Evaluation of the impacts of soil and water conservation practices on ecosystem services in Sasumua watershed, Kenya, using SWAT model

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

I dedicate this work to mum (Margaret), dad (Onesmus) and my siblings (Irene, Susan, Beth, Obadiah, Gilson and Julius).

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ABBREVIATIONS AND ACRONYMS

DEM	Digital Elevation model
GIS	Geographical Information Systems
GWW	Grassed Waterway
HRU	Hydrologic Response Unit
ICRAF	World Agroforestry Center
MA	Millennium Ecosystem Assessment
MUSLE	Modified Universal Soil Loss Equation
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
NCWSC	Nairobi City Water and Sewerage Company
PES	Payment of Ecosystem Services
PRESA	Pro-poor Reward for Environmental Services in Africa
RUSLE	Revised Universal Soil Loss Equation
USLE	Universal Soil Loss Equation
VFSMOD	Vegetative Filter Strip Model
SWAT	Soil and Water Assessment Tool
USDA	United States Department of Agriculture
CN	Curve Number
USLE_P	Universal Soil Loss Equation practice factor

ABSTRACT

Degradation of agricultural watersheds reduces the capacity of agro-ecosystems to produce Ecosystem Services such as improving water quality and flood mitigation. Conservation of degraded watersheds can abate water pollution and regulate stream flows by reducing flash floods and increasing base flow as a result of enhanced infiltration. The objective of this study was to evaluate the effect of soil and water conservation practices on hydrology and water quality in Sasumua watershed, Kenya using Soil and Water Assessment Tool (SWAT) model. Vegetative filter strips, contour farming, bench terraces and grassed waterways were the conservation measures assessed. They were represented by adjusting relevant parameters in the model and the resulting effect on sediment yield and stream flow assessed. The width of the filter strip was adjusted to simulate vegetative filter strip, USLE-P and CN were adjusted to simulate contour farming and terraces were simulated by adjusting CN, USLE-P and slope length appropriately. Grassed waterways were simulating by adjusting *CH_N2, CH_EROD* and *CH_COV* parameters in the model. Two additional simulations were also done to compare alternative management scenarios.

It was found that the reduction in sediment yield increased with increase in width of the filter strip but the increase was logarithmic. A 5-meter width was predicted to reduce sediment loading by 38% when simulated in the agricultural part of the sub-watershed. Simulation of contour farming reduced sediment yield for entire Sasumua sub-watershed

($67.44\ Km^2$), from the base simulation value of 32,620 tyr^{-1} to 16,600 tyr^{-1} representing a 49% decrease. Contour farming decreased the surface runoff by 16% from 193 mm for base simulation to 162 mm and increased base flow from 304 mm to 327 mm an increase of about 7.5%. A combination of 5 meter vegetative filter strip and contour farming were predicted to result in a reduction of 73% of sediment yield. The sediment yield reduced to 8720 tyr^{-1} from the base simulation value 32,620 tyr^{-1}. Simulation of bench terraces reduced sediment load to 4930 tyr^{-1}. This represents 85% decrease. The surface runoff decreased by 22% from 193mm to 151 mm while base flow increased from 304mm to 335mm which is an increase of 10%. Both the contour farming and terraces resulted in only a slight change in total water yield. Grassed waterway simulated for some drainage ditches in the watershed reduced sediment load from 20,600 tyr^{-1} to 12,200 tyr^{-1} at the outlet downstream of the drainage channels that represents a reduction of 41%. For the entire sub-watershed, grassed waterway reduced the sediment yield from 32,600 tyr^{-1} to 25,000 tyr^{-1} which represents a 23.5% decrease. A management scenario that simulated less intensive cultivation in agricultural lands and proper managed grazing in grasslands resulted in a reduction of 34% sediment yield. The sediment yield reduced from 32,620 tyr^{-1} to 21,430 tyr^{-1}. The surface runoff reduced by 28% from 278 mm to 138 mm and the base flow increased by about 14% from 304 mm to 346 mm for this scenario. A management scenario that simulated more intensive cultivation in agricultural lands and overgrazing in grasslands was found to have a 53.6% increase in sediment yield, 44% increase in surface runoff and about 10% decrease in base flow. The sediment yield for this scenario increased from 32,620 tyr^{-1} to

50,100 tyr^{-1} while the surface runoff increased to 278 mm from 193 mm and the base flow reduced from 304 mm to 272 mm.

Thus all the conservation practices investigated were found to have a positive impact in enhancing the ecosystem services. Soil erosion 'hotspots' which should be prioritized in conservation were identified. Bench terraces were found to be the most effective. It is recommended that bench terraces should be constructed in the watershed especially on the soil erosion 'hotspots'. For the farmers who may not be able to construct the bench terraces due to cost, grass strips should be planted as they would evolve to bench terraces with time. Grassed waterways should also be constructed on the drainage channels that feed Mingotio stream. The Nairobi City Water and Sewerage Company and Water Resources Management Authority should rehabilitate the gauge stations and be collecting stream flow and water quality data. This would be important for better planning and would be of more help in future research work. Further research on the willingness of the farmers to accept to engage in soil and water conservation should be done. The cost of implementing the conservation practices should also be carried out.

CHAPTER 1

INTRODUCTION

1.0 Background

Ecosystems produce services which are important and beneficial to human beings. Ecosystem services are the benefits the ecosystems provide for human wellbeing. (Millennium Ecosystem Assessment, MA, 2003). Ecosystem services range from provision of products such as food, timber, fuel wood and fresh water to other non tangible benefits such as flood regulation, water purification and aesthetics among others. Human livelihoods form an integral part of the ecosystem and ecosystem services are linked to the sustainability of human life (Millennium Ecosystem Services, MA, 2003). Indeed life on earth depends of sustainable flow of these services. Ecosystems are complex in structure, composition and in the interactions of their components. Sustainable management calls for a thorough understanding of the effects of over exploitation of natural resources, otherwise the exploitation may lead to adverse consequences (Chi, 2000). Therefore, proper management of watersheds is required for continued enjoyment of the ecosystem services.

Sasumua watershed located in the central highlands of Kenya is a key ecosystem to the Kenyan economy. Some of the ecosystem goods and services produced by Sasumua watershed include food, fuel wood, timber, freshwater, water flow regulation and water purification. The watershed has a reservoir (Sasumua) which supplies about a fifth of the water consumed in Nairobi. The watershed is partly agricultural and its proximity to Nairobi makes the place it a major supplier of agricultural produces such as potatoes, cabbages and milk to the city.

In the last 10 years more people have settled in the area because of the favourable climate. Based on demographic data of Njabini location, where Saumua watershed is located, the population growth rate was 3.8% per year (Mireri, 2009). Based on the 1999 population census and projections indicates that in 2008, population of the location was 41,029 people having risen from 30,486 in 1999 (Mireri, 2009). This increase in population has caused an increase in demand in natural resources including land and water (Mireri, 2009).

Human activities in Sasumua watershed are causing changes on the ecosystem and limiting its capability to sustainably produce these services and goods. Intense cultivation and overgrazing in some parts of the watershed has caused land degradation. Research done in the area revealed that overgrazing in some parts of the watershed has reduced the water infiltration rates of water increasing the overland flow. The increased surface runoff greatly increases soil erosion risk, and leading to further degradation (Vagen, 2009).

1.1 Problem statement

The pressure on the natural resources namely land and water in Sasumua has increased in the recent past due increase in population (Mireri, 2009). Soil erosion in the watershed has increased due to intense cultivation of land and high runoff which results from low infiltration rates in the degraded land (Vagen, 2009). The soil eroded from the watershed is washed to the streams and eventually to the Sasumua reservoir (Gathenya *et al.*, 2009). Water treatment process at the reservoir includes removal of sediments some of which result from soil erosion. Accelerated soil erosion in the watershed result in high treatment cost of the water from the reservoir.

Water resources are also dwindling against the increasing demand (Mireri, 2009). The Sasumua dam which supplies 20% of water to Nairobi experiences shortage of water in dry seasons of the year and this has been partly blamed on the anthropogenic activities in the watershed (Mireri, 2009). With reduced infiltration of water in the watershed, high flash floods occur whenever it rains. The increased runoff fills the reservoir and the most goes over the spillway. However, less water infiltrates to recharge the aquifer and thus low flows characterize the streams in the watershed immediately after the rains as a result of reduced base flows (Vorosmarty *et al.*, 2003).

Therefore, the main problems in Sasumua watershed addressed in this study are the high rate of soil erosion from the agricultural part of the watershed and declining water levels in the Sasumua dam. Thus the intention of this study was to simulate the effect of soil and water conservation practices on sediment yield and hydrology in Sasumua Watershed using Soil and Water Assessment Tool (SWAT) model.

1.2 Justification

Previous studies by Gathenya *et al*. (2009) and Vagen, (2009), have recommended the implementation of soil and water conservation measures in the watershed. The implementation of which will address the issue of soil erosion and regulation of stream flows to the Sasumua reservoir.

There are many soil and water practices that can reduce soil erosion and regulate the water flows by increasing the infiltration of water to the ground. Such practices include terraces, contour farming, riparian buffer strips, contour grass strips, and hedges (Biamah *et al*., 1997). Implementation of any of these soil and water conservation practices in the Sasumua watershed would solve the problem of soil erosion and low levels of water in the reservoir to different degrees. Thus it is important to study the level to which each of these measures would address the problem of soil erosion on the land, sedimentation in the rivers and the Sasumua dam, and regulation of flows in the watershed. To do these, a watershed model was used to simulate scenarios of sediment yield and hydrology with different agricultural practices. For these reasons this study used a physically based watershed hydrological model, SWAT to simulate the effect of different agricultural conservation measures to water and sediment yield of the Sasumua watershed.

1.3 Objectives:

1.3.1 Main Objective:

To predict the effect of soil and water conservation practices on water quality and hydrology of Sasumua watershed.

1.3.2 Specific objectives:

1) To validate the SWAT model for Sasumua watershed
2) To assess the effect of implementing agronomic and vegetative conservation practices on water and sediment yield in Sasumua watershed
3) To assess the effect of implementing structural conservation practices on water and sediment yield.

1.4 The Study area

Sasumua watershed on the slopes of Aberdare ranges lies between longitudes 36.58°E and 36.68°E and latitudes 0.65°S and 0.78°S and has an altitude of between 2200m and 3850m (Figure 1.1) It is located in South Kinangop District of Central Province and in Nyandarua County. Sasumua reservoir receives water from three sub-watersheds (Figure 1.1). Sasumua sub-watershed (67.44 km^2) which is seasonal and provides water only during the rainy season. Chania (20.23 km^2) and Kiburu (19.30 km^2) sub-watersheds are perennial and connected to the reservoir via tunnel and pipe diversions respectively. The total catchment area feeding the reservoir is therefore 107 km^2 about half of which is in the forest reserve (Gathenya *et al.*, 2009). Sasumua sub-watershed is mainly agricultural, with only a small portion under forest. The intakes of Chania and Kiburu are in the forest. The reservoir design capacity is 16 million m^3 of water and supplies about 64,000 m^3 of water daily to Nairobi City at normal operating conditions, which is about 20% of water used is Nairobi.

Slopes in the watershed range from 1% to 50%. However, in the agricultural part they range from 1% to 10% (Appendix 1). So, high slopes are in the forest. Slope is a very important factor affecting soil erosion and gentle slopes are desired because they relatively yield less soil erosion.

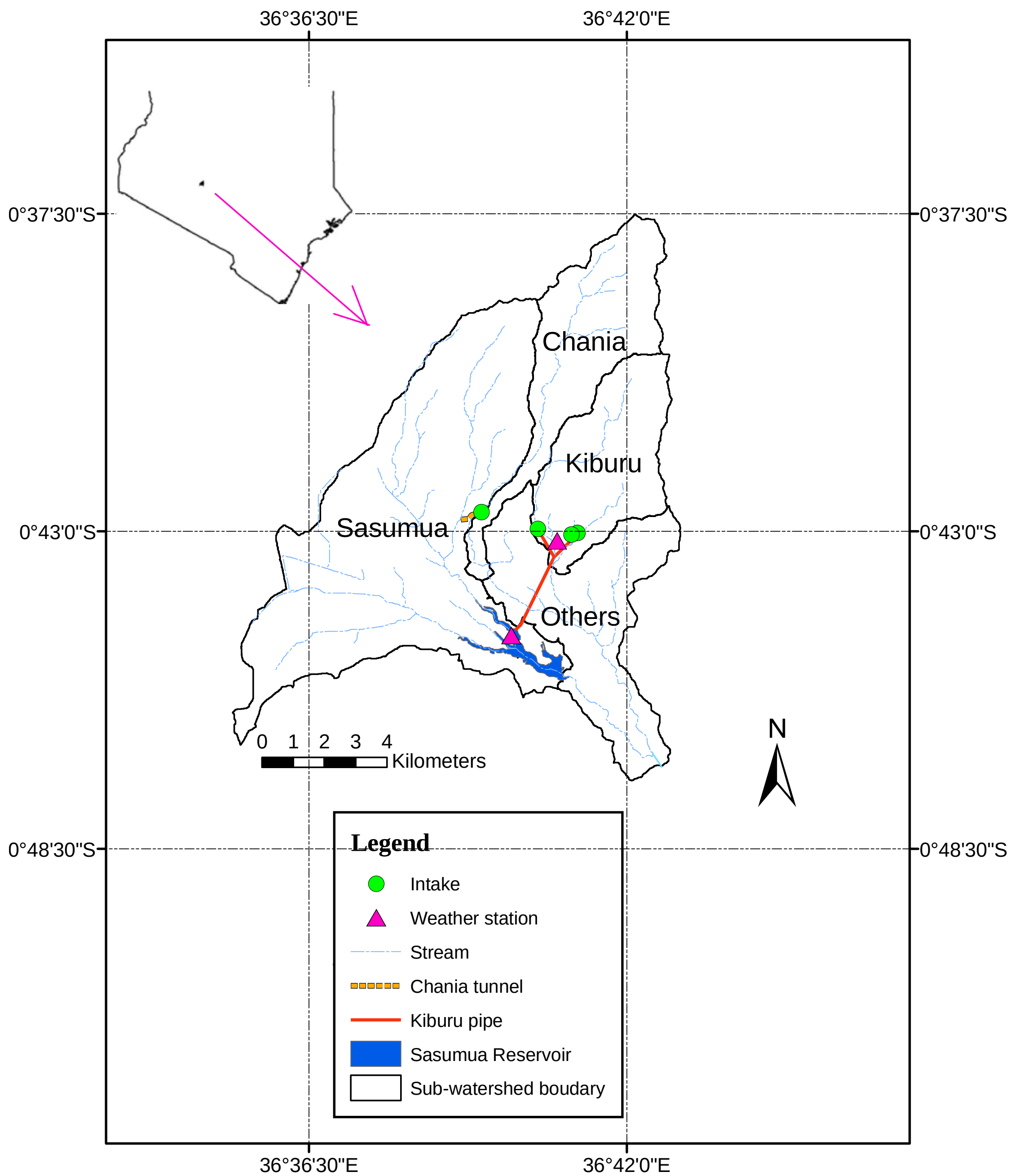

Figure 1.1: Sasumua watershed showing sub-watersheds (inset- location of Sasumua in map of Kenya)

1.4.1 Soils

The soils in Sasumua from the high mountainous Northeastern end are Histosols, Nitisols, Acrisols, Phaeozems, and Planosols on the lower Southwestern plateau area (Figure 1.2). Andosols are also present downstream of the dam (Vagen, 2009). The main agricultural part of Sasumua sub-watershed is composed mainly of Planosols, characterized by a weakly structured surface horizon over an albic horizon with `*stagnic soil properties'*. The texture of these horizons is coarse and there is an *abrupt textural change* to the underlying deeper soil layers. The finer textured subsurface soil may show signs of clay illuviation. It is only slowly permeable to water. Periodic stagnation of water directly above the denser subsurface soil produced typical stagnic soil properties in the bleached, eluvial horizon. (FAO, 2001)

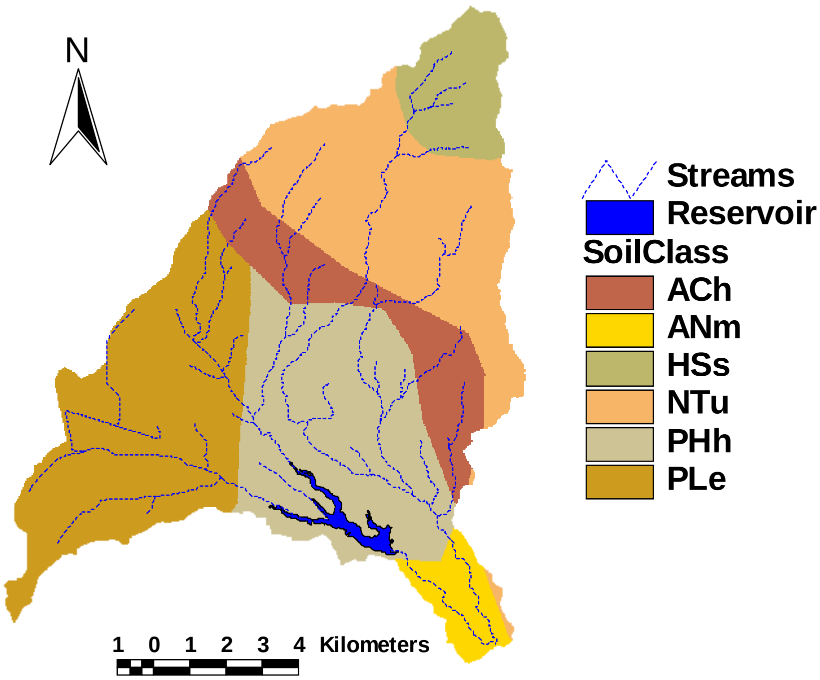

Figure 1.2: Soils in Sasumua watershed

Key to soil names

ACh- Haplic Acrisols	ANm- Mollic Andosols
HSs- Teric Histosols	NTu - Humic Nitisols
PHh- Haplic Phaozems	PLe - Eutric Planosols

1.4.2 Land use/land cover

The land tenure in the agricultural part of the watershed is freehold and thus privately owned. Vegetables, particularly Irish potatoes and cabbages are the major crops grown in the area and are the main cash and food crops. Other crops grown are peas, carrots and kales. In the recent past, few farmers have also turned to growing cut flowers for export. The agricultural area borders a forest reserve (Aberdare forest) to the North of the watershed. The farmers also keep livestock and some portions of the farms are reserved for grazing. A land cover thematic map developed by digital image classification of ASTER satellite images of the year 2007 is shown in Figure 1.3 and a summary of the percentage land use is shown in Table 1.

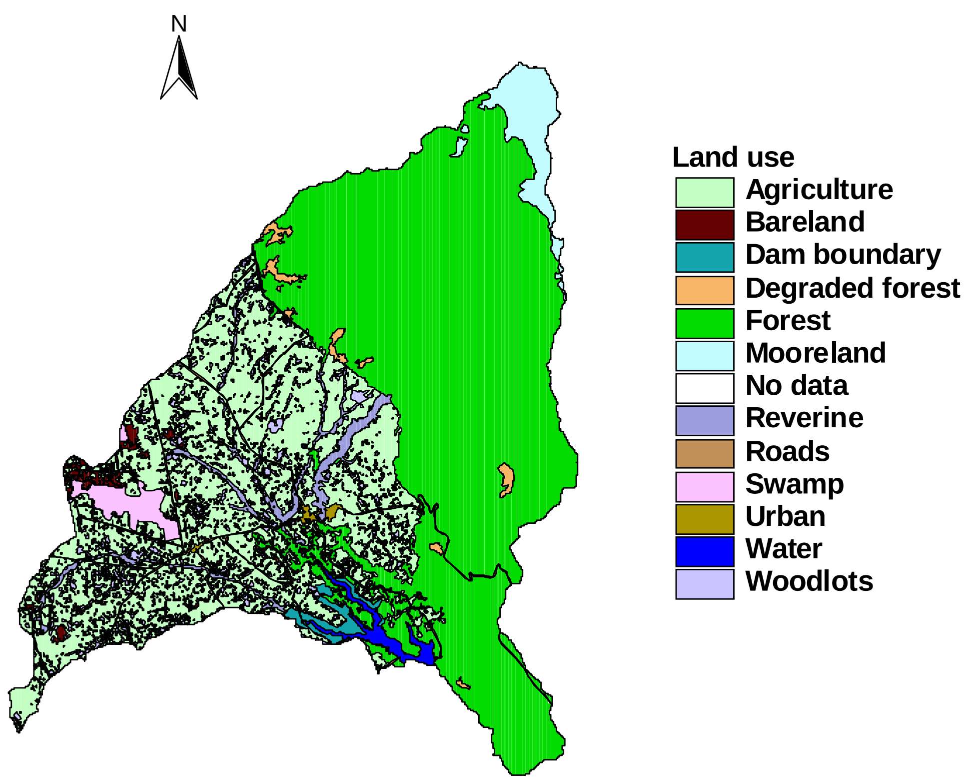

Figure 1.3 Land use/Land cover for Sasumua

The same thematic map was used as the input in the SWAT model. Forest and agriculture cover the biggest area of the watershed. Also to note is the wetland (swamp) which the farmers are slowly opening for cultivation.

Table 1: Percentage land use/land cover

Land use	**Area (km^2)**	**% land use**
Forest	68.6	51.5
Agriculture	42.8	32.1
Woodlots	6.2	4.6
Mooreland	3.8	2.9
Reverine	3.3	2.5
Bare land	2.0	1.5
Swamp	1.8	1.3
Water	1.1	0.9
Roads	1.1	0.9
Dam boundary	1.1	0.8
Degraded forest	1.0	0.8
Urban	0.3	0.2
No data	0.0	0.0

1.4.3 Rainfall and temperature

The mean annual rainfall in Sasumua ranges from 800- 1600 mm with two main rainfall seasons (Figure 1.4). Long rains from March to June and the short rains from October to December (Gathenya *et al.* 2009). The mean daily temperature ranges from 6^0C to 21^0C.

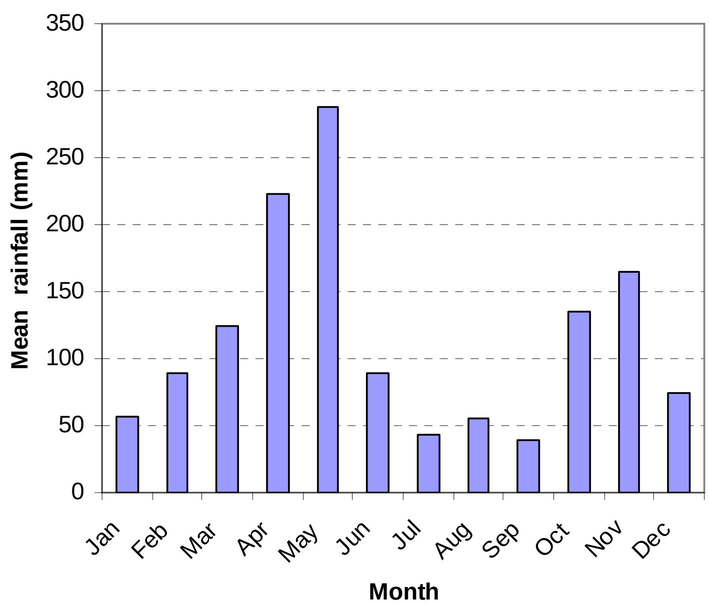

Figure 1.4: Monthly rainfall distribution for Sasumua dam station (9036188)

CHAPTER 2

LITERATURE REVIEW

2.1 Ecosystem services and livelihoods

In general, ecosystems are dynamic complexes of plant, animal and micro-organism communities and their nonliving environment interacting as functional units (MA, 2003). The Millennium Ecosystem Assessment (MA, 2003) defines ecosystem services as the benefits ecosystems provide for human well-being. Based on this, four main classes of ecosystem services can be identified. These are the provisioning, regulating, supporting and cultural services. Provisioning services cover natural resources and products derived from ecosystems such as food, fuel, fiber, fresh water, and genetic resources and represent the flow of goods. Regulating or supporting services are the actual life-support functions ecosystems provide. In other words, they are the benefits people obtain from the regulation of ecosystem processes, including air quality maintenance, climate regulation, erosion control, regulation of human diseases, and water purification and are normally determined by the size and quality (the stock) of the ecosystem. Cultural services refer to the non-material benefits obtained from ecosystem services such as spiritual and religious significance and other benefits like recreation and aesthetic experiences. Supporting services are those that are necessary for the production of all other ecosystem services, such as primary production, production of oxygen, and soil formation (Iftikhar *et al.*, 2007; MA, 2003).

Ecosystems are linked to people and they offer benefits to the human-beings and especially the poor. Figure 2.1 depicts the links between ecosystem services and human beings. The MA framework assumes that there is a dynamic interaction that exits between people and other parts of the ecosystems. Changes in the human conditions can directly or indirectly drive change in the ecosystems and changes in ecosystems can also cause change in human well-being. Changes in ecosystem services affect human well-being through impacts on security, the basic material for a good life, health, and social and cultural relations (MA, 2003). Security can for example be affected by changes in the provisioning services which would affect the supply of food and other goods. A community's food security would be threatened if the ecosystem fails to produce enough food. Security is also affect by the conflict over the declining resources such as water and grazing land. Food and clean fresh drinking water are basic commodities for human livelihood. Therefore there is a strong link between '*Access to basic material for a good life*' and provisioning services such as food and fiber production and regulating services, including water purification. Health is strongly linked to both provisioning services such as food production and regulating services, including those that influence the distribution of disease-transmitting insects and of irritants and pathogens in water and air. Health is also linked to cultural services through recreational and spiritual benefits. Social relations are affected by changes to cultural services, which affect the quality of human experience. Freedom of choice and action is based on the existence of the other components of well-being and are thus influenced by changes in provisioning, regulating, or cultural services from ecosystems.

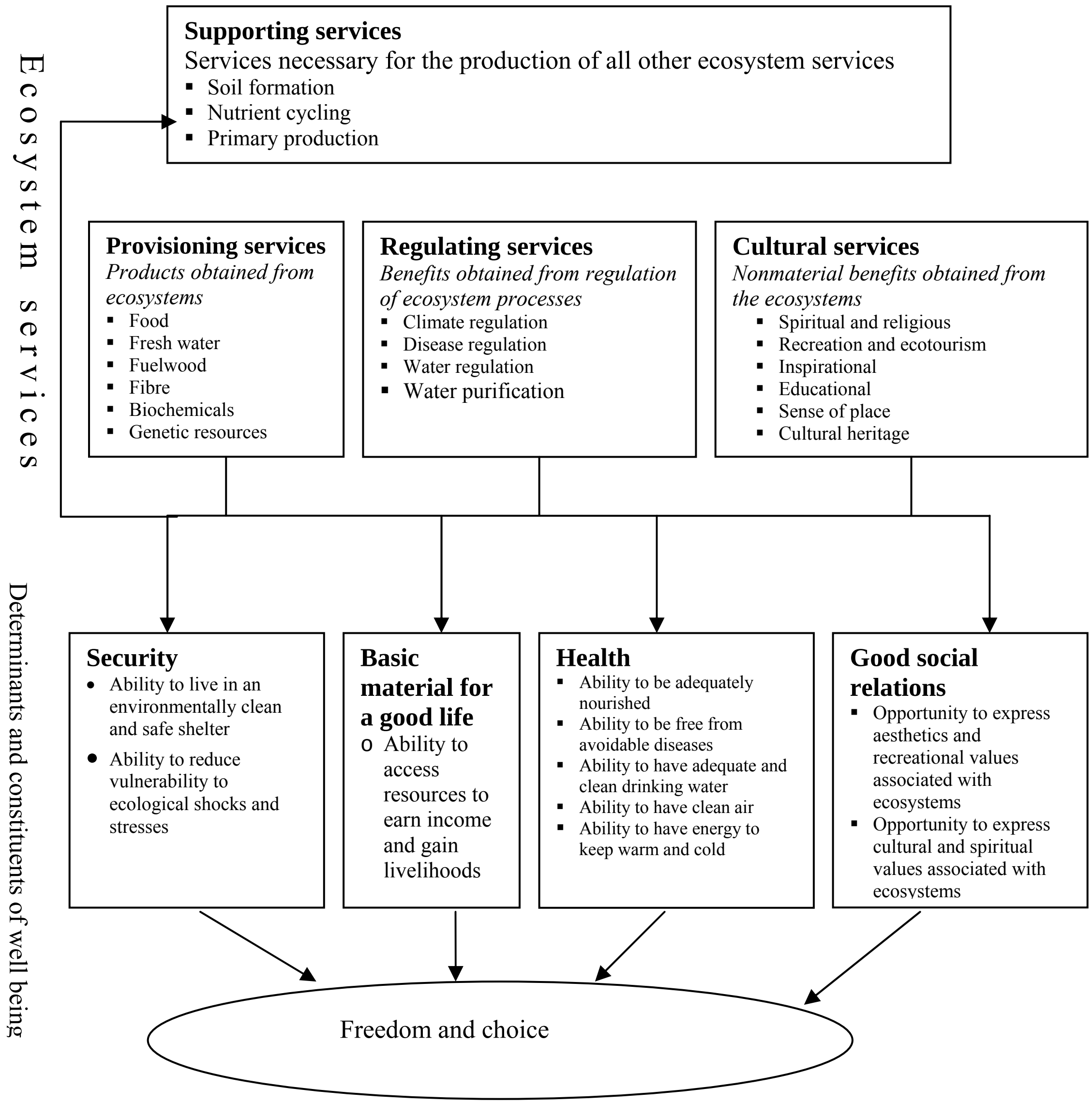

Figure 2.1: Ecosystem services and their link to human well being (Iftikhar *et al.*, 2007)

The complex interactions of ecosystem services and human well being call for proper management of natural resources. MA, (2003) suggests that some of the options available for sustainable use, conservation and restoration of ecosystems and the services they provide include incorporating the value of ecosystems in decisions, channeling diffuse ecosystem benefits to decision-makers with focused local interests, creating markets and property rights, educating and dispersing knowledge, and investing to improve ecosystems and the services they provide. Decision making is thus a key point of intervention in proper management of natural resources. Technical input in the decision making process is an important element because it offers various approaches including tools that will aid in analyzing the management options available as well as the cost benefit analyses. Computer modeling simulation is one approach that can and has been used in evaluating management options by or for decision makers. The assessment would for example help understand the spatial distribution of ecosystem services and where tradeoffs and synergies among ecosystem services exist and come up with intervention measures suitable at different location of watersheds. Swallow *et al*. (2009), for example, assessed the spatial distribution of provisioning and regulating ecosystem services in Lake Victoria in Kenya covering Nyando and Yala River basins. Agricultural production and reduction in sediment yield represented the provisioning and the regulating ecosystem services they studied respectively. They used GIS to spatially overlay sediment yield output data from SWAT analysis and value of agricultural production at a scale of SWAT generated sub-basins. They were able to spatially show the locations that have tradeoffs and those that have synergies between agricultural production and sediment yield.

2.2 Soil erosion

Soil erosion can either be caused by wind (wind erosion) or water referred as water erosion. Water erosion can be classified as splash, sheet, rill and gully erosion. Splash erosion occurs when the rain drops hits bare soil surface. Sheet erosion is washing of the surface soil by water. Rill erosion happens when water concentrates in small channels and gully erosion happens when the eroded channels get larger (Hudson, 1989). Soil erosion involves two main processes, the detachment and the transport of soil particles by the erosive forces of the raindrops and surface flow of water (Neitsch *et al.*, 2005). Erosion can be defined as a process in which soil particles are detached from within the surface of a cohesive soil matrix and subsequently moved down slope by one or more transport agents. Detachment may be caused by raindrop impact on the soil surface or by shear of the flowing water in case of rainfall erosion. Down slope movement may be caused by splash erosion, or by interaction between raindrop impact and flow (raindrop-induced saltation and rolling) or by flow alone (suspension, flow driven saltation and rolling) (Kinnell, 2010).

Together with soil particles, surface runoff and irrigation return flows carry other pollutants from the agricultural land. Agricultural chemicals, pathogens (bacteria and viruses) and nutrients such as phosphorous and nitrogen are some of the examples. These pollutants if they get into water bodies lower their water quality.

2.2.1 Universal soil Loss Equation (USLE)

Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is the most widely used equation in estimation of soil loss all over the world (Kinnell, 2010). USLE was originally developed from over 10,000 plot-years of basic runoff and soil loss data and data from rainfall simulators applied to field plots in the USA. The main purpose of developing the equation was to come up with a guide for decision making in the conservation planning. The equation enables the planners to predict the average soil erosion rates for different combination of management techniques, cropping system and control practice for a particular site (Wischmeier and Smith, 1978).

USLE was designed to calculate longtime average soil losses from rill and sheet erosion under specific conditions. It combines physical and management variables that affect soil erosion and computes soil loss as a product of six factors that are related to climate, soil, topography, vegetation and management. It is based on unit plot which is 22.1 m long and 9% slope and cultivation up and down the slope. The USLE soil loss equation is;

$$A = R\ K\ L\ S\ C\ P \tag{1}$$

Where A is the mean annual soil loss (mass/area/year), R is the rainfall-runoff “erosivity” factor, K is Soil “erodibility” factor, L is the slope length factor, S is the slope steepness factor, *C* is the cover and management factor and *P* is the support practice factor.

Rainfall-Runoff erosivity (R) factor- *USLE* assumes that when factors other than rainfall are held constant, storm soil losses from cultivated fields are directly proportional to a rainstorm parameter, *EI,* which is a product of total storm energy (*E*) and the maximum 30 minute rainfall intensity (I_{30}). The relationship however does not have a direct consideration of runoff and this has been cited as one of its limitation (Kinnell, 2010).

Soil erodibility (*K*) factor- this is the soil loss rate per erosion index unit for a specific soil as measured on a unit plot (22.1 m long, 9% slope, in a continuous fallow tilled up and down the slope). Soil erodibility describes the situation where some soils erode more easily than others even when all other factors such as topography, rainfall characteristics, cover and management are the same. The difference is soil erosion is solely caused by differences soil properties (Wischmeier and Smith, 1978). Thus soil erodibility is a function of soil physical and chemical properties but silt fraction plays a major role. The *K* values can be estimated using soil erodibility nomographs (Wischmeier and Smith, 1978) since direct field measurements can be very expensive. In cases where the soil contains less than 70% silt fraction, the mathematical approximation of *K* factor (as used in the nomograph) can be expressed as;

$$K = \{2.1M^{1.14}(10^{-4})(12-om)+3.25(sc-2)+2.5(p-3)\}100^{-1} \qquad (2)$$

Where *M* is the particle size parameter which is the product of the primary particle size fractions (percent silt times the quantity 100-minus percent clay), *om* is the pecent organic matter, *sc* is the soil structure class used in the soil classification and *p* is the profile permeability class.

Topographic factors (*L* and *S*) - slope length is the distance from the origin of the overland flow to the point where either the slope decreases enough that the deposition begins or runoff water enters a well-defined channel that may be part of the drainage network or a constructed channel. The slope length (*L*) and the slope steepness factor *S* are usually combined in the topographic factor *LS* and are calculated as in equation 14.

Cover and management (*C*) factor- is the ratio of the long term soil loss from a land with specific vegetation to the soil loss from clean-tilled continuous fallow on the same soil cultivated up and down a 22 m long slope with a gradient of 9% (Wischmeier and Smith, 1978; Kinnell, 2010). It measures the combined effect of all the interrelated cover and management variables.

Support practice (*P*) factor- is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope cultivation. The support practices are intended to slow runoff water and thus reduce the amount of soil that it can carry.

Examples of such support practices include; contour farming, contour-strip cropping and terrace systems.

Revised USLE (RUSLE) (Renard *et al.*, 1997) is a revision of USLE and uses the USLE equation with changes on how some of the factors are determined (Kinnell, 2010). RUSLE1 is a computer program that was developed for implementation of RUSLE while RUSLE2 provides an approach that takes into account the deposition resulting in changes in slope gradient on one dimensional hill slopes (Kinnell, 2010). Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), is a version of USLE model that directly considers runoff to estimate sediment yield unlike USLE and RUSLE and was designed to model erosion at the watershed.

2.3 Soil and water conservation practices

Land owners and managers use various methods to reduce soil erosion and subsequent pollution of water bodies. The soil and water conservation practices are applied to agricultural land to abate soil erosion. The practices can be applied at different location of the agricultural fields and their effectiveness in reducing soil erosion also varies. World Overview of Conservation Approaches and Technologies (WOCAT) defines Soil and water conservation as local-level activities that maintain or enhance the productive capacity of the land in areas affected by, or prone to, degradation. These include activities that prevent or reduce soil erosion, compaction and salinity; conserve or drain soil water; and maintain or improve soil fertility (Van Lynden and Liniger, 2002).

Various attempts have been made to categorize the soil and water conservation approaches and technologies. Morgan, (1986), for example, classifies soil conservation approaches broadly as agronomic measures, mechanical measures and soil management. Agronomic or biological measures utilize the role of vegetation in helping to minimize soil erosion. Soil management is concerned with ways of preparing the soil to promote dense vegetative growth and improve its structures so that it is more resistant to erosion. Mechanical or physical methods depend upon manipulating the surface topography, e.g. by construction of terraces to control the movement of water. Hudson (1989), classifies soil erosion control measures as either mechanical or non-mechanical where in mechanical measures, mechanical protection works such as earth moving and soil shaping measures are used. Non-mechanical measures are all practices which influence and reduce soil erosion by management of growing crops or animals (Hudson, 1989)

WOCAT, a global network of institutions and individuals involved in soil and water conservation, proposes that the main conservation measures are subdivided as management, agronomic, vegetative and structural (Liniger *et al*., 2002). Combinations are possible and each of these conservation categories is split up into subcategories.

2.4 Agronomic and Vegetative Conservation measures

According to WOCAT, agronomic measures are usually associated with annual crops; are repeated routinely each season or in a rotational sequence; are of short duration and not permanent; do not lead to changes in slope profile; are normally not zoned; and are normally independent of slope. Mixed cropping, contour cultivation and mulching are some of the examples of agronomic measures. Vegetative measures involve the use of perennial grasses, shrubs or trees; are of long duration; often lead to a change in slope profile; are often zoned on the contour or at right angles to wind direction and are often spaced according to slope. Grass strips, hedge rows, windbreaks, alley cropping and agroforesty systems are some of the examples of vegetative conservation measures (Liniger *et al*., 2002; Biamah *et al.*, 1997). Contour farming and vegetative filter strips are discussed in the next sections.

2.4.1 Contour farming

Contour farming is a form of agriculture where farming activities such as ploughing, planting cultivating and harvesting are done across the slope rather than up and down the slope (NRCS, 2006). Crop row ridges built by tilling and planting on the contour create many small dams. These ridges or dams act as barriers to water flow reducing its velocity and allowing it more time to infiltrate which reduce surface runoff and soil erosion. This subsequently reduces sedimentation and siltation of water bodies and thus improves the water quality. (NRCS, 2006; Quinton and Catt, 2004).

Contour farming has been studied well in different parts of the world either through experimental plots or modeling. Quinton and Catt, (2004) assessed the impacts of minimal tillage and across-slope cultivations on runoff generation, soil erosion and yields under arable cropping using the results from 10 years of monitoring water erosion and runoff at the Woburn Erosion Reference Experiment in Bedfordshire, United Kingdom. The study reported that cultivation across the slope would reduce the mean soil loss to 6.4 tons/ha compared to that of up and down slope of 16.5 tons/ha. Although they acknowledge that the difference was not statistically significant, they recommend across slope cultivation. This study also found out that the mean event surface runoff from experimental plots tilled across the slope was about 0.8 mm as compared to 1.32 mm from the experimental plots with up and down cultivation. Gassman *et al*. (2006) evaluated the impact of contouring and other BMPs on sediment and nutrient loss in the upper Maquoketa River watershed in North Eastern Iowa, U.S.A using simulations by Agricultural Policy Environmental eXtender (APEX) and SWAT models. They found that contouring reduced sediment loss by an average of 34% from the base simulation using SWAT over 30 years period of simulation. In another study in Southern Uganda, Brunner *et al*. (2008), investigated the influence of different land management methods on soil erosion by modeling soil loss for individual soil-landscape units on a hillslope using Water erosion Prediction Project (WEPP) model. They found out that simulated soil loss for contour farming reduced from 0 to 13% depending on the topography and soil conditions of the hill slopes as compared to hand hoe tillage practiced by the farmers. Stevens *et al*. (2009) evaluated the effect of contour cultivation on soil erosion on experimental field in Leicestershire, England. They found that contour cultivation reduced surface runoff and sediment yield as compared to up and down cultivation although the trend was not significantly different. Despite the differences in the percentage of reduction in surface runoff and sediment yield in these studies or even in the experimental plots with the same study, they all agree that contour farming reduces surface runoff and soil erosion if practiced in agricultural watersheds compared to up and down cultivation methods.

Some of the challenges that have been cited for the adoption of the contour farming are that on very steep slopes water can accumulate in low points and then break through to form large rills or gullies. Machinery stability when working a cross slope has also been identified as a challenge in adoption of the practice by managers of mechanized farms (Quinton and Catt, 2004).

2.4.2 Vegetative filter strips

The discussion herein refers to Vegetative Filter Strips (VFS) which could be riparian buffer strips or contour buffer strips. United States Department of Agriculture, Natural Resource Conservation Service, USDA-NRCS, (2008) defines a filter strip as strip or area of herbaceous vegetation that removes contaminants from overland flow. The vegetation could be grass (Figure 2.2), trees or shrubs or a combination of trees and shrubs and established at the edge of fields along the streams or any other water body (Yuan *et al.*, 2009). Contour buffers are strips of perennial vegetation alternated with wider crop strips, farmed on the contour. These strips of permanent vegetation, slow runoff and trap sediment but do not border bodies of water. Sediments, nutrients and pesticides and bacteria loads in surface runoff are reduced as the runoff passes the filter strip (Neitsch *et al.*, 2005). Maintenance of the filter strips is required if the strips will remain effective in reducing the pollutants. Compaction by animals or machinery should be avoided and sediments removed occasionally (Lovell and Sullivan, 2006).

The main effectiveness of the filter strips in prevention of Non-Point Source (NPS) pollution is based on its trapping efficiency which is mainly affected by the width of the filter strip (Yuan *et al.,* 2009; Abu-Zreig, 2001). The trapping efficiency increases with the increase in the width of the filter strip. Some other secondary factors that influence the trapping efficiency include; slope, vegetation, inflow rate and particle size. Trapping efficiency has been found to increase with increase of vegetation cover and to decrease with increase in inflow rates (Abu-Zreig *et al.,* 2004; Fox *et al.,* 2010). Trapping efficiency has also been found to decrease with increase in slope (Gilley *et al.*, 2000).

Figure 2.2: Grass filter strip in Sasumua

Evaluation of effectiveness of vegetative filter strips through computer simulations

Several researchers have evaluated the effectiveness of filter strips in reduction of pollution to water bodies. Some have used simulation models like SWAT and Vegetative Filter Strip MOdel (VFSMOD) (Munoz-Carpena *et al.*, 1999; Abu-Zreig, 2001; Fox *et al.*, 2010) and others have used experimental plots. Sahu and Gu (2009), for example, investigated the effectiveness of the contour and riparian buffer strips with perennial plant cover (switch grass) in reducing nutrient (NO_3-N) loading to streams in an agricultural Walnut creek watershed in Iowa, USA using the hill slope option in SWAT. Parajuli *et al.* (2008) studied the effectiveness of the vegetative filter strip lengths in removing overland process sediment and fecal concentrations using SWAT in 950 km^2 upper Wakarusa watershed in northeast Kansas.

SWAT has a limitation in that it uses the same trapping efficiency for sediments, nutrients and pesticides (Arabi *et al.*, 2008). It also does not consider the effect of flow concentration. Considering these limitations, White and Arnold, (2009), developed a field scale Vegetative Filter Strip (VFS) sub-model for SWAT which would enhance the ability of SWAT to evaluate the effectiveness of vegetative filter strips at the watershed scale. They used data from literature studied in many different countries and simulations from Vegetative Filter Strip MOdel (VFSMOD) (Munoz-Carpena *et al.*, 1999). The sub-model developed has three additional model parameters added as SWAT inputs: the drainage area to VFS area ratio ($DAFS_{ratio}$), the fraction of the field drained by the most heavily loaded 10% of the VFS (DF_{con}), and the fraction of the flow through the most heavily loaded 10% of the VFS which is fully channelized (CF_{frac}), all are specified in the Hydrological Response Unit (HRU) file.

Evaluation of effectiveness of vegetative filter strips through field experiments

Experimental plots have also been used to study the effectiveness of VFS in abatement of pollution. Abu-Zreig *et al.* (2004) used 20 field experimental plots to study the performance of VFS in reducing cropland runoff in Ontario, Canada, and to assess the influence of filter length, the flow rate of incoming runoff and the type of vegetation. They found that the filter width, had the greatest effect on sediment trapping, followed by vegetation density and inflow rate. They also found that sediment-trapping efficiency increased with the width of the filter strip. Borin *et al.* (2005) investigated the effect of a 6 m buffer strip in reducing runoff, suspended solids and nutrients from a field growing maize, winter wheat and soybean in a field experiment in North-East Italy over a period of 4 years. The study found that on average the total suspended solids reduced from 6.9 to 0.4 t ha^{-1}. Duchemin and Hogue, (2009) evaluated the effectiveness of an integrated grass/tree strip system (after one year of establishment) in filtering runoff and drainage water from grain corn fields fertilized with liquid swine manure in Quebec Canada. They reported that after the first year of the establishment of the experiment, the grassed strips reduced runoff water volumes by 40%, Total Suspended Solids (TSS) by 87% whereas the grass/tree strips reduced runoff volumes by 35%, TSS by 85%. They however, note that the inclusion of trees in the grass trip did not indicate any significant increase in filtering capacity. The trees were only 2 years old and not well established in biomass.

These studies, whether through computer simulation or field experimental work, show that VFS are quite effective in reducing non point source pollution. By altering some variables such as the width, or the type of vegetation, the effectiveness of the filters can be enhanced.

2.5 Structural conservation Practices

Structural measures often lead to a change in slope profile; are of long duration or permanent; are carried out primarily to control runoff, wind velocity and erosion; often require substantial inputs of labour or money when first installed; are often zoned on the contour against wind direction; are often spaced according to slope; and involve major earth movements and / or construction with wood, stone and concrete (Liniger *et al*., 2002; Biamah *et al*., 1997). They involve design and construction of soil erosion control structures. Examples include various types of terraces, diversion ditches, waterways, grade stabilization structures and retention ditches. Some structural conservation practices are briefly described next.

2.5.1 Terraces

Terraces are conservation structures which comprise of a series of horizontal ridges made on a hillside (Neitsch *et al*., 2005). Terraces divide and shorten a long slope into a series of shorter and more relatively level steps. The slope length is the terrace interval. The reduced slope steepness and length allows water to soak into the ground and as a result have less surface runoff and thus less soil erosion. There are different types of terraces which include broad base and bench terraces. Broad base terraces consist of a ridge which has a broad base and a flatter slope. The ridge is also cultivated and therefore no agricultural land is lost. These terraces could also be classified as graded or level. Bench terraces are constructed on steeper slopes where the ridge is steep and not cultivated. They are made by re-shaping a steep slope to create flat or nearly flat ledges or beds, separated by vertical or nearly vertical risers (Mati, 2007). In some cases especially in East Africa, bench terraces are developed over time from other methods of terracing such as stone lines, grass strips and trash lines or “fanya juu” terraces, so as to reduce labor and avoid having to move large volume of soil (Mati, 2006)

Terraces have been studied on their effectiveness to reduce soil erosion and to reduce surface runoff. Yang *et al*. (2009) assessed the impact of flow diversion terraces on stream water and sediment yield in BlackBrook watershed in Canada by adjusting the *USLE_P* factor in SWAT and found out that the implementation of the Flow diversion terrace in the watershed reduced sediment yield by about 56% and also reduced water yield by about 20% in summer growing seasons. Arabi *et al.* (2008) evaluated the impacts of parallel terraces and other conservation practices on water quality in Indiana, U.S.A. and found out that terraces, if implemented on 30% of the 7.3 km^2 Smith Fry watershed, could reduce sediment yield by about 15%. In this study they used SWAT to simulate the impact of terraces. They represented terraces using a method they developed of representing BMPs in SWAT. In their study the slope length, curve number, and universal soil loss equation practice factor (USLE_P) were adjusted to represent terraces. Gassman *et al*. (2006) and Santhi *et al*. (2006) varied *USLE_P* to represent terraces in SWAT. Both studies found terraces to be very effective in reducing sediment that cause water pollution.

Design of terraces- In the design of terraces, terrace spacing is an important parameter to consider. The slope length is equal to the terrace interval (Neitsch *et al.*, 2005) and is equal to the horizontal interval. The horizontal interval method (equation 3) is one of the methods used in the calculation of the terrace spacing (NRCS, 2009).

$$\text{H.I} = (xs + y) * (100 / s) \tag{3}$$

Where; H.I. is the horizontal interval (m) (*SLSUBBSN* in SWAT), s is slope of the HRU, x is a dimensionless variable with values ranging from 0.12-0.24 and y is also a dimensionless variable with values between 0.3 and 1.2. Values of y are influenced by soil erodibility, cropping system and crop management systems. The low value of 0.3 is used for highly erodible soils with tillage systems that provide little or no residue cover while the high value of 1.2 is used for erosion resistant soils with a tillage system that leave a large amount of residue (3.3 tons/ha) on the surface (NRCS, 2009; Arabi *et al.*, 2008). This variable is thus related to the USLE erodibility factor (*USLE_K*) and USLE cover management factor, *USLE_C*. Typical y factor values are given in Table 2.

Table 2: Typical y values for determining terrace intervals

	Soil Erodibility Factor (K)		
Ground cover	**0-0.2**	**0.2-0.28**	**0.28-0.64**
10 %	0.75	0.53	0.3
40 %	0.98	0.75	0.53
80 %	1.2	0.98	0.75

Source: NRCS, 2009

2.5.2 Grassed waterway

Grassed waterways are channels or drainage ways (thalweg) either natural or artificial planted with vegetation that carry runoff water to safe disposal without causing soil erosion (Morgan, 1980). The vegetation traps sediments and absorbs chemicals and nutrients washed from the agricultural lands by runoff water. Grassed waterways have been studied and found to reduce surface runoff and water pollutants (Evrard *et al.*, 2008; Fiener and Auerswald, 2005; Fiener and Auerswald, 2006a; Gassman *et al.*, 2006). In their study, Fiener and Auerswald (2005), found that two grassed waterways in Munich, Germany under different morphological, soil and management condition reduced surface runoff by 90% and 49% respectively. In another study, Fiener and Auerswald (2006a), found that one of the grassed waterways could have a total sediment reduction of 93% over a period of 8 year of observation. Evrard *et al*. (2008) reported that a 12 hectare grassed waterway reduced about 93% of sediment discharge in the Belgian plateau belt over a monitoring period of 2002-2004.

These studies show that grassed waterway is an important and effective management option to abate water pollution. Grassed waterways are structural BMPs and thus other than the roughness offered by the vegetation, other parameters like the cross section, the grade and the hydraulic properties of the thalweg also affects their effectiveness in reducing surface runoff and trapping of pollutant to certain degrees. Fiener and Auerswald, (2005) reported that wide, flatted bottom and long grassed waterway efficiently reduced runoff volume and peak discharge rates and that slope and soil conditions had little effect.

Channel Manning's coefficient, channel cover and channel erodibity are some of the factors that affect the effectiveness of the channel in trapping the sediments and reducing degradation of the channel. Several studies have been done to determine these factors. For example, Fiener and Auerswald (2006a), suggested that for dense grasses and herbs under non submerged runoff condition, the channel Manning's coefficient varies between 0.3 and 0.4 s $m^{-1/3}$ over the year provided the grass or herb do not bend or break. Bracmort *et al*. (2006) used a channel Manning coefficient value of 0.24 s $m^{-1/3}$ to represent grassed waterway in good condition in Black Creek watershed in Indiana

U.S.A while Arabi *et al*. (2008), suggested a value of 0.1 for grassed waterway in poor conditions. Fiener and Auerswald, (2006b) used a value of 0.35 s $m^{-1/3}$.

2.6 Soil and water conservation in Kenya

The soil conservation service in Kenya was started in 1930's when the land which was mainly occupied by European settlers had serious erosion problems that warranted immediate attention. The government studied the situation and recommended that practicing soil conservation was a must from 1937 (Biamah *et al.,* 1997). In 1938, a soil conservation service was introduced (Kamar, 1998). At that time, the government mostly emphasized on simple cross-slope barriers such as trash-lines, rows of stones and vegetative strips. African farmers then practiced conservation techniques such as shifting cultivation, trash-lines and simple terracing. A number of conservation policies and strategies were later introduced and strongly enforced administrative and agricultural extension personnel employed to ensure compliance. Anybody who did not comply was punished or prosecuted. Such conservation policies included, discouraging ploughing on steep land, contour planting and ploughing, stopping cultivation along water courses, encouraging terracing, planting trees on the hillsides, planting Napier grass, controlling forest clearing and promoting de-stocking. Immediately after independence, soil conservation practice was very low. The rapid drop in soil conservation practices then was mainly because of reaction of farmers who believed that soil conservation activities were part of colonialism. The use of force to do conservation activities was stopped after independence. The effect of this was that most activities stopped, conservation structures such as terraces were not maintained, and many were even destroyed. Steep slopes under good vegetation cover were cleared for cultivation, forests were cut down for timber, building materials and fuel wood and closed grazing areas were reopened. This saw soil erosion features started re-appearing. The main focus of the new government then was settling of landless people in the then newly created settlement schemes. Although there have been several attempts to address the problem of soil erosion by the post independence government with the help of international assistance, such as Kenya National Soil Conservation Project in 1974, soil erosion is still a major problem. The population pressure has strained the land resources and cultivation is practiced with little regard of soil conservation (Kamar, 1998; Biamah *et al.,* 1997).

2.7 Hydrological modeling

A model is simply an abstraction of a real system. Models are built for a specific purpose which could be prediction, exploratory analysis, communication or learning. Models are based on scientific knowledge and the information derived from them is used to aid decision making. In natural resource management, it is a common practice to build models to predict, in space or time, the states of the system to be managed. Hydrologic models are used to investigate and aid in understanding the complex relationship between climate and water resources (Singh and Frevert, 2002) and partitions water into various pathways of the hydrological cycle.

Based on process description, models can be classified as either empirical (black box) or physically based model (Refsgaard, 1996). An empirical model does not consider the physical laws of the underlying watershed processes. They only reflect the relation between the input and outputs. Physically-based models describe the natural system in a watershed using mathematical representation of flows of mass and energy. Models can also be classified as either lumped or distributed depending on the spatial representation of parameters and variables. A lumped model is one where a watershed is regarded as one unit where the variables and the parameters are represented by average values for the whole watershed while a distributed model takes into account the spatial variation of all variables and parameters.

Refsgaard, (1996) gives the following steps that are involved in hydrologic modeling process. The first step is to evaluate the problem that need to be solved and then look around to find if there is an existing model that can solve the problem or a new model may need to be developed. If a model is selected from existing ones, it should be able to give an acceptable solution to the problem or produce desirable outputs. The next step involves model setup. This involves delineation of the watershed, setting boundary and initial conditions, feeding the input data and parameterization. The model is then calibrated and validated using measured data. Model calibration involves manipulation of a specific model to reproduce the response of the watershed under study within a range of the desired accuracy. This can be done by trial and error estimation of model parameters or automatically using developed algorithms. Model validation involves the application of the calibrated model without changing the parameters set in the calibration procedure. The model should be able to simulate the processes in another period different from the one used in the calibration process. For example, a validated model should be able to reproduce measured stream flow data series for a chosen period which is different from the period of the stream flow data used in the calibration exercise. The model performance is usually tested during the calibration and validation exercises by statistically comparing the goodness of fit of the simulated output and the observed (measured) data. Coefficient of determination, R^2, bias, Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and Root Mean Square Error (RMSE) are the common statistics used to measure model performance (Singh and Frevert, 2002; Sang, 2005). Once a model is satisfactory calibrated and validated, it can be used for desired simulations.

2.8 SWAT overview: Sediment and hydrology theory

In SWAT, a watershed is partitioned into sub-basins. The number of sub-basins will be determined by the 'critical source area' chosen by the user. Critical source area is the minimum area required by the model for the initiation of channel processes (Bracmort *et al.,* 2006; Arabi *et al.*, 2008). The sub-basins are further divided into HRUs. A HRU has unique land use, soil attributes and management.

Water balance is the driving force behind all the processes in a watershed in SWAT. Therefore accurate predictions of pesticides, sediments and nutrients will only be possible if hydrological processes are well simulated in the model. Hydrological cycle of a watershed is divided into land phase and the routing phase of the hydrological cycle. The former controls the amount of water, sediments, nutrients and pesticides that enter the main channel in each sub-basin while the later deals with their movement through the channel network of the watershed to the outlet (Neitsch *et al.*, 2005). The land phase of hydrological cycle in SWAT is based on equation 4;

$$SW_t = SW_o + \sum_{t=1}^{t} (R - Q_s - E_a - W_{seep} - Q_{gw}) \qquad (4)$$

Where, SW_t is the final soil water content (mm), SW_o is the initial water content on day i (mm), t is time in days, R is amount of precipitation on day i (mm), Q_s is the amount of surface runoff on day i (mm), E_a is the amount of evapotraspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is the amount of return flow on day i (mm)

2.8.1 Climatic inputs for SWAT

Climate provides the moisture and the energy inputs that control the water balance (Neitsch *et al.*, 2005). SWAT requires several climatic data which include daily precipitation, maximum and minimum temperature, solar radiation data, relative humidity, and wind speed data. These climatic variables can be input from measured records or can be simulated by the weather generator. SWAT includes a weather generator, WXGEN, to generate climate data or fill in gaps in the measured records (Neitsch *et al.,* 2005). The weather generator requires average monthly climate values analyzed from long-term measured weather records and generates daily weather values for each sub-basin.

2.8.2 Calibration of SWAT model

Calibration can be done manually or automatically in SWAT. The model can be calibrated for stream flow, sediments and chemicals (Neitsch *et al.,* 2005). Automatic calibration requires use of good observed data and is very convenient for gauged catchment with long-term continuous data. However, in many developing countries like Kenya, hydrological data is not oftenly collected for many rivers and even where they are collected, data management is quite a challenge. Researchers working in such watersheds face a big challenge in calibration and validation of hydrological. Appreciating this problem, Ndomba *et al*. (2008) validated the applicability of SWAT model in a data scarce catchment in Pangani River basin in Tanzania. Based on the sensitivity analysis done, the study found that hydrological controlling parameters could be identified using SWAT runs without observed data. From their study they suggest that SWAT model can be used in ungauged catchment for identifying hydrological controlling parameters. In fact, SWAT is a physically based distributed model and was designed for use in ungauged watershed (Gassman *et al.,* 2007) making it a suitable model for watersheds with little or no data. Thus the model has been used for many studies in similar situations where stream flow and/or pollutants (sediments, chemicals and nutrients) data was not available. For example, Santhi *et al*. (2006) used SWAT to evaluate the impact of implementation of Water Quality Management Plans on non-point source pollution in West Fork watershed of Trinity River basin in Texas, U.S.A. They didn't have good continuous sediment data. They used few grab samples data, expertise and experience from previous studies to calibrate the model for sediments. In a recent study, Galvan *et al*. (2009) used SWAT model to generate reservoir inflow that they used as observed stream flow for the calibration of the model in Meca River basin in Spain.

2.8.3 Hydrology in SWAT

From precipitation, the water can be intercepted by the vegetation or fall to the soil surface. The water that is intercepted by the vegetation (Canopy storage) is made available for evaporation. The water that falls on the soil surface can either infiltrate or flow as surface runoff. For each HRU, surface runoff is predicted separately and routed to get the total runoff for the entire watershed. Surface runoff volumes and peak runoff rates are calculated for each HRU. Peak runoff rate is calculated using Modified rational formula (equation 17). SWAT either uses the SCS curve number method or Green & Ampt infiltration method to compute surface runoff volumes. The curve number method was used for this study and the surface runoff is calculated from equation 5;

$$Q_{SR} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (5)$$

Where Q_{SR} is the accumulated runoff (mm), R_{day} is rainfall depth for the day (mm) I_a is initial abstraction (surface storage, interception and infiltration prior to runoff (mm)- this is estimated as 0.2 S and S is the retention parameter (mm) which is calculated;

$$S = 25.4(\frac{1000}{CN} - 10) \qquad (6)$$

Where CN is SCS Curve Number of the day and is a function of soil permeability, land use and antecedent soil moisture condition.

Runoff will occur only when $R_{day} > I_a$

The water that infiltrates into the ground can be stored in the soil as soil moisture and later removed through evepotranspiration or could move laterally in the soil profile to contribute to stream flow or can percolate below the soil profile and recharge the aquifer. Evapotranspiration is a collective term that includes all the processes by which water in the earth's surface is converted to water vapour and includes water that evaporates from the plant canopy, transpiration, sublimation, and evaporation from the soil (Neitsch *et al.*, 2005). Evapotranspiration is usually limited by the availability of enough moisture in the soil and is also affected by other factors such as weather parameters, vegetation (crop) factors, and management and environmental conditions

(Allen *et al.*, 1998). Thus, the concept of potential evapotranspiration was developed to study the evaporative demand of the atmosphere independent of plant type, plant development and management practices. In SWAT, potential evapotranspiration is first determined, and then actual evapotranspiration is then determined by calculation of evaporation, transpiration and sublimation separately. SWAT gives the flexibility of using any of the three methods of calculating potential evapotranspiration incorporated in the model. The methods are; Penman-Monteith, Priestly and Taylor and the Hargreaves methods.

Lateral subsurface flow also known as the interflow, is the water that flows through the soil profile below the soil surface and above the saturation zone and contributes to the stream flow. SWAT uses a kinematic storage model to predict lateral flow in each soil layer. Hydraulic conductivity, slope and soil water content are the governing parameters in the model (Neitsch *et al.*, 2005).

The water that percolates below the soil profile moves through the vadose zone and recharges the shallow and/or deep aquifer. This water is partitioned between the shallow and the deep aquifer. Shallow aquifer contributes the base flow to the streams. Return flow to the stream system and evapotranspiration from deep - rooted plants (termed “revap”) can occur from the shallow aquifer.Water that recharges the deep aquifer is assumed lost from the system (Gassman *et al.*, 2007).

Water routing- In channels (streams and ditches) Manning's equation (25) is used to define the rate and velocity of flow in SWAT. Water is routed through the channel network using the variable storage routing method (Williams, 1969) or the Muskingum river routing method. Both of these methods are variations of kinematic wave model. Muskingum river routing method was used for this study and is thus briefly explained. The Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages (Figure 2.3) (Neitsch *et al.*, 2005).

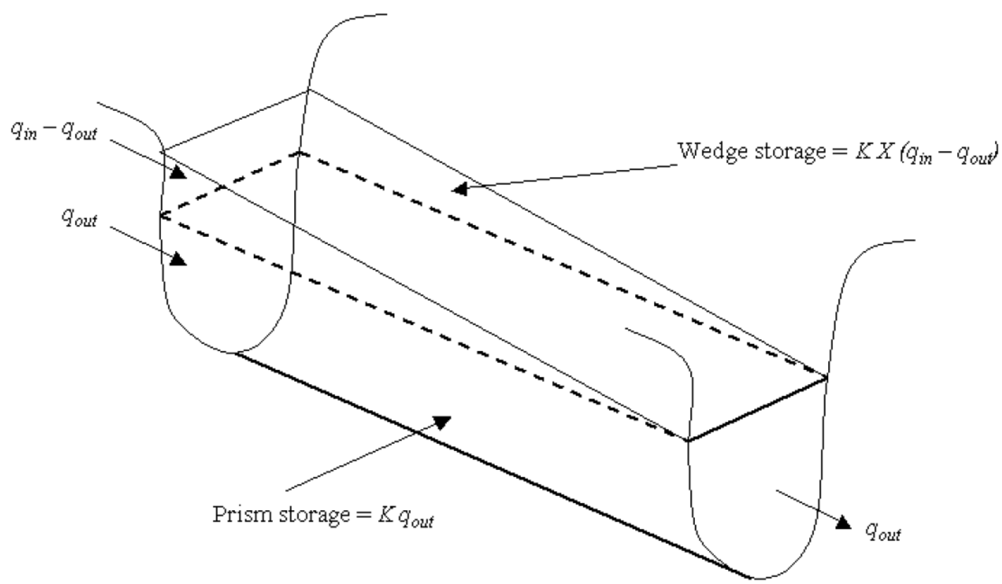

Figure 2.3: Prism and wedge storages in a reach segment (Neitsch *et al.*, 2005)

A wedge is produced as a flood wave advances into the reach segment when the inflow exceeds outflow. As the flood recedes, a negative wedge is produced when the outflow exceeds inflow in the reach segment. The reach segment also contains a prism storage formed by a volume of constant cross-section along the reach length (Figure 2.3). The volume of prism storage can be expressed as a function of discharge, $K \cdot q_{out}$ where K is the ratio of storage to discharge and has the dimension of time. The volume of the wedge storage can be expressed as $K \cdot X \cdot (q_{in}-q_{out})$ where X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in the reach. Therefore the total storage given by summing the wedge and the prism storages is given in equation 7 below (Neitsch *et al.*, 2005).

$$V_{stored} = K.q_{out} + K.X.(q_{in} - q_{out}) \quad (7)$$

Where V_{stored} is the storage volume (m^3), q_{in} is the inflow rate (m^3/s), q_{out} is the discharge rate (M^3/s), K is the storage time constant for the reach and X is the weighting factor.

$0.0 \leq X \leq 0.5$

The weighting factor X is a function of the wedge storage and has a value of 0.0 for reservoir type of storage and 0.5 for a full wedge while for rivers it falls between 0.0 and 0.3 with a mean value of 0.2.

When the storage equation 7 is incorporated in the continuity equation and simplified, the resulting equation is

$$q_{out,2} = C_1.q_{in,2} + C_2.q_{in,1} + C_3.q_{out,1} \quad (8)$$

Where $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the outflow rate at the end of time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s).

In terms of volume, both sides of equation 7 are multiplied by the time step and gives

$$V_{out,2} = C_1.V_{in,2} + C_2.V_{in,1} + C_3.V_{out,1} \quad (9)$$

$$C_1 = \frac{\Delta t - 2.K.X}{2.K.(1-X)+\Delta t} \quad (10)$$

$$C_2 = \frac{\Delta t + 2.K.X}{2.K.(1-X)+\Delta t} \quad (11)$$

$$C_3 = \frac{2.K.(1-X)-\Delta t}{2.K.(1-X)+\Delta t} \quad (12)$$

Where $C_1 + C_2 + C_3 = 1$

Soil erosion- In SWAT, erosion and sediment yield are calculated using Modified Universal Soil Loss Equation (MUSLE). The difference between MUSLE and Universal Soil Loss Equation (USLE) is that USLE uses rainfall as indicator of erosive energy while MUSLE uses the amount of runoff to simulate erosion and sediment yield. The advantages of using MUSLE over USLE are; prediction accuracy of the model is increased, the need of sediment delivery ratio is eliminated and estimates of sediment yields for a single storm can be computed (Neitsch *et al.*, 2005). The MUSLE equation is given in equation 13;

$$Sed = 11.8.(Q_s.q_{peak}.A)^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \qquad \textbf{(13)}$$

Where *Sed* is the sediment yield on a given day (tons/ha), Q_s is the surface runoff (mm/ha), q_{peak} is peak runoff rate (m^3/s), *A* is Area (of HRU) (ha), K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover management factor, P_{USLE} is the USLE support factor, LS_{USLE} is the USLE topographic factor and *CFRG* is course fragmentation factor

K_{USLE}, C_{USLE}, P_{USLE} and LS_{USLE} are as described in the USLE equation (1).

Effect of slope length on sediment yield

Slope length affects the topographic factor, *LS* as well the peak runoff rate. SWAT uses MUSLE equation (13) to estimate soil erosion. The topographic factor, *LS*, is calculated by equation 14 .

$$LS_{USLE} = (\tfrac{L_{hill}}{22.1})^m.(65.41.\sin^2(\alpha_{hill}) + 4.56.\sin\alpha_{hill} + 0.065) \qquad (14)$$

Where; LS_{USLE} is topographic factor, L_{hill} is slope length which is equal to SLSUBBSN in SWAT (m) and α_{hill} is the angle of slope and exponent *m* is computed;

$$m = 0.6 \times (1 - \exp[-35.835.slp]) \quad (15)$$

Where; *slp* is slope of the HRU (m/m) and

$$slp = \tan \alpha_{hill} \quad (16)$$

Modified Rational method (equation 17) is used to model peak runoff rate in SWAT.

$$q_{peak} = \frac{\alpha_{tc} \times Q \times Area}{3.6 \times t_c} \quad (17)$$

Where; q_{peak} is peak runoff rate (m/s), Q is surface runoff (mm), α_{tc} is fraction of the daily rainfall that occurs during the time of concentration, *Area* is sub-basin area in km^2 and t_c is the time of concentration for the sub-basin (hrs).

The time of concentration t_c, is calculated as;

$$t_c = \frac{L_{slp}^{0.6} \times n^{0.6}}{18 \times slp^{0.3}} \quad (18)$$

Where; L_{slp} = *SLSUBBSN* is slope length (m), n is Manning's roughness coefficient and *slp* is slope of the sub-basin (m/m).

In SWAT, the slope length,

$$L_{hill} = L_{slp} = SLSUBBSN \tag{19}$$

By substituting equations 14, 17, 18, and 19 in the MUSLE equation (12), the total effect of slope length (SLSUBBSN) on upland soil erosion can be estimated as (Arabi *et al.*, 2008);

$$Sed \propto SLSUBBSN^{(-0.6\times0.56)} \times SLSUBBSN^{m} =$$

$$Sed \propto SLSUBBSN^{(m-0.336)} \tag{20}$$

Where; *Sed* is sediment yield computed in MUSLE equation (13).

From (13), it can be seen that the contribution of the slope length to the sediment yield will be equal (unit) for any sub-basin length when *m* equals 0.336. Since exponent *m* (computed from equation 15) depends on the slope of the sub-basin, a value of 0.336 will correspond to a slope of 0.023. Above this slope, a reduction in slope length would have an overall reduction in soil erosion (Figure 2.4). However, below that slope, a reduction in slope length would actually result in an increase in the simulated sediment yield (Arabi *et al.*, 2008). For that reason, terraces are best simulated for HRUs whose average slope is above 2.3 %.

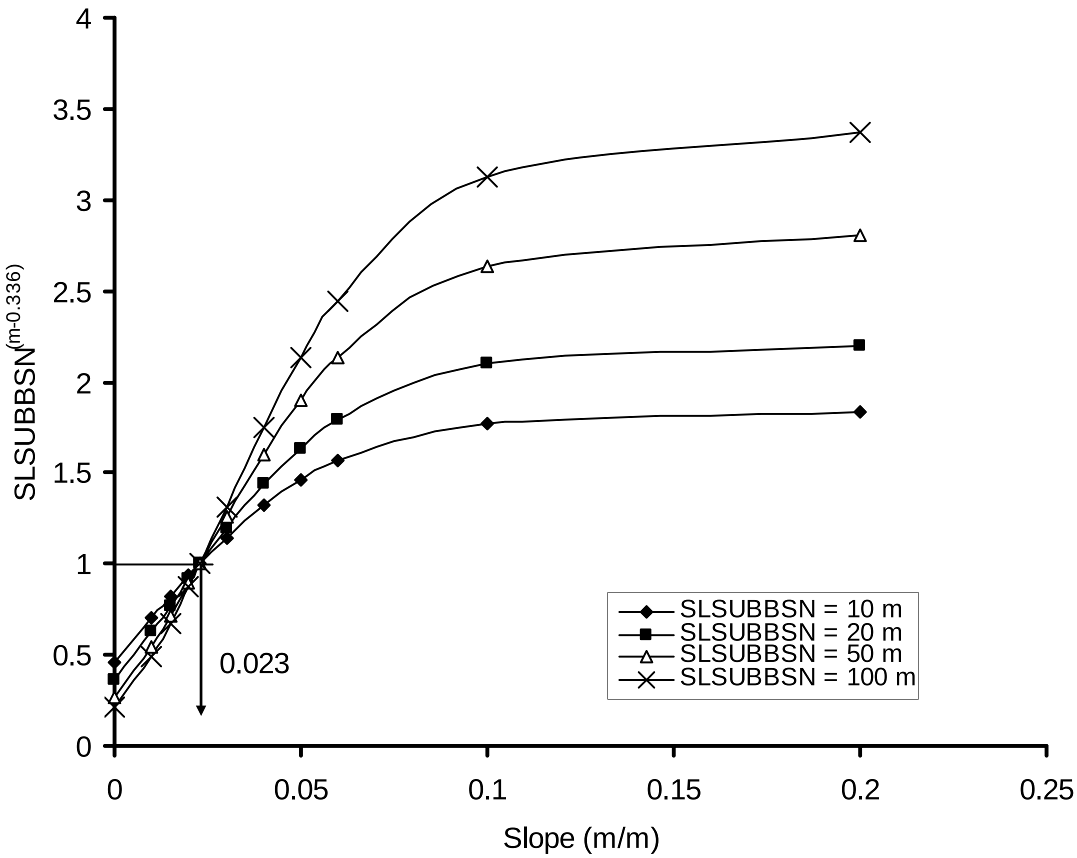

Figure 2.4: Relationship between slope and slope length on SWAT upland erosion estimation (Modified from Arabi *et al.*, 2008)

Sediment channel routing- Deposition and degradation are the two main processes that are involved in the sediment transport in the channel network (Neitsch *et al.*, 2005). Degradation of a channel represents a response to a disturbance in which an excess of flow energy, shear stress or stream power (sediment-transporting capacity) occurs relative to the amount of sediment supplied to the stream (Simon and Rinaldi, 2006). Degradation causes systematic bed-level lowering over a period of time can affect long stream reaches, entire lengths of one stream, or whole stream networks. It is different from scouring which is erosion of the stream bed or bank and limited in magnitude as well as in spatial and temporal extent. Scour can occur over periods of hours to days and affects localized areas in response to storm flow (Simon and Rinaldi, 2006). Deposition occurs when the sediment in the water settle on the river bed as a result of reduced transport capacity. In SWAT degradation is modeled as a function of stream power determined by channel slope and flow velocity (equation 25). If the sediment concentration in the water is greater than the maximum sediment that can be transported in the flow (equation 27), then sediment deposition occurs. The reverse is true for the degradation process.

Only the main hydrological, soil erosion and sediment transport process are highlighted here. Many of these processes have other sub processes which are not highlighted. Other than climate, hydrology and sediment (soil erosion), other components of SWAT include plant growth, nutrients, pesticides, bacteria, pathogens and land management. Complete descriptions of theory and underlying processes and governing equations in SWAT can be found in Neitsch *et al.* (2005). Nutrients, pesticides bacteria and pathogens were not modeled in this study.

CHAPTER 3

MATERIALS AND METHODS

This chapter describes the materials and methods used to simulate soil and water conservation practices. The study was carried out in Sasumua watershed, Kenya. SWAT model was first calibrated and validated for Sasumua and then used to simulate the conservation practices. The Sasumua reservoir inflow data calculated from reservoir water balance was used for calibration and validation of the model. Field visits and farmers interviews were done to get the land management information necessary for the model setup. The major inputs for the SWAT model include, Digital Elevation Model (DEM), soil data, land use and land management, weather data (rainfall, temperature, relative humidity, radiation and wind speed) and Weather generator information which require statistics of weather pattern over a period of time. Stream flow and water quality data such as sediments may also be used for model calibration and validation. Input data to the model were collected from different sources and are described in the chapter.

3.1 Data collection

3.1.1 DEM, Land use/Land cover and Soil Data

The data collected for this study included, a DEM with a spatial resolution of 10 m, a land use/land cover map generated using digital image classification of aster satellite images of 2007 (both from World Agroforestry Center, Nairobi). Soil data for the watershed were extracted from the Digital Soil and Terrain Database of East Africa (SOTER) (FAO, 1997). Soil properties required by the model are hydrological soil groups, soil depth, textural fractions, saturated hydraulic conductivity, available water capacity, bulk density and organic matter content for various soil layers. Some of these parameters were derived directly from the SOTER database while others were found in literature.

3.1.2 Climatic data

Twenty seven years of rainfall data (1970-1996) for meteorological station number 9036188 at the dam site area and twenty one years (1970-1990) for south Kinangop forest rainfall station were used. Wind speed data for the Sasumua dam site station was used. Wind speed data was required in the calculation of evapotranspiration using the Penman Monteith equation by the model. For the other weather parameters such as temperature, solar radiation and humidity were simulated by the weather generator in SWAT. SWAT includes WXGEN weather generator model to generate climate data and to fill in gaps in the measured records (Neitsch *et al.*, 2005). Statistical climate data of a station in or within the vicinity of the watershed is required for the weather generator. The data for this was obtained from Kimakia Forest meteorological station (station ID 0936233) neighboring the Sasumua watershed.

3.1.3 Reservoir levels data

Stream flow data needed to calibrate the model was not available for the gauging stations in the watershed. Reservoir levels data was collected from the Nairobi Water and Sewerage Company offices at the dam site and were used for the calibration and validation of the model.

3.1.4 Site visits and farmer interviews

To get the baseline conditions that are necessary for the modelling purposes, site visits to the watershed were made to assess the condition of the land and water resources. During the site visits twenty farmers from the watershed were selected and interviewed (Figure 3.1). The criteria for selection of the farmers were on the basis of the location of the land in terms of topography, farm size and also the wealth of the farmer. These criteria ensured that the farmers selected were representative of the watershed. Questionnaires (Appendix 2) were administered to the farmers. For this study, the information that needed to be extracted from the farmers was the crops grown and the cropping pattern and also to assess the existing soil and water conservation measures on the farms. This baseline information was necessary for model setup before simulation of conservation practices. Table 3 gives a one-year rotation management operation that was modelled for the agricultural part of Sasumua Sub-watershed based on the interviews from the farmers.

Figure 3.1: Interview with one of the farmers

Table 3: Management operations modelled for the agricultural land

Operation	Date
Planting potatoes	1st March
Harvesting (harvest and kill)	31st May
Planting cabbages	15th June
Harvesting (harvest and kill)	15th September
Planting potatoes	1st October
Harvesting (harvest and kill)	31st December

3.2 Model setup for base scenario

The DEM, Land use and soil maps were configured to a similar projection (Custom Traverse Mercator, WGS 1984). The watershed was subdivided into 62 sub-basins (Figure 3.2).

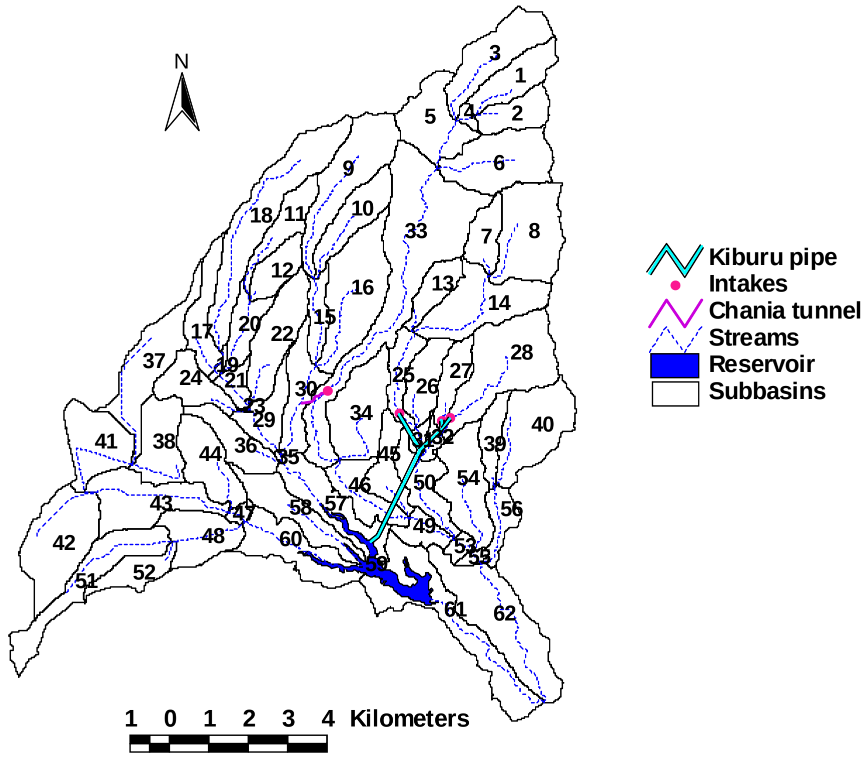

Figure 3.2: Sub-basins as simulated in SWAT model

Dominant land use and soil was used as the criteria for HRU definition. Dominant land use and soil criteria mean that a HRU is modeled with only a single land use/land cover and soil. This is normally the land use or the soil with the largest percentage in that HRU. The land use/land cover and soils with the smaller percentages are ignored for that particular HRU. Recorded rainfall data for Sasumua meteorological station for Kinangop forest rainfall stations were used. Wind data for Sasumua metrological station was used. All the other parameters i.e. (temperature, solar radiation and relative humidity, were simulated from weather generator data used for Kimakia Forest metrological station.

Management operations were scheduled by dates. In SWAT operations can be scheduled either by heat units or by dates (Neitsch *et al*., 2005).

The SCS Curve number method (equation 5) was used to model the surface runoff. Muskingum routing method (equations 7) was used to rout the water through the streams and Penman Monteith equation was used to calculate the evapotranspiration.

For the watershed delineation in the model, the main outlet was chosen to be at the confluence of Rivers Chania and Sasumua which is slightly downstream of the reservoir. This was necessary so that the model would include the Chania and Kiburu sub-watersheds in the watershed boundary. Kiburu sub-watershed has its intakes falling in sub-basins 25, 27 and 28 while Chania has its intake at sub-basin 33. To exclude the flow from the sub-basins that are downstream of the intakes at Chania and Kiburu sub-watershed, the stream flow and sediment outputs at the outlets of sub-basins 25, 27 and 28 for Kiburu and 33 for Chania were summed up with that of the outlet of Sasumua sub-watershed at sub-basins 57 and 59.

3.3 Parameter Sensitivity analysis

In order to guide the calibration process, parameter sensitivity analysis was done to identify parameters which had the most impact on model outputs.

3.4 Model Calibration

Water balance in the reservoir was used to calculate the inflow data which was then used for calibration and validation of the model. For sediments, proper parameterization guided by literature and field visits was carried out. For calibration purpose, a 'theoretical gauge' was put at the location of the dam. The inflow into the reservoir was used as to represent the measured stream flow at the 'theoretical gauging station'. The inflow was computed from the water balance equation (21) of a reservoir;

$$V_{\inf low} = (V_{end} - V_{beginning}) + V_{flowout} + V_{evap} + V_{seep} - V_{pcp} \quad (21)$$

Where V_{inflow} is the volume of water entering the reservoir during the day (m^3), V_{end} is volume of the water at the end of the day (m^3), $V_{beginning}$ is volume of water in the reservoir at the beginning of the day (m^3), $V_{flowout}$ is the volume of water flowing out of the reservoir during the day (m^3), V_{pcp} is volume of precipitation falling on the reservoir during the day (m^3), V_{evap} is volume of water removed from the reservoir by evaporation during the day (m^3), V_{seep} is volume of water lost from the reservoir through seepage (m^3) this was assumed to be in significant and its value assumed to be zero.

To get the base simulation selection of model parameters guided by literature was done. For model parameters that could not be measured or found from literature, manual calibration of stream flow was carried out. The period between 1988 and 1993 was used for calibration. The first two years were used as the warm up period.

After running the model, the simulated outflows were plotted along the 'observed' stream flow. Both visual and statistical methods were used to assess the goodness of fit between the simulated and the observed stream flow. Coefficient of determination (R^2) was used to numerically test the model performance. R^2 varies between 0 and 1 with one being ideal for a perfect fit. An R^2 of 0.5 and above was considered reasonable for this study considering the accuracy of the data used.

3.5 Model Validation

To demonstrate that the calibrated model was capable of making accurate predictions, the model was validated. The reservoir inflow data was used for the validation just as in the case of calibration. The model was validated by data for the period between 1994 and 1997. Both calibration and validation periods were chosen to correspond to the time when there was relatively good data for calculation of the reservoir water balance components. During validation process, the model parameter values set during the calibration were maintained constant. The resulting stream flow (simulated) was compared visually in a graph with the observed stream flow. Coefficient of determination was also determined.

3.6 Simulation of soil and water conservation Practices

Sasumua sub-watershed (Figure 1.1) which is mainly agricultural was the only portion of the watershed which was considered for the simulation of the conservation practices. Chania and Kiburu sub-watersheds which are under forest were left out since the forest provides enough soil cover. For Sasumua sub-watershed, the main outlet at the dam was considered at the outlet of sub-basins 57 and 59 (Figure 3.2) which capture the flow and pollutants from the entire sub-watershed. The methodology used for the simulation of conservation practices in this study is based mainly on the methodology developed for simulation of conservation practices in SWAT by Arabi *et al*. (2008). In this study, the agronomic and vegetative conservation practices considered were the contour farming and vegetative filter strips. Bench terraces and grassed waterway were simulated in case of structural conservation practices. Two more simulations were done to compare management scenarios in the watershed. The first management scenario simulated a situation where less intensive cultivation in agricultural lands and proper managed grazing in grasslands are practiced. The second management scenario simulated a situation where intensive cultivation in agricultural lands and overgrazing in grasslands would cause degradation of the watershed.

3.6.1 Vegetative Filter strips

The width of edge-of-field filter strip parameter (*FILTERW*) in SWAT was adjusted to simulate this conservation practice. The filter strips were simulated for all the sub-basins in the agricultural part of Sasumua sub-watershed except sub-basins 57, 58 and 60 where a wide riparian buffer exists (Figure 3.2). This buffer is managed by Nairobi City Water and Sewerage Company NCWSC and was left to protect the reservoir from siltation. The width of the filter strip was increased at interval of 5 meters from 0 to 35 m. Only the parameter *FILTERW* was adjusted for each simulation. The sediment loading at the outlet of sub-basins 57 and 59 (reference sub-basins) for various widths of filter strip was determined. The effectiveness on the filter strips in the reduction of the sediment yield is based on the trapping efficiency.

3.6.2 Contour farming

To represent contour farming, the *CN* was decreased by three units from the calibration/parameterization values according to the method developed by Arabi *et al*. (2008). *USLE_P* was adjusted depending on the slope of the HRU according to Table 4 given by Neitsch *et al*. (2005). The table gives recommended *USLE_P* values for contour farming, strip cropping and terracing. The *USLE_P* values for the target sub-basins in the agricultural part of the sub-watershed were reduced from the base simulation value of 0.85.

Table 4: USLE-P values for contour farming, strip cropping and terracing

Land slope (%)	*USLE_P*			
	Contour farming	Strip cropping	Terracing	
			Type 1[a]	Type 2[b]
1 to2	0.60	0.30	0.12	0.05
3 to 5	0.50	0.25	0.10	0.05
6 to 8	0.50	0.25	0.10	0.05
9 to 12	0.60	0.30	0.12	0.05
13 to 16	0.70	0.35	0.14	0.05
17 to 20	0.80	0.40	0.16	0.06
21 to 25	0.90	0.45	0.18	0.06

[a] Type 1: graded channel sod outlet

[b] type 2: Steep backslope underground outlets

Source: (Weischmeier and Smith, 1978)

To further evaluate how much the a combination of the filter strips and contour farming would have on the sediment yield and stream flow, another simulation was run with a 5 m filter strip width and the *CN* and *USLE_P* values selected to represent the contour farming.

Only the sub-basins in the agricultural part of the watershed in the Sasumua sub-watershed were included in the simulation of contour farming.

3.6.3 Bench terraces

To simulate bench terraces in SWAT, slope length within sub-basin (*SLSUBBSN*), *USLE_P*, and *CN* were adjusted (Arabi *et al.*, 2008). In SWAT, slope length is represented by the parameter *SLSUBBSN*. Adjusting this parameter downwards represented reduced slope length. The reduced soil loss was factored in by reducing the *USLE_P* in the Modified Universal soil loss equation used to model soil erosion in the SWAT model. Implementation of bench terraces would affect all these processes together and thus all the parameters were adjusted simultaneously in a single run.

The *CN* values were reduced by 7 units from the calibration values for each HRU. The value of 7 was selected based on the values for *CN* for different practices given in Neitsch *et al*. (2005). *USLE_P* values for terracing type 1 (graded channels sod outlets) in Table 4 were used depending on the average slope of the HRU. To determine the appropriate slope length for each HRU after implementation of bench terraces, Horizontal Interval method (section 2.5.1) was used. The original slope length calculated by the model from the DEM was reduced to the slope length calculated by the

Horizontal Interval method for each HRU. A set of the three parameters, CN, USLE_P and SLSUBBSN was adjusted for each HRU and the model run when adjustment was done for all the appropriate HRUs.

Bench terraces were only simulated in sub-basins whose average slope was above 2.3 % (Refer to section 2.8.3). The highlighted sub-basins in Figure 3.3 show the areas where the bench terraces were simulated which is equal to 3.5 km^2.

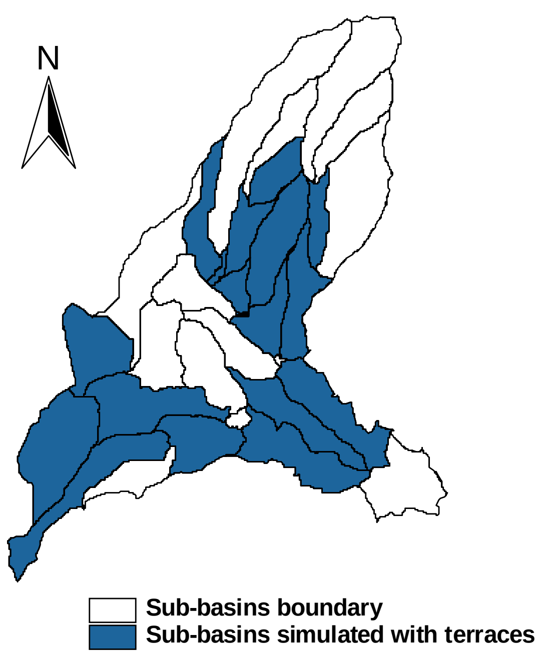

Figure 3.3: Sub-basins simulated with bench terraces

3.6.4 Grassed waterway

Grassed waterways were simulated in several drains that feed Mingotio stream. These drains fall in sub-basins 37, 38, 41, 42 and 51. The drains collect the runoff from the agricultural lands and the fast growing towns and discharge at Mingotio stream. The total length of these drains is 14km. To represent this conservation practice, channel Manning's roughness coefficient (*CH_N2),* Channel cover factor (*CH_COV)* and channel erodibility factor (*CH_EROD)* were adjusted. Channel Manning's roughness coefficient (*CH_N2)* after the implementation of the grassed waterway was selected to be 0.3 s $m^{-1/3}$. Both CH_COV and CH_EROD were adjusted from 0.2 for the condition to 0.00. These values were based on literature of other similar studies (Fiener and Auerswald, 2006; Arabi *et al.,* 2007; Auerswald 2006a; Bracmort *et al.*, 2006; Arabi *et al.*, 2008; Auerswald 2006b). Section 2.5.2 also gives more information about the range of some these parameters used in other studies.

3.6.5 Additional management scenarios

Two additional land management scenarios to compare a good and a poor land management practices by the farmers in the watershed was carried out. Good management scenario simulated less intensive cultivation and well managed grazing. This practice would encourage more infiltration of water into the ground and reduce both surface runoff and soil erosion. The poor land management scenario simulated the degradation of the watershed where intensive cultivation and overgrazing dominates.

This practice would impede infiltration of water and increase surface runoff and subsequent soil erosion.

Good management scenario was simulated by decreasing the *CN* by 6 units from the base simulation case. The poor management scenario was done by increasing the *CN* by 6 units from the base simulation scenario. Decreasing the curve number will increase the infiltration in the curve number method and thus increase the surface runoff. The vice versa is true.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter the results of the study are presented and discussed. The result of the farmer interview whose information was used during model setup is presented first. The output of the sensitivity analysis, calibration and validation of SWAT model is then presented. Lastly the results and discussion of simulation of soil and water conservation practices on water and sediment yield follow.

4.1 Farmer interviews

4.1.1 Land use/land cover

From the interview with the farmers, it was found out that Irish potato is the main crop grown in the area as it can be seen in Figure 4.1. Irish potato is grown in rotation with cabbages and there are three growing seasons in a year mainly. Similar results have been observed in other studies (Bhattarai, 2009). This information was used in the model setup to simulate land management operations (Table 3). Most farmers in the watershed practice shift cultivation where they grow crops on one section of their farms and leave other sections as fallow where they normally graze (Figure 4.1). After several years of cultivation, the farmers leave the land and open new land which had been left fallow.

Figure 4.1 shows that 66% of the land as fallow. The percentages were based on the total area of the land owned by the farmers interviewed. Twenty farmers were interviewed and the size of the land they own was one factor considered during selection of the farmers. Some farmers (majority) own as small as a quarter acre of land while others have as much as 100 acres. Farmers with small pieces cultivate their entire piece of land and don't practice shift cultivation. Farmers with big chunks of land leave large parts of their land fallow. However, these farmers are only few and therefore, the percentage represented by the fallow land in Figure 4.1 only represents the percentage of the twenty farms but not for the entire watershed.

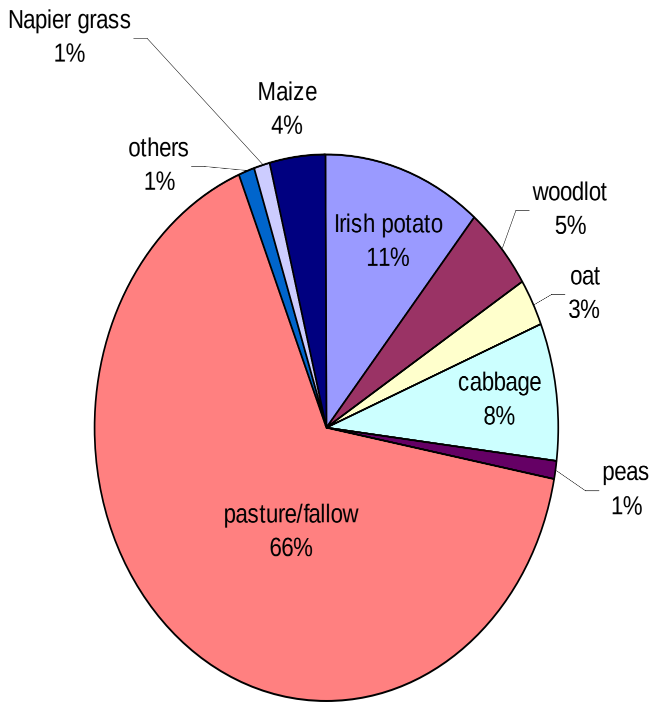

Figure 4.1: percentage Land use (based on 20 farms visited)

4.1.2 Soil conservation practices in Sasumua

Field visits to the watershed and interview with farmers revealed that there is minimum soil conservation practiced in the area. Some of the soil conservation measures found in the watershed were bench terraces and fanya juu terraces in very few farms on the steep slopes. On the flat area of the watershed where flooding happens during the rainy season, drainage ditches are common and farmers usually plant napier grass for fodder on the embankment along the drainage channels (Figure 4.2). Grass strips are also found in few farms in the watershed. At the individual farms where some of these conservation measures are undertaken, they have managed to control soil erosion to some extent. However, the adoption rate of these conservation measures is generally low for the entire watershed and therefore their impact on reducing soil erosion and sedimentation of the streams and the reservoir is still very low (Figure 4.3). Other studies have also found that high soil erosion is occurring in the watershed (Gathenya *et al*., 2009; Vagen, 2009). This information was used to select the USLE_P factor for the watershed during the model setup phase of the study.

Figure 4.2: Napier grass strip in one of the farms in Sasumua.

Figure 4.3: Highly turbid water in Sasumua stream upstream of the Reservoir

4.2 Parameter Sensitivity analysis

The top most sensitive parameters for both stream flow and sediment are presented (Table 5). Curve Number (*CN*) resulted to be the most sensitive parameter in the sensitivity analysis for both the flow and the sediment. The *CN* given in Neitsch *et al.* (2005) are for 5% slope. Since some areas of the watershed especially in the forested areas have a steeper slope, the *CN* values were adjusted for slope using the following equation;

$$CN_{2s} = \frac{(CN_3 - CN_2)}{3}.[1 - 2.\exp(-13.86.slp)] + CN_2 \tag{22}$$

Where CN_{2s} is the Curve Number for soil moisture condition II adjusted for slope, CN_3 is the Curve Number for moisture condition III for the 5% slope, CN_2 is the Curve Number for moisture condition II for 5% slope and *Slp* is the average slope for the sub-basin.

Curve Number for moisture condition III was calculated as follows;

$$CN_3 = CN_2.\exp[0.00673.(100 - CN_2)] \tag{23}$$

Table 5: Top most sensitive parameters for stream flow and sediment and the range of values used for base simulation

Rank	Parameter	Description	Value used (base simulation)	Min – Max
		Stream flow		
1	CN_2	Curve Number for moisture condition II	53-88	35-98
2	GWQMN	Threshold depth for water in the shallow aquifer (mm)	1000	0-5000
3	Slope	Average slope steepness (m/m)	0.012-0.58	0.00-0.60
4	Sol_Z	Depth from soil surface to bottom of layer (mm).	0-1000	0-3500
5	ESCO	Soil evaporation compensation factor	0.75	0.0-1.0
		Sediments		
1	CN_2	Curve Number for moisture condition II	53-88	35-98
2	SP-CON	Linear coefficient for in-stream channel routing	0.001	0.001-0.01
3	Sol_Z	Depth from soil surface to bottom of layer (mm).	0-1000	0-3500
4	Slope	Average slope steepness (m/m)	0.012-0.58	0.00-0.60
5	USLE_P	USLE_equation support practice factor	0.85-1.00	0.10-1.00

Esco was found to be sensitive and affecting all the components of the water balance. A decrease in *esco* showed a decrease in water yield, surface runoff and base flow and an increase in evapotranspiration. The value of *ESC0* varies between 0 and 1. As *esco* is reduced the model is able to extract more of the evaporative demand from the lower layers. This has also been shown by other studies (Kannan *et al.*, 2007; Sang, 2005).

Threshold water depth in the shallow aquifer (GWQMN) was found to be very sensitive parameter to the groundwater components of the water balance and used to adjust the base flow. A decrease in this parameter yielded more base flow and a corresponding increase in stream flow and vice versa. This has also been observed elsewhere (Kannan *et al.*, 2007; Sang, 2005). Water that percolates from the soil layers enters the shallow aquifer and/or deep aquifer. Shallow aquifer contributes flow to the main channel as base flow. SWAT will only allow the base flow to enter the stream if the depth of water in the shallow aquifer exceeds GWQMN. GWQMN was found to have very slight (insignificant) effect on surface runoff. This is because it only deals with the water that have already infiltrated and percolated into the aquifer.

The average slope steepness was found to have quite a big effect on the water balance and sediment yield. The slope affects the velocity of overland flow thus affecting the surface runoff volumes and peak runoff rates. Slope is directly proportional to velocity of the surface runoff and is computed using Manning's method (equation 26) in SWAT. Peak runoff rates have a great influence on soil erosion as modelled in the modified rational formula (equation 17) in SWAT. The average slope also affects the movement of lateral flow. The average slope represent the topography of the sub-basin therefore there is little adjustment that can be made about this parameter especially in areas where the sub-basin has more or less uniform slope. On the hilly North Eastern part of the watershed, a slight adjustment (within 10%) was done during the calibration.

Available soil water content (SOL_AWC) which is the difference between the Field capacity of the soil and the wilting point was only adjusted within ± 0.004 m/m. This component represents the soil storage and an increase would reduce all the other water balance components. A comprehensive description of all the parameters is given in Neistch *et al*. (2005)

4.3 Model Calibration

Figure 4.4 shows the calibration plot for stream flow. Monthly data was used for calibration. The figure shows the 'measured' (generated from the reservoir) and simulated stream flow in addition to mean monthly reservoir data for the same period. The fit between the simulated and 'measured' flow hydrographs with an R^2 of 0.6 was found satisfactory under the existing conditions considering the water that was not accounted for in the reservoir water balance which was used to generate the flow data. The reservoir capacity when full is 16 million cubic meters of water.

As it can be seen the reservoir was full during the periods of April and July 1990 and 1993. This is during the rainy season (Figure 1.4). When the reservoir is full, the water goes over the spillway. The flow over the spillway is not gauged at the reservoir. This water was therefore not accounted for in the reservoir water balance which was used to calculate the inflow into the reservoir. The reservoir inflow was used as the 'measured' stream flow in the calibration and validation of the model. During the rainy season when the stream flow is high, the pipe from Kiburu sub-watershed can only carry a limited capacity and so when full, the rest of the water goes downstream through Kiburu River and thus do not go to the reservoir. The simulated flow would however include this water. In 1991 and 1992, there is a relatively close agreement between the simulated and the 'measured' stream flows. Although April-July is a rainy season, the reservoir was not full during that period in 1991 and 1992 as shown in Figure 4.4. This means that no or little water was lost through the spillway during that period. In November- December of 1992, the reservoir was running full hence the reason we have relatively smaller peak for simulated stream flow higher than the observed. There are also some cases where the simulated flow was smaller than the observed flow this could be caused by the times when the abstraction from the reservoir (outflow) was less than 64,000 m^3 /day during the dry seasons.

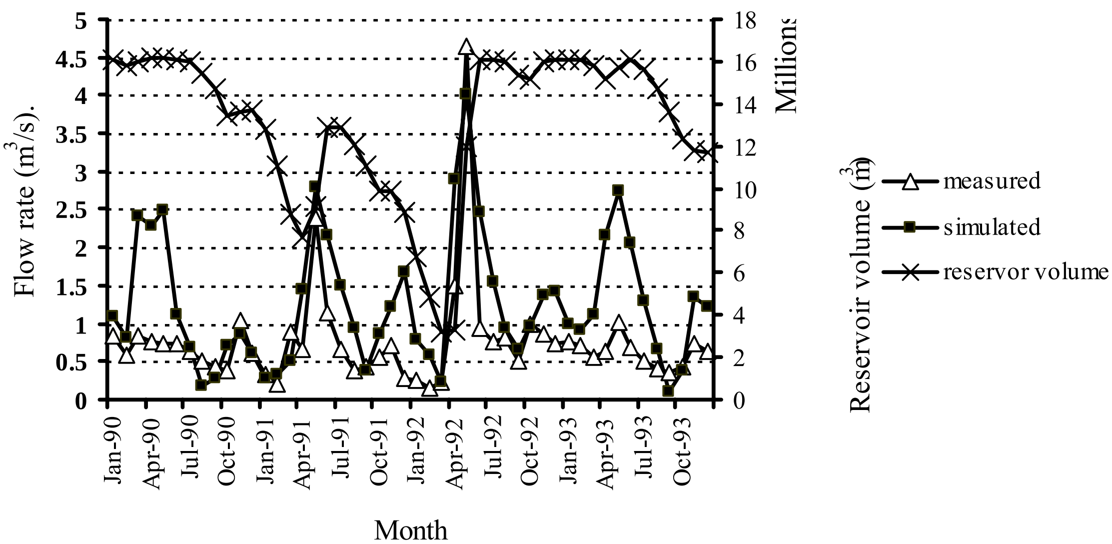

Figure 4.4 'Measured' and simulated stream flows comparison with mean monthly reservoir volumes

4.4 Model Validation

The validation period was from 1994 to 1997. On average, there was reasonable agreement between the 'measured' and the simulated stream flows with an R^2 of 0.5. Like in the case of the calibration, the simulated stream flows was slightly higher than the 'measured' flow during the rainy seasons of April-July of 1995, 1996 and 1997. Again, this is a wet season and there was unaccounted for water in the reservoir water balance. This is as shown in the Figure 4.5 which represents the mean monthly simulated and 'measured' steam flows together the reservoir volumes. In 1994, the reservoir was not full (Figure 4.5). Therefore little or no water was lost from the system and hence the close fit in the hydrographs.

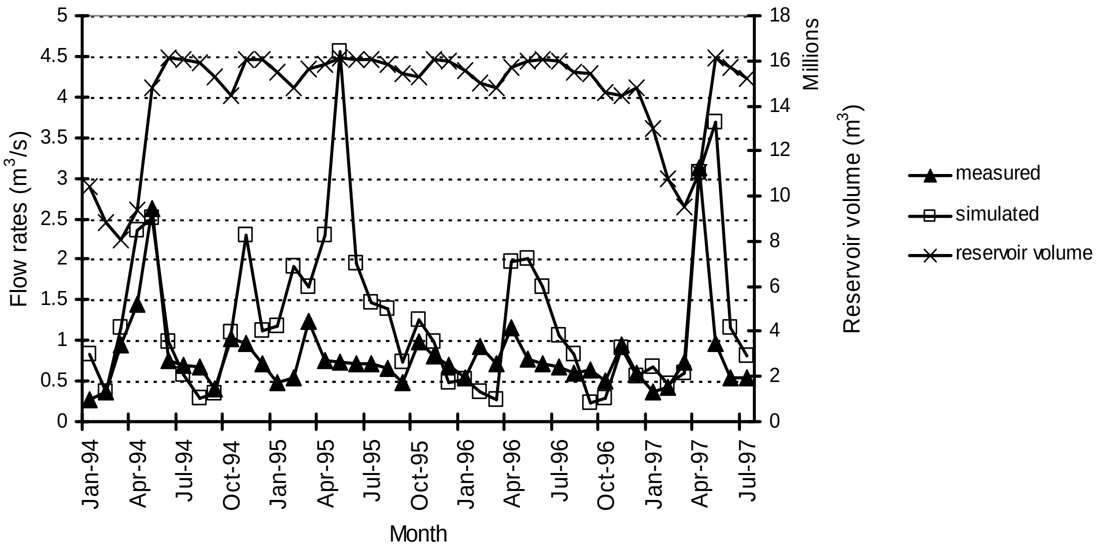

Figure 4.5: Measured and simulated stream flow comparison with mean monthly reservoir volumes

4.5 simulation of soil and water conservation practices

4.5.1 Vegetative filter strips

An increase in the width of the filter strip resulted in a decrease in the sediment loading (Figure 4.6) with the first few meters having the greatest impact on reducing the loading into the streams.

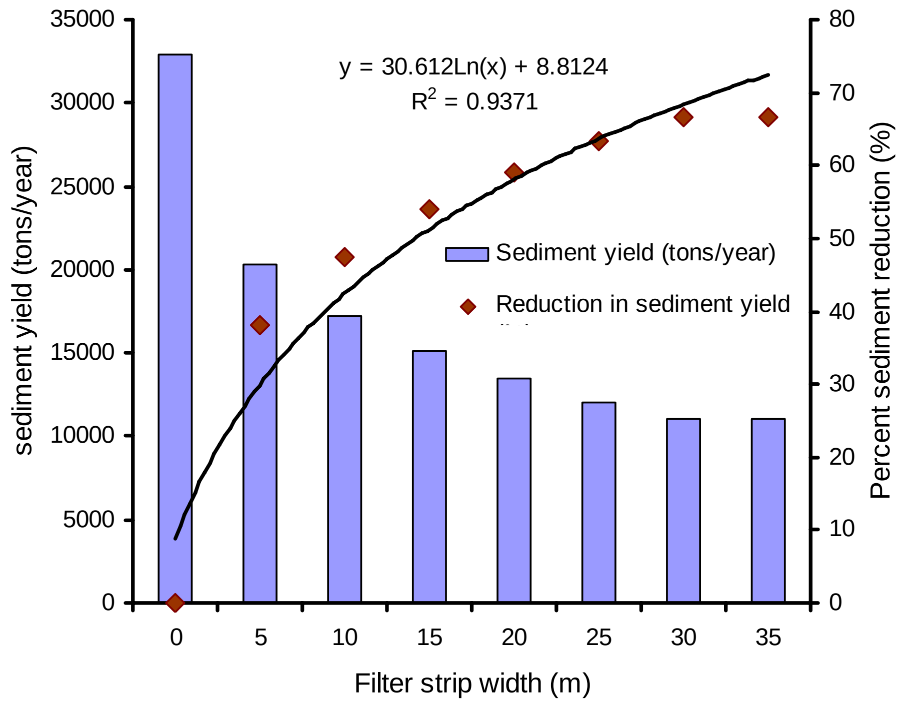

Figure 4.6: Total decrease and percent reduction in sediment yield as a function of the width of the filter strip.

This trend is similar to what has been found in other studies (Arabi *et al.*, 2008; Abu-Zreig *et al.,* 2004; Yuan *et al.,* 2009; Abu-Zreig, 2001). The figure also shows that in SWAT increasing the filter strip width beyond 30 m would not be effective in reducing sediments loading in the channels. This is because the model uses trapping efficiency equation (24) to model filter strips and according to the equation, a filter width of 30 m would have a trapping efficiency of 1 (Parajuli *et al.*, 2008).

$$trap_{eff\_sed} = 0.367 \times FILTERW^{0.2967} \tag{24}$$

Where $trap_{eff\_sed}$ is trapping efficiency of the sediments and *FILTERW* is the width of the filter strip (m).

In Sasumua, the small sizes of land (as small as a quarter of an acre) owned by many of the small scale farmers can not allow large grass strips on the fields. Wolde and Thomas, (1989), recommend installation of grass strips of 1.0 m to 1.5 m wide where land is not scarce and 0.5 m where land is scarce in Kenya. This recommendation is valid for contour grass strips and taking the advantage of the logarithmic relationship between the sediment yield reduction and grass filter strip width. This relationship means that even smaller widths of grass strips would still be beneficial in reducing soil loss. Wider filter strips can be installed on the riparian areas where the government prohibits cultivation in the agriculture act.

The logarithmic trend can be attributed to equation 24 which incorporates higher efficiencies in the front portion of the strip in trapping the sediments (Arabi *et al.*, 2008). Yuan *et al*. (2009) after reviewing several studies on the effectiveness of the buffer strips concludes that the trapping efficiency of the buffer width would be best fitted in a logarithmic model and that a 5 m buffer can trap up to 80% of the sediments. Other studies that have observed the similar results include; Robinson *et al*. (1996) who found that the initial 3 m of vegetative filter strips removed more than 70% of the sediment, Borin *et al.* (2005) found out that a 6 m buffer strip composed of trees and grass reduced total suspended sediment load by about 78%, Ullrich and Volk, (2009) found out that a 2 m filter strip would result in a reduction of total sediment loading by about 45% when simulated using SWAT. In Kenya, Ogweno, (2009) found that a 10m filter strip reduced sediment yield by over 95% in Malewa watershed, in Naivasha Kenya.

The trapping efficiency of the filter strips depends on many factors but the width is the major one (Abu-Zreig, 2001). Other factors include; vegetation type, density and spacing, Manning's roughness coefficient, flow concentration, soil type, sediment particle size and the slope (Yuan *et al.,* 2009; Abu-Zreig, 2001; Fox *et al.*, 2010; White and Arnold, 2009).

Buffers decrease the velocity of the surface runoff due to increased roughness provided by the vegetation and in effect allow the sediments to settle due to the reduced sediment transport capacity of the runoff. Buffers also enhance the infiltration of reducing the amount of runoff thus aiding in sediment deposition also due to reduced sediment transport capacity (Yuan *et al.,* 2009; Borin *et al.,* 2005; Abu-Zreig *et al.,* 2004; White and Arnold, 2009; Duchemin and Hogue, 2009).

In Sasumua, other than the reparian buffer strips at the reservoir and extending some distance upstream of the feeding streams, very few farms have grass strips on their land. Some farmers cultivate right into the streams banks and since some streams are seasonal, they cultivate right into the channels when they are dry. Thus, Implementation of vegetative strips in the whole watershed would ensure that the sediments are trapped and retained on the land as opposed to the current state where they are washed into thee streams. One of the ecosystem services that the watershed is expected to provide is regulation/improvement of water quality. From the simulation results obtained here it is quite clear then that vegetative filter strips would enhance this ecosystem service as far as sedimentation is concerned.

Farmers in the watershed would have to compromise some of the crop land for conservation if filter strips are to be implemented. This may not be easy due to the small sizes of land that most of the farmers in the watershed have. For filters strips implementation, the farmers need to be educated on the need for conservation and where possible compensated for the land they would forgo for the purpose of the conservation. Payment for Ecosystem Services (PES) should be evaluated for the watershed to find ways of giving incentives to the farmers who do conservation and more so if they will have to give up part of their land they use for crop production like in the case of filter strips. The vegetation in the filter strip can also be selected to have multiple functions. Other than NPS pollution abatement, filter strips comprising of trees and grass could offer other benefits like timber production, carbon dioxide sequestration, aesthetics (Borin *et al.,* 2010), increasing the biodiversity of flora and fauna and providing habitat for wildlife (Lovell and Sullivan, 2006). The grass can also be used as fodder for livestock. In this way, the farmers will have a direct economic benefit from the trees and the fodder and would be encouraged to preserve and maintain the filter strips for pollution prevention purposes.

4.5.2 Contour Farming

The simulation result for contour farming shows that on average the sediment loading to the streams (outlet at the reservoir) would reduce by 49% from the base simulation. Table 6 shows the mean sediment load for the base scenario and simulation with contour farming, contour farming plus 5 m width filter strip and terracing over 36 years of simulation.

Most of the sediment loads in the streams would result from the soil erosion on the watershed. It is thus necessary to show the spatial variation of soil erosion in the watershed.

Table 6: Mean simulated sediment yield for contour farming, contour farming and 5 m filter strip width and terracing

	Mean sediment yield ($\times 10^3$ tons/year)	Percent change
Base simulation	32.62	
Contour farming	16.60	-49
Contour farming and 5 m filter strip width	8.72	-73
Terracing	4.93	-85

Figures 4.7 (a) and (b) shows spatial distribution of the annual sediment yield in ton/ha from various sub-basins in the Sasumua sub-watershed before and after the implementation of the contour farming respectively clipped from the entire Sasumua watershed used in the simulation. The sediment yield values for the respective sub-basins are shown in appendix 3. The base simulation results of sediment yield compares well with that obtained by other studies in the area. Kigira, (2007) for example, found that the sediment yield ranges between 2.0 -70 tons/ha/yr for the same location of the watershed when he modelled the larger Thika watershed using SWAT model. Sasumua River is a tributary of Chania River which is in turn a tributary of Thika River. Thus Sasumua watershed is part of the larger Thika watershed. Other sediment studies that have been done on the Chania watershed include; Dunne, (1974), who found that the Chania watershed (522.4 km^2) has a sediment yield of 0.19×10^6 tons/year, Ongwenyi, (1978), 0.3×10^6 tons/year and Maingi, (1991) who found a sediment yield of 0.87×10^6 tons/year

Figure 4.7 (a) shows that sub-basins 9, 10, 11, 16, 18 and 61 which are under forest cover have relatively low sediment yield. Low CN values were used, in equation 6, to represent forest land cover in the model. Sub-basins 41, 42, 43, 47 and 60 were found to have a relatively higher sediment yield. These are soil erosion hotspots which should be prioritized when implementing soil conservation measures. This is in consistent with earlier study by Gathenya *et al.* (2009). The main factors contributing to high sediment yield in this part of the watershed is the low infiltration rates characteristic of planosols

(Fig. 1.2) which generates much runoff that cause more soil erosion. Sub-basins like 43 which are adjacent to the main streams also have higher averages slopes.

The results indicate that implementation of contour farming would reduce the soil erosion in the farmlands. In general, contour farming can reduce soil erosion by 50% compared to up and down cultivation (Mati, 2007). Other studies (Quinton and Catt, 2004; Arabi *et al.*, 2008; Brunner *et al.*, 2008) have also found that contour farming have a positive effect in reducing sediment yield. For example, Quinton and Catt, (2004) found out that on average over a period of 10 years experiment, across the slope plots had a mean soil loss of 6.4 tons/ha compared the mean soil loss from the plots cultivated up and down slope was 16.5 tons/ha. Gassman *et al.* (2006) found out that contouring reduced sediment loss by 34% on average using 30 year simulation period by SWAT model and by 53% by Agricultural Policy Environmental eXtender (APEX) model over the same simulation period.

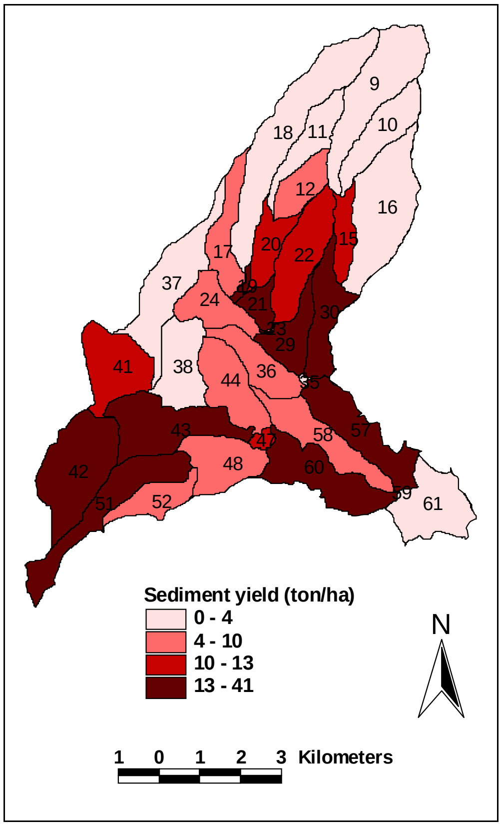

Figure 4.7 (a): sediment yield for base simulation

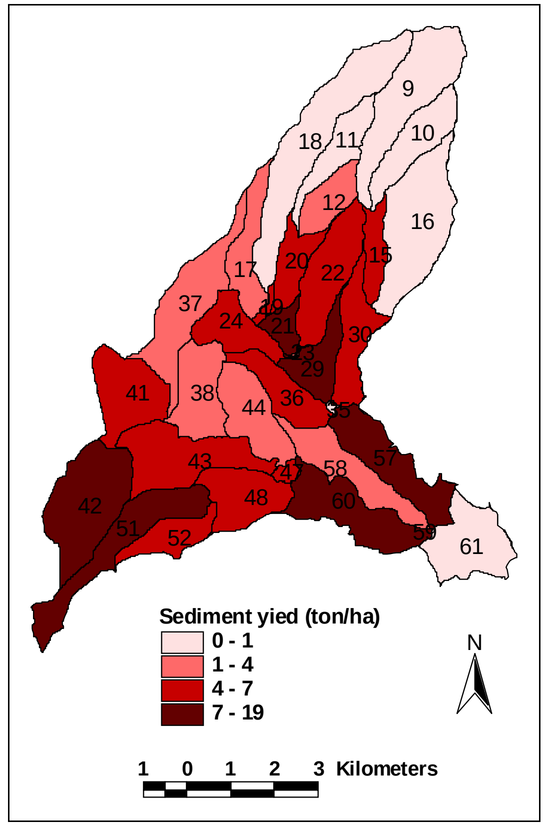

Figure 4.7 (b): sediment yield after implementation of contour farming

Revised Universal Soil Loss Equation (RUSLE) simulation in Wangjiaqiao watershed in China by Shi *et al.* (2004) found that contour tillage could reduce soil loss by 31%. Contour farming is mainly associated with cultivation using agricultural machinery and the contour farming parameter values found in literature would be more associated with mechanized farming. In Sasumua however, most farmers practice hand hoe tillage. There is minimal use of machinery tillage except when opening new land. Thus the surface roughness that can be achieved by hand hoe tillage may not be equal to that of machinery and therefore the sediment yield reduction may be lower than the values simulated for this study.

Contour farming creates surface roughness blocking the surface runoff and encourages infiltration as water pond in the depressions. This reduces the erosive power of surface runoff and thus reduces soil erosion (Quinton and Catt, 2004; Arabi, *et al.*, 2008).

From the water balance point of view, implementation of contour farming would result in a decrease of surface runoff of 16% and an increase of base flow of 7.6% with only a slight decrease in the total water yield (Table 7; Figure 4.8). In other studies, Quinton and Catt, (2004) found out that event surface runoff from experimental runoff plots was 0.8 mm for cultivation across the slope compared to 1.32 mm when cultivation was done up and down slope

The decrease in the surface runoff is a result of increased infiltration into the ground of water. Contour farming would cause impounding of water into the small depressions and thus more water would infiltrate into the ground (Quinton and Catt, 2004). This would in effect enhance the recharge of the shallow aquifer and water will be released to the streams as base flow.

Table 7: Water balance for base simulation and for simulation of contour farming

Simulation	Surface runoff (mm)	Lateral flow (mm)	Base flow (mm)	Water yield (mm)
Base simulation	193	184	304	680
Simulation with contour farming	162	187	327	675
% change	**-16.06**	**+1.63**	**+7.57**	**-0.7**

Thus it can be seen that the base flow has increased as a result. The implication of this phenomenon on the ground is that there would be reduced flash floods in the area and more recharge of the shallow aquifer. Therefore there would be increased base flow into the rivers even long after the rains. The increased base flow would result in more water going to the reservoir during the dry periods after the rains. This would reduce the incidences where the dam authorities have to deal with very low volumes in the reservoir causing them to reduce the daily volume of water that they treat and release to Nairobi.

The results here show that implementation of contour farming would improve water quality and regulate flows i.e. increase dry weather flows and reduce flash floods. Thus contour farming would improve the capacity of the watershed to provide the two regulatory ecosystem services (water quality improvement and flow regulation).

4.5.3 Contour farming and filter strips

Results for the simulation of a combination of filter strip and the contour farming implemented in the watershed would have a significant reduction in the sediment loading to the streams. A combination of contour farming and 5 metre wide filter strip would result in 73 % reduction in sediment loading from the base simulation (Table 6). Contour farming would reduce soil erosion in the farms and the filter strips would trap the eroded soil before it gets to the streams.

Implementing contour farming together with grass filter strips would be more beneficial than implementing either of the conservation practice on its own. Contour farming is an *insitu* soil conservation method and would ensure minimum soil displacement and minimum loss of soil fertility. On the other hand the filter strips will trap sediments that have been eroded and carried by the runoff before they get to the streams thus ensuring good water quality. This would also reduce the sedimentation of the reservoir which would offer some benefits to the dam management authorities. There would be less loss of reservoir storage capacity from siltation. The reduced sedimentation would offer a direct benefit in reduction of the water treatment costs associated with the turbidity. Aluminum sulphate (alum) is used for coagulation and flocculation of the suspended particles in the water treatment process. More of this chemical is used during the rainy season when the water contains more sediments. Thus reduction in the sedimentation of the streams and subsequent siltation of the reservoir would result in the reduction of water treatment cost.

4.5.4 Terracing

The results of sediment loading into the streams and the reservoir from Sasumua sub-watershed show that terracing would reduce the sediment loading by 85% (Table 6). Implementation of bench terraces in the watershed would reduce the sediment loading to the reservoir. Less sediment into the reservoir will reduce the cost of treatment of water due to turbidity and also reduce the loss of capacity of the reservoir due to siltation. These results compares well with other studies on the effectiveness of terraces in reducing sediment yield. Gassman *et al*. (2006) found out that terraces would reduce sediment yield by about 63.9 % and 91.8% using SWAT and APEX models simulations respectively. Santhi *et al*. (2006) found that contour terraces would reduce sediment yield by between 84 and 86% using SWAT simulations at the farm level.

Terraces enhance the ponding of water on the surface hence allowing higher rates of infiltration. The velocity of the remaining surface runoff would be reduced and thus the erosive power would be significantly reduced. Terraces also reduce the length of the slope which reduces the peak runoff rate (Arabi *et al.*, 2008). Peak runoff rate is directly proportional to the soil erosion rate. This explains the significant reduction of the sediment loading to the reservoir in the simulation of terraces.

The water balance after the implementation of the bench terraces (Table 8) shows that, bench terraces would reduce the surface runoff by 21.8% and increase the base flow by 10.2% (Figure 4.8). There is only a slight change in the total water yield (Table 8). The enhanced infiltration by terraces would recharge the shallow water table reducing the surface runoff. The water stored in the shallow aquifer will be released to the streams as the base flow. The implication of this is that, flooding incidences would reduce as the surface runoff is reduced and there would be more regulated stream flows which would run for an extended time because the base flow takes longer time to reach the streams than does the surface runoff. This would reduce the incidences of low storage volumes in the reservoir in dry seasons. During the rainy season, the reservoir receives a lot of water from the increased stream flow mostly due to high runoff. When full, much of this water flows over the spillway and sometimes causing damage to the spillway like the collapse of the spillway that happened in 2003. After the rains and when the dry season sets in, the reservoir volume gets low causing a reduction in the volumes treated daily for consumption by Nairobi residents. Therefore it would be a good idea to increase the recharge of the shallow aquifer and have this water released slowly to the reservoir.

Table 8: Water balance for the simulation of bench terraces in Sasumua watershed

	Surface runoff (mm)	Lateral flow (mm)	Base flow (mm)	Water yield (mm)
Base simulation	193	184	304	680
Simulation with terracing	151	190	335	674
% change	-21.8	+3.3	+10.2	-0.9

Bench terraces were therefore found to be more effective in enhancing both regulatory ecosystem services under study than contour farming. Bench terraces were found to have more effect in improving water quality as a result of reduced sediment loading into the streams and reservoir. Their effect on regulating flow was also higher than in the case of contour farming.

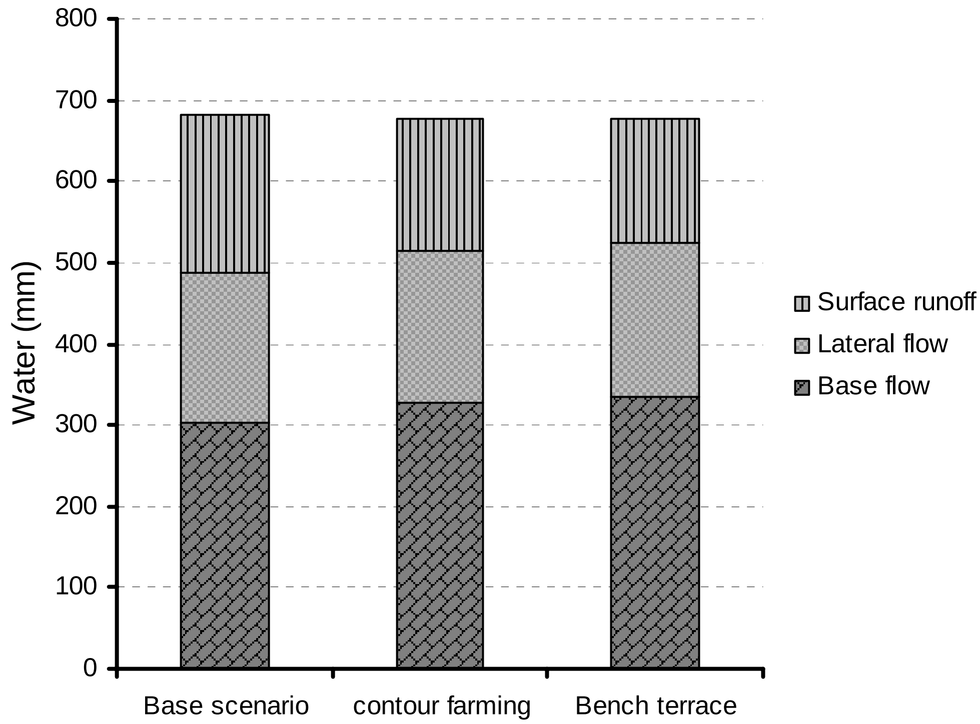

Figure 4.8: Effect of contour farming and Bench terraces on water balance components

4.5.5 Grassed waterway

The results from the simulation of the grassed waterway (Table 9) show that, they would have a sediment reduction of 40.72% when simulated at the outlet of Mingotio stream at the reservoir (sub-basin 60) and 23.45% for the whole Sasumua sub-watershed (simulated at the outlet of sub-basin 61). There was only a very slight change in the stream flow.

This shows that grassed waterways can play a great role in the reduction of sediments in Sasumua. Other studies that have found similar results on the reduction of sediment yield by grassed waterways include; Fiener and Auerswald, (2006a) who found a sediment reduction of about 93% for a 290 m long and 37 m wide grassed waterway.

Table 9: Simulated sediment yield and stream flow reduction with and without grassed waterway.

	Sediment Yield (× 10^3 tons/year)		Streamflow (m^3/s)	
	Outlet at Mingotio stream (sub-basin 60)	Main Sasumua sub-watershed outlet (at sub-basin 61)	Outlet at Mingotio stream (sub-basin 60)	Main Sasumua sub-watershed outlet (at sub-basin 61)
Without GWW	20.60	32.75	0.603	1.483
With GWW	12.21	25.07	0.601	1.481
% change	**40.72**	**23.45**		

Implementation of grassed waterway takes a relatively big land and is usually not much practiced in Kenya where the land sizes are small to the extent of quarter an acre in some areas. However, in Sasumua grassed waterway would be of much importance as a way of reducing the sediments that are usually washed from the cultivated lands near the seasonal streams/channels during the rainy season.

This is because the farmers cultivate so close to the channels which are usually dry during the dry season and when the rains come the sediments and sometimes crops from these lands are washed by the increased water in the channels/streams.

The increased roughness of the channels has a great effect in the reduction of the sediment yield. The grass would reduce the velocity of the water in the waterway and in effect reduce the stream power and its sediment transporting capacity hence causing deposition (Simon and Rinaldi, 2006). In SWAT sediment routing, the maximum sediment that can be transported is modeled as a function of the peak channel velocity (V cm/s) calculated as (Neitsch *et al.*, 2005);

$$V = \frac{q_{pk}}{A} \qquad (25)$$

Where, A is the cross sectional area of flow in the channel segment (m^2) and q_{pk} is the channel peak flow rate (m^3/s) adjusted by a factor from the average rate of flow, q calculated as shown in equation 26;

$$q = \frac{A.R^{2/3}S^{1/2}}{n} \qquad (26)$$

Where; R is the hydraulic radius for the depth of flow (m), S is the slope of the channel segment (m/m) and n is the Manning's coefficient for the channel section which is the parameter *CH_N2* adjusted in the model. The maximum sediment that can be transported from a reach segment is then calculated as;

$$Conc_{sed} = c_{sp} \times v^{sp\exp} \tag{27}$$

Where $conc_{sed}$ is the maximum concentration of sediment that can be transported by water (tons/m^3), C_{sp} is a coefficient defined by the user and *spexp* is an exponent defined by the user (between 1.0 and 2.0). Deposition of the sediment in the reach occurs if the sediment in the water is more than the maximum concentration of sediment that can be transported by the water in that part of the reach.

From equation 27, it is evident that the reduction in velocity of water in the channel would reduce the maximum sediment that can be transported by the water and if the sediment in the reach is more than that capacity then the excess sediments will be deposited in the channel. It is worth emphasizing that the values adopted for the Manning's channel roughness is for dense grasses under non sub-merged condition, if the grasses bend, break or get submerged, the value would drop (Fiener and Auerswald, 2006a). Thus, the effectiveness of this conservation practice in Sasumua would largely depend on the maintenance of the waterway.

4.5.6 Additional management scenarios

A comparison of alternative land management practices in the agricultural part of the watershed shows that sediment loading to the streams would increase by 53.6% for the poor land management scenario (intensive cultivation and overgrazing) and reduce by 34.3% in the case of good land management scenario (less intensive cultivation and well managed grazing), both in reference to the base simulation. Table (10) shows the sediment loading and the water yield for the two scenarios simulated for 36 years.

An increase in *CN* resulted in an increase in the sediment load (Table 10). Continued poor management of the agricultural land in Sasumua would result in reduction in infiltration of rain water into the ground. This would result in an increase in the peak runoff rates and thus more soil erosion. A reduction in *CN* resulted in a decrease in sediment loading. This is because of the improved infiltration conditions which were modeled by reducing the *CN*. The increased infiltration would result in a decrease in the surface runoff rates and thus less soil erosion.

Good land management will result in an increase in the infiltration of the rain water and a result a reduction in the surface runoff and an increase in the base flow. The good land management scenario, which was simulated by decreasing the *CN* by 6 units from the base simulation, resulted in a 28.5 % decrease in surface runoff, a 13.8% increase in base flow and a slight decrease in total water yield of 1.2% (Table 10).

Table 10: Sediment loading and water balance for good (CN-6) and poor (CN+6) management cases

	Sediment yield ($\times 10^3$ tons/year)	Surface runoff (mm)	Lateral flow (mm)	Base flow (mm)	Water yield (mm)
Base simulation	32.62	193	184	304	680
Poor management scenario [a] (CN+6)	50.11	278	176	272	724
% change	**+53.6**	**+44**	**-4.3**	**-10.5**	**+6.5**
Good management scenario [b] (CN-6)	21.43	138	190	346	672
% change	**-34.3**	**-28.5**	**+3.3**	**+13.8**	**-1.2**

[a] Intensive cultivation and overgrazing scenario

[b] Less intensive cultivation and well managed grazing

On the other hand, a poor management scenario would lead poor infiltration of rain water into the ground thus increasing the surface runoff and decreasing the base flow. This scenario which was simulated by an increase in the *CN* by 6 units from the base simulation resulted in an increase in surface runoff by about 44 %, a 10.5 % reduction in base flow and 6.5% increase in water yield.

CHAPTER 5

CONCLUSIONS AND RECOMMEDATIONS

5.1 Conclusions

Sasumua watershed currently is limited to produce some of environmental services it is expected to produce mainly because of human activities. In particular, the watershed is limited in offering two environmental services namely improvement of water quality and regulation of stream flows. Poor land management activities currently being practiced such as over-cultivation and overgrazing have increased sediment loading to the streams and the reservoir thus impairing water quality and also reducing infiltration of water into the ground. This has resulted in flash flood during the rainy seasons and low dry weather flows. This study has however found that the two environmental services would be enhanced if soil and water conservation measures are implemented in the watershed.

The study obtained that the grass filter strips reduce sediment yield as a function of their width. The first few increments of 5 m intervals had more reduction in sediment yield. This implies that even narrower strips would be relatively effective in trapping the sediments. This is attributed to the trapping efficiency that SWAT uses to model sediment yield in the filter strips which places a higher efficiency in the front part of the filter strip in trapping sediments. Simulation of contour farming was found to reduce sediment yield by about 49%. A combination of 5 meter filter strips and contour farming would have a sediment reduction of 73%. Installation of bench terraces would result in about 85% reduction in sediment load. Both the contour farming and bench terraces reduced surface runoff and increased base flow with only minimal decrease in total water yield. Reduced surface runoff will reduce incidences of flash floods while increased base flows will ensure increased dry weather flows. Bench terraces were the most effective soil conservation practice in reducing sediment yield as well as increasing water infiltration.

If implemented in four sub-basins that have a drainage ditch, grassed waterway would result in a 41% decrease in the sediment load in the outlet of Mingotio stream and a 23% reduction for the entire Sasumua sub-watershed. There was no significant change in the steam flow in the simulation of grassed waterway.

Improved land management methods would reduce sediment yield by 34% and surface runoff by 28.5%. It would increase the base flow by 14%. Poor land management would increase sediment yield by 53.6% surface runoff by 44% and reduce the base flow by 10.5%.

In summary, implementation of soil and water conservation practices in Sasumua watershed would enhance its capacity to provide some key ecosystem services i.e. water quality improvement and flow regulation. Soil and Water conservation practices would reduce the incidences and magnitudes of flash floods and slightly increase the dry weather flows. It would also reduce the soil erosion from the farmland and therefore reducing the loss of soil fertility and subsequently reduce the sediments washed into the streams as well as the siltation of the reservoir.

5.2 Recommendations

Soil erosion ‘hotspots’ were identified, and I recommend that these areas should be prioritized in the implementation of soil and water conservation measures. Implementation of soil conservation measures in these areas would reduce soil erosion and reduce the sedimentation into the streams and the reservoir thus boosting the capacity of the watershed to produce the environmental service of improving the water quality.

Bench terraces were found to be the most effective conservation practice in reducing sediment yield and increasing infiltration. It is recommended that bench terraces should be constructed in the watershed. However, terraces are structural conservation practices and involve some earth work during their implementation and therefore relatively expensive. For farmers who can meet the cost, I recommend that they should directly construct the terraces especially in the erosion hotspots identified. For those who may not be able to meet the cost, I recommend that they install grass strip which will eventually evolve into bench terraces.

I further recommend construction of grassed waterway in the drainage channels that feed water to Mingotio stream.

Further research should be conducted to identify the willingness of the farmers to invest in soil and water conservation. The research should also identify what conservation practices are the farmers more willing to embrace. A Payment for Ecosystem Services (PES) scheme should also be evaluated whether it can work in the watershed. A PES scheme identifies buyers (beneficiaries) and sellers (stewards) of ecosystem services and assesses the willingness of the buyers to give incentives to the sellers to engage in activities that enhance the environmental services.

Stream flow data for the gauging stations in the watershed was not available since it is not collected. Hydrological projects and studies like hydrological modelling rely on these data. Availability of that data would improve the calibration and validation of the model. The ministry of water through Water Resources Management Authority should put mechanisms of collecting the data.

Water balance in the reservoir has also been shown as a method that can be used for the calibration and validation of the model. To improve the calibration exercise the NWSC should keep better records of water abstraction from the reservoir and also have a gauge at the spillway. Daily recorded data would improve the calibration and validation of the model as compared to the monthly approach used.

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APPENDICES

Appendix 1: Slope length of sub-basins.

SUBBASIN	SLOPE (m/m)	SUBBASIN	SLOPE (m/m)
1	0.350	32	0.180
2	0.350	33	0.245
3	0.370	34	0.030
4	0.450	35	0.030
5	0.370	36	0.019
6	0.580	37	0.012
7	0.270	38	0.016
8	0.340	39	0.112
9	0.290	40	0.200
10	0.250	41	0.040
11	0.090	42	0.050
12	0.058	43	0.080
13	0.200	44	0.012
14	0.270	45	0.030
15	0.058	46	0.030
16	0.029	47	0.080
17	0.054	48	0.030
18	0.145	49	0.030
19	0.063	50	0.075
20	0.030	51	0.040
21	0.067	52	0.020
22	0.032	53	0.380
23	0.036	54	0.085
24	0.020	55	0.540
25	0.155	56	0.099
26	0.113	57	0.030
27	0.144	58	0.030
28	0.240	59	0.030
29	0.030	60	0.030
30	0.030	61	0.125
31	0.160	62	0.492

Appendix 2: Questionnaire

Questionnaire and key point to discuss with key farmers
QID:

a **Type**	b **Area (Acres)**	c **Distance from HH (m)**	d **Soil fertility enhancement**	e **Uses of farm product**	f **Farm Management (Rotation, tillage, irrigation)**	g **Soil conservation activity**	h **Possible environmental benefits**	i **Remarks**

1) Household (HH) information

a) Household head name: b) Address: C) Plot No.:

d) Sex: e) Age: f) Family size (supported by the farm)

g) Total farm size (acres/hectares): h) Land tenure: Freehold/ Leasehold

i) Major source of livelihood:

2) Land holdings

3) Livestock

Type	**Number**	**Source of fodder/feed**
Cattle		
Sheep		
Chicken		
Duck		

4) Presence of tree/vegetative species on farm and surroundings and their environmental services/disservices.

5) Is the tree density or number of trees available on the farm important? How about the historical development of woodlots or agroforesty? Are trees on the farm level increasing or decreasing?

6) Any preferred tree/vegetative species and preferred arrangement/pattern (e.g. hedgerows, woodlot) and location and why?

7) What do you consider when planting trees on the farm?

a) Species in terms of water use?

b) Time it takes to mature?

c) Environmental benefits?

d) Other intermediate benefits e.g. fuel wood, fodder?

e) Other (specify)

8) Do you have Eucalyptus in your farm? a) Yes b) No

9) When did you plant them and why?

10) Have the eucalyptus met your objectives for planting them?

11) What is your attitude towards the species?

12) Would you consider replacing them? Yes No?
Why?

13) Under what kind of arrangement (woodlot, hedgerow) would you prefer and why?

Arrangement	**Purpose**

14) Would you spare some land for tree planting? What is the nature of the land?

15) Do your farm border a stream or the Nairobi City water and Sewerage Company buffer strip?
a) Yes b) No

16) If next to a stream what have you planted on the riparian area? Are you aware of the law prohibiting cultivation of riparian zones?

17) If next to NCWSC buffer zone, do your livestock graze there?
b) Yes b) No

18) Do you think there has been a change in rainfall?
a) Increased b) Decreased? c) No change

19) What do you think is the cause?

20) What is the possible solution?

21) **Do you think changes in rainfall (pattern, amount, distribution, etc) have an effect on crop production in your farm (production per unit area)?**

22) **Any water harvesting –runoff or roof water? Why and what purpose (domestic use, irrigation, etc)?**

23) **Have you left a flood strip next to the road or a drainage channel? Yes No**

24) **How wide is the strip?**

25) **Would you consider planting trees on the strip?**

Key points for discussions during semi-structured interviews/focus group discussion/transect walks

- **Historical changes in the landscapes (including common lands) e.g. what used to be there**
- **Historical perspectives on amount of trees and other vegetation present on common lands, is it increasing or decreasing? Why?**
- **Why eucalyptus has been planted extensively? Are there any other tree species planted together or at the same extent as eucalyptus? Why? Who planted the trees and who is taking care of them? Are there any uses of these trees planted on the common lands?**
- **What are the common pool of resources, who is managing these resources and how? Do local resident benefit from the management?**
- **What are the sources of water pollution? How easier is to get water from the farmland to the river/reservoir? Is there any vegetation or structure to filter the water before it reaches the river or the reservoir?**
- **What types of lands are prone to get converted into settlements?**
- **Farm processes**
- **Land use processes**
- **Common pool of resource management**

Appendix 3: Sediment yield for base simulation for Sasumua sub-watershed

Sub-basin	Sediment yield (ton/ha) base simulation
9	0.29
10	0.21
11	0.04
12	13.69
15	13.13
16	0.01
17	23.66
18	0.09
19	23.46
20	10.69
21	29.98
22	12.14
23	8.26
24	6.95
29	9.59
30	17.50
36	7.11
37	4.45
38	5.89
41	16.64
42	25.44
43	40.97
44	4.93
47	38.39
48	12.39
51	17.12
52	7.42
57	18.13
58	14.20
60	24.59
61	0.09