significant correlations ($0.77 \leq r_s \leq 0.99$, $p < 0.05$). PC2 explained 17% of the total variability. This component was described by TSS ($r = 0.69$) and TS ($r = 0.89$). PC2 was associated with sediment load introduced into the river via surface runoff especially in the wet seasons. The fourth PC described 14.70% of total variance and associated strongly with OM (0.96) which also correlated significantly with TS ($r_s = 0.51$, $p < 0.05$) (Table 3-8).

Table 3-2: Temporal variability of physicochemical parameters in different land uses at Kabianga. Values are given as mean (±SE). NV = Natural Vegetation; WF = Weedy-Fallow; S-R = Short-Rains; D-S = Dry-Season; L-R = Long-Rains.

Land use	Period		pH	EC (μS cm^{-1})	Temp (° C)	DO (mg l^{-1})	TDS (mg L^{-1})
NV	S-R 2010	**Mean**		**30.2 ± 6.7**	**22.2 ± 0.5**	**6.2 ± 0.2**	**18.7 ± 4.6**
		Min-max	6.6-7.5	10.4-51.6	20.6-23.3	5.5-6.8	6.63-33.1
	D-S 2011	**Mean**		**156.9 ± 21.7**	**26.6 ± 0.9**	**5.3 ± 1.1**	**135.2 ± 53.2**
		Min-max	6.0-8.5	95.9-238.0	20.6-26.2	0.1-7.2	47.2-397.0
	L-R 2011	**Mean**		**5.9 ± 0.9**	**21.2 ± 0.8**	**6.1 ± 0.2**	**3.8 ± 0.6**
		Min-max	5.9-6.5	3.2-13.0	18.5-24.7	5.0-6.9	2.1-8.3
WF	S-R 2010	**Mean**		**40.2 ± 17.7**	**22.6 ± 0.7**	**5.2 ± 1.3**	**25.7 ± 11.3**
		Min-max	6.2-8.3	10.6-101.7	20.5-24.2	0.1-7.1	6.8-65.1
	D-S 2011	**Mean**		**143.3 ± 39.6**	**24.0 ± 1.6**	**4.6 ± 1.5**	**70.8 ± 31.8**
		Min-max	6.1-7.8	84.6-260.0	21.6-28.5	0.1-6.9	11.2-160.9
	L-R 2011	**Mean**		**8.3 ± 2.0**	**22.2 ± 0.8**	**5.9 ± 0.3**	**5.4 ± 1.3**
		Min-max	5.5-6.8	3.1-20.8	19.2-26.6	4.7-7.0	2.0-13.5
Cropped	S-R 2010	**Mean**		**29.2 ± 7.3**	**22.9 ± 0.6**	**5.5 ± 1.1**	**18.7 ± 4.7**
		Min-max	6.7-8.3	9.9-55.6	20.9-25.3	0.2-7.0	6.4-35.6
	D-S 2011	**Mean**		**97.9 ± 29.6**	**23.5 ± 1.0**	**6.7 ± 0.3**	**52.8 ± 20.2**
		Min-max	6.0-8.2	12.1-197.3	20.2-26.2	5.9-7.3	7.5-131.2
	L-R 2011	**Mean**		**5.4 ± 0.6**	**22.4 ± 0.9**	**6.6 ± 0.2**	**3.5 ± 0.4**
		Min-max	5.7-6.9	3.4-7.5	18.7-25.8	5.8-7.3	2.2-4.9

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Table 3-3: Variability of physicochemical parameters in different land uses in Sondu. Values are given as mean (±SE). NV = Natural Vegetation; WF = Weedy-Fallow; S-R = Short-Rains; D-S = Dry-Season; L-R = Long-Rains.

Land use	Period		pH	EC (µS cm^{-1})	Temp (° C)	DO (mg l^{-1})	TDS (mg L^{-1})
NV	S-R 2010	**Mean**		**26.4 ± 3.2**	**26.4 ± 0.6**	**5.1 ± 0.7**	**16.8 ± 2.0**
		Min-max	6.7-7.1	19.9-41.4	24.6-28.6	2.0-7.0	12.8-26.4
	D-S 2011	**Mean**		**88.9 ± 20.4**	**32.1 ± 0.9**	**5.2 ± 0.2**	**53.5 ± 11.9**
		Min-max	6.1-6.6	68.5-109.3	31.2-33.0	5.0-5.4	41.6-65.4
	L-R 2011	**Mean**		**5.0 ± 1.8**	**27.1 ± 0.8**	**4.8 ± 0.5**	**3.3 ± 1.2**
		Min-max	5.7-7.3	2.3-15.7	24.3-29.3	2.7-5.9	1.5-10.2
WF	S-R 2010	**Mean**		**41.7 ± 19.9**	**27.0 ± 0.7**	**4.5 ± 1.1**	**26.7 ± 12.7**
		Min-max	6.4-7.1	15.3-120.8	25.0-29.0	1.3-6.3	9.8-77.3
	D-S 2011	**Mean**		**177.9 ± 58.8**	**29.1 ± 1.1**	**2.3 ± 1.1**	**88.7 ± 31.6**
		Min-max	7.0-7.9	60.6-244.0	27.1-30.8	0.2-4.0	38.0-146.8
	L-R 2011	**Mean**		**6.0 ± 1.7**	**27.1 ± 0.6**	**4.7 ± 0.7**	**3.9 ± 1.1**
		Min-max	5.4-7.5	2.2-18.8	23.5-30.3	0.3-6.4	1.4-12.1
Cropped	S-R 2010	**Mean**		**28.2 ± 2.8**	**26.3 ± 0.9**	**5.7 ± 0.5**	**17.9 ± 1.9**
		Min-max	6.5-7.1	21.6-38.6	23.3-29.0	4.4-7.8	13.4-24.7
	D-S 2011	**Mean**		**97.4 ± 45.7**	**32.7 ± 2.5**	**2.8 ± 1.4**	**53.4 ± 24.8**
		Min-max	6.8-7.5	7.5-156.4	28.1-36.7	0.8-5.4	4.6-85.2
	L-R 2011	**Mean**		**10.6 ± 3.5**	**27.8 ± 0.5**	**4.8 ± 0.6**	**6.9 ± 2.3**
		Min-max	5.0-7.1	5.1-34.5	24.5-29.5	1.1-6.3	3.2-22.4

Table 3-4: Temporal variability of physicochemical parameters at Kabianga and Sondu sampling stations along River Sondu-Miriu. Values are given as mean (±SE). S-R = Short-rains; D-S = Dry-season; L-R = Long-rains.

Station	Period		pH	EC (µS cm^{-1})	Temp (° C)	DO (mg l^{-1})	TDS (mg L^{-1})
Kabianga	S-R 2010	**Mean**		**17.1 ± 1.2**	**18.5 ± 0.2**	**6.3 ± 0.1**	**11.6 ± 0.1**
(R. Ainapkoi)		Min-max	6.5-6.6	11.2-18.6	18.0-19.5	5.9-6.4	11.2-11.9
	D-S 2011	**Mean**		**39.2 ± 3.9**	**17.6 ± 0.7**	**6.5 ± 0.1**	**26.0 ± 3.6**
		Min-max	6.7-7.7	27.8-51.7	15.5-19.1	6.2-6.8	15.9-38.2
	L-R 2011	**Mean**		**5.7 ± 0.1**	**19.7 ± 0.5**	**6.6 ± 0.1**	**3.7 ± 0.0**
		Min-max	6.1-6.6	5.5-5.9	17.5-22.7	6.3-6.8	3.5-3.9
Sondu	S-R 2010	**Mean**		**31.8 ± 1.5**	**21.0 ± 0.3**	**7.4 ± 0.0**	**20.4 ± 1.0**
(R. Sondu-Miriu)		Min-max	6.5-7.3	28.4-35.6	20.4-21.6	7.35-7.43	18.2-22.8
	D-S 2011	**Mean**		**45.1 ± 0.5**	**23.4 ± 0.4**	**8.2 ± 0.1**	**29.1 ± 0.2**
		Min-max	7.3-7.6	44.1-45.9	22.8-24.2	8.10-8.24	28.8-29.5
	L-R 2011	**Mean**		**7.4 ± 0.6**	**23.2 ± 0.2**	**7.4 ± 0.1**	**4.8 ± 0.4**
		Min-max	6.8-7.7	5.6-9.6	22.5-24.4	6.9-7.9	3.6-6.2

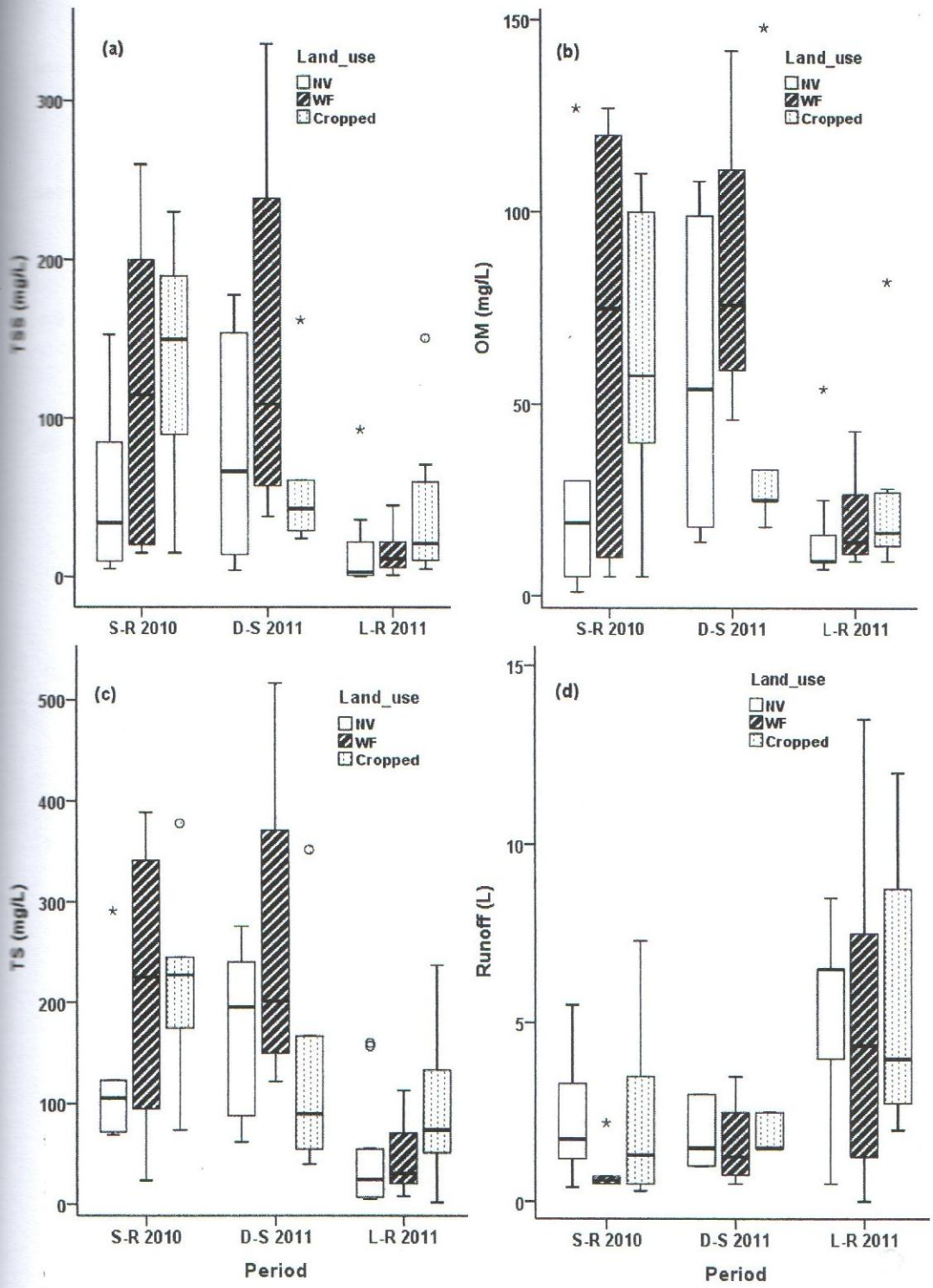


Figure 3-5: Temporal variability of (a) TSS, (b) OM, (c) TS, and (d) surface runoff from different land uses at Kabianga. Outliers are represented by circles (°) and extreme outliers by (*). NV = Natural vegetation; WF = Weedy-Fallow; S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

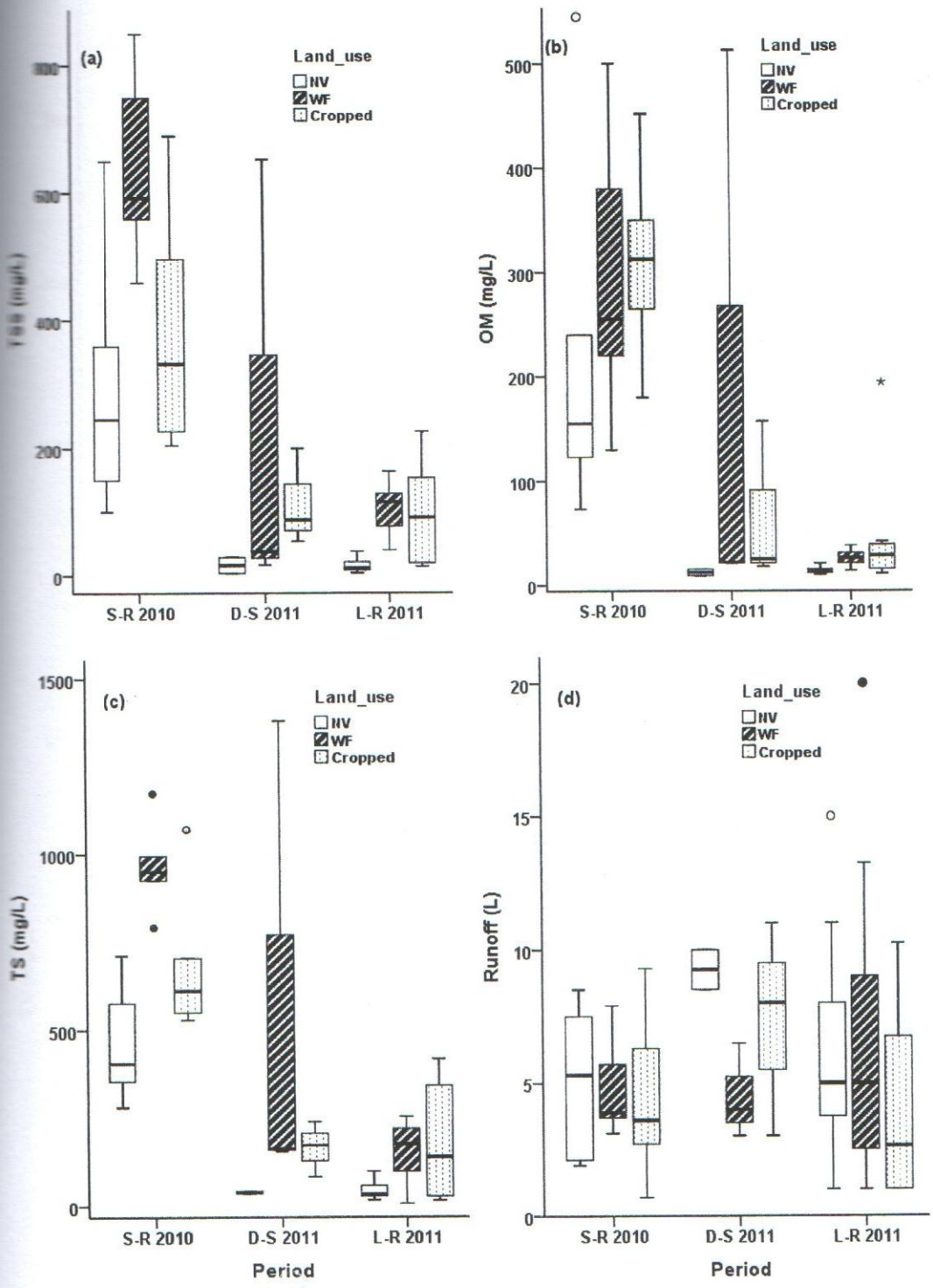


Figure 3-6: Temporal variability of (a) TSS, (b) OM, (c) TS, and (d) surface runoff from different land uses in Sondu. Outliers are represented by circles (°) and extreme outliers by (*). NV = Natural vegetation; WF = Weedy-Fallow; S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

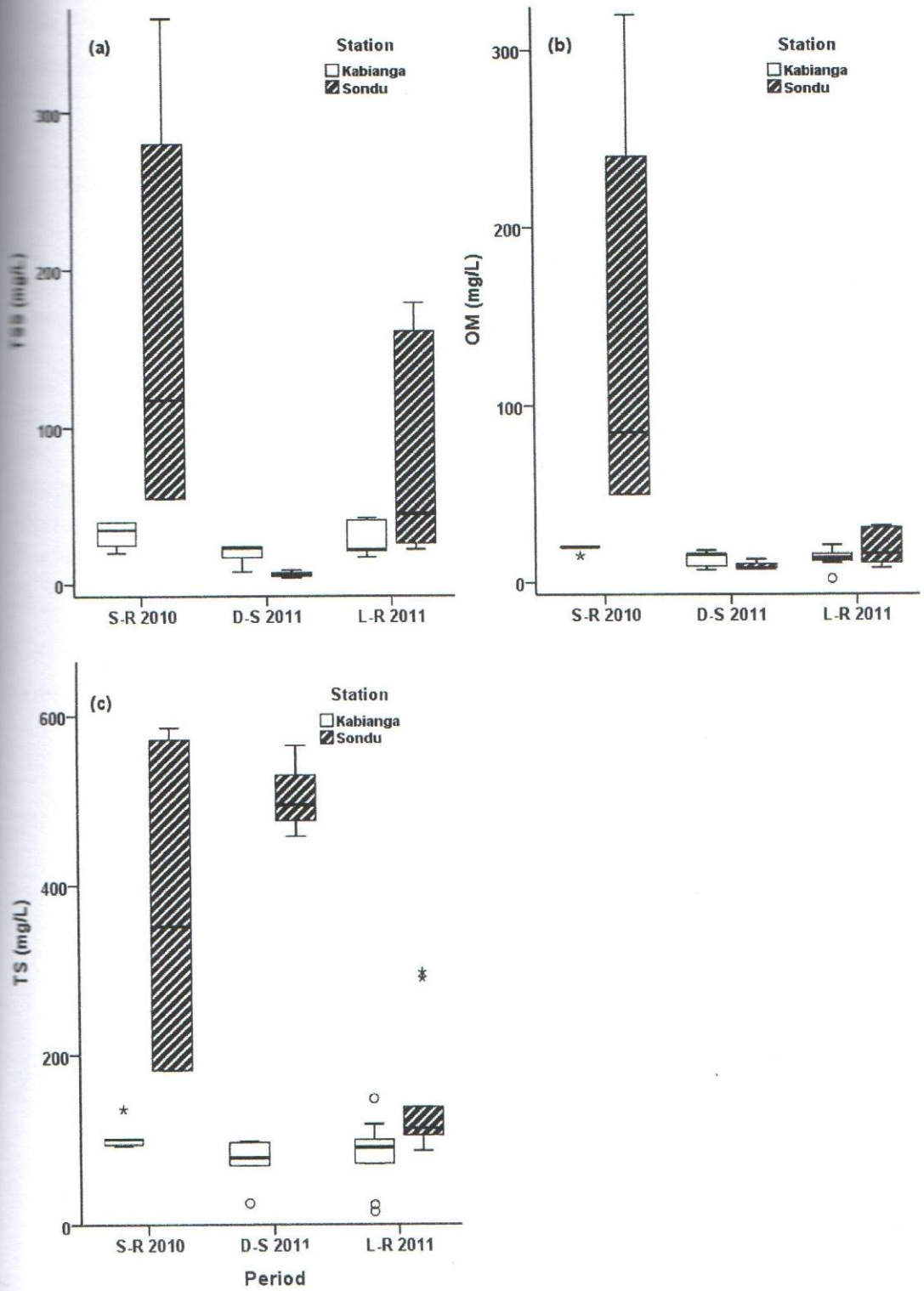


Figure 3-7: Temporal variability of (a) TSS, (b) OM and (c) TS at Kabianga and Sondu stations along River Sondu-Miriu. Outliers are represented by circles (°) and extreme outliers by (*). S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

Table 3-5: Factor loadings on principal components of water quality parameters, solids and surface runoff from different land uses at Kabianga and Sondu.

	Principal Components							
	Kabianga				Sondu			
Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
pH	0.27	0.32	**-0.72**	-0.21	0.23	**0.61**	0.48	0.40
EC	0.28	**0.78**	0.24	-0.30	0.17	**0.92**	-0.13	-0.20
TDS	-0.03	**0.79**	0.39	-0.24	0.11	**0.92**	-0.17	-0.16
Temp	0.31	**0.78**	0.05	0.13	-0.36	**0.65**	0.15	-0.31
DO	-0.02	-0.07	**0.94**	-0.04	-0.01	-0.35	-0.08	**0.85**
TSS	**0.94**	0.13	-0.08	-0.13	**0.94**	0.03	0.06	-0.02
TS	**0.91**	0.19	-0.07	-0.15	**0.93**	0.04	0.09	0.10
OM	**0.92**	0.18	-0.14	-0.12	**0.97**	0.09	0.06	-0.03
Runoff	-0.24	-0.15	0.06	**0.92**	-0.11	0.14	**-0.92**	0.09
Variance	2.85	2.06	1.63	1.11	2.92	2.62	1.17	1.07
Variance (%)	31.70	22.90	18.20	12.40	32.50	29.10	13.00	11.90
***CV (%)**	31.70	54.60	72.80	85.20	32.50	61.60	74.60	86.50

*CV = Cumulative Variance. Factor loadings (correlation coefficients) in bold give the corresponding variable(s) considered in each principal component (PC).

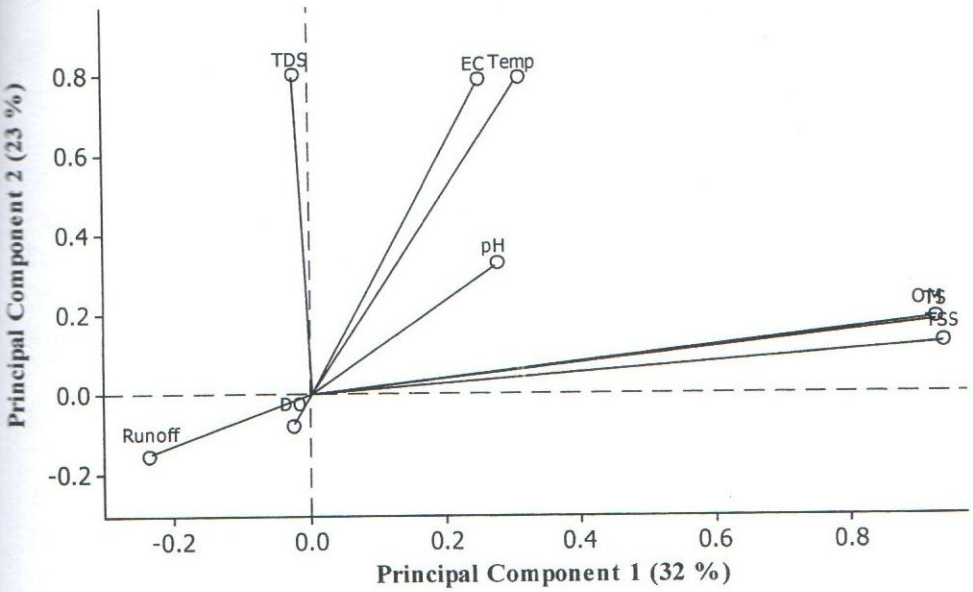


Figure 3-8: Principal component analysis of physicochemical parameters, solids and surface runoff for the first two PCs in different land uses at Kabianga.

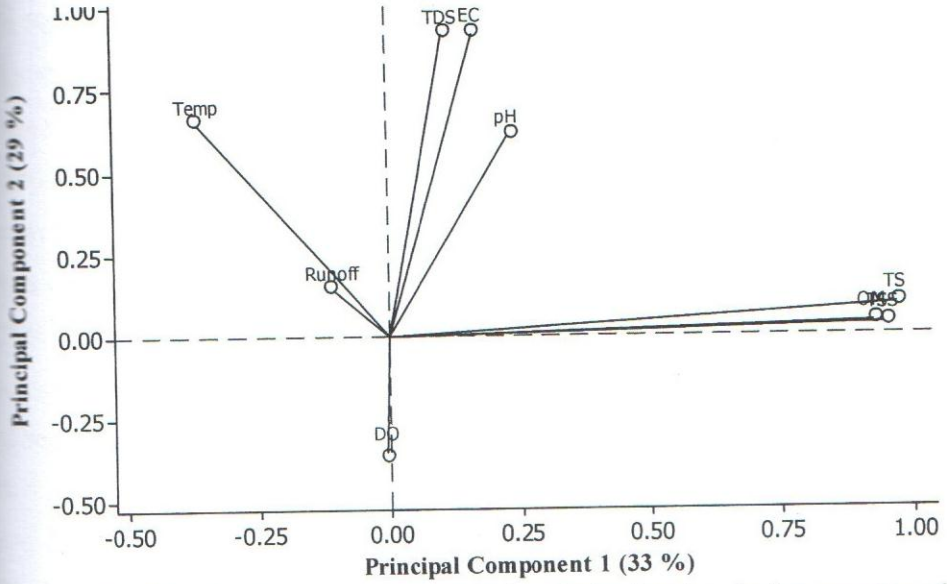


Figure 3-9: Principal components analysis of physicochemical parameters for the first two PCs in different land uses in Sondu.

Table 3-6: Spearman's rank correlation matrix (r_s) of physicochemical parameters, solids and surface runoff data for different land uses at Kabianga and Sondu.

Parameter	pH	EC	TDS	Temp	DO	TSS	TS	OM
				Kabianga				
EC	**0.65****							
TDS	**0.64****	**0.98****						
Temp	**0.27***	0.22	0.25					
DO	**-0.26***	-0.12	-0.11	0.04				
TSS	**0.39****	**0.49****	**0.50****	**0.33***	0.25			
TS	**0.49****	**0.53****	**0.52****	**0.35****	0.09	**0.76****		
OM	**0.43****	**0.54****	**0.54****	**0.36****	0.13	**0.88****	**0.72****	
Runoff	**-0.36****	**-0.53****	**-0.56****	-0.25	-0.09	**-0.47****	**-0.42****	**-0.41****
				Sondu				
EC	**0.47****							
TDS	**0.47****	**1.00****						
Temp	0.17	0.20	0.20					
DO	-0.07	-0.26	-0.25	**-0.37****				
TSS	0.20	**0.37****	**0.37****	**-0.32***	0.09			
TS	0.23	**0.46****	**0.46****	**-0.31***	0.07	**0.94****		
OM	**0.33***	**0.43****	**0.42****	**-0.36***	0.13	**0.92****	**0.91****	
Runoff	-0.25	0.14	0.13	-0.19	-0.14	-0.05	-0.019	-0.068

* Significant correlations at $p < 0.05$. **Significant correlations at $p < 0.01$; n = 57 (Kabianga), n = 49 (Sondu)

In Sondu, the quality of stream water was explained by three retained PCs, which accounted for 92.9% of the total variability (Table 3-7). Comparing the first two components, PC1 principally associated with changes in ionic pollutants, OM and DO levels, and explained 40% of the total variability (Figure 3-9). However, only EC and TDS were significantly correlated ($r_s = 0.99$, $p < 0.05$) as well and DO and OM ($r_s = -0.75$, $p < 0.05$) in PC1. PC2 was characterised by sediment factor loads, TSS ($r = -0.98$) and TS ($r = -0.88$) and explained 28% of total variance. This component was linked to hydrological changes relating to seasonal variability frequently marked by changes in river discharges volumes. PC3 ascribed to seasonal variability in the quality of surface runoff discharged into River Sondu-Miriu. The two parameters in PC3 displayed strong negative factor loadings (pH, $r = -0.93$; temperature, $r = -0.85$) (Table 3-7) with a positively significant correlation ($r_s = 0.50$, $p < 0.05$) (Table 3-8). The factors in PC3 were associated with the seasonal variability in the physicochemical characteristics of load frequently introduced into streams via erosion and transportation in surface runoff with the onset of wet seasons.

Table 3-7: Principal components matrix for Kabianga and Sondu stations along RSM.

	Principal Components						
	Kabianga				**Sondu**		
Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**
pH	**-0.95**	0.04	-0.15	-0.20	0.17	0.11	**-0.93**
EC	**-0.96**	-0.16	-0.14	0.05	**0.98**	-0.06	0.10
TDS	**-0.97**	-0.15	0.04	0.03	**0.98**	-0.05	0.10
Temp	0.39	-0.06	**-0.81**	-0.22	-0.27	0.20	**-0.85**
DO	0.38	0.08	**0.75**	-0.24	**0.62**	0.53	-0.51
TSS	0.26	**0.69**	-0.17	0.36	-0.01	**-0.98**	0.16
TS	0.00	**0.89**	0.22	0.07	0.31	**-0.88**	0.19
OM	0.05	0.24	0.01	**0.94**	**0.83**	-0.44	-0.20
Variance	3.12	1.38	1.34	1.18	3.19	2.27	1.96
Variance (%)	39.00	17.20	16.80	14.70	39.90	28.40	24.60
***CV (%)**	39.00	56.20	73.00	87.70	39.90	68.30	92.90

***CV** = Cumulative Variance. Factor loadings in bold give the variable(s) considered in each principal component (PC).

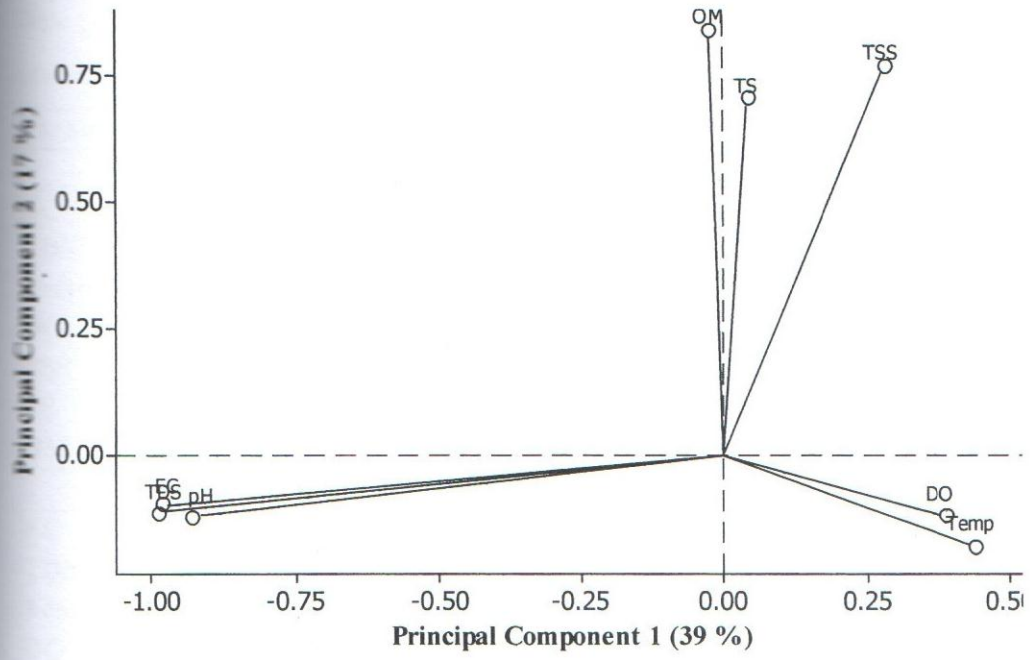


Figure 3-10: Principal components analysis of physicochemical parameters at Kabianga sampling station along RSM.

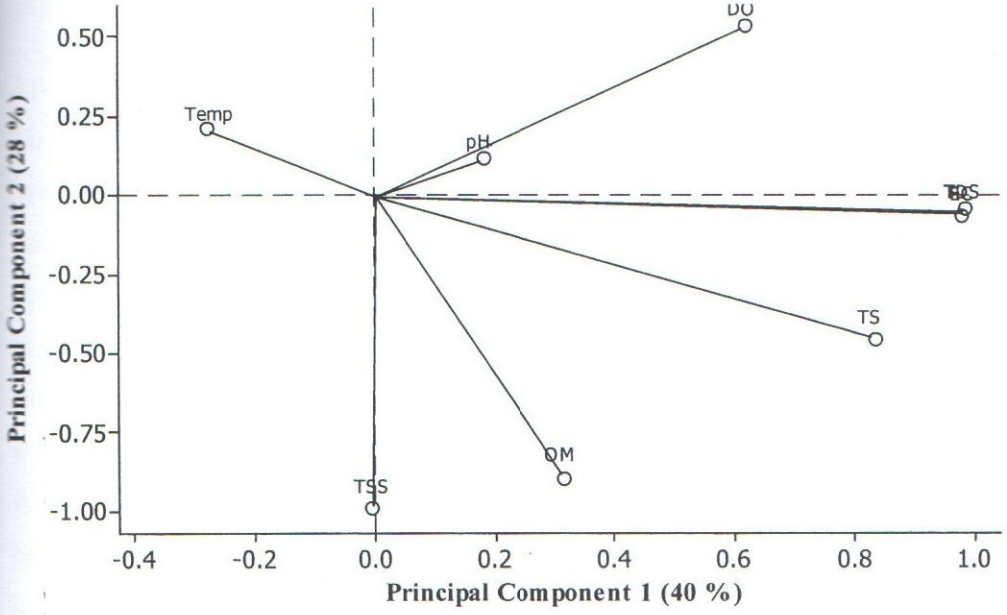


Figure 3-11: Principal components analysis of physicochemical parameters at Sondu station along RSM.

Table 3-8: Spearman's rank correlation matrix (r_s) for physicochemical water parameters and sediments at Kabianga station along RSM.

Parameter	pH	EC	TDS	Temp	DO	TSS	TS
			Kabianga				
EC	**0.77****						
TDS	**0.80****	**0.99****					
Temp	-0.25	**-0.48***	**-0.44***				
DO	-0.32	**-0.44***	**-0.47***	-0.17			
TSS	-0.14	-0.29	-0.31	0.29	0.12		
TS	-0.04	-0.19	-0.17	-0.15	0.05	0.34	
OM	-0.04	0.05	0.047	-0.22	-0.10	0.49	**0.51***
			Sondu				
EC	0.17						
TDS	0.16	**0.99****					
Temp	**0.50***	-0.15	-0.18				
DO	**0.72****	0.34	0.35	0.40			
TSS	**-0.48***	-0.14	-0.14	**-0.60****	**-0.85****		
TS	0.13	**0.65****	**0.64****	**-0.48***	0.06	0.27	
OM	**-0.61****	0.07	0.06	**-0.77****	**-0.75****	**0.90****	0.45

* Significant correlations at $p < 0.05$. **Significant correlations at $p < 0.01$; n = 21 (Kabianga), n = 18 (Sondu)

3.5. Discussion

The variability in most of the surface water quality parameters coincided with temporal hydroperiodical changes in SMB. The impact of anthropogenic activities on the basin is demonstrated by the variability in water quality from different land uses as well stream water across the three sampling periods. The physicochemical parameters indicated elevated levels of pollutants and low water quality in cropped and weedy-fallow land especially during the short-rain season. This was possibly influenced by land preparation activities and build-up of loose soil and organic matter; a potential source of sediment at the onset of rains. Anthropogenic activities have been observed to override natural sources of surface water pollution in agricultural catchments (UNEP, 2006; Shrestha and Kazama, 2007; Najafpour *et al.*, 2008; Bu *et al.*, 2010). Additionally, the complex dynamics of surface runoff, interflows, erosion rates and subsurface flows are influenced by site specific land use/land covers systems (Saenyi, 2002; Kandrika and Venkatatram, 2005). Factor analysis of the physicochemical parameters and solids significantly loading on the principal components clearly indicated the influence of seasonality at Kabianga and the significance of

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anthropogenic impacts on surface water quality in Sondu. In the tropics and sub-tropics, high intensity rainfall generates significant surface runoff which can easily erode loose soil, debris and contaminants into the respective sinks (Dabrowski *et al.*, 2002) including surface water bodies (Saenyi, 2002; Antikainen *et al.*, 2008). The changes in EC and TDS are related to ionic pollutants (Zhang *et al.*, 2011) since conductivity levels reflect the status of dissolved inorganic constituents in water such as metal ions, nitrates, phosphates and chlorides originating from surface runoff (Chapman, 1996; Jonnalagadda and Mhere, 2001). The temporal differences in EC and TDS also suggested the influence of seasonality on water quality in the basin.

Although not evident in this study, historically; cropped and bareland have predominantly been the main source of human-enhanced sediments in water bodies (Baker, 2003). Previous studies indicate that conversion of forest to grass and cropland over the last century in LVB has been a major factor contributing to declines in soil fertility, soil physical condition, and increased soil erosion. Further, compared to forest and bushland, areas dominated by grass and crops are 16 times more likely to be affected by severe erosion (e.g. Swallow, 2006). The conversion of land under natural vegetation cover to cropland or bare land can increase soil erosion and the associated sedimentation in streams, particularly when soil is exposed. A similar trend was observed in this study when sediment levels from different land uses were compared over three seasons.

Sediments are an integral and inseparable part of aquatic environments and are important in the physicochemical and ecological dynamics of any aquatic ecosystem. Sediments are important in the transport and retention of ions, organic and particulate compounds, such as phosphorus (Kitaka *et al.*, 2002; Adegoun *et al.* 2011). Therefore, there is a high potential of such pollutants to be retained in sediments, especially ions than their release in the water column (Chapman, 1996). In this study, sediments correlated significantly with EC, TDS and temporal trends in river Sondu-Miriu suggesting the influence of seasonality and antecedent conditions. During dry weather, which precedes long wet seasons, land preparation and sparse vegetation together with the huge build-up of loose soil and debris on land creates potential surface runoff loads. These materials and other contaminants are easily eroded into streams as surface runoff with the onset of rains (SUMAWA, 2005; Yillia *et al*, 2009). The temporal trend of TSS, OM and TS observed in RSM concurred with that observed in similar river studies (Yillia *et al*, 2009; Khadka and Khanal, 2008; Mtethiwa *et. al*, 2008). Seasonal

variability in precipitation intensity and amount, and surface runoff strongly alter river discharges and consequently the concentrations of sediments and pollutants in stream water (Sing *et al*, 2004). In addition, other natural factors such as geology, soil type, topography and vegetation cover affect water quality in aquatic systems. In-stream activities of humans and livestock have been previously identified as important contributors to diffuse pollution in streams (e.g. Yillia *et al*., 2007). Fluctuations in river discharge is also affected by anthropogenic activities; for instance, due to abstraction, urbanization or impounding; discharges from industry, agriculture or sewerage among others. Many of these anthropogenic influences are part of the larger process of catchment land use or land cover changes that can affect water quality in both rivers and lakes (Baker, 2003).

3.6. Conclusion

The sediment loads in surface runoff from different land uses varied across the short-rains, dry and long-rains seasons with higher levels at the onset of the rainy seasons. In general, the highest sediment load in surface runoff occurred during the long-rains. Cropped land was the largest contributor to sediment loss via surface runoff while land under natural vegetation least contributed. The study established that sediment loads in surface runoff in different land uses is influenced by temporal changes in seasonality particularly rainfall variability in SMB.

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CHAPTER FOUR

4. TEMPORAL VARIABILITY OF NITROGEN AND PHOSPHORUS LOADS IN SURFACE RUNOFF IN SONDU-MIRIU BASIN

4.1. Abstract

Nitrogen and phosphorus fluxes from different land uses in Sondu-Miriu basin were measured between November 2010 and May 2011 using runoff plots to determine the temporal variability. At Kabianga, NH_4-N and NO_3-N concentrations of 0.09 and 0.13 mg L^{-1} respectively, were lowest during short-rains from land under natural vegetation. Maximum NH_4-N and NO_3-N levels were 5.95 mg L^{-1} from cropped and 8.84 mg L^{-1} from weedy-fallow land in the dry season. The highest SRP concentration of 1.43 mg L^{-1} was from cropped land during the short-rains. Generally, there were significantly low NO_3-N concentrations during short-rains and during the long-rains season but high SRP levels during the long-rains season ($p < 0.05$). In Sondu, NH_4-N concentrations ranged between 0.09 and 6.93 mg L^{-1} in weedy-fallow land in dry season. NO_3-N concentration from natural vegetation peaked at 8.73 mg L^{-1} in dry season. The lowest NO_3-N concentration of 0.09 mg L^{-1} was recorded from the weedy-fallow land during the long-rains season. However, the highest SRP value was 4.05 mg L^{-1} from the weedy-fallow land in the dry season. Significantly low NH_4-N concentrations were recorded during the short-rains. NO_3-N levels were also significantly varied across the 3 seasons ($p < 0.05$). SRP varied significantly between the dry and long-rains season ($p < 0.05$). Principal components analysis associated the levels of nutrient pollution on surface runoff to the influence of seasonality and changes in land-use. Nutrient levels in surface runoff varied temporally and significantly increased at the onset of rains and during the long-rains seasons.

4.2. Introduction

Different land use activities often determine nutrient concentrations in surface runoff, particularly in intensive agricultural regions (Baker, 2003). Surface runoff transports nutrients and other pollutants from land to watercourses both in solution and in suspension. In many low-input agriculture regions in the tropics, nutrient balance of the farming systems is negative. Nutrient loss due to soil erosion caused by surface runoff is often an important contributor to the negative balance (Van den Bosch *et al.*, 1998). Total N and P in the soil is not usually a good measure of the amount of N and P that is available for plant growth because a large portion may exist in forms that are not available for bio-uptake by plants. The

soluble forms such as NO_2-N, NO_3-N, NH_4-N and PO_4-P, are more readily available for plant growth and therefore are considerably a better measure of the nutrient level in soil (Owino *et. al*., 2006). Loss of plant nutrients due to soil erosion by water contributes to productivity decline in most agricultural watersheds. Therefore, soil conservation through surface runoff control is necessary.

Runoff from land into surface waters may contain pesticides (Brown *et al*., 1995) and nutrients, especially phosphorus (Quinton *et al*., 2001). The detrimental impacts of increasing concentrations of the nutrients phosphorus (principally as orthophosphate (PO_4-P)) and nitrogen (principally as nitrate (NO_3-N)) on the water quality of surface waters have been observed for several decades (Burt *et al*., 2011; Jarvie *et al*., 2011). The keys drivers of elevated nutrient inputs include rapid population growth, intensification of agriculture and increasing industrialisation (Cordell *et al*. 2009; Ashley *et al*., 2011). Water enriched by phosphate, mostly attached to soil particles, can support the formation of toxic algal blooms in reservoirs and slow flowing streams and rivers as well as enhancing proliferation of unwanted macrophytes. This reduces the biodiversity of the aquatic environment (Environment Agency, 2000). Water treatment to remove sediment and its attached pollutants, and cyanotoxins, to make it fit to drink is usually more expensive (Pretty *et al*., 2001; Environment Agency, 2002). Therefore, it is necessary that measures to reduce or control aquatic pollution from drainage basins be investigated and integrated as components of Best Management Practises (BMPs) in Integrated Water Resources Management (IWRM) policies. Understanding agricultural land use-water quality relationships would enable the application of these land uses to estimate and understand water quality in rivers suffering from diffuse pollution particularly from agricultural activities. This study aimed to determine the temporal variability of nitrogen and phosphorus loads in surface runoff from different land uses in SMB.

4.3. Materials and Methods

Details of the study area, design and layouts of experimental plots, and field sampling activities have been previously described in chapter three section 3.3.1 to 3.3.3.

4.3.1. Laboratory Analysis for Nutrients

APHA (2005) standard analytical procedures were followed in the analysis of nutrients. Samples were filtered through pre-dried and pre-weighed Whatman GF/C glass micro-fibre filters (0.6-0.7 µm-pore-size and 47-mm-diameter). Filtered samples were used to

colorimetrically analyse SRP, NH_4-N and NO_3-N. SRP was determined using the ascorbic acid method. The phenol-hypochlorite method was used for NH_4-N while NO_3-N was analysed using the sodium-salicylate method. The light absorbance of duplicate samples was measured in 1 cm-quartz cuvettes using a scanning spectrophotometer (GENESYS® 10uV, ver. 2.001) and the nutrient levels determined against known standard concentrations.

4.3.2. Data Analysis

Details of data analysis have been described in chapter three section 3.3.5.

4.4. Results

4.4.1. Physicochemical Variables

Results for the physicochemical variables have been described in chapter three section 3.4.2.

4.4.2. Variability in Nutrient Levels

Land uses

In Kabianga, NH_4-N and NO_3-N concentrations were at minimum during the short rains in the natural vegetation (0.09 and 0.13 mg L^{-1} respectively). Maximum NH_4-N and NO_3-N levels were 5.95 mg L^{-1} in cropped and 8.84 mg L^{-1} in weedy-fallow lands respectively, in the dry season. The long-rains season was distinctly characterised by very low (< 0.001 mg L^{-1}) concentrations of SRP in the respective land uses. The highest SRP concentration (1.43 mg L^{-1}) was from cropped land during short-rains (Figure 4-1). The NO_3-N concentrations varied from 0.3 mg L^{-1} during short-rains, 0.8 mg L^{-1} in the dry season and 1.7 mg L^{-1} during the long-rains season. There was significantly low NO_3-N concentration during the short-rains (ANOVA, $df = 2$, $p < 0.05$; Dunn's test). Significantly high SRP levels were noted during the dry season in Kabianga (ANOVA, $df = 2$, $p < 0.05$; Dunn's test).

In Sondu, NH_4-N concentrations ranged between 0.09 and 6.93 mg L^{-1} in weedy-fallow land over the dry season. NO_3-N concentration peaked in the natural vegetation at 8.73 mg L^{-1} in the same period. The lowest NO_3-N concentration (0.09 mg L^{-1}) was evident in the weedy-fallow land during the long-rains season. Minimum SRP concentrations were below 0.001 mg L^{-1} in all the land uses. However, the highest SRP value was 4.05 mg L^{-1} in weedy-fallow land in the dry season (Figure 4-2). Generally, NH_4-N varied from 0.7 mg L^{-1} during short-rains to 2.4 mg L^{-1} in dry season and 1.4 mg L^{-1} during the long-rains season. NO_3-N concentrations were recorded at 0.5 mg L^{-1} during short-rains, 4.6 mg L^{-1} in dry season and 1.1 mg L^{-1} during the long-rains season. The concentrations for SRP were 0.1 mg L^{-1} during

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short-rains, 0.7 mg L^{-1} in dry season and 0.1 mg L^{-1} during the long-rains season. The NH_4-N concentration was significantly low particularly during the short-rains. NO_3-N concentration significantly varied across all the three sampling seasons. The SRP level varied significantly particularly between the dry and long-rains seasons (ANOVA, $df = 2$, $p < 0.05$; Dunn's test).

River Sondu Miriu

From Figure 4-3, Kabianga station recorded the lowest and highest NH_4-N concentration (0.01 and 2.88 mg L^{-1}), and maximum NO_3-N level in the dry season. The lowest concentration of NO_3-N (0.18 mg L^{-1}) and SRP (< 0.001 mg L^{-1}) was recorded during the long-rains season. The highest SRP levels of 0.04 mg L^{-1} were during the short-rains. Generally, SRP concentrations were below 0.10 mg L^{-1} at Kabianga over the sampling period. However, there was no significant temporal variability in all the nutrient concentrations at Kabianga.

At Sondu station, NH_4-N concentration ranged from 0.001 to 4.0 mg L^{-1} while SRP varied from < 0.001 mg L^{-1} during the long-rains to 0.74 mg L^{-1} in the dry season. Temporal comparisons of NH_4-N displayed significantly low concentrations during the long-rains season. SRP concentrations were significantly different between the dry and long-rains seasons (ANOVA, $df = 2$, $p < 0.05$; Dunn's test). NO_3-N content ranged between 0.59 mg L^{-1} and 1.44 mg L^{-1} over the dry season.

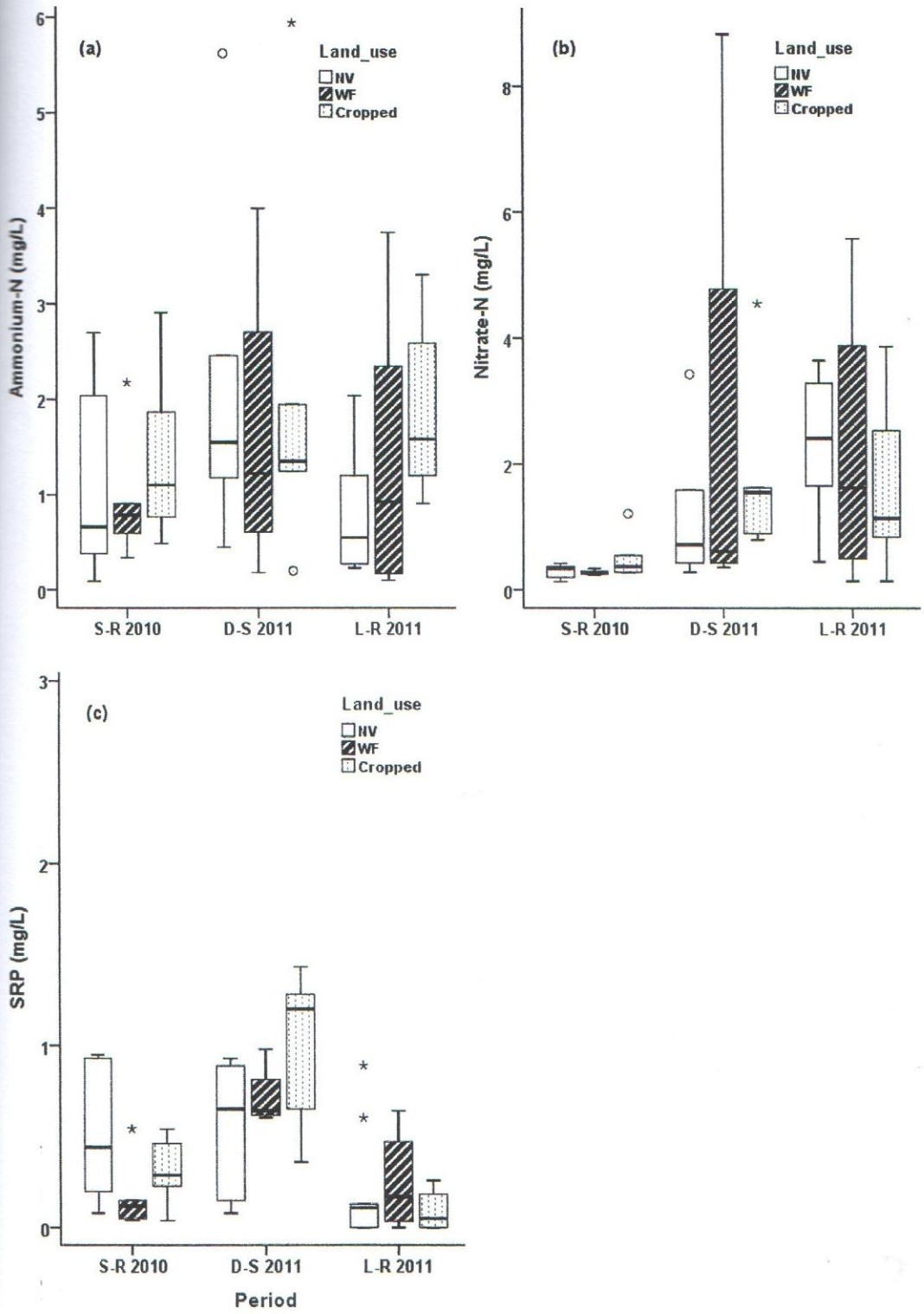


Figure 4-1: Temporal variability in (a) Ammonium-N, (b) Nitrate-N and (c) SRP levels in different land uses at Kabianga. Outliers are represented by circles (°) and extreme outliers by (*). NV = Natural vegetation; WF = Weedy-Fallow; S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

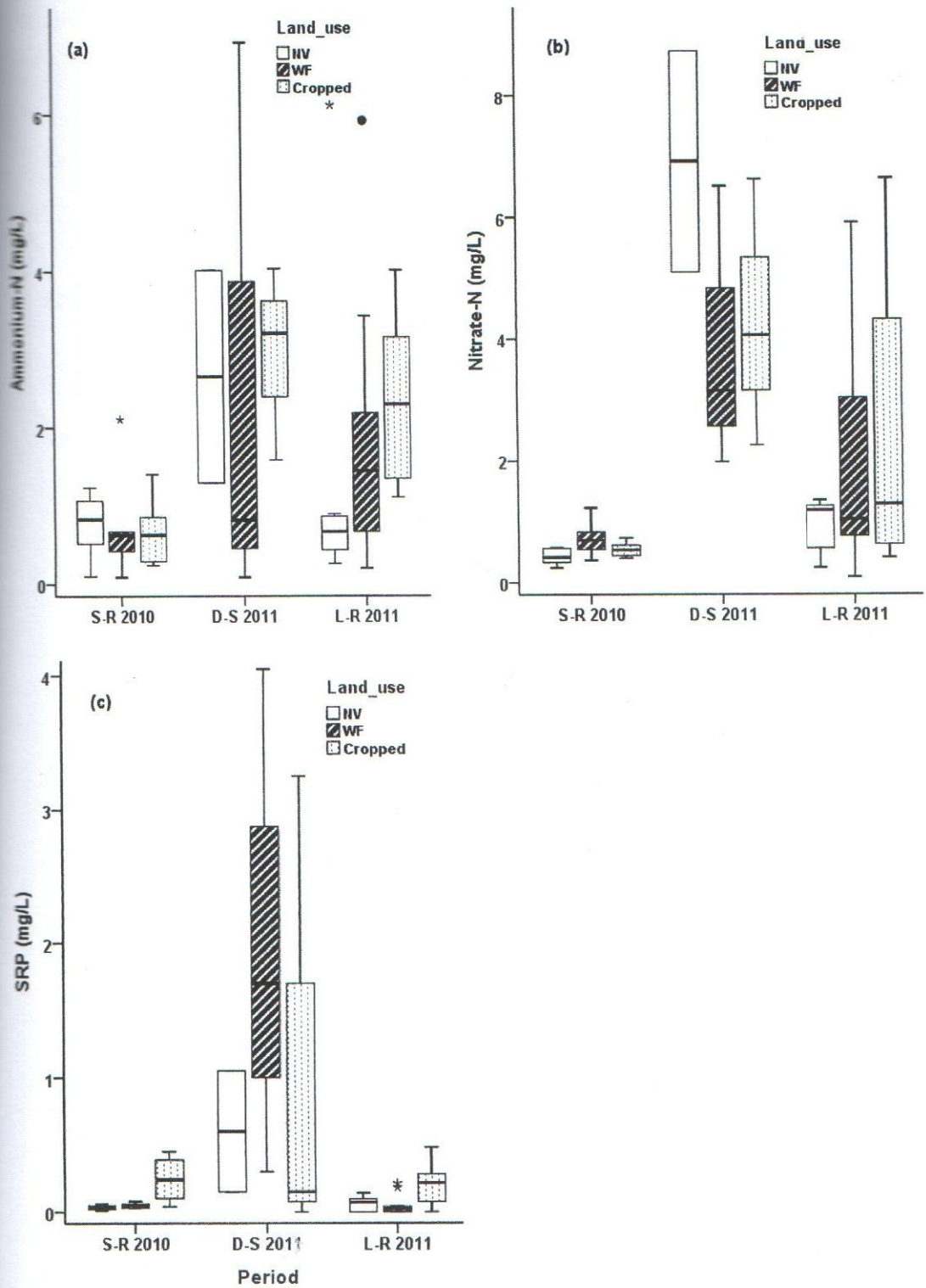


Figure 4-2: Temporal variability in (a) Ammonium-N, (b) Nitrate-N and (c) SRP levels in different land uses in Sondu. Outliers are represented by circles (°) and extreme outliers by (*). NV = Natural vegetation; WF = Weedy-Fallow; S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

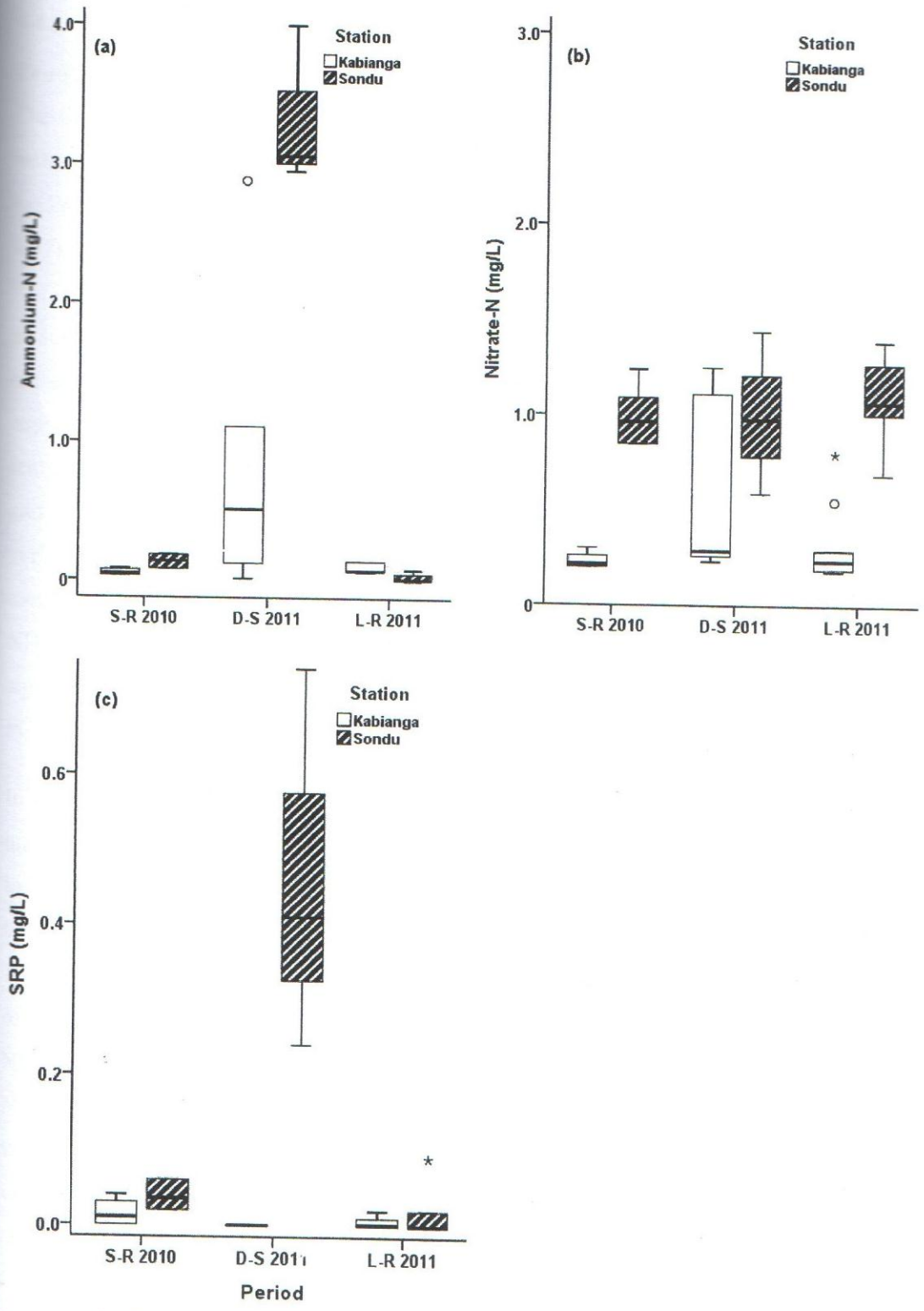


Figure 4-3: Temporal variability in (a) Ammonium-N, (b) Nitrate-N and (c) SRP levels at Kabianga and Sondu stations along River Sondu-Miriu. Outliers are represented by circles (°) and extreme outliers by (*). S-R 2010 = Short-rains in 2010; D-S 2011 = Dry-Season in 2011; L-R 2011 = Long-Rains in 2011.

4.4.3. Principal Components Analysis (PCA)

Land uses

The five extracted principal components accounted for 83.3% of the total variance in surface water quality at Kabianga (Table 4-1). PC1 with 24.2% variance was defined by high loadings on EC (r = 0.85) and TDS (r = 0.89) and moderate loading on temperature (r = 0.67). EC correlated significantly with TDS ($r_s = 0.64$, $p < 0.05$) and temperature ($r_s = 0.27$, $p < 0.05$) (Table 4-2). PC2 accounted for 18.1% of the total variance, loaded positively on dissolved oxygen (r = 0.90) and but negatively on pH (r = -0.67). The PC2 group variables correlated negatively but significantly ($r_s = -0.26$, $p < 0.05$). Generally, pH also correlated significantly with PC1 parameters; strongly with TDS ($r_s = 0.64$, $p < 0.05$) and weakly with temperature ($r_s = 0.27$, $p < 0.05$). PC3 was described by moderate loading on SRP (r = 0.62) and strong loading on surface runoff volumes (r = -0.89) representing 15.3% of total variance. The two factors exhibited a significant correlation ($r_s = -0.46$, $p < 0.05$). NO_3-N loaded negatively and strongly in PC4 (r = -0.98) while PC5 was also described strongly by NH_4-N (r = 0.91) each accounting for 13.2% and 13.0% respectively. NO_3-N correlated significantly with pH ($r_s = -0.48$, $p < 0.05$) while NH_4-N correlated significantly with DO in PC2 ($r_s = 0.27$, $p < 0.05$).

In Sondu, PC1 with 32.80% accounted for more than half of the variance in surface runoff quality accounted for by the four retained PCs (Table 4-1). This factor group realized high loadings on EC (r = 0.92) and TDS (r = 0.88), and moderately on DO (r = -0.67) and SRP (r = 0.64). Significant correlations among PC1 variables were noted between EC and TDS ($r_s = 1.0$, $p < 0.05$), EC and SRP ($r_s = 0.38$, $p < 0.05$) (Table 4-2). PC2 factors accounted for 18.4% of the total variability with strong loadings on temperature (r = -0.61), NH_4-N (r = -0.83) and NO_3-N (r = -0.75). Temperature correlated significantly with NH_4-N ($r_s = 0.42$, $p < 0.05$) and NO_3-N ($r_s = 0.47$, $p < 0.05$). Temperature also correlated weakly and significantly with a PC1 variable, SRP ($r_s = 0.36$, $p < 0.05$). PC3 and PC4 represented 14.3% and 12.9% of the total variance respectively and ascribed strongly to pH (r = -0.91) and runoff (r = -0.84) respectively. The PC3 variable correlated moderately but highly significantly with two PC1 factors, EC and TDS ($r_s = 0.47$, $p < 0.05$).

Table 4-1: Principal components matrix for nutrients and physicochemical water parameters in different land uses in SMB.

	Principal Components								
	Kabianga					Sondu			
Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC1**	**PC2**	**PC3**	**PC4**
pH	0.35	**-0.67**	0.30	0.44	0.14	0.27	-0.03	**-0.91**	0.15
EC	**0.85**	-0.18	0.31	0.01	-0.03	**0.92**	-0.09	-0.21	-0.20
TDS	**0.89**	-0.26	0.08	0.00	-0.07	**0.88**	-0.12	-0.19	-0.29
Temp	**0.67**	-0.00	0.04	0.11	0.45	0.52	**-0.61**	0.01	-0.04
DO	-0.18	**0.90**	0.05	0.02	0.14	**-0.67**	0.13	-0.25	-0.37
NH_4-N	0.02	0.04	0.06	-0.07	**0.91**	-0.16	**-0.83**	-0.31	0.15
NO_3-N	-0.01	0.03	-0.01	**-0.98**	0.08	0.30	**-0.75**	0.33	-0.13
SRP	0.07	-0.53	**0.62**	-0.12	0.32	**0.64**	-0.04	-0.29	0.36
Runoff	-0.23	-0.04	**-0.89**	-0.09	0.02	0.08	0.00	0.14	**-0.84**
Variance	2.17	1.63	1.37	1.19	1.17	2.95	1.66	1.29	1.16
Variance (%)	24.20	18.10	15.30	13.20	13.00	32.80	18.40	14.30	12.90
***CV (%)**	24.20	42.30	57.60	70.80	83.80	32.80	51.20	65.50	78.50

*CV = Cumulative Variance. Factor loadings (correlation coefficients) in bold give the corresponding variable(s) considered in each principal component (PC).

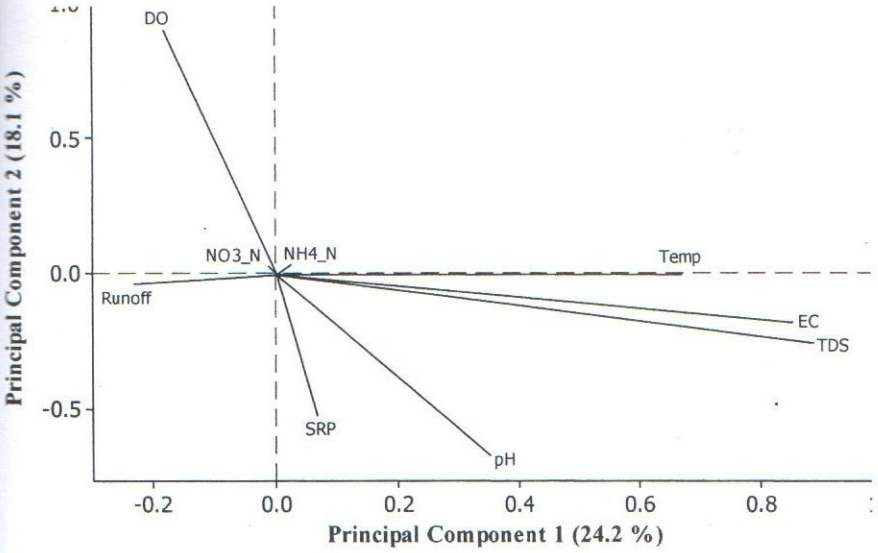


Figure 4-4: Principal component analysis of physicochemical water parameters and nutrients for the first two PCs in different land uses at Kabianga

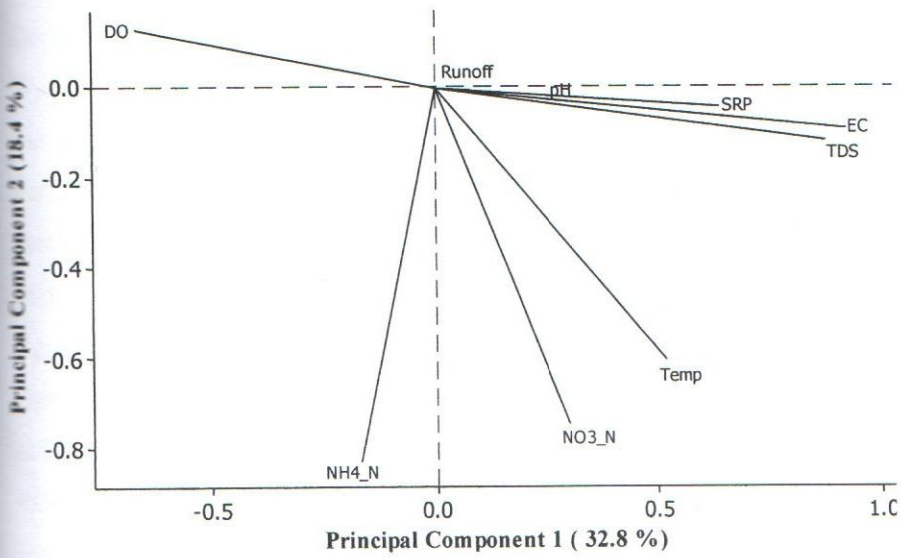


Figure 4-5: Principal component analysis of physicochemical water parameters and nutrients for the first two PCs in different land uses in Sondu

Table 4-2: Spearman's Rank correlation coefficient matrix of water quality and nutrient variables from different land uses in SMB.

Parameter	pH	EC	TDS	Temp	DO	NH_4-N	NO_3-N	SRP
				Kabianga				
EC	**0.65****							
TDS	**0.64****	**0.98****						
Temp	**0.27***	0.22	0.25					
DO	**-0.26***	-0.12	-0.11	0.04				
NH_4-N	0.01	0.04	0.07	0.25	**0.27***			
NO_3-N	**-0.48****	-0.23	-0.23	0.03	-0.18	0.05		
SRP	**0.45****	**0.63****	**0.63****	**0.36****	-0.08	0.12	0.01	
Runoff	**-0.36****	**-0.53****	**-0.56****	-0.25	-0.09	0.02	**0.27***	**-0.46****
				Sondu				
EC	**0.47****							
TDS	**0.47****	**1.00****						
Temp	0.17	0.20	0.20					
DO	-0.07	-0.26	-0.25	**-0.37****				
NH_4-N	0.17	0.00	0.00	**0.42****	-0.08			
NO_3-N	-0.24	0.09	0.09	**0.47****	**-0.33***	**0.39***		
SRP	0.24	**0.38****	**0.38****	**0.36***	-0.27	**0.29***	**0.33***	
Runoff	-0.25	0.14	0.13	-0.19	-0.14	-0.18	0.05	-0.27

* Significant correlations at $p < 0.05$. **Significant correlations at $p < 0.01$; n = 57 (Kabianga); n = 49 (Sondu)

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River Sondu-Miriu

Water quality parameters in RSM were also subjected to PCA discern similar 'fingerprints' in the quality of stream water. PC1 to PC4 accounted for 44.8% to 91.9% of the overall variability among water quality indicators at Kabianga (Table 4-3). PC1 consisted of strong factor loadings on pH (r = 0.95), EC (r = 0.87), TDS (r = 0.91) and NH_4-N (r = 0.90) and explained 44.8% of total variance. All the factors in this group except NH_4-N were significantly correlated ($0.70 < r_s < 0.99$, $p < 0.05$) (Table 4-4). In PC2, DO correlated significantly with EC and TDS ($-0.44 < r_s < -0.47$, $p < 0.05$) in PC1. Temperature in PC3 indicated strong loading (r = 0.96) and correlated significantly with two PC1 factors, EC (r_s = -0.48) and TDS ($r_s = -0.44$, $p < 0.05$). NO_3-N in PC4 contributed 13.3% of total variance and correlated significantly with EC, TDS and NH_4-N in PC1 ($0.48 < r_s < 0.63$, $p < 0.05$).

In Sondu, three PCs were retained with a cumulative variance of 89.6% (Table 4-3). PC1, which explained 46.6% of the total variance, indicated dominance by 5 factors with strong loadings on EC (r = 0.94), TDS (r = 0.94), DO (r = 0.65), NH_4-N (r = 0.87) and SRP (r = 0.85). There were significant correlations between EC, TDS and NH_4-N ($0.78 < r_s < 0.99$, $p < 0.05$) (Table 4-4). EC correlated significantly with SRP ($r_s = 0.54$, $p < 0.05$) in PC1. PC2 accounting for 28.3% of total variance related to pH (r = -0.88) and temperature (r = -0.90) which correlated significantly ($r_s = 0.50$, $p < 0.05$). The pH also significantly correlated to DO in PC1 ($r_s = 0.72$, $p < 0.05$).

Table 4-3: Principal components matrix for physicochemical parameters and nutrients at Kabianga and Sondu stations in River Sondu-Miriu

	Principal Components						
	Kabianga				**Sondu**		
Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**
pH	**0.95**	0.11	-0.08	0.15	0.17	**-0.88**	-0.02
EC	**0.87**	-0.01	-0.38	0.22	**0.94**	0.19	0.17
TDS	**0.91**	0.03	-0.28	0.29	**0.94**	0.18	0.15
Temp	-0.14	0.16	**0.96**	0.03	-0.17	**-0.90**	-0.12
DO	-0.37	**-0.76**	-0.24	0.00	**0.65**	-0.62	0.26
NH_4-N	**0.90**	-0.08	0.26	0.12	**0.87**	-0.39	-0.06
NO_3-N	0.31	-0.06	0.03	**0.95**	-0.04	-0.04	**-0.98**
SRP	-0.21	**0.89**	0.00	-0.06	**0.85**	-0.31	-0.29
Variance	3.59	1.43	1.27	1.07	3.73	2.27	1.18
Variance (%)	44.80	17.90	15.90	13.30	46.60	28.30	14.70
***CV (%)**	44.80	62.70	78.60	91.90	46.60	74.90	89.60

CV = Cumulative Variance. Factor loadings (correlation coefficients) in bold give the corresponding variable(s) considered in each principal component (PC).

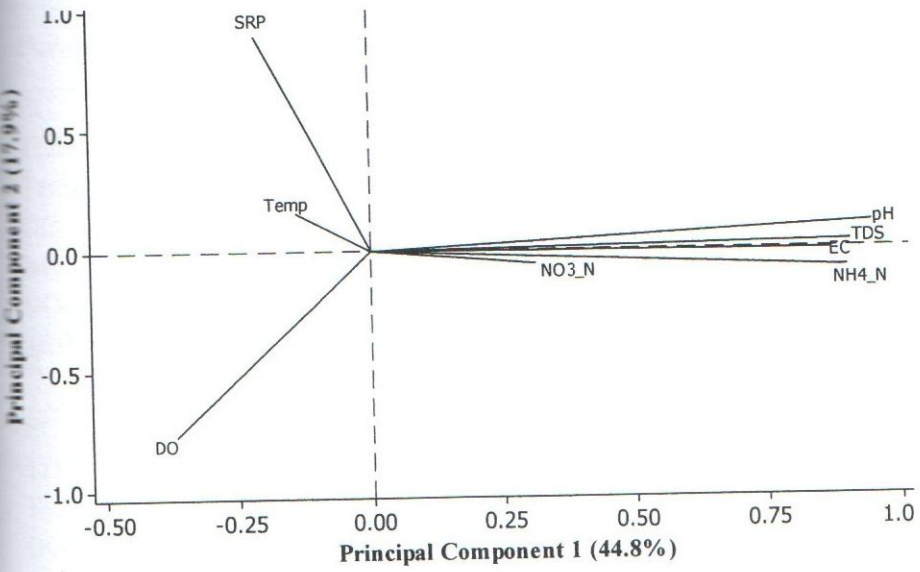


Figure 4-6: Principal component analysis of physicochemical water parameters and nutrients for the first two PCs at Kabianga station in River Sondu-Miriu

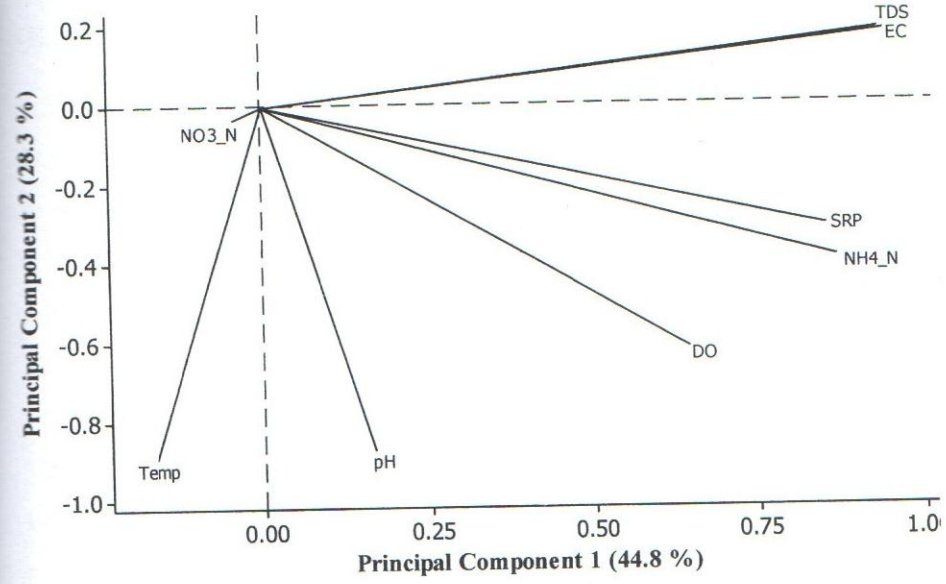


Figure 4-7: Principal component analysis of physicochemical water parameters and nutrients for the first two PCs at Sondu station along River Sondu-Miriu

Table 4-4: Spearman's correlation matrix (r_s) for different variables at Kabianga and Sondu stations in River Sondu-Miriu

Parameter	Kabianga						
	pH	EC	TDS	Temp	DO	NH_4-N	NO_3-N
EC	**0.77****						
TDS	**0.80****	**0.99****					
Temp	-0.25	**-0.48***	**-0.44***				
DO	-0.32	**-0.44***	**-0.47***	-0.17			
NH_4-N	0.25	0.24	0.25	0.34	-0.21		
NO_3-N	0.35	**0.48***	**0.50***	-0.26	-0.13	**0.63****	
SRP	-0.05	-0.40	-0.39	0.32	-0.23	-0.09	-0.38
	Sondu						
EC	0.17						
TDS	0.16	**0.99****					
Temp	**0.50***	-0.15	-0.18				
DO	**0.72****	0.34	0.35	0.40			
NH_4-N	-0.19	**0.78****	**0.79****	-0.39	0.07		
NO_3-N	0.09	-0.16	-0.11	0.10	-0.23	-0.17	
SRP	0.34	**0.54***	**0.55***	-0.22	0.33	**0.58***	0.05

* Significant correlations at $p < 0.05$. **Significant correlations at $p < 0.01$; n = 21 (Kabianga), n = 18 (Sondu)

4.5. Discussion

Different land uses often determine the variability in nutrient concentrations in surface waters in both intensive and extensive agricultural catchments. Nutrient loss from different land use activities in SMB was measured as dissolved nutrients only although a higher percentage of nutrients transported during soil erosion process are usually sediment bound (Buck, 2000). Reduction in nutrient loss from the land uses in both study sites was also influenced by volume of surface runoff, which varied significantly with seasonal changes and land use type. This concurs with results obtained by Zobisch *et al.*, (1995) while Owino *et al.* (2006) noted that increased vegetation cover was more effective in reducing runoff and nutrient loss from soil. The loss of N (NH_4-N and NO_3-N) and P (PO_4-P) directly related to the increase in runoff volume, which also corresponded to changes in hydrological periods (seasons). In most sub-Saharan African countries that rely heavily on rain-fed farming, the use of fertilizers is intensified during long-rain seasons (SUMAWA, 2005) which are also characterized by higher runoff volumes and loads, and erosion rates (Brown *et al.*, 1995; Quinton *et al.*, 2001). Alteration in site-specific land use activities in drainage catchments also partially define the amount of nutrients lost via surface runoff (Saenyi, 2002; Kandrika

and Venkataratnam, 2005; Cordell *et al.* 2009; Ashley *et al.* 2011). Analysis of the principal components in SMB identified recent diffuse anthropogenic sources of surface water contamination principally from different land use activities, such as application of N and P-based fertilizers on soils that are easily eroded and cultivation on steep terrain (SUMAWA, 2005). The sources also correlated to another major component, temporal/seasonal changes, known to determine cropping patterns and activities. Other studies have also shown that diffuse inputs from the drainage catchments fluctuations in climate and hydrodynamics are significant (Harris and Heathwaite 2005; Tappin *et al.*, 2012), particularly during the wet periods (Jagals, 1997).

The variability in nutrient concentrations in RSM was fairly responsive to seasonal differences, typical of small catchments (Tappin *et. al.*, 2012) and seasonal land use activities, e.g. intensive use of fertilizers during planting (Raj and Azeez, 2009). Significant seasonal differences in levels of NH_4-N and SRP in RSM and the processes driving nutrient mobility within SMB play a major role in defining river water quality (Harris and Heathwaite 2005; Bouraoui and Grizzetti, 2011). However, the concentrations of soluble N and P in River Sondu-Miriu were generally lower compared to the agricultural land possibly due to presence of sinks including retention pools, uptake by terrestrial vegetation and denitrification within riparian buffer strips. Terrestrial vegetation and riparian buffer strips are more efficient in reducing sediment and nutrient loads in both surface runoff and groundwater flow (Lam *et al.*, 2011). A primary mechanism of vegetative buffer strips is to reduce flow velocities because the vegetation provides greater resistance to surface water flow. The reduction in surface runoff velocity then causes deposition of suspended particles and increased infiltration, allowing sufficient time for sediment-water-atmosphere exchanges (Stow *et al.*, 2001). The main mechanisms for nutrient removal from buffer strips zones include: (a) uptake by vegetation; (b) denitrification; (c) immobilization of sediment bound and particulate nutrients by settled sediments. Denitrification is an important mechanism for removal of nitrate in vegetative buffers (Vidon and Hill, 2004). Studies by Devito *et al.* (2000) and Gold *et al.* (2001), for instance, have identified biological denitrification as a key process in nitrate reduction beneath a variety of buffer vegetation and groundwater condition. These reductions are mainly due to denitrification in the presence of abundant organic carbon available beneath the buffer strips and particularly plant uptake. Presence of SRP, on the other hand, is possibly from the agricultural farm run-off, other anthropogenic activities such as point discharge of domestic and industrial effluents, or in-stream human and animal

activities; also observed elsewhere (Yillia *et al.*, 2007; Raj and Azeez, 2009). The nutrient and sedimentation rate could also be influenced by basin characteristics such as topography, geology and soil characteristics, high rainfall and sediment transportation index, which increase nutrients transportation, in dissolved and particulate form, attached to particulate matter and soil sediments (Odada *et al.*, 2004). Nevertheless, the low values observed for N and P suggests that these nutrients are released into the river in quantities that are buffered by aquatic-plants and facultative algae, which constitute part of the river's self-purification mechanisms (Fakayode, 2005; Adeogun *et al*, 2011).

4.6. Conclusion

The nutrient levels in surface runoff in the different land uses varied temporally and increased at the onset and during the long-rains seasons. There was a general increase in the nutrient load during the rainy season especially in the cropped and weedy-fallow lands. No significant variability in nutrient loads in surface runoff was observed among the different land uses. However, a comparison of the total loads in runoff from all the land uses for the respective nutrients established significantly higher loads during the long-rains.

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CHAPTER FIVE

5. ESTIMATION OF SEDIMENT AND NUTRIENT LOADING IN SURFACE RUNOFF FROM DIFFERENT LAND USES IN SONDU-MIRIU BASIN USING ArcSWAT

5.1. Abstract

Temporal variability in the expansion and intensification of different land-use activities is a major driver influencing hydrology and increasing non-point source pollution in drainage basins. To explore these, land-use change was forecast, and long-term runoff, sediment and nutrient loading estimated in the Sondu-Miriu Basin from 2014 to 2020. The ArcGIS geospatial analysis model and the ArcGIS-based Soil and Water Analysis Toolkit (ArcSWAT) were used. The ArcGIS analysis revealed significant differences among the Landuse-Landcover classes with respect to percentage changes in spatial coverage ($p < 0.05$). Between 1985 and 2013, there was 477 % increase in urban settlements, 30 % loss in bushland, 21 % increase in rural settlements and farmlands, and nearly 2 % loss in natural forest cover. The ArcSWAT projections indicated that the surface water quality in Sondu-Miriu Basin will deteriorate from increased sedimentation by 4 %, surface runoff volume and nutrient loads respectively by 6 % between 2013 and 2020. Intensification of farming and expansion of bareland will increase sediment and nutrient losses via surface runoff erosion. These projections are significant in water resource management and decision making to protect and remediate surface water and habitat quality of Sondu-Miriu Basin.

5.2. Introduction

Modelling has become an important tool for research particularly focusing on inherently geographic aspects of our environment. Environmental models have enhanced understanding of distributions and spatial relationships of multi-scale environmental components (Parks, 1993). In the case of soil erosion, sediments and nutrient losses, simulation models have become important tools for the analysis of hillslope and watershed processes and their interactions (Santhi *et al.*, 2006; Miller *et al.*, 2007). Modelling is also crucial in the development and assessment of watershed management scenarios (He, 2003; Lu *et al.*, 2005; Metternicht and Gonzales, 2005). Since erosion adversely affects ecosystems on-site as well as off-site, the estimation of runoff, nutrient and soil loss in agricultural catchments is becoming more important, as concerns on surface water quality increases (Cochrane and Flanagan, 1999). Increasing contamination of surface waters within catchments has generated

substantial concern since the 1940s (Larson *et al.*, 1995). The primary mode of non-point source pollution transport is sediment and water runoff, leading to contamination of surface waters in catchments (Domagalksi, 1996). Therefore, modelling accurately the characteristics of non-point pollution hotspots, is the first step in mitigating surface water pollution. The use of water quality modelling is key in predicting surface water contamination with sediment and chemical during runoff. Water quality modelling thus serves as a valuable tool in determining the temporal and spatial variability of sediment and nutrient pollutant sources (Ficklin *et al.*, 2012).

Environmental models provide information for catchment-scale management and restoration programmes. However, many of the predictive models do not examine the problem in a geographic context (Pullar and Springer, 2000). Under these circumstances, a Geographical Information System (GIS) becomes a valuable tool. A GIS is a powerful set of tools for collecting, storing, retrieving, transforming and displaying spatial data from the real world (Burrough, 1986). GIS has made a tremendous impact in many fields of application, because it allows the manipulation and analysis of individual layers of spatial data, and at the same time providing tools for analysing and modelling the interactions between geospatial data layers (Bonham-Carter, 1996). Coupled to an environmental model such as the Soil and Water analysis Toolkit (SWAT), a GIS can interpret simulation outputs in a spatial context (Pullar and Springer, 2000). The SWAT utilizes readily available digital geo-referenced information from accessible internet sources like topographic maps, digital elevation models, land use and soil maps (Renschler *et al.*, 2002), with the aim of evaluating various land-use scenarios in relation to assist with soil and water conservation planning. Detailed description of SWAT model are widely documented (e.g. Arnold *et al.*, 1999 and Neitsch *et al.*, 2001).

In a review of different watershed-scale hydrological and non-point-source pollution models, Borah and Bera (2003) denoted the SWAT as a model with a high potential to modelling the hydrology, sediment and chemical variables of a complex large basin. The SWAT model has been successfully applied globally in different scenarios for long-term continuous simulation of flow, sediment and nutrient transport in a range of hydrogeological and climatic conditions over drainage areas covering 5.5 to 491700 km^2 on a monthly time-scale (Borah and Bera, 2004; Gassman *et al.*, 2007). The application of SWAT model in East Africa has shown its potential in data-scarce river basins (Mulungu and Munishi, 2007; Ndomba *et al.*, 2008). In Kenya, Jayakrishnan *et al.* (2005) used the SWAT model to identify the drivers behind land

use changes particularly those associated with dairy farming on stream discharge, water quality and sedimentation rate in approximately 3050 km^2 of the Sondu-Miriu Basin. Jayakrishnan *et al.* (2005) noted that the monthly-simulated surface runoff discharge into River Sondu-Miriu from the dairy farms in SMB compared well to the observed values with a Nash-Sutcliff Efficiency (NSE) of 0.1 (Nash and Sutcliff, 1970). Similarly, in Lake Tana Basin in Ethiopia, satisfactory performance and applicability of SWAT has been reported (Setegn *et al.,* 2009; Betrie *et al.,* 2011; White *et al.*, 2011). Based on these reviews and applications amongst other studies in numerous watersheds globally, SWAT model qualified for use in this study to model sediment and nutrient loading rates in Sondu-Miriu Basin.

While applying the ArcGIS model and the ArcGIS-based SWAT, the SMB study dealt with simulation of sediment and nutrient loading rates, and trend analysis, under different scenarios. Estimates and comparisons of sediment yields, nitrogen and phosphorus loads from the basin under different land uses were documented. The objective was to estimate the temporal variability in the loads of sediment and nutrients transferred via surface runoff from different LULC activities in SMB using ArcSWAT model.

5.3. Materials and Methods

5.3.1. Study Area

Detailed description of this section is provided in chapter 3 section 3.3.1.

5.3.2. Digital Elevation Models for Sondu-Miriu Basin

The date of satellite image acquisition, area of interest and pre-processing procedure greatly determine the spectral responses of surface features (Jensen, 2007). These properties were considered during image selection. In this study, a 28-year period (1985-2013) was considered based on the observed satellite images which showed significant LULC changes over 10-year intervals. In order to compare the changes, the reference years selected based on Digital Elevation Models (DEMs) generated in February of 1985, 2000 and 2013 respectively, using 30 m x 30 m-spatial resolution LANDSAT digital images. The 1985 DEM was developed from LANDSAT 5 (LANDSAT TM) while LANDSAT 7 was used for the 2000 (LANDSAT ETM+) and 2013 (LANDSAT ETM SLC off) DEMs based on the periodically upgraded space satellite stations.

Preliminary watershed delineation of the Sondu-Miriu basin was conducted using the GIS-based ArcSWAT after which satellite images/indices were used to capture the SMB

LANDSAT images (Row/Path: 60/170, 60/169 and 161/169). The LANDSAT images were downloaded from the United States Geological Survey (USGS) website for polygon overlays (USGS, 2013). The best images were selected based on <10% cloud cover, the periods of interest, the availability and ability to download selected images from the USGS website.

Three multispectral bands (2, 3 and 4) were selected from each image for processing. New satellite images were then created (mosaicking) by spatially orienting overlapping images and optionally balancing the numeric characteristics of the image set based on the overlapping areas of bands 2, 3 and 4 for respective images. This created single satellite images for February in 1985, 2000 and 2013 respectively. Using the ArcSWAT delineated watershed, a sub-image was extracted from each mosaic to obtain three new sets of images defining the study area. Compositing (production of composite images of the three bands) of the images produced Colour Infra-Red (CIR) composites images for display and visual analysis.

Geo-referencing (assigning true ground coordinates to an image) using overlay images from different periods was done to check for conventional 1:1 overlay ratio. For any shifts, co-registration (shifting one image based on an absolute location) processing produced a perfect 1:1 fit of the overlays. The images generated were then enhanced (stretching) to distinguish the LULC features in SMB. The ArcGIS unsupervised image interpretation and classification categorized the basin into different LULC classes for logical and descriptive and statistical analysis of changes in LULC. The LULC classes generated from the satellite imagery were further integrated into ArcSWAT as part of input components to model sediment and nutrient loading rates in SMB.

5.3.3. Land Use/ Land Cover Change Analysis

Post-classification analysis (Bauer *et al.*, 2003) was done to detect LULC changes from the multispectral satellites images of Sondu-Miriu basin acquired over the 1985, 2000 and 2013 periods. Classified images of 1985, 2000 and 2013 with the respective thematic classes obtained above were analysed to identify the trajectory of LULC changes through 28 years. The coded and attributed raster images database was queried using GIS analytical tools of IDRISI Kilimanjaro. The area covered by each LULC class was computed and change in percentage determined according to equation 1.

$$\% \text{ change} = \frac{Area_{year\ k+t} - Area_{year\ k}}{Area_{year\ k}} \times 100 \qquad (5\text{-}1)$$

where,

Area $_{year\ k}$ = Area of $LULC_i$ at initial date

Area $_{year\ k+t}$ = Area of $LULC_i$ at the next date

A further analysis of the inter-class changes between the three periods was done in IDRISI Kilimanjaro and mathematical computations executed in MS Excel software.

5.3.4. Modelling in ArcSWAT

In ArcSWAT, the sub-basin components can be classified into weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management. In the terrestrial phase of the hydrological cycle, surface runoff is predicted separately for each Hydrologic Response Unit (HRU) and routed to obtain the total runoff for the watershed. Once the loadings of water, sediment and nutrients to the main channel were determined, they were routed through the mainstream network of the catchment.

Conceptual Modelling

The ArcSWAT conceptual model for SMB is a four step-process: recognition, monitoring, mitigation and rectification (Verstraeten *et al.*, 2003), based on socio-economic and biophysical conditions of the basin (Figure 5-1). This model attempts to identify problem situations and actors, and employs a systems analysis approach towards problem-solving. The systems approach in analysis is useful for map calculation and scenario analysis of different basin management alternatives. Model outputs are displayed in vector-based ArcGIS software. The model also integrates participatory-GIS (PGIS) tools which are fundamental in participatory learning activities (PLAs) which generate GIS relevant data for further modelling and generating more information. Datasets from different sources (Table 5-1), were overlaid in ArcGIS to produce LULC classes, erosion risk and ultimately a net erosion and nutrient loss map for simulating sediment and nutrient loss rates using ArcSWAT in SMB.

The conceptual model illustrates the entry points for input and processing components used in generating relevant thematic maps in ArcGIS which are overlaid at different stages. The information from the overlays and the primary or secondary data is then input and processed in ArcSWAT. The simulated outputs of runoff, sediment and nutrients provide a basis for adaptive management strategies which are vital in enacting policies for community participatory watershed resources management.

Table 5-1: Data sources for modelling of nutrient and sediment yields using ArcSWAT.

	Data type	Source
1.	Climate (rainfall, air temperature)	• Kenya Meteorological Department-Kericho station
2.	Land Use/Land Cover	• USGS LANDSAT satellite images
3.	Soils map	• Soil and Terrain database of Kenya (KENSOTER)
4.	River Discharge & Nutrients	• WRMA-Lake Victoria South Basin
5.	Satellites Images for generating DEMs	• United States Geological Survey (USGS) 30m-Digital Elevation Multispectral Databases

ArcSWAT Model Setup

a) Basin Delineation

The Sondu-Miriu Basin and sub-basin delineation was carried out using the basin's DEM. The DEM was loaded and a layer of the existing river network burnt to it to support successful and accurate definition of streamflow direction and accumulation. The basin was further delineated into 17 sub-basins to facilitate generation and analysis of results for the different parts of SMB. Eventually, basin parameters such as area, flow path and length among others were automatically computed within the system.

b) Hydrologic Response Unit (HRU) Definition

The HRU definition involved initial definition of the land use classes, soil types and slope categories linked to the respective look-up tables. Look-up tables allow the system to understand the different classes through reclassification. An overlay of all these classes combined the three layers. The resultant sub-classes (HRUs) from the overlay were then defined by the ArcSWAT model.

c) Writing Input Files

The datasets used in writing input files included: model configuration, soil, weather, main channel, groundwater, management, sub-basin, HRU, master file and watershed. This operation is carried out by the system automatically. Important input data was processed prior to the ArcSWAT model setup to ensure that the datasets fitted correctly into the model.

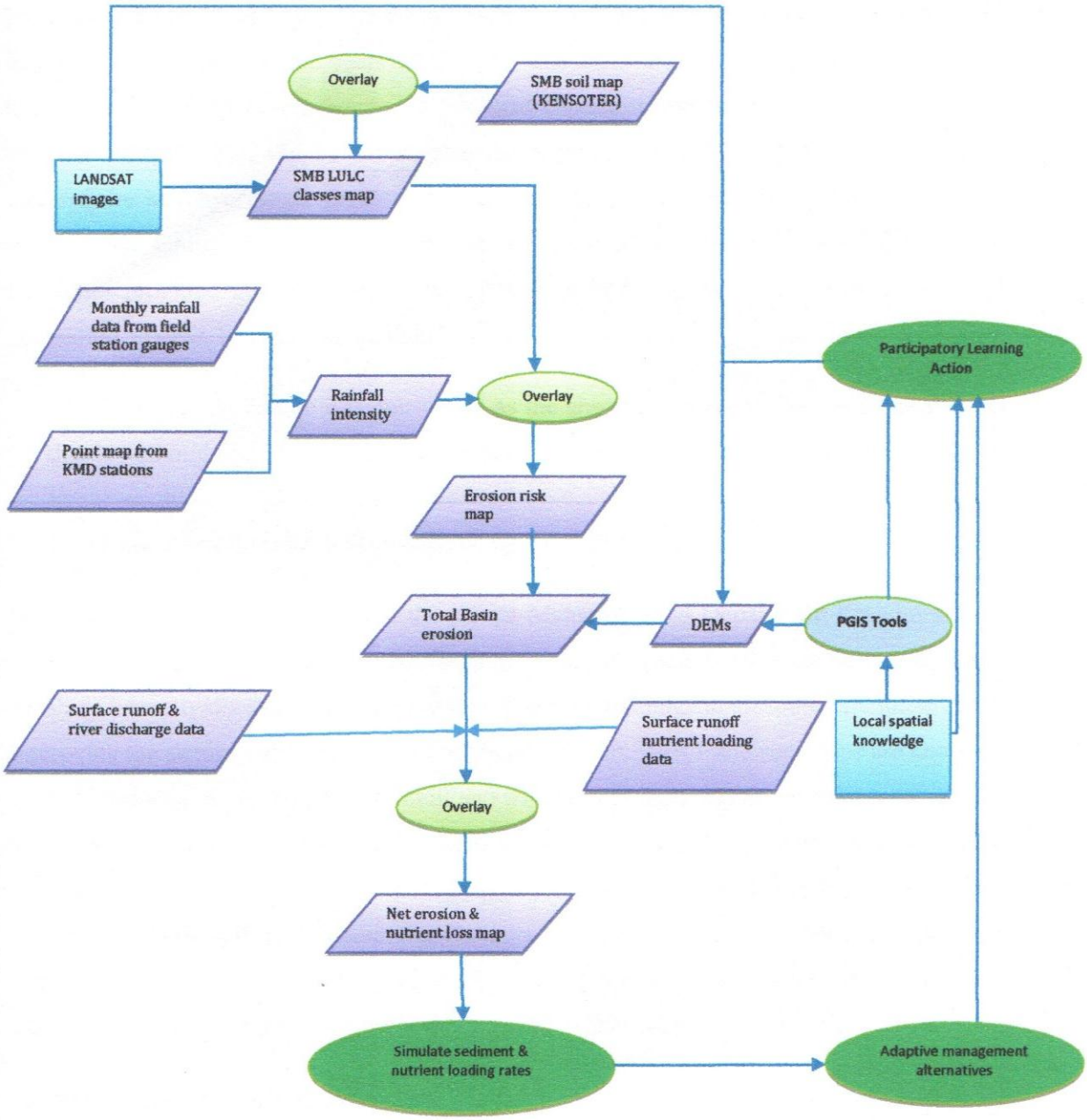


Figure 5-1: Conceptual model integrating biophysical and socioeconomic drivers for simulating sediment and nutrient loading in surface runoff in SMB.

Community-based mitigation options involving local knowledge and participatory learning in developing best management practices are also shown. KMD-Kenya Meteorological Department; KENSOTER - Kenya Soil and Terrain database.

The four key datasets included LULC, Soils, DEMs and Climate data. The data layers were projected into the Universal Transverse Mercator (UTM) projection system and WGS84 datum. LULC layers for the years 1985, 2000 and 2013 were used for the SWAT model input. The LULC layer represented 7 land-use classes in the basin. The soils layer was extracted from the Soil and Terrain database of Kenya (KENSOTER), which also contained most of the key hydrologic parameters needed to support successful setup of the SWAT model. The United States Geological Survey (USGS) Digital Elevation Multispectral Databases provided the 30-m resolution DEM used in the model setup. During the DEM generation process, it was assumed that:

1. The 2000 satellite image was considered as the absolute reference year based on the fact that it was midway of the 3 processing periods. Hence the errors in processing the 2000 image would be distributed either way.
2. Curvature corrections have been done on the projected images.

Rainfall and temperature data from the Kenya Meteorological Department-Kericho station, located within SMB was processed for input into the model. Datasets on wind speed, sunshine intensity/duration were unavailable. These climatological attributes are important in improving the accurate and precision of predictions in ArcSWAT and such gaps are known to increase noise in model outputs. Rainfall and temperature data, which were the most critical, were however provided with some minimal percentage gaps. The weather generator within ArcSWAT was used to estimate the missing datasets for wind speed, sunshine duration and intensity, rainfall and air temperature. Datasets on water physicochemical parameters and stream flow from gauging stations along River Sondu-Miriu was provided by the WRMA-Lake Victoria South Basin for input into the model (Table 5-1).

Model Simulation and Validation

The ArcSWAT model processing was split into warm-up (1999-2002) and actual simulation periods (2010-2012). The model was configured to produce results at yearly time-steps for surface runoff, sediments and nutrients for the 17 sub-basins from 2010 to 2012. These results were compared against the surface runoff, sediments and nutrients data collected in the field from the experimental plots at Kabianga and Sondu for the same period. This procedure objectively checks for consistency and validity as a measure of the model performance.

Measure of Model Performance

The simulated and measured values were compared using the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency, NSE (Nash and Sutcliffe, 1970). The R^2-value (Equation 5-2) was used to assess whether the simulations had reproduced observed variability of the natural sediment and nutrient flow processes while minimizing the overall deviation.

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})\right]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad \text{..... (5-2)}$$

where, O_i is the i^{th} observation for the constituent being evaluated, S_i is the i^{th} simulated value for the constituent being evaluated, O is the mean of observed data for the constituent being evaluated, and S is the mean of simulated data for the constituent being evaluated. R^2 varies between 0 and 1 and is optimal at 1.

The NSE is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (Equation 5-3).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right] \quad \text{..... (5-3)}$$

where Y_i^{obs} is the i^{th} observation for the constituent being evaluated, Y_i^{sim} is the i^{th} simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

The NSE measures performance during high flow events and ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is statistically a better estimate or predictor than the simulated value.

Forecasting with ArcSWAT

In the model, a file containing a series of statistical parameters that the SWAT weather generator uses for different climatic components in its prediction was prepared. The forecast tool was then activated in the ArcSWAT model window and the forecast period 2013-2020

specified. Forecasting was then performed to generate projected sediments and nutrient yields for each sub-basin over the 8-year period.

During forecasting, several variables in the sub-basins were not explicitly accounted for by the model framework. Assumptions were made on the contribution of sediment and nutrient pollutants via surface runoff from other sources (e.g. small-scale mixed farms, urban runoff, and gully erosion) in each sub-basin:

1. Surface runoff from the small-scale mixed farms, urban settlements and other anthropogenic activities in SMB were not directly considered. Instead, the effects of such activities were assumed to be reflected in yields from the different land uses studied.
2. Climatic variability: While it is possible that Kabianga may have experienced a high number or intensity of precipitation events during the forecasting period, the unit-area rainfall yields for Kabianga and Sondu were assumed to be similar.
3. Soil properties: The ArcSWAT model utilised the generalised soil classes within the basin and assumed little impact of the minor soils on sediment and nutrient loads.
4. Slope length (LS-Factor) GIS layer: The LS-factor was derived in ArcSWAT. The minimum value of the slope exponent was set to 0.2 instead of 0.0, and the maximum at 0.5 instead of 0.6 (Wischmeier and Smith, 1978). This enabled the creation of the LS-factor GIS layer with a single equation/operation rather than several operations. The derived operation was applied across the sub-basins irrespective of the site-specific differences in topography.

The effect of climate change was not adequately by the model. Paleoclimatic studies in the Lake Victoria Basins have indicated long-term periodic climate variability characterised by cyclical changes in orbital insolation, global and atmospheric hydrologic circulation (e.g. Stager, 1997). Studies indicate that the effects of climate change could exacerbate environmental degradation in the basins of Lake Victoria including SMB (Masese *et al.*, 2012: Shepherd *et al.*, 2000). Climate change is known to determine changes in crop type and management, flood regimes and water availability, and other changes in human use and management of watershed resources (Johnson *et al.* 2012; Masese *et al.*, 2012).

5.4. Results

5.4.1. Digital LULC Patterns in Sondu-Miriu Basin

The 1985, 2000 and 2013 DEMs were used in the digital classification of LULC features in February for 1985, 2000 and 2013 respectively (Figure 5-2, 5-3 and 5-4). Image classification

generated six major LULC classes: commercial farms, degraded forest, natural forest, rural settlements/farms, shrub/bushland and urban settlements. There were temporal changes in proportions for different LULC classes in the three periods considered (Table 5-2). In general, farming is the dominant land use across the three periods with commercial and subsistence farming constituting above 58% of LULC over the 1985-2013 period. Predictably, with increased demand for farmland and settlement, shrub/bareland and natural forest cover decreased especially with intensified degradation between 1985 and 2000. However, notably is the significant halt on forest degradation and total conversion of degraded forest to farmland between 2000 and 2013 coupled with decrease in forest cover by nearly 9.5 km^2.

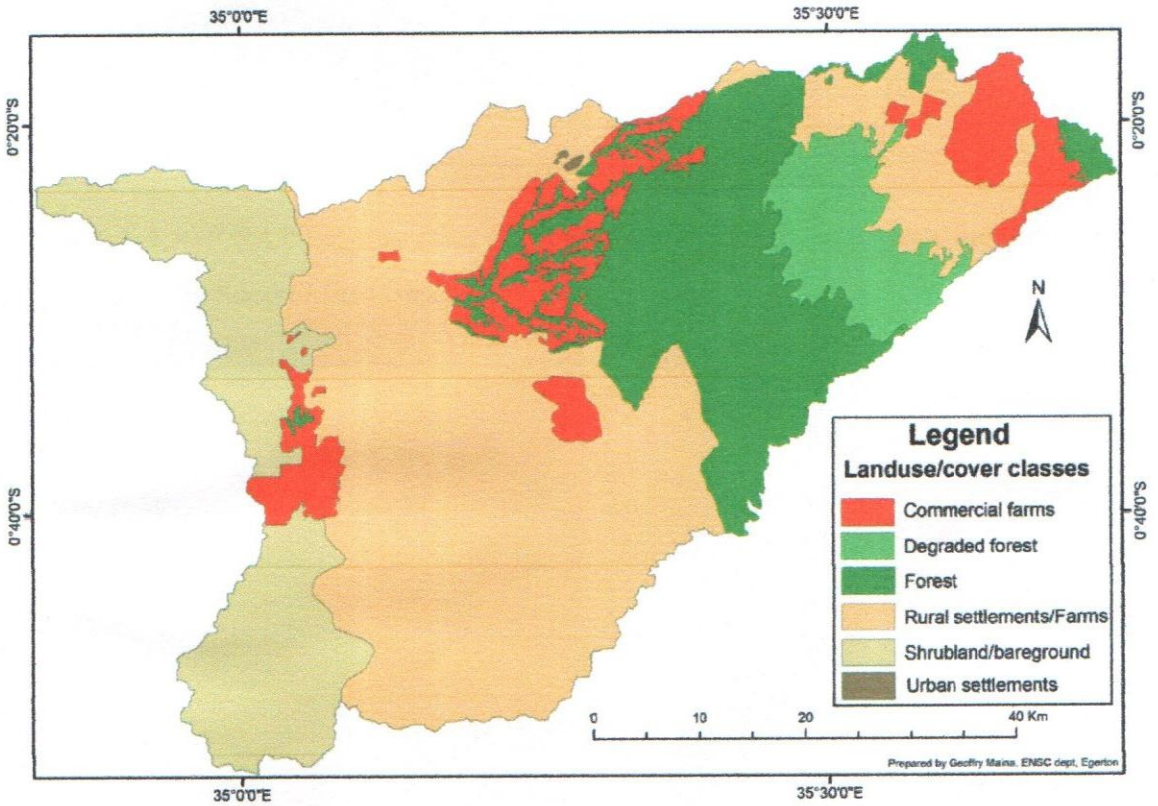


Figure 5-2: Classified February 1985 LULC features from LANDSAT imagery generated from Sondu-Miriu Basin.

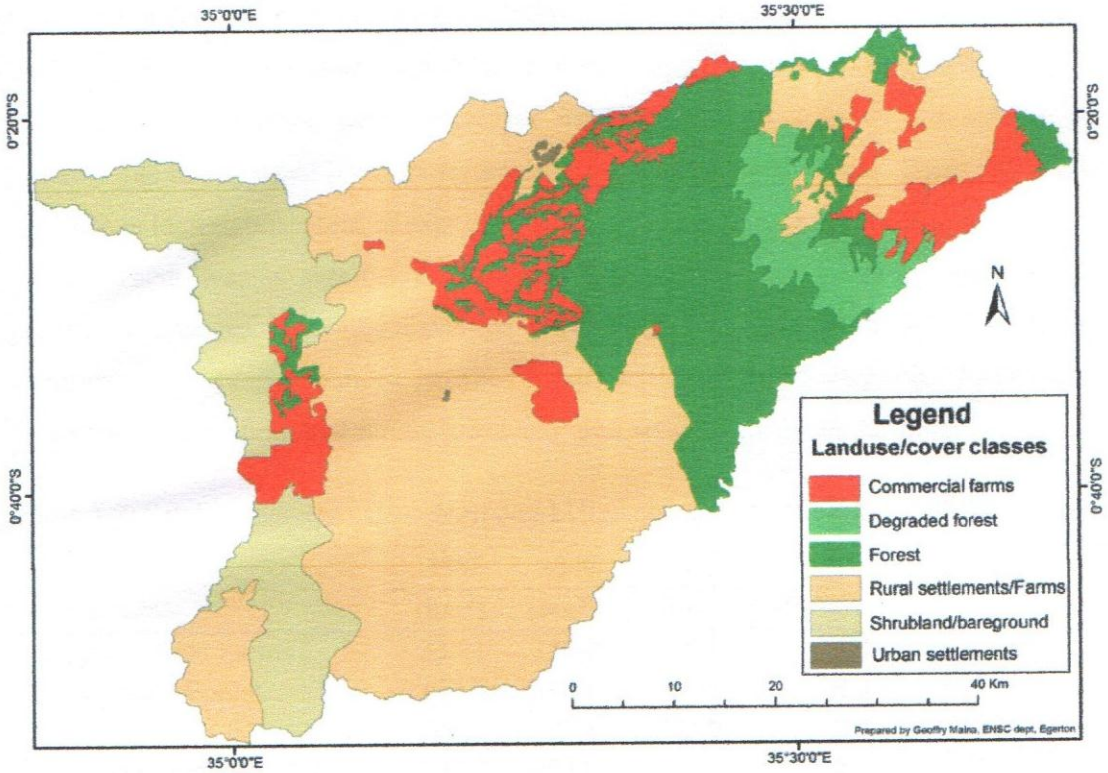


Figure 5-3: LANDSAT imagery class assignments for February 2000 isolating the dominant LULC classes in Sondu-Miriu Basin.

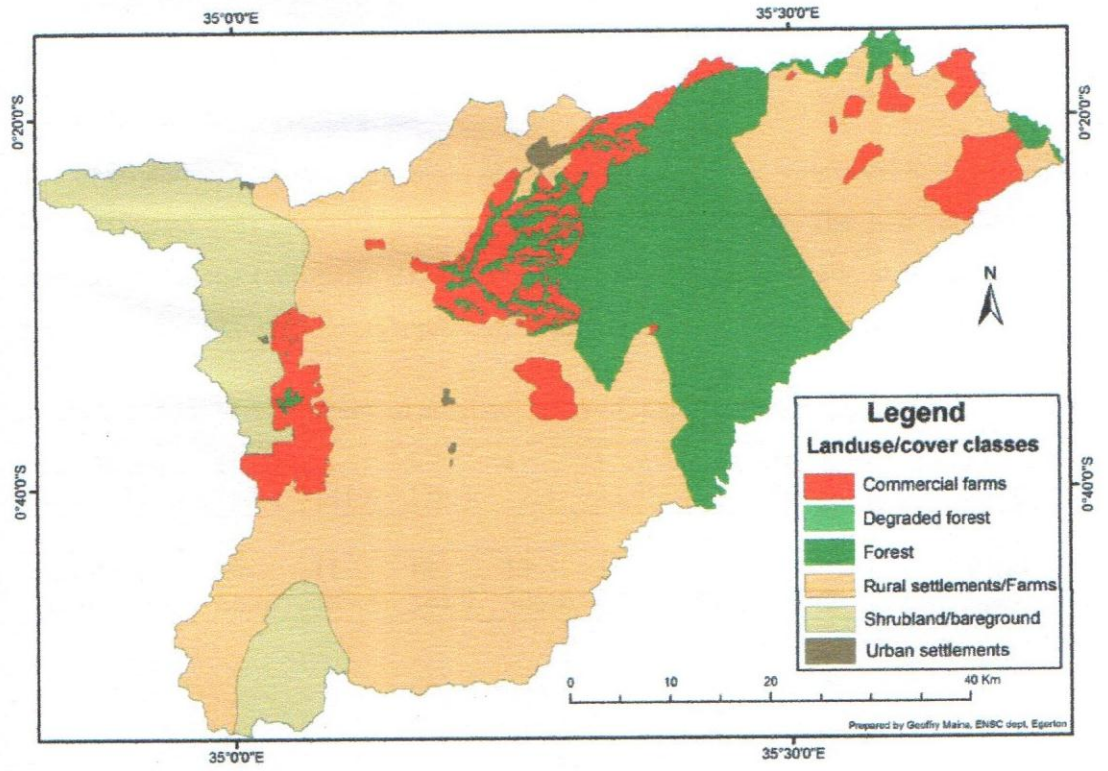


Figure 5-4: LULC classification for February 2013 generated from LANDSAT imagery in Sondu-Miriu Basin.

Percentage changes in LULC patterns for different periods (Table 5-2) revealed the highest increment under urban settlements from 126% (1985 and 2000) to 477% by 2013. Demand in land used for rural settlements/farming increased from 2.8% in 1985 to 20.7% in 2013. However, shrub/bareland cover decreased between 9.5 and 30% over a similar period possibly due to increased pressure for land for farming and settlements. There was a general decrease in the establishment or expansion of commercial farms by 7% during the 2000-2013 period. There was a significant difference among the LULC classes with respect to percentage changes in spatial coverage (ANOVA, $F_{2,\ 5} = 5.275$, $p < 0.05$). There was significant percentage changes between urban settlements and degraded forest sections, shrub/bareland, commercial farms, forest and rural settlements/mixed farming.

Table 5-2: Satellite-detected spatiotemporal LULC change classification in SMB.

	1985	2000	2013	% change		
LULC Class	**(km²)**	**(km²)**	**(km²)**	**('85-'00)**	**(00-'13)**	**('85-'13)**
1 Commercial Farms	358.1	380.3	354.8	**6.2**	**-6.7**	**-0.9**
2 Degraded Forest	159.6	146.8	0	-8.0	-100.0	-100.0
3 Forest	716.8	713.8	705.0	-0.4	-1.2	-1.7
4 Rural settlements/ Farms	1609.2	1653.8	1942.7	**2.8**	**17.5**	**20.7**
5 Shrub/Bare land	563.2	509.5	394.4	**-9.5**	**-22.6**	**-30.0**
6 Urban Settlements	2.1	4.7	12.1	**126.7**	**154.8**	**477.6**

5.4.2. ArcSWAT Model Outputs

Sondu-Miriu Basin Delineation

The SMB and sub-basins delineation process sub-divided the watershed in 17 serialised sub-basins (Figure 5-5) covering varying proportions (Table 5-3). The two sub-basins studied here are Kabianga (sub-basin 3), and Sondu (sub-basin 9). Sondu is about twice as large as Kabianga. The two sub-basins represented approximately 10% of the 3409 km² SMB.

Table 5-3: ArcSWAT-generated areal coverage of major sub-basins in SMB.

Sub-Basin	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Area (Km²)	165.4	141.4	130.3	17.3	33.3	7.7	179.9	65.7	265.0

Sub-Basin	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**Total**
Area (Km²)	66.6	189.5	584.9	506.1	479.6	46.2	303.7	227.6	**3409**

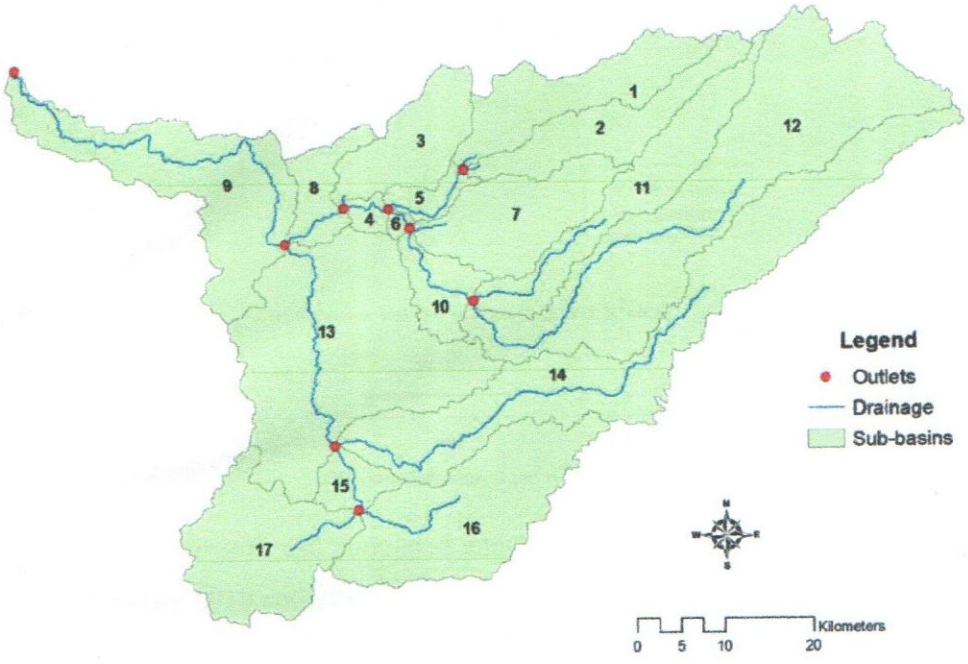


Figure 5-5: Sondu-Miriu Basin with major sub-basins. Basin 3 = Kabianga, and 9 = Sondu.

Discharge, Sediment and Nutrients

In general, there was increased annual observed and simulated discharge from 2010 to 2012 at both sites although Sondu recorded higher volumes (Figure 5-6). Simulated annual discharge output correlated positively with the observed at Sondu ($R^2 = 0.52$) but highly at Kabianga ($R^2 = 0.79$). The model was considered suitable for predicting discharge trends from 2013 to 2020 (Figure 5-7). Sondu forecast discharge ranged between 60 and 117 $m^3 s^{-1}$ with marked fluctuations and reductions from 2015 to 2017 followed by a sharp rise in 2018 and peaking in 2020 at 124 $m^3 s^{-1}$ per annum. At Kabianga, the low but relatively stable annual discharge volumes were projected for the 2013-2020 period. The annual forecast for discharge at Kabianga was below 50 $m^3 s^{-1}$.

The measured and simulated sediment concentrations from surface runoff in Kabianga (Figure 5-8) and Sondu (Figure 5-9) were highly and positively correlated. Simulated sediment levels accounted for 78.5% at Kabianga and 91.4% at Sondu respectively, of the total variability. Initial predictions estimated annual sediment concentrations for Kabianga at 135 mg L^{-1} in 2013. The highest concentrations of 157 mg L^{-1}, will be expected in 2015, and the lowest at 82 mg L^{-1} in 2017. In Sondu, sediment concentrations will generally be higher compared to Kabianga ranging from 492 to 323 mg L^{-1} in 2015 and 2017 respectively (Figure 5-10).

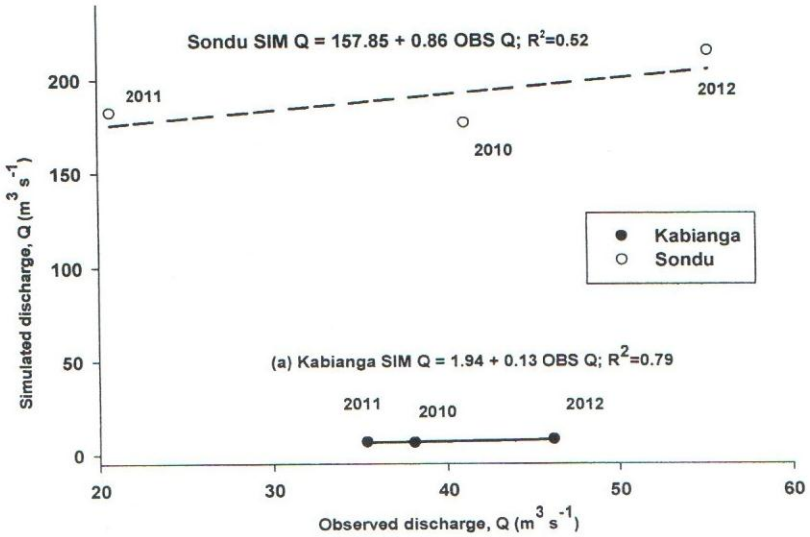


Figure 5-6: Measured and simulated annual discharge from surface runoff at Kabianga and Sondu between 2010 and 2012.

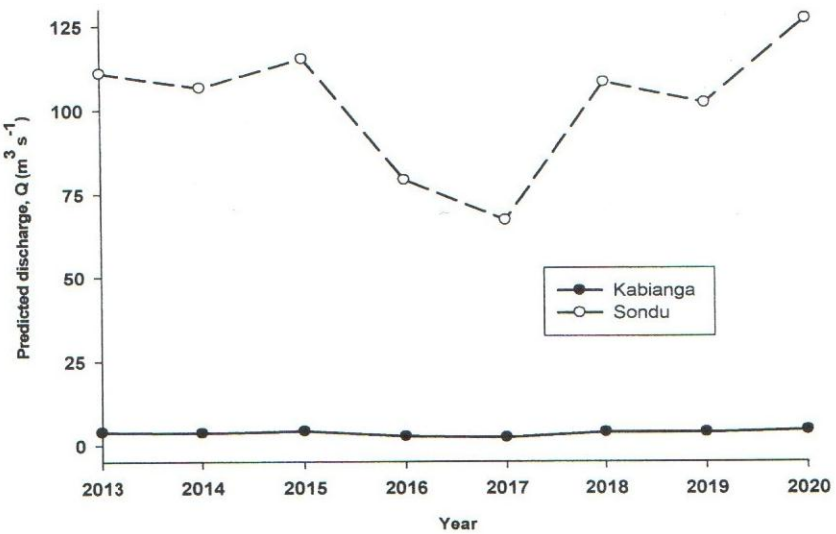


Figure 5-7: Trends in predicted mean annual discharge of surface runoff at Kabianga and Sondu from 2013 to 2020.

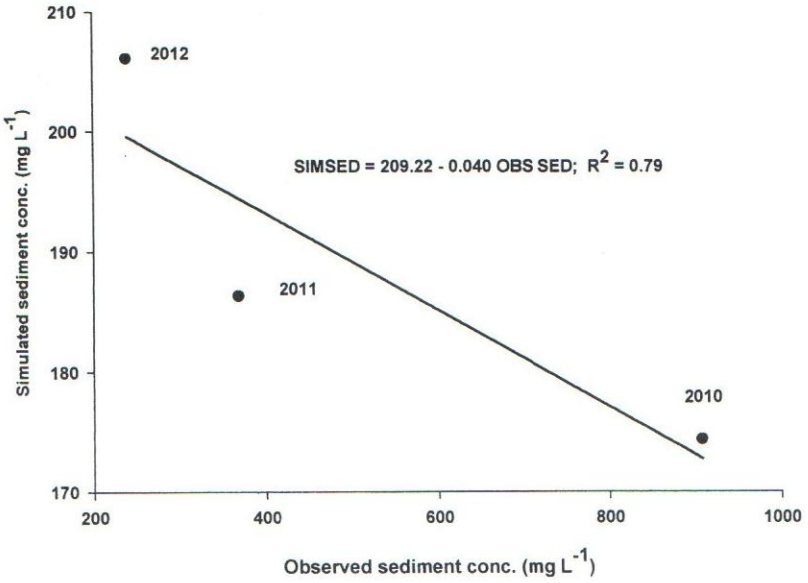


Figure 5-8: Comparison between measured and simulated sediment concentrations in surface runoff at Kabianga from 2010 to 2012.

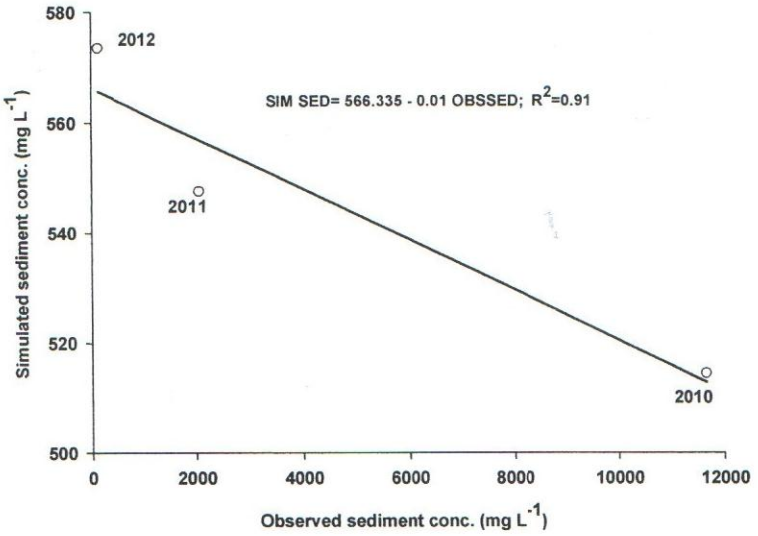


Figure 5-9: Comparison between measured and simulated sediment concentrations in surface runoff in Sondu from 2010 to 2012.

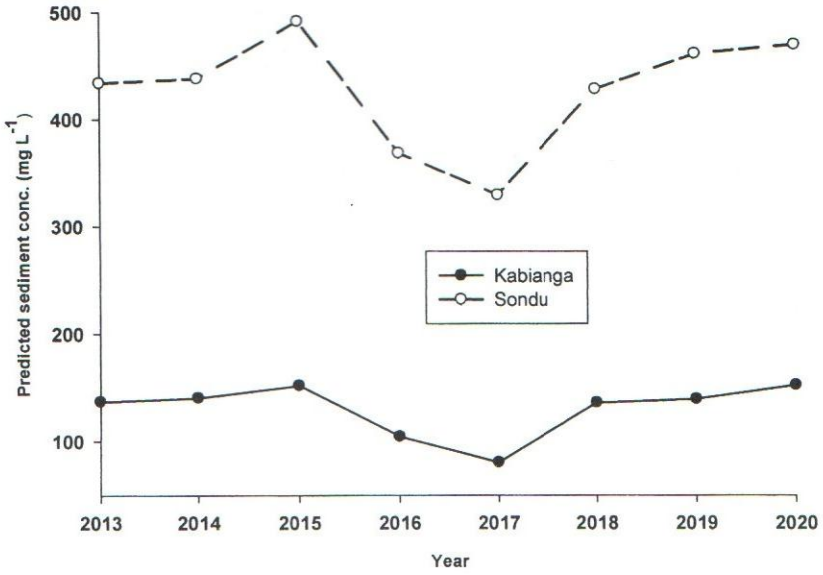


Figure 5-10: Eight-year forecast of annual trends of sediment concentration in surface runoff at Kabianga and Sondu.

At Kabianga, the measured versus simulated yields of NH_4-N could not be compared since the model generated zero values. In Sondu, the correlation between the two variables was generally weak with the model accounting for only 11% of the total variability in the measured values. Hence, the model was unreliable in prediction of NH_4-N trends in Sondu. Nevertheless, Sondu recorded 2 peaks in the annual NH_4-N yields at 955 and 1,011 kg N km^{-2} in 2015 and 2018 respectively. The lowest concentration over the whole period was 423 kg N km^{-2} in 2016.

The modelled and measured NO_3-N yields displayed weak correlations at both sites (Sondu, $R^2 = 0.15$; Kabianga, $R^2 = 0.42$) (Figure 5-11). Generally, an increase in NO_3-N annual yields from the agricultural land uses is expected from 2013 at both sites. Between 2013 and 2014, the annual NO_3-N yield at Kabianga is predicted to decrease while there will be an increase over the same period in Sondu. The yields in Sondu will remain above that at Kabianga for the entire period as predicted by the model. The highest yield for both sites will be in 2020 at nearly 3,100 and 44,000 kg N km^{-2} at Kabianga and Sondu respectively. Kabianga will have 2 lowest yield years in 2016 and 2017, with average annual yields of 2,290 kg N km^{-2}. In Sondu, the expected lowest output over the entire period will be in 2017 estimated at 2,400 kg N km^{-2} (Figure 5-12).

The SWAT model did not adequately correlate the observed versus simulated annual yields of SRP at Kabianga ($R^2 = 0.02$) and Sondu ($R^2 = 0.03$). The 2013-2020 annual predictions for SRP yields revealed an average of 82% higher values at Sondu compared to Kabianga. However, both sites displayed a similar SRP yield trend with 2 peaks in 2015 and 2019 at Kabianga, and 2015 and 2018 in Sondu. Overall, Kabianga is predicted to record an average 2 kg P km^{-2} increase in SRP yields 2020. In contrast, Sondu will have reduced output of SRP by nearly 12 kg P km^{-2} over this period (Figure 5-13).

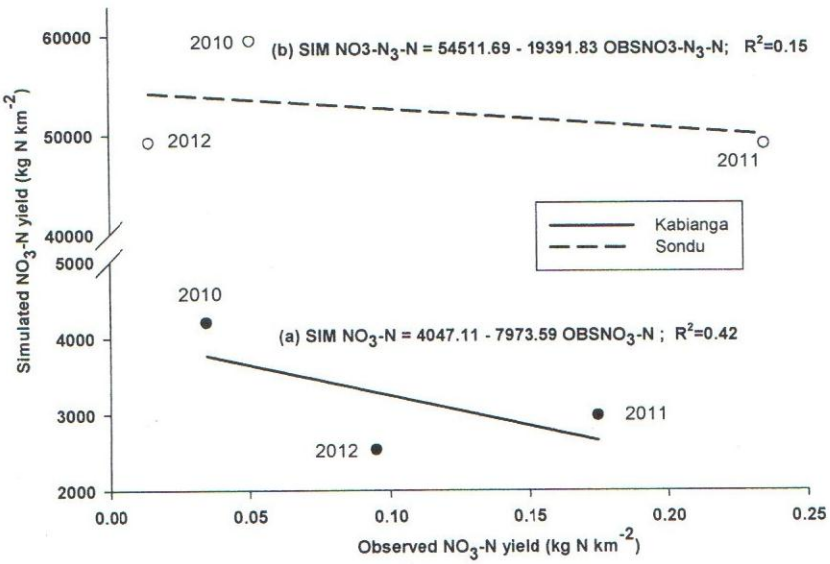


Figure 5-11: Correlation between observed and simulated annual NO_3-N yields between 2010-2012 at Kabianga and Sondu.

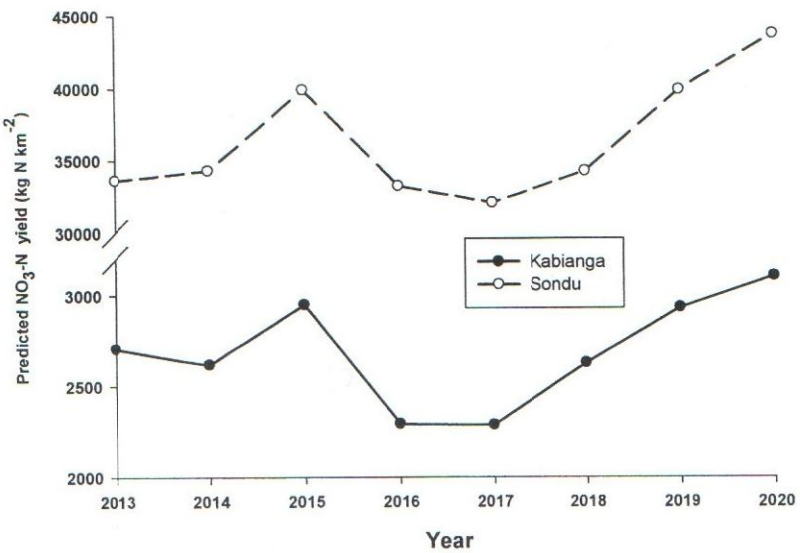


Figure 5-12: Annual predictions in NO_3-N yields via surface runoff from different land uses at Kabianga and Sondu.

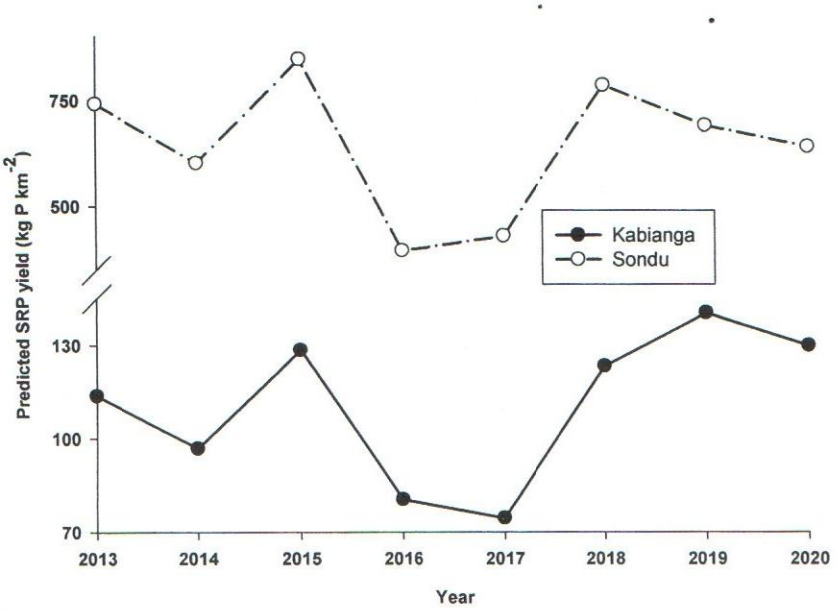


Figure 5-13: Predicted annual yields for SRP from different land uses between 2013 and 2020 at Kabianga and Sondu.

The trends for discharge, sediments and nutrients in the two sites were expressed in percentage change between successive years from 2013 to 2020 to establish the variability in yields (Figure 5-14). Generally, the highest percentage increase (30%-84%) in annual discharge volume, sediment and SRP at Kabianga and Sondu is predicted to occur during the 2017-2018 period while NH_4-N will have three peak percentage increases (2014-15, 2017-18 and 2018-19). The highest percentage decrease in discharge, sediments and nutrients is expected to range between 16% and 56% during the 2015-16 period. However on average, discharge will increase by 5.7% and 5.4%, sediment by 5.3% and 2.5%, NO_3-N by 2.8% and 4.5%, SRP by 6.5% and 6.1% at Kabianga and Sondu respectively. NH_4-N is projected to change on average by approximately 10% in Sondu over the entire duration.

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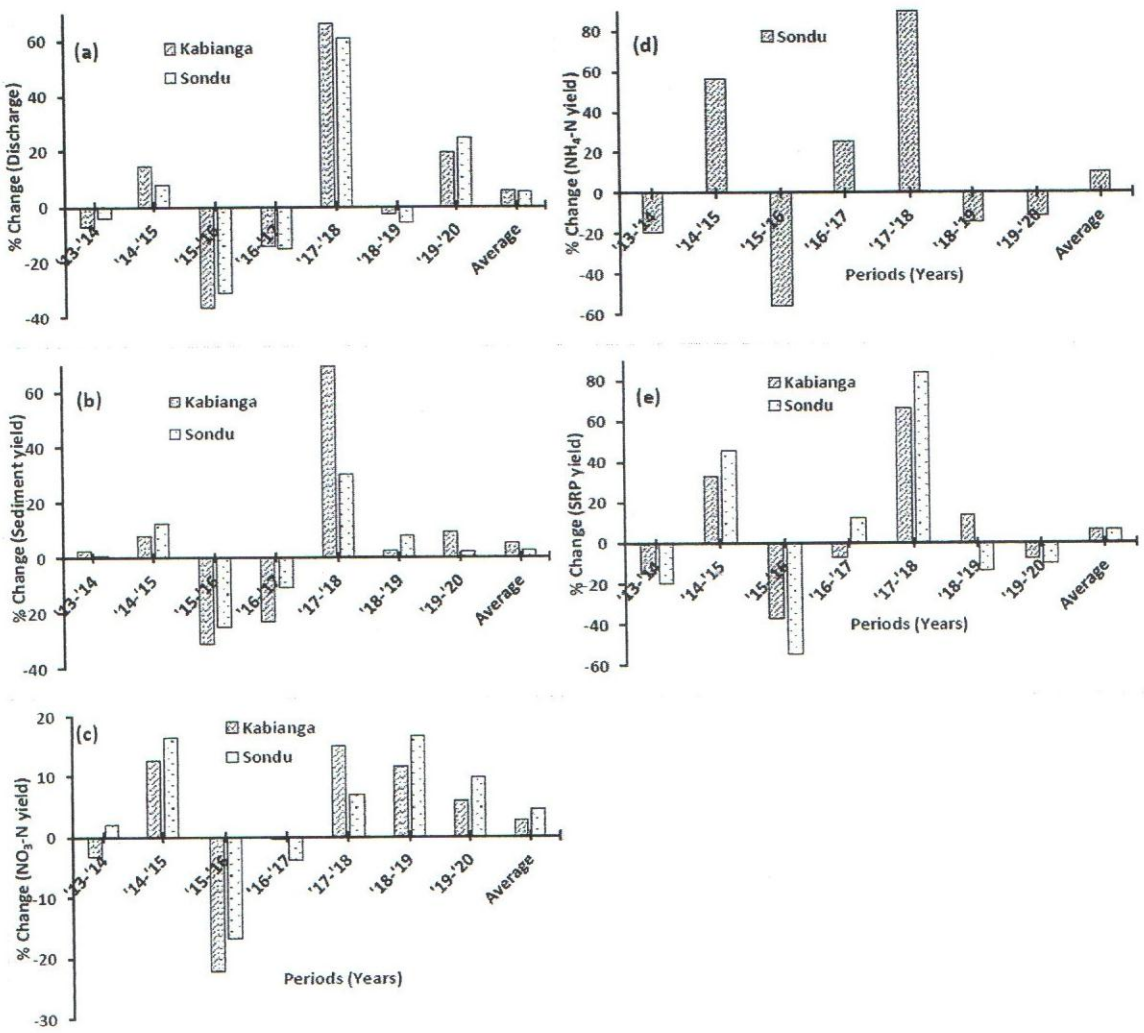


Figure 5-14: Percentage changes in discharge, sediment and nutrient yields from ArcSWAT model output for the years 2013 to 2020 in SMB.

During the 8-year model predictions, there were highly significant relationships between the annual discharge pattern, and the sediment and nutrient yields at both sites (Table 5-4). The annual sediment yields directly related to the discharge patterns with strong correlations ($0.80 < R^2 < 0.90$,) which were significant at both sites ($p < 0.05$). Discharge strongly influenced NO_3-N yields at Kabianga ($R^2 > 0.80$) and Sondu ($R^2 > 0.50$) with significant varibility ($p < 0.05$). In Sondu, the yields of NH_4-N were also strongly correlated and significantly corresponded to discharge ($R^2 > 0.70$, $p < 0.05$). Discharge at Kabianga highly correlated and significantly determined the annual output of SRP ($R^2 > 0.70$, $p < 0.05$).

Table 5-4: Influence of predicted annual discharge (Q) on projected 2013-2020 sediment (Sed), NO_3-N, NH_4-N and SRP annual yields at Kabianga and Sondu in SMB.

Site	Equation	R^2-value	$F_{(1,6)}$	p-value
Kabianga	Sed = 11.9 + 32.5Q	0.95	115.65	<0.001*
	NO_3-N = 1348.1 + 363.5Q	0.86	35.67	<0.001*
	SRP = 4.1 + 30.1Q	0.70	13.92	0.010*
Sondu	Sed = 168.9 + 2.5Q	0.85	33.30	0.001*
	NO_3-N = 1525.4 + 12Q	0.53	6.79	0.040*
	NH_4-N = -4.1 + 0.6Q	0.72	6.56	0.043*
	SRP = 11.9 + 0.5Q	0.45	4.86	0.070^{ns}

* = Significant, ^{ns} = not significant at $p < 0.05$

5.5. Discussion

5.5.1. Land use and Land cover changes in Sondu-Miriu Basin

The SMB is facing unprecedented environmental threats related to the expansion of agriculture, deforestation, urbanization and human settlement, erosion and sedimentation, periodic flooding, and point and nonpoint nutrient pollution of aquatic ecosystems. Urbanization increased rapidly between 1985 and 2013 while the increased demand for land for small-scale and plantation farming also went up. Urban land use has been associated with water quality degradation through the release of soluble pollutants and sediment transported via surface runoff (Ibitoye and Eludoyin, 2010). In contrast, increased land cover by natural vegetation and forests in high proportions leads to better water quality (Lee *et al.*, 2009) and higher biodiversity (Clarkson *et al.*, 2007). In SMB, different land use activities and conversion of previously vegetated surfaces for urban expansion and farming are major drivers for increased surface runoff causing sediment and nutrient transfer into surface water systems. From this study, there was reduction in forest cover and shrubland, and subsequent increase in farmland over the 28-year period. However, the rehabilitation of Mau forest previously excised to commercial farms, and eviction of illegal settlers from the forest has seen significant reduction in commercial farming towards 2013. Similar studies (e.g. Sanli *et al.*, 2008) have identified increased human settlement (peri-urban and urban) and intensification of agriculture (small and large-scale) among the contributors of LULC changes and environmental degradation. Njoroge *et al.* (2011) identified a 98 % decrease in forest land from 270 to 105 km^2 between 1976 and 2000 within Nairobi city watersheds. In the study, agricultural land reduced by 25 % from 141 to 106 km^2 over the same period.

The upper reaches of the SMB has been characterised by reclamation of about 21% and 10% of forests and bushland respectively, for farming and settlement between 1986 and 2009 (Masese *et al.*, 2011). Similar trends characterise other river basins in the East African region, including the Njoro, Nyando, Yala, Nzoia in Kenya, and Simiyu-Duma, in Tanzania (Matiru, 2000; Raini, 2009; Twesigye *et al.*, 2011).

5.5.2. Sediment, discharge and nutrient trends

The SWAT 2013 to 2020 projections estimated an increase in sediment loss from different land uses resulting from increase in annual discharge from surface runoff. This is a potential significant contributor to the increase in sediment loads into River Sondu-Miriu. The variability in sediment and nutrient yields is attributable to changes in LULC (Masese *et al.*, 2011) and the climatic changes that determine rainfall patterns and consequently runoff volumes in river basins (Stager, 1997; Shepherd *et al.*, 2000). Rainfall trends in turn influence farming patterns and management approaches, flood regimes and water availability. Reduced land cover or changes in land use that expose soils to water erosion and increase in surface flow rates are potential causes of increased sediment transport into surface waters. Intensification of agriculture, deforestation and increased urban settlements have been linked to increase in magnitude and frequency of runoff events, surface runoff pollution and sedimentation in SMB and other Lake Victoria basins (Osano *et al.*, 2003; Okungu and Opango, 2005; Mati *et al*, 2008; Raini, 2009).

Generally, nitrogen (NO_3-N and NH_4-N) and phosphorus yield is projected to increase between 2013 and 2020. The regression outputs corroborate the average percent increase in annual discharge and the subsequent increase in the sediment and nutrient yields over this period. This signifies the impact of surface runoff as a medium of transport of sediments and nutrients from the terrestrial ecosystems in the tropics (Tondersski, 1996; Dabrowski *et al.*, 2002). Also, the temporal variability in the annual sediment and nutrients yields will depend on the LULC changes and rainfall patterns in SMB.

However, due to the challenges and uncertainties encoutered during modelling, the simulated and predicted yields for some variables and periods may have been overstated or poorly correlated. In SMB, the percentage gaps of input data, including climate data, and other critical basin parameters, which were estimated and autogenerated by the model contributed to uncertainties in model outputs. Ficklin *et al.* (2012) documented uncertainties such as: (1) lack of runoff retetion or diversion data for domestic and agricultural use, (2) lack of

complete knowledge of surface-groundwater interaction, (3) lack of knowledge of the contribution of sediments and nutrient pollutants from urban runoff and development projects. In this study, the above uncertainties were unaccounted for. This was a major challenge during the modelling process. Sediment and nutrient yields in runoff from farmlands and urban settlements have been identified to significantly contribute to such outputs from watersheds (Ibitoye and Eludoyin, 2010).

There are several possible approaches to improving accuracy and increasing reliability of output from river basin models. Climatic differences, particularly rainfall and temperature variability within and between sub-basins necessitate generation of additional sets of unit-area yields by including other weather stations. This increases the confidence in the relative simulation and predicted differences between sub-basins. The utilisation of climate data from only one station, Kericho, which was closest to the two sub-basins may have lowered the confidence in the outputs during the analysis. Soil properties, such as, permeability, greatly influences sediment and nutrient loads from watersheds (Baugmart, 2002). Increasing the resolution of the soil databases by using individual county soil surveys to substitute primary modelling unit layers would improve the simulation and prediction results. Provision and availability of critical input data is instrumental in eliminating uncertainties during modelling.

In general, nutrients will increase possibly due to the changes in LULC that introduce these nutrients to the soil coupled with increase in surface runoff over exposed soil surfaces. The projected sediment and nutrient concentrations in surface runoff from the different land uses in SMB are above the WHO (2012) guideline values and the Kenyan NEMA (2006) Environmental Management and Coordination (WQ) Regulations (TSS: 1200 mg L^{-1} NEMA, NO_3-N: 10 mg L^{-1} NEMA and 11 mg L^{-1} WHO, NH_4-N: 0.5 mg L^{-1} NEMA and 1.5 mg L^{-1} WHO, SRP: 2.5 mg L^{-1} WHO) in surface waters. This implies that the annual loads of sediments and nutrients from surface runoff from the land uses and other anthropogenic activities poses a potential environmental threat to aquatic systems in SMB. There will be deterioration in water quality, possible loss of aquatic biodiversity besides failure in the ecological functioning of the river and other recipient aquatic systems in the Lake Victoria basin. Significant runoff increases and losses of nutrients, sediments, and other pollutants with similar consequences in watersheds and sub-watersheds have also been forecast elsewhere. Tang *et al.* (2005) projected a 5 to 12 % increase in surface runoff volume caused by expansion of settlements between 1978 and 2040. Nitrogen and phosphorus loads in

runoff increased by less than 3 % in about the same period. The reduced loading was possibly due to loss of agricultural land which has a higher nutrient contribution potential. Nagarajan *et al.* (2013) classified watersheds with cropland and fallow/harvested land to be 'very high' while those with higher proportions of dense forests were categorised as 'moderate' runoff potential areas.

5.6. Conclusion

This study evaluated the applicability of ArcSWAT model for long-term sediment and nutrient estimation in SMB. Generally, there was a significant increase in demand for land for settlements and farming. This consequently caused a loss in bushland and natural forest cover over the 28-year period (1985-2013) in the basin. It is projected that increased demand for settlement/urbanisation, farmland and intensification of different land use activities in SMB will increase sediment and nutrient loads in surface runoff in the next decade. The surface runoff water quality in SMB will deteriorate from increased sedimentation. In addition, the increase in nutrient loads in surface runoff from land use activities is predicted to occur between 2013 and 2020. These results showed the potential use of ArcSWAT in understanding the ecosystem processes of basins.

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CHAPTER SIX

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

Natural and anthropogenic factors influence surface water quality and sediment load in drainage basins at different magnitudes over temporal scales. This study, conducted at Kabianga and Sondu, in Sondu-Miriu Basin (SMB) between November 2010 and May 2011, using runoff plots. The objective was to determine the temporal variability of sediments and soluble nutrients (NH_4-N, NO_3-N and SRP) in surface runoff from different land uses. Estimation of the temporal variability in annual surface runoff volumes, sediment and nutrient yields was also carried out using a GIS-based ArcSWAT for SMB for the period 2013 to 2020.

The findings of the study indicate that:

1. There was temporal variability in sediments in surface runoff from the different land uses. This variability in sediment load correlated significantly to the short-rains, dry season dry and the long-rains season. Sediment concentration in surface runoff was higher at the onset and during the rainy seasons.
2. Nutrient levels in surface runoff varied temporally and significantly increased at the onset of rains and during the wet seasons particularly during the long rains.
3. There were temporal changes in proportions for different LULC classes over the three periods (19585, 2000 and 2013). Generally, farming is the dominant land use with commercial and subsistence farming constituting above 58% of the land uses. The highest land-use increment was under urban settlements from 126 (1985 and 2000) to 477%. Rural settlements/farming increased from 3 to 21% over the same period. Shrub/bareland cover decreased between 10 and 30%.

   From the ArcSWAT model outputs, the SMB is predicted to experience a general annual increase in surface runoff volume, sediments and nutrient yields between 2013 and 2020. Intensification of land use activities will considerably increase surface runoff particularly from farmland and settlements. This will eventually increase sediment and nutrient losses via surface runoff erosion.

6.2. Conclusions

1. The sediment loads in surface runoff from different land uses varied across the short-rains, dry and long-rains seasons with higher levels at the onset of the rainy seasons. In general, the highest sediment load in surface runoff occurred during the short-rains. Cropped land was the largest contributor to sediment loss via surface runoff while land under natural vegetation least contributed. The study established that sediment loads in surface runoff in different land uses is influenced by temporal changes in seasonality particularly rainfall variability in SMB.
2. The nutrient levels in surface runoff in the different land uses varied temporally and increased at the start and during the long-rains. There was a general increase in the nutrient load during the rainy season especially in the cropped and weedy-fallow lands. No significant variability in nutrient loads in surface runoff was observed among the different land uses. However, a comparison of the total loads in runoff from all the land uses for the respective nutrients established significantly higher loads during the long-rains.
3. Generally, there was a significant increase in demand for land for settlements and farming, which consequently caused a loss in bushland and natural forest cover over 28-year period in the basin. It is projected that a further increase in demand for land for settlement/urbanisation, farming coupled with intensification of different land use activities, will increase sediment and nutrient loads in surface runoff in the next decade. The surface runoff water quality is thus expected to deteriorate from increased sedimentation. In addition the increase in nutrient loads in surface runoff is predicted to occur further deteriorating the quality of runoff. The results showed the potential use of ArcGIS-SWAT in understanding the ecosystem processes of basins.

6.3. Recommendations

Some of the land-use activities and priorities in drainage basins, coupled with human and animal population increase, are very complex and require long-term integrated management. However, others are less intricate and could be tackled in the short-term with appropriate management approaches. In SMB, possible management measures include:

1. Addressing the land-use activities that significantly increase sediment and nutrient loads in surface runoff. This is through improvement and adoption of best management practices (BMPs) in land use. Improved farming methods and control of effluents and

leakage from farmlands will reduce nutrient loads in surface runoff from agricultural activities.

2. Increase in sediment and nutrient pollutant loads in surface runoff is predicted to continue in the basin. Therefore, adoption of land-use activities that contribute to conservation of surface water quality is paramount. Such measures include increased natural vegetation/forest cover, soil erosion control and conservation tillage particularly in areas vulnerable to erosion by surface runoff.

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