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Impact of Land Management Practices on Water Balance and Sediment Transport in the Morogoro Catchment, Uluguru Mountains (Tanzania)

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By

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Declaration of the candidate

I confirm that this copy is identical with the original dissertation titled:
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I hereby declare that this thesis is my own work and effort. Where other sources of information have been used, they have been acknowledged.

Morogoro, 10.09.2017

Dominico Benedicto Kilemo

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Abstract

Tanzania, like other developing countries in the tropics is severely affected by the degradation of water resources owing to improper land management practices. Such practices affect water supply through soil erosion which does not only cause sedimentation of rivers and water bodies but also leads to a reduction in the rainwater infiltration capacity of soils. This thesis seeks to demonstrate how the implementation of proper land management measures can reduce soil erosion and increase water supply in the Morogoro River catchment (Uluguru Mountains). The proper practices referred to are the soil and water conservation (SWC) approaches which include contour farming, fanya juu terracing and bench terracing. The thesis combines social science and geoscience methods in a synergetic manner to address this research problem. To understand how and to what degree SWC methods affect water fluxes and sediment yields, the hydrological model SWAT (Soil and Water Assessment Tool) was applied. Before carrying out the modelling procedures, it was necessary to examine the level of SWC adoption among farmers and factors influencing the process so as to establish the baseline. To this end, biophysical and socio-economic factors assumed to affect farmers' adoption tendency were examined using a household questionnaire.

Modelling results indicate that if correctly implemented contour farming, fanya juu terracing and bench terracing would significantly reduce sediment yield at different rates. The reduction would range approximately between 1% - 85% with the highest percentage change achieved by practicing the three SWC methods simultaneously. However, such SWC measures would not increase water flow annually owing to evapotranspiration losses. Nevertheless, according to modelling results groundwater storage would be increased by about 14% and hence contributing to water supply during the dry season. The household questionnaire survey suggests that the adoption of SWC methods in the study area is very low and complex. While age of the head of household, access to extension (professional) services, household annual income and proximity to the farm significantly influenced farmers' decision to adopt SWC, gender of the head of household, slope characteristics of the farm, number of adults in the household and farmer's perception on soil erosion effects had no considerable influence on adoption. Therefore, to successfully realize the SWC benefits demonstrated by the modelling results, smallholder farmers upstream of the catchment should be incentivized to implement proper land management practices. Payment for ecosystem services scheme appears to be a suitable strategy. To make this operational, the Tanzanian government should establish a national water fund which will finance watershed management activities. The methodological approach employed in this thesis is transferrable to other sites with problems comparable to the studied catchment.

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List of Abbreviations and Acronyms

CN	Curve number
DEM	Digital Elevation Model
HRU	Hydrological Response Unit
IPCC	Intergovernmental Panel on Climate Change
KGE	Kling-Gupta Efficiency
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
PTFs	Pedotransfer functions
SCS	Soil Conservation Service
SCSA	Soil Conservation Society of America
SWAT	Soil and Water Assessment Tool
SWC	Soil and Water Conservation
USDA	United Sates Department of Agriculture
WOCAT	World Overview of Conservation Approaches and Technologies

Chapter 1: Introduction

1.1 Problem overview and significance of the study

Land degradation is the global environmental threat facing many countries in the world. Its environmental ramifications impair the sustainability of ecosystems and ecosystem services such as food and water supplies (Pla, 1992). Among several land degradation drivers, soil erosion is the major threat to soil and water resources. The susceptibility of soils in the tropics to water erosion is on the average not much higher than in other climatic regions of the World, but the erosive power of rainfall is generally much higher (El-Swaify and Fownes, 1992 cited in Pla, 1997). According Hudson (1981) cited in Morgan (2005), the threshold level of intensity at which a rain becomes erosive is about 25 mm/h. In temperate regions only 5% of the rain falls at intensity great enough to be erosive while in tropical regions as much as 40% of the rain contributes to erosion (Hillel, 2004). Erosion is enhanced by deforestation, intensification of agriculture, overgrazing, and improper maintenance of the farming land. Water erosion processes have been accelerated in most of the tropical regions in recent decades, due to population pressure and limited resources, which have also led to increased and more continuous use of steeper lands for agriculture (Pla, 1997). Estimates are that agricultural land degradation can be expected to depress world food production by the year 2050 (Alexandratos and Bruinsma, 2012). This forecast underscores the need to implement proper land management practices. Soil erosion is known to affect surface runoff, soil water-holding capacity, soil organic matter content, nutrients, soil depth, and soil biota. All of these influence soil productivity in both natural and managed ecosystems (Pimentel, 2006).

Soil erosion is a major problem in many watersheds of developing countries causing significant loss of soil fertility, loss of productivity and environmental degradation (Senti et al., 2014). Degradation of watersheds in recent decades has brought the long-term reduction of the quantity and quality of land and water resources (World Bank, 2008). Loss of soil productivity, sedimentation of water courses, increased runoff and flash flooding, reduced infiltration to groundwater, and water quality deterioration are among the adverse impacts of watershed deterioration (World Bank, 2008).

Globally, there are several counter-measures to control soil erosion which are collectively known as soil and water conservation (SWC) methods (WOCAT, 2007; Morgan, 2005; Napier and Cockerill, 2015). The type of method to be used is dependent on the topographical characteristics of the site, climate and readily available materials (WOCAT, 2007). Among the SWC measures, terracing and contour farming are well known methods to control soil erosion worldwide. Their main task is to retard the erosive power of running rainwater and to trap the eroded soil particles. In so doing, they increase rainwater infiltration into the soil and reduce sedimentation of rivers and water bodies. Terraces exist in different forms depending on the terracing objective (Schwab et al., 1995; Sheng, 2000; Arnáez et al., 2015). In Uluguru Mountains and some parts of Tanzania, bench terraces and fanya juu terraces are practiced to some extent (Lopa et al., 2012). Fanya juu ('throw it upwards' in Kiswahili) terracing is practiced in East Africa notably in Kenya, Tanzania and Uganda (WOCAT, 2007). But it is also found in Ethiopia (Hurni, 1986).

Hydrological modeling tools have proved to be very effective in studying the watershed responses to environmental changes and anthropogenic activities (Cao et al., 2006). The application of hydrological models in studying catchment hydrological response to various human induced disturbances in the Uluguru Mountains is still scant. There have been some studies in the region on this topic, but such studies were limited to the application of regression techniques and time series analysis (e.g. Yanda and Munishi, 2007; Ludovic, 2012). Such approaches are unable to quantify the impact of land management practices on water and sediment dynamics at different temporal and spatial scales, because they are not physically based and are not spatially distributed. Platts (2012) modeled the impact of deforestation on water flow and sediment yield in the Ruvu River basin using the SWAT model. But no attempt was done to assess the effect of SWC practices on water discharge and sediment transport in the catchment. Several studies on soil erosion and sediment yield in Uluguru Mountains have been conducted (e.g. Rapp et al., 1972; Kimaro et al., 2008; Msaghaa, 2012). While the studies quantified the magnitude of soil loss and sediment yield, none of them assessed the effect of implementing SWC measures on soil erosion and sediment yield. In particular, there has been no published study specific to Morogoro catchment that explicitly assesses the impact of SWC practices on sediment export and water flow. Therefore, this study sought to bridge this existing research gap and contribute to the hydrological knowledge base in the Uluguru Mountains which are a typical example for the Eastern Arc Mountains at large.

This work is envisaged to contribute to the national efforts in water resources management. Specifically, the study augments the ongoing activities in the Morogoro catchment by the Wami-Ruvu Basin Water Board whose main task is to ensure sustainable water resources management. Moreover, the study is beneficial to the water utility authority in Morogoro, the Morogoro Urban Water and Sewerage Authority (MORUWASA) to understand areas of intervention for dealing with sedimentation, turbidity and eutrophication problems in their water supply system, notably the Mambogo water intake. Modeling the impact of SWC interventions on the watershed guides decision makers on appropriate management options that can ensure reduced soil erosion, reduced runoff and reduced sediment yield and improved protection of water resources.

1.2 Research objectives

The overall objective of this study was to simulate and assess the effect of SWC practices on water flow and sediment export in Morogoro catchment. The specific objectives were:

(i) To Examine factors affecting the adoption of SWC measures by small holder farmers;

(ii)To parameterize the Morogoro Catchment for SWAT so as to build water flow and sediment models;

(iii) To apply the built water flow and sediment models in simulating the impact of SWC measures on water flow and sediment yield.

1.3 Research questions

To achieve these objectives, the following research questions were addressed:

(i) What are the biophysical and socio-economic factors influencing small holder farmers' decisions to adopt SWC?

(ii) How is the quality of the available data sets for SWAT application in Morogoro Catchment? To what extend do such datasets affect the model performance? Are there other factors affecting model performance?

(iii) What parameters are necessary for developing water flow and sediment yield models for the studied catchment?

(iv) What would be the effect of contour farming, fanya juu terraces and bench terraces on water flow?

(v) What would be the effect of contour farming, fanya juu terraces and bench terraces on sediment yield?

1.4 Structure of the thesis

This thesis consists of 5 chapters. whereby chapter 1 states the research problem. objectives and research questions. Chapter 2 provides an extensive overview of the theory behind the research topic with relevance to the study area. Chapter 3 describes the study area and methods employed to address the research questions. Chapter 4 presents the research findings and their discussions. In particular, the chapter systematically reports the results and discussions in accordance with the research objectives and research questions. Chapter 5 concludes the thesis. provides implications, perspectives and puts forward some recommendations for researchers. watershed managers and policy makers.

Chapter 2: Theoretical background

2.1 Definition of basic concepts and terminologies

2.1.1 Land degradation

There are several definitions of land degradation, but they all share the fact that it results from detrimental activities and processes. FAO (2013) defines land degradation as a decline in the capacity of the land to provide ecosystem goods and services, over a period of time, for its beneficiaries. Such a decline involves chemical and biophysical changes of the land thus rendering it unproductive. This can be temporary or permanent whereby temporary changes can be restored to original state while permanent changes will be irreversible. The most common form of land degradation is soil erosion.

2.1.2 Soil erosion

Soil 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 downslope by one or more transport agents (Kinnell, 2010). Erosion happens when the soil is disturbed and thus loosening the soil particles. Tillage and trampling resulting from overgrazing or other human activities are the main causes of soil disturbance. When the loosened soil particles are acted upon by rainfall or wind they are detached from the land surface and subsequently transported to other places in the landscape. Rainsplash and wind are the main well-known agents of soil erosion. The detached soil particles are normally transported from sources and deposited to other places on the surface (Morgan, 2005). In hydrology, soil erosion by water (mainly from rain) is of great interest. Soil erosion and resulting sediment transport is a function of many processes. Erosion from the land surface takes place in the form of sheet erosion, rill and inter rill erosion, or gully erosion part of which is delivered to rivers (Kimaro et al., 2008; Schmidt & Zemadim, 2014). The transporting agents can be grouped into two, those which act areally and contribute to the removal of a relatively uniform thickness of soil, and those that exert their action in channels. The first group comprise of rain splash and surface runoff which is also known as overland flow. The second group involves water in small channels known as rills or the larger more permanent features of gullies and rivers. Inter rill erosion may develop as a result of water erosion between rill erosion and erosion on the land between the rills by the combined action of raindrop impact and overland flow (Morgan, 2005).

Toy et al. (2002) categorize water erosion into splash. sheet, rill and gully erosion. They further contend that splash erosion takes place when the rain drops hits bare soil surface. Sheet erosion refers to washing of the surface soil by water. Rill erosion is manifested when water concentrates in small furrows while gully erosion occurs when the eroded furrows get larger.

Principally. soil erosion is illustrated by two main processes, the detachment and the transport of soil particles by the erosive forces of the raindrops and surface flow of water. The physical impact of a raindrop on unprotected soil serves as the primary detachment mechanism, loosening soil particles and freeing them to be transported. When a raindrop strikes a surface, the force of the impact acts to destabilize the particles (Neitsch et al., 2011). Energy is required to facilitate the soil erosion process. Two forms of energy are involved. potential energy (PE) and kinetic energy (KE) whose units are in Joules. Potential energy is the energy possessed by an object /substance due to its position, i.e. results from the difference in height of the object with respect to another. It is usually expressed as a product of mass. height and acceleration due to gravity (Morgan, 2005).

Thus $$\mathrm{PE} = \mathrm{mgh} \tag{1}$$

When the object is in motion, the potential energy is converted into kinetic energy and it expressed by the relationship between mass and velocity of erosion agent as shown in equation (2)

$$\mathrm{KE} = \frac{1}{2}\mathrm{mv}^2 \tag{2}$$

The severity of soil erosion at a given point is determined by several factors. According to Morgan (2005) soil erosion is influenced mainly by erosivity of the eroding agent, the erodibility of the soil, the slope of land and nature of the plant cover. Rainfall erosivity refers to the power of raindrops responsible for detachment of soil particles. It is measured in terms of rainfall intensity, expressed as mm h^{-1}. This suggests that there is a rainfall intensity threshold that must be reached for significant erosion to place. In tropics, a rainfall intensity of 25 mm h^{-1} is needed to initiate noticeable erosion process (Hudson, 1981 cited in Morgan, 2005). However, the threshold levels are lower in temperate countries and vary from one country to another (*ibid*). When the rainfall intensity is combined with the rainfall kinetic energy, considering the transport capacity of the water running on the surface, another term called ***rainfall erosivity index*** is considered. The relationship between rainfall kinetic energy and intensity is widely studied. Such studies have also attempted to derive mathematical relationships which are either linear, log-linear or exponential (see in Salles etal., 2002; Fornis et al., 2005; Morgan 2005). The fundamental relationship was established by Wischmeier and Smith (1958) as shown in equation (3). Then after several other researchers across the globe made modifications.

$$KE = 0.0119 + 0.0873 \log I \qquad (3)$$

where I = rainfall intensity (mm h^{-1})

KE = Kinetic energy (MJ $ha^{-1}mm^{-1}$)

Soil erodibility is another important factor influencing soil erosion. It is simply the ease with which soil particles can be detached from the surface by an eroding agent. It demonstrates the resistance of soil particles to erosion. Wang et al. (2013) define soil erodibility as the amount of soil loss per unit exogenic force or erosivity such as rainfall or surface flow. They further argue that both inherent soil factors and exogenic factors ought to be considered in determination of soil erodibility. These are essentially soil properties and the erosivity of the eroding agent. Soil erodibility varies with the type of soil erosion e.g. sheet erosion vs. rill erosion (Bryan, 2000). Soil textures, aggregate stability, shear strength and infiltration capacity of the soil are key inherent soil properties influencing erodibility (Bryan, 2000; Morgan, 2005).

Slope gradient of the land surface contributes significantly to the erosion process. Soil erosion increases with slope steepness and slope length. Steepness is determined by a slope angle. A relationship between slope gradient and soil erosion can be expressed mathematically according to the empirical equation developed by Zingg (1940) cited in Liu et al. (2001) as follows:

$$y = ax^b \qquad (4)$$

where y is quantity of soil erosion, x is slope in degree, a = 0.065 and b = 1.48. Morgan (2005) suggests another expression of the relationship between slope and erosion as shown in equation (5)

$$E \propto \tan\theta^m L^n \qquad (5)$$

Where E is soil loss per unit area θ is the slope angle and L is the slope length. The letters m and n are exponents which are determined empirically from field experiments.

Plant cover is pivotal in controlling soil erosion. Soil erosion rate reduces exponentially as the vegetation cover increases (Gyssels et al., 2005). According to Morgan (2005) vegetation serves as a protective layer between the atmosphere and the soil. The leaves and stems intercept rainfall thus reducing the energy of falling raindrops. so that less hits the soil. The root system contributes to the mechanical strength of the soil. This suggests that land with significant plant cover experiences less erosion compared to that with no sufficient plant cover. However, the nature of plant cover determines the effectiveness in controlling erosion. The plant cover includes plant residues (also known as mulch) and vegetation which comprises of annual crops, perennials, grasses, shrubs and trees. The effectiveness of these categories of plant cover in controlling soil erosion varies from one to another (Zuazo and Pleguezuelo, 2008).

2.1.3 Watershed and catchment

Physically, a watershed or catchment is defined as an area of land that topographically contributes all the water which passes through a given cross section of a stream (Dingman, 2002). In other words, the terminologies imply that the area is analogous to a basin where all water moves towards a common point (Lal, 2000: Davie, 2008). According to Vishnudas (2006) the terms watershed, catchment, drainage area and river basin are all used to describe a land surface from which water flows downhill to a specified point on a watercourse. The difference between them is essentially a question of scale, whereby the watershed relates to the smallest size of catchments, generally located on the steepest slopes of a river basin. The location of the stream cross section (common outlet point) that defines the watershed is determined by the purpose of analysis. Hydrologists are often interested in delineating watersheds above stream gauging stations (Dingman, 2002).

Wagener et al. (2007) define catchment as the drainage area that contributes water to a particular point along a channel network (or a depression), based on its surface topography. The catchment forms a landscape element (at various scales) that integrates all aspects of the hydrologic cycle within a defined area that can be studied, quantified, and acted upon (Wagener et al., 2004). People are the integral part of watershed and their activities affect the productive status of watersheds and vice versa (Wani et al., 2008). From the hydrological perspective, the different phases of hydrological cycle in a watershed are dependent on the various natural features and land-uses. A watershed is not simply the hydrological unit but also socio- political-ecological entity which plays crucial role in determining food, social, and economical security and provides life support services to rural people (Wani et al., 2008).

2.1.4 Watershed divide and drainage area

The boundary which delimits a watershed, separating it from another watershed is called *divide* (see Figure 2.1), while the *drainage area* refers to the area receiving precipitation and contributing all the water reaching the common outlet (gauging station). The drainage area is defined during watershed delineation which can be done manually using a topographic map or automatically using a topographical data stored in digital elevation model (DEM) format. Watershed delineation defines the watershed boundaries and is normally done during hydrological modeling studies.

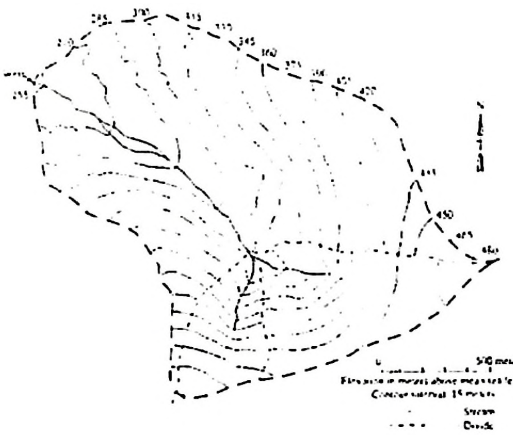


Figure 2.1: Watershed delineation on a topographic map (Dingman, 2002)

2.1.5 Water balance equation

The water balance follows the law of conservation of mass. A water balance is an inventory of water moving through a hydrologic system and can be assessed at various stages of the hydrological cycle. Its main components are divided into inputs and outputs or gains and losses. In hydrology, water balance is normally expressed as an equation as:

$$P = ET + Q + GWD \pm SMC \pm GWS \tag{6}$$

where

P = Precipitation (gain)

ET = Evapotranspiration (loss)

Q = Streamflow (loss)

GWD = Groundwater discharge (loss)

SMC = Soil moisture content (gain/loss)

GWS = Groundwater storage (gain/loss)

Dingman (2002) established a watershed water balance equation expressed as:

$$\Delta S = P + G_{in} - (Q + ET + G_{out}) \tag{7}$$

ΔS = Change in water storage within the watershed

P = Precipitation

Gin = Groundwater inflow

ET = Evapotranspiration

Q = Stream flow

Gout = Groundwater outflow

According to Dingman (2002) the watershed water balance equation can be simplified by assuming that, the long-term difference between groundwater inputs and outputs is small compared to other parameters, thus the difference between G_{in} and G_{out} is zero. Change in storage may be large in the short term, particularly from the beginning to the end of the rain season. But in long term water balance that begins and ends at the same time of the year, the net change in storage is often negligible compared to other parameters, and it can be assumed that ($\Delta S \approx 0$). Considering these assumptions, the water balance equation simplifies to:

$$0 = P - (Q + ET) \tag{8}$$

Thus

$$P = ET + Q \tag{9}$$

Since P and Q can be measured easily, ET can be estimated from this equation.

2.1.6 Evapotranspiration

Evapotranspiration (ET) refers to water loss from the land to the atmosphere through water evaporation from the soil and land surface and transpiration by plants through stomata aperture. There are two types of ET, potential evapotranspiration (ET_p) and actual evapotranspiration (ET_a). Both are plant specific implying that each plant type has its own ET_p and ET_a values that differ from other plants. Thus, ET_p of a given plant/vegetation is defined as soil evaporation and plant transpiration under unlimited soil water supply and actual meteorological conditions (Łabędzki et al., 2011). In other words, ET_p is the capacity of the atmosphere to remove water from the land surface into the atmosphere. ETa is the evapotranspiration actually taking place in a given area under the prevailing conditions. Normally ET_a is lower than ET_p due to water supply limitations, soil properties and vegetation characteristics (Łabędzki et al., 2011; Allen et al., 1998).

2.1.7 Underground water and Groundwater

Underground water is a general term describing all the water beneath the land surface (subsurface water) as compared to water on the land surface (surface water). Underground water occurs into two different zones, namely the *unsaturated zone* and *saturated zone* (Heath, 1987). The unsaturated zone is found immediately below the land surface and contains water and air. This zone is known as vadose zone. The saturated zone is the zone where all soil pores are filled with up with water. Hence, the term *groundwater* refers to underground water in the saturated zone. The groundwater is important source of water for wells and springs. It is delineated by water table, a level at which the hydraulic pressure is equal to the atmospheric pressure (*ibid*). Groundwater recharge occurs by percolation of surface water through the unsaturated zone. In watershed water balance (equation 7), groundwater inflows and outflows are common processes. Groundwater inflow (G_{in}) refers to water percolating into the saturated zone from the unsaturated zone whereas groundwater outflow (G_{out}) is the part of the groundwater flowing to the river stream, contributing to the stream discharge.

2.1.9 Soil Water Balance

The soil water balance is used in soil-plant-water relations studies. It accounts for water movement in the soil profile; the unsaturated zone is normally the reference point. Rainfall or irrigation reaching a unit area of soil surface, may infiltrate into the soil, or leave the area as surface runoff. Water may (i) evaporate directly from the soil surface, (ii) be taken up by plants for growth or transpiration, (iii) drain downward beyond the root zone as deep percolation, or (iv) accumulate within the root zone (Zeleke and Wade, 2012). Like the general water balance, the soil water balance also obeys the law of conservation of mass, i.e. change in soil water content of a root zone of a crop is equal to the difference between the amount of water added (Q_i) to the root zone and the amount of water withdrawn (Q_o) from it (Hillel, 1998). The water content of a given soil volume cannot increase without addition from the outside, nor can it diminish unless transported to the atmosphere by evaporation or to deeper zones by drainage (Hillel, 1971). Equation (10) summarizes the soil water balance equation.

$$\Delta S = Q_i - Q_o$$

(10)

Considering the Qi and Q_o components, equation (10) can be expanded as follows:

$$\Delta S = P + I - R - ET - U - D \tag{11}$$

Where ΔS = change in root zone soil moisture storage, P = Precipitation, I = Irrigation, U = upward capillary rise into the root zone, R = Runoff, D = Deep percolation beyond the root zone, ET = evapotranspiration. All quantities have units of volume per unit time which result in terms of flux (volume/time).

2.2 Watershed Management

The literature provides a broad range of definitions and approaches of watershed management. SCSA (1982) defines watershed management as the integrated utilization, regulation and care of the water and land resources in a watershed with the aim of meeting predefined development goals. FAO (1987) defines watershed management as the process of developing and implementing a series of actions for the management of natural, agricultural and human resources within a watershed to provide required and appropriate goods and services to the society under the precondition that land and water resources are not negatively affected. Watershed management needs to consider the prevailing socio-economic and institutional factors, within and beyond the watershed.

Watershed management must embrace the three core elements of sustainability, namely environmental, economic and social sustainability. However, optimizing the three elements is still a daunting task especially in developing countries. Watershed management is a complex undertaking that requires a holistic approach and participatory planning to ensure that both the upstream and downstream users of the watershed benefit while keeping the watershed at optimal hydrological standards. The heterogeneity of watershed users complicates the management, thus leading to degradation of watershed resources. Moreover, watersheds do not follow political boundaries but rather their topographically delineated drainage divides. This necessitates comprehensive and collaborative management approaches that involve all stakeholders within and beyond the watershed boundaries. A policy intervention that addresses the heterogeneity of users and fosters the watershed protection is of foremost importance for attaining sustainable watershed management. Watershed degradation can be ameliorated and degraded watersheds restored by appropriate watershed management. Contemporary watershed management kicked-off during the twentieth century as a technical practice, largely based on major hydraulic engineering and forestry interventions. However, experience has shown that technical measures alone are not enough to address watershed problems (FAO, 2007). Thus, it is important to recognize that watershed management relies on the participation of the population in planning, utilization and monitoring and hence supporting to build the democratic structures, especially in developing countries (cf. Mwangi et al., 2015a). Furthermore, this concept is suitable for providing a framework for utilization of traditional social structures and traditional knowledge for development (Förch and Schütt, 2004).

Watershed management measures have been traditionally characterized by programs and projects that aim to control soil erosion through implementation of SWC measures. Reduced soil erosion improves agricultural productivity and enhances water quality for urban supplies. Key to such measures is the involvement of farmers upstream of the watershed, they play very crucial role in shaping the watershed landscape due to their agricultural practices. In developing countries like Tanzania, most of the upstream farmers are poor and reside in rural areas.

Since SWC are labor intensive and may involve leaving some portion of the farmland uncultivated, the farmers upstream are normally unable and reluctant to implement such management measures. However, through projects which provide incentives in forms of agglomeration payment or payment for watershed services scheme, some farmers have been able to implement soil and water conservation measures (Asquith et al., 2008; Ferraro, 2009; Drechsler et al., 2010; Lopa et al., 2012; Mwangi et al., 2015b)

2.3 Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is an erosion model designed to predict the longtime average soil losses in runoff from specific field areas in specified cropping and management systems (Wischmeier and Smith, 1978). It is the most widely used equation in estimation of soil loss all over the world (Kinnell, 2010). It enables planners to predict the average soil erosion rates for different combination of management techniques, cropping system and control practice for a particular site. The equation was designed to calculate longtime average soil losses from rill and sheet erosion under specific conditions (Wischmeier and Smith, 1978). 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 (*ibid*). The USLE soil loss equation is given by:

$$A = RKLSCP \tag{12}$$

where A represents the average (mean) annual soil loss (mass/area/year) over the long term, R is the rainfall–runoff "erosivity" factor, K is the soil "erodibility" factor, L and S are the topographic factors that depend on slope length and gradient, C is the crop and crop management factor, and P is the soil conservation practice factor. R is the average annual value of the product of the storm kinetic energy (E) and the maximum 30-min rainfall intensity (I_{30}).

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 degree at which a particular soil can be eroded even when all other factors such as topography, rainfall intensity, cover and management are the same. The difference in soil erosion is mainly caused by differences in soil properties. Hence soil erodibility is a function of soil physical and chemical properties, but silt fraction plays a key role. Usually the *K* values are estimated using soil erodibility nomographs (Wischmeier and Smith, 1978). The slope length (L) and the slope steepness factor (S) are usually combined in the topographic factor LS and are calculated as one value.

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. The support practice (P) factor- represents 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 down the slope.

The Revised Universal Soil Loss Equation (RUSLE) is a revision of USLE and uses the USLE equation with changes on how some of the factors are determined (Kinnell, 2010). In RUSLE the rainfall-runoff factor contained in USLE becomes erosivity factor. Other parameters remain the same.

2.4 Soil and Water Conservation Measures

According to WOCAT (2007) soil and water conservation (SWC) involve activities at the local level which maintain or enhance the productive capacity of the soil in erosion-prone areas, through prevention or reduction of erosion, conservation of soil moisture, and maintenance or improvement of soil fertility. Such activities can also be referred to as measures which demonstrate a particular farming technology. A SWC technology is either agronomic, vegetative, structural or management (WOCAT, 2007). Agronomic technology includes measures such as intercropping, contour farming and mulching while vegetative technology is characterized by tree planting, hedge barrier and grass strips. Structural technology may include graded banks, or bunds and bench terraces while management technology entails measures such as land-use change, area closure and rotational grazing. There are several SWC technologies being practiced worldwide ranging from indigenous to conventional ones. A detailed analysis of the SWC technologies and measures globally can be found in WOCAT (2007). Further account on SWC is available in Napier and Cockerill (2015).

According to Drechsel et al. (2006) SWC measures can be divided into three categories namely *traditional*, *exogenous* and *improved*. Traditional measures are those developed and practiced by farmers themselves in their local context. Exogenous measures are those introduced through national and international agricultural research institutions, NGOs and individual initiatives. Improved SWC measures represent a set of measures that may be a combination of traditional and exogenous measures. Normally, the improved measures are developed as a result research activities and modification by land-users. Thus, SWC technology is site specific, what works well in one site may not necessarily produce good results in another site. This study focuses on few SWC measures common to Morogoro catchment and Uluguru Mountains at large though inadequately practiced. These are contour ridges, fanya juu terraces and bench terraces as described in the sections below.

2.4.1 Contour ridges

Contour ridges, sometimes called contour furrows or contour bunds are small earthen banks, with a furrow on the higher side which collects runoff from an uncultivated strip between the ridges (Figures 2.2 and 2.3). Through their shape, soil moisture is increased under the ridge and the furrow, in the vicinity of plant roots (Anschtz et al., 2003). Normally, the ridges are stabilized by planting crops such as sweet potatoes, cassava, maize and vegetables. They are mainly constructed for reducing the erosive power of surface runoff flowing through the cultivated land resulting in reduction in soil erosion. They are simple to construct using locally available hand tools hence requires less labor. Thus, they are easy to manage for small farmers. Contour ridges are most effective on slopes between 2% and 10 % (USDA-NRCS, 2007).

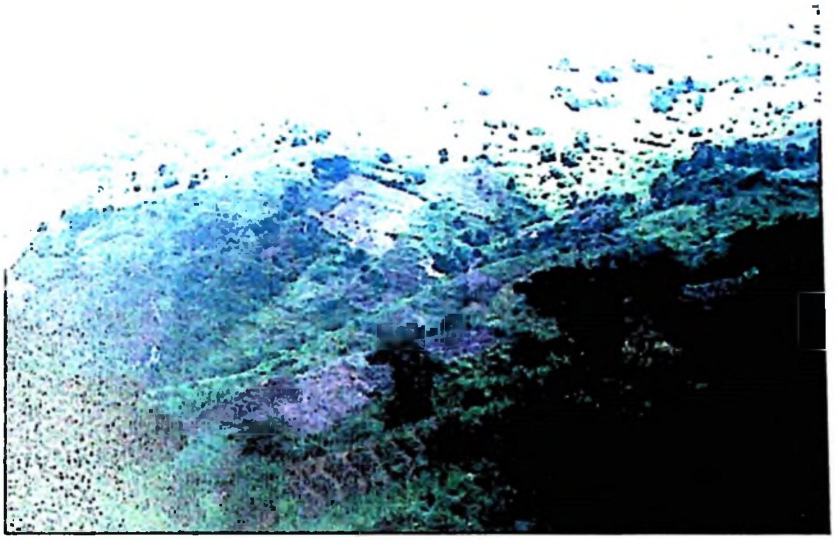


Figure 2.2: A portion of the Morogoro catchment study area with patches of contour ridges (D. Kilemo, 02/2015)

Figure 2.3: Maize crop grown on contour ridges in the Morogoro catchment study area (D. Kilemo, 02/2015)

2.4.2 Fanya juu terraces

Fanya juu ('throw it upwards' in Kiswahili) terraces comprise embankments (bunds), which are constructed by digging ditches and heaping the soil on the upper sides to form the bunds (Figure 2.4). A small ledge or 'berm' is left between the ditch and the bund to prevent soil sliding back (WOCAT, 2007). In semi-arid areas, fanya juu terraces are normally constructed on the contour to hold rainfall where it falls, whereas in sub-humid zones they are laterally graded to discharge excess runoff. The main purpose of fanya juu is to prevent soil and water loss thus enhancing plant growth. The fanya juu structure would eventually lead to the development of bench terraces over a period of time if properly maintained (Critchley, 1991; Million, 2003; WOCAT, 2007). This happens as the land between embankments/bunds levels off as a result of sediments accumulation. The field then develops the characteristic "steps" of bench terraces. Soil and water are conserved between the fanya-juu bunds (Hailu et al., 2012). The bunds created are usually stabilized with strips of grass, often napier (*Pennisetum purpureum*), which may serve as fodder for livestock. Multipurpose trees may be planted immediately above the embankment such as *Grevillea robusta* and *citrus* (WOCAT, 2007). The fanya juu terraces first came into prominence in Kenya in the 1950s, but the period of rapid spread occurred during the 1970s and 1980s with the advent of the National Soil and Water Conservation Programme. Then later spread to other Eastern African countries (WOCAT, 2007). To date Fanya juu is practiced in Kenya, Tanzania, Uganda and Ethiopia (Hailu et al., 2012).

Figure 2.4: An agricultural officer demonstrating fanya juu terrace construction in the study area (P. Luwanda, 01/2012)

2.4.3 Bench terraces

Terraces are broad earthen embankments constructed perpendicular to the slope to intercept runoff water and control erosion (Schwab et al., 1995). They are known from ancient history and are used to transform landscape to stepped agrosystems in many hilly or mountainous regions of the world (Beach and Dunning, 1995; Garner and Gerrard; Zuazo et al., 2005). It is a structural SWC which can be constructed directly on a slope or gradually develops from grass bunds or fanya juu. Bench terraces usually consist of a series of level or nearly level platforms constructed along the contour lines of terraced slope (Ramos et al., 2007; Tenge et al., 2005). Platforms are separated by embankments known as risers. The main task of level platforms (also known as benches) is to reduce the length of the slope and its steepness, so the amount and velocity of surface runoff is also being reduced and the nearly level platforms retain surface water and allow infiltration into top soils (Widomski, 2011). The main observed disadvantages of bench terraces are construction and maintenance costs as well as observed reduction of cropping area (Ramos et al., 2007). There are two types of bench terraces, namely irrigation or level bench terraces and upland bench terraces (Figures 2.5 and 2.6). Irrigation/level bench terraces are used where the crops need flood irrigation and impounding water. Upland bench terraces are sub divided in to reverse sloped (back-sloping) type and outward sloped type (Sheng, 2000). In the Morogoro catchment, upland bench terraces can be found. Generally, bench terraces may be used on slopes up to 55% (Widomski, 2011).

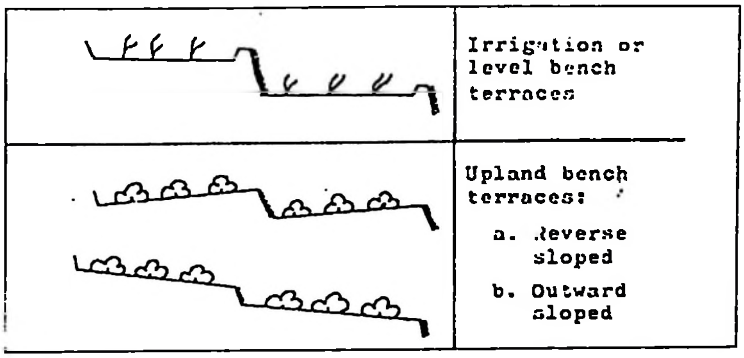


Figure 2. 5: Cross sectional view of bench terrace types (Sheng, 2000)

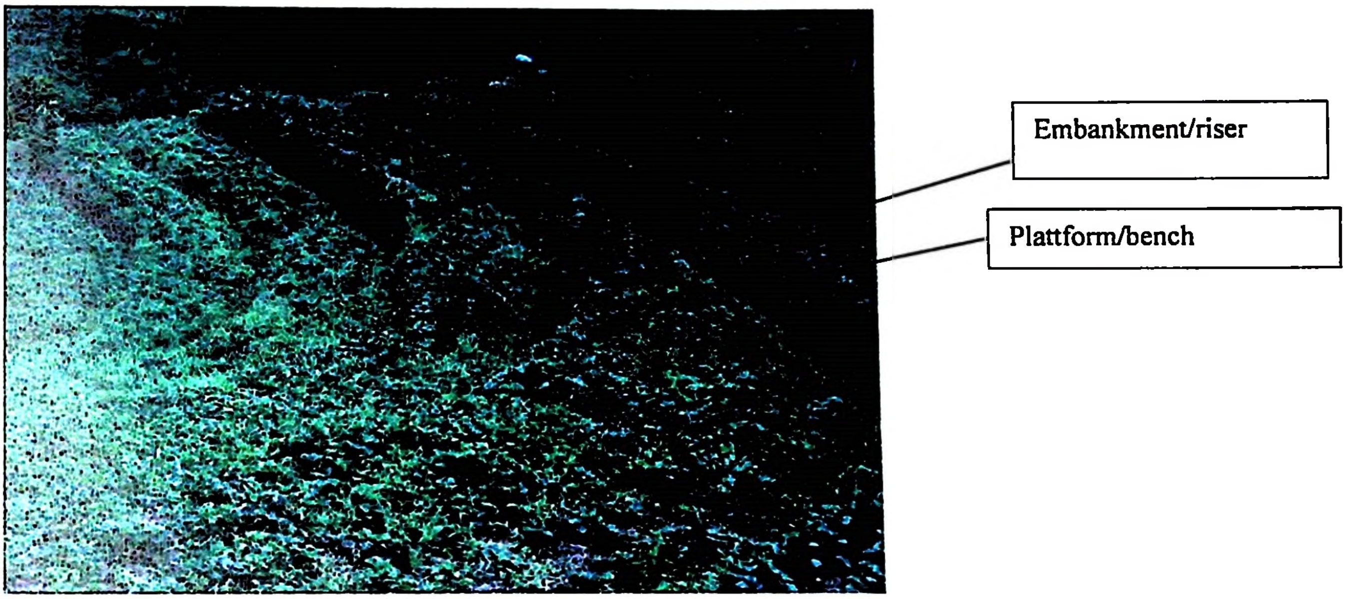


Figure 2.6: Bench terraces in the study area (D. Kilemo, 02/2015)

2.5 Adoption of SWC measures

SWC technologies were designed for land managers the vast majority of whom are farmers, with dual purposes of enhancing agricultural productivity and protecting watersheds. However, the uptake of the technologies by farmers has been invariably different globally due to complexity of farmers′ attitudes towards technologies and the dynamics in socio-ecological, socio-economic, socio-cultural and socio-political settings. Unless barriers to adoption of conservation systems at the farm level can be identified and removed, subsistence farmers in least developed countries will continue to exploit the land and environmental degradation will continue until cropland is no longer useful for any agricultural purpose (Napier and Cockerill, 2015).These account for continued failure of SWC initiatives worldwide especially in the developing countries where farmers incentives and capacity to practice SWC measures are still inadequate. For example, in Sub Saharan Africa, land degradation is on increase due to unsustainable land management practices (Liniger et al., 2011). This is compounded by poverty among rural communities and inadequate extension services. Anthony et al. (1998) contends that soil erosion will continue to exist in poor countries because subsistence farmers have no alternative to operating small farms on sloped land. Nevertheless, in some parts of Sub Saharan Africa; a sizeable number of farmers practice SWC in their farming systems which in turn have led to increase in agricultural production. For example, much of the progress in rainfed agriculture in countries such as Burkina Faso, Niger, Tanzania, etc. is due to local adaptive research and innovative dialogue which have allowed traditional and introduced techniques to be adapted to local conditions (Drechsel et al., 2006).

2.5.1 Adoption theories

Literature provides a great deal of adoption theories (e.g. Griliches, 1957; Rogers, 1983; Feder and Slade, 1984; Morrison, 2005). Innovation adoption theory is commonly applied to studies of farm-based conservation initiatives (Smithers and Furman 2003). According to Rogers 1983, this theory which is also called *Innovation Diffusion Model* identifies four main factors which influence the adoption decision of a farmer. These are (i) the characteristics of the farmer including his/her attitudes and motivations; (ii) the situational characteristics of the farm, such as land and labor constraints; (iii) the qualities of the innovation, including its compatibility and complexity, and (iv) the extension activities used to promote the innovation. These factors work in a four-step innovation decision process involving exposure, persuasion, a decision, and ongoing confirmation as farmers continue to evaluate their decision (Guerin and Guerin, 1994; Rogers and Shoemaker, 1971). On the qualities of an innovation, Rogers (1983) elaborates five attributes of the innovation which determine whether a farmer will adopt it or not. These are relative advantage, compatibility, simplicity, trialability, and observability. The innovation demonstrating these attributes is more likely to be adopted by farmers than others. Rogers (1983) further categorizes adopters into innovators (they are active information seekers about new ideas. They have a high degree of mass media exposure and their interpersonal networks extend over a wide area, usually reaching outside of their local system), early adopters, early majority adopters, late majority adopters and laggards (will never adopt any new innovation, very conservative to old systems).

Napier and Cockerill (2015) give an in-depth analysis of factors affecting adoption of SWC practices worldwide based on the traditional diffusion model. They identify several factors such as access to information about soil and water conservation problems, access to information about possible solutions to environmental problems. access to technical training to develop requisite skills to effectively implement conservation production systems and access to information delivery systems that disseminate relevant agro-ecological information about local socio-environmental situations.

Two theories further explain farmer motivations for adoption. The first. socio-cultural theory, suggests that farmers are predisposed to accept or reject conservation initiatives due to a set of socio-cultural values and attitudes, such as environmental sympathies. feelings towards governmental programs. and willingness to accept techno-managerial change. These predispositions can motivate some to adopt innovations despite economic costs, and others to reject them despite economic incentives (Potter and Gasson. 1988; Wilson, 1996). The second, liberal economic theory, argues that farmers are rational economists. primarily motivated by economic incentives. They will adopt any techno-managerial innovation that comes with assured economic benefits, as long as they do not face significant barriers, such as limits to labor or an onerous permitting process (Wandel and Smithers. 2000: Wilson and Hart, 2000). Generally, farmers' attitudes to risks tend to influence their willingness to invest in SWC. The decision on whether to invest in SWC is mediated by the extent to which this increases or reduces the overall risks of agricultural production relative to not doing so. The adoption of SWC practices can be regarded as a risk reduction strategy. whereby the overall resilience of the farming system may be enhanced and the impact of any stress (such as erratic and untimely rainfall) are less dramatic (Boyd et al, 2000).

2.5.2 Adoption analytical model

Adoption studies traditionally apply some analytical methods used in econometrics and social sciences. Of much interest are the models that predict the probability of individuals in the study sample to have a predefined attribute, behavior or response. In micro-econometrics, they are known as discrete choice models (Train. 2002). This is because their fundamental focus is modeling of discrete outcomes such as purchase decisions. Discrete regression models are often applied which consist of *logit* and *probit* models (Maddala, 1983; Wooldrige, 2010). A Logit model is also known as a logistic regression model. A logistic regression model can be referred to as binary logistic regression when the dependent variable has two outcomes while it is known as multinomial logistic regression when the dependent variable has more than two outcomes. The

Probit model is similar to Logit model and often they produce the same results. The only difference is that the logit model assumes that the dependent variable follows a logistic distribution while the probit model assumes a cumulative normal distribution.

Aggregate models of technology diffusion in the past were generally founded upon the epidemic or logistic model, wherein the diffusion process is viewed to be formally akin to the spread of an infectious disease (Feder and Umali, 1993). The analogy is that contact with other adopters and exposure to information on the innovation leads to adoption (Arrow, 1968). The demonstration effects and learning from the experience of others underlie the logistic model (Feder and Umali, 1993). It assumes that the population is homogeneous and the members have an equal probability of coming into contact with each other.

A maximum likelihood method is used to estimate the parameters of each independent variable in the logistic regression model at a given level of statistical significance (Train, 2002; Landau and Everitt, 2004; Wooldrige, 2010). This is achieved by analyzing the probability density function (PDF) of each independent variable. Normally, a joint PDF is used to express a discrete regression model which takes into account all variables. According to Feder and Umali (1993), a logistic model follows the general form:

$$\frac{\partial n_t}{\partial t} = \beta \frac{n_t}{N} (N - n_t) \qquad (13)$$

Where n_t is the number of individuals who have adopted the innovation at time t, N is the total population of potential adopters, and β is a parameter reflecting the rate of adoption. The basic characteristic of the adoption process is imitative behavior (Thirtle and Ruttan, 1987). The value of β will depend on some factors such as the nature of the specific innovation, economic factors, the social system in which it is introduced, and the channel and change agent used to diffuse it (Feder and Umbali, 1993).

In binary logistic regression, the response variable takes values between 1 and 0. In this case 1 for adoption and 0 for not adopting. The expected value is the probability, p that the response variable takes the value of 1. This means the probability of not adopting is 1-p. Due to nonlinearity of the logistic distribution normally a log transformation, thus the name "logit" is used. Thus, the logistic model can be rewritten as shown in equation (14). By applying the log transformation, the *log-odds* of adoption is modeled as a linear function of the explanatory variables (Landau and Everitt, 2004).

$$\text{Log} \frac{p}{1-p} = \beta_0 + \beta_1 X_1 \ldots . \beta_q X_q \tag{14}$$

where β is the estimated coefficient and X stands for independent variable (explanatory variable). The logistic coefficient represents the log-odds of explanatory variable relative to others in respect to the modeled outcome. The β coefficients are normally exponentiated to provide results in odds. Therefore, the logistic function of p can be written as:

$$\frac{\text{Prob(adoption)}}{\text{Prob(non} - \text{adoption)}} = e^{\beta_0 + \beta_t X_1 + \cdots \beta_i X_i} \tag{15}$$

where e raised to the power of β_i is the factor by which the odds change when the ith independent is changed by one unit. When β_i is positive, E (β_i) >1, thus the odds are increased. When β_i is negative, E (β_i) < 1 implying that the odds are decreased. If β_i =0, E (β_i) = 1 meaning that the odds are not changed. The logistic model is characterized by a symmetric S-shaped diffusion trend (Figure 2.7) which attains a maximum diffusion rate when 50% of the potential cumulative adopters have adopted the innovation (Mahajan et al., 1985; Jabbar et al., 1998).

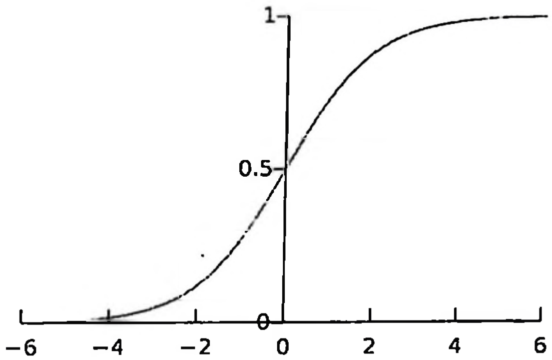


Figure 2.7: A logistic curve
Source: https://en.wikipedia.org/wiki/Logistic_function#/media/File:Logistic-curve.svg

2.5.3 SWC measures in Tanzania

Soil and water conservation practices in Tanzania date back in the late 19th century when soil erosion began to be a serious problem in pre-colonial and in then German East-Africa. Since then a number of policy instruments were put in place in an attempt to mitigate soil erosion (Kalineza et al., 1999). For example, on Uluguru Mountains, the colonial government declared about 277 km^2 as forest reserve in 1909 (Temple and Rapp, 1972). In the 1930s soil erosion problem was not limited only to Uluguru Mountains but to the entire territory of Tanganyika (Kauzeni et al., 1987). This necessitated the British colonial government to formulate strategies for addressing soil erosion. Thus, SWC measures were enforced. The major SWC measures applied in the 1940s were ridges, contours, banking of the cultivated land, gully control, rotational grazing and reforestation (Kalineza et al., 1999). However, the enforced SWC measures failed. According to Kalineza et al. (1999) three main reasons contributed to the failure. First, the authorities enforced rules towards natives only, this caused people to develop negative attitudes towards SWC measures. Second, the soil conservation activities were sometimes carried out as punishment to disobeying local chiefs or poll tax evasion, hence making them unpopular. Third, the colonial administrators did not appreciate the fact that some groups had already adapted their own agricultural systems which controlled soil erosion. After independence (1961 and thereafter), many SWC measures were abandoned. This led to serious land degradation reaching an advanced stage in the first decade after independence (Kauzeni et al., 1987). In the 1970s SWC activities resumed under the auspices of the government and international aid agencies (Lundgren and Taylor, 1993). In the 1970s through 1980s various projects with SWC components were established in different parts of the country (Kalineza et al., 1999) including the Uluguru Mountains. Table 2.1 summarizes a number of SWC practiced in Tanzania during various time periods.

Table 2.1: SWC measures practiced in Tanzania during pre-colonial, colonial and post-colonial periods (modified from Boyd et al., 2000)

S/N	Type of SWC measure	Remarks/Analysis
1	Live barriers	Introduced during the colonial period and abandoned immediately after independence (1961) due to the politicization of SWC issues, the weakening of support institutions and drought.
2	Supplementary irrigation systems	Existed since pre-colonial times (prior to 1900) and make the cultivation of maize possible.
3	Deep tillage	Introduced during the period following the Arusha Declaration (1968) as a result of publicly-funded tractor hire schemes.
4	Bunded basins	For the purpose of holding water for rice cultivation.
5	Tree planting	Introduced during the German and British colonial period (1906–1961), expanded during the post-Arusha Declaration (1968–85) and liberalization periods (1985 to date) due to ongoing campaigns and programs and the establishment of tree nurseries.
6	Stone bunds	Part of the supplementary irrigation system, expanded during the liberalization period; associated with increased vegetable production.
7	Cut-off drains or contour bunds	Introduced during the colonial period and abandoned immediately after Independence due to the politicization of SWC issues and the weakening of support institutions.
8	Terraces	Introduced during the colonial period but widely abandoned
9	Trash lines	Did not survive after the Arusha Declaration period; currently not widely used because they are considered to harbor vermin and other crop pests.
10	Forest and bush protection	Clan forests are still protected, but smaller patches of trees ('microforests') in household fields have died out. The introduction of 'reserved forests' resulted in the removal of any sense of local ownership. Modern religious teachings also prohibited followers from performing traditional rituals associated with protected forests; microforests disappeared during the liberalization period due to reduced enforcement of by-laws.
11	Traditional land-use planning (including allocation of grazing land, protection of watersheds and hilltops from cultivation and grazing)	Traditionally enforced by local chiefs and peer pressure, but disappeared during the liberalization period due to reduced enforcement of by-laws.

2.6 Hydrological modeling

A model is a simplified representation of a real-world system (Sharma et al., 2008) or an abstraction of reality in the simplest way that is adequate for the purpose of the modeling (Mulligan, 2004). According to Sharma et al. (2008) the best model is the one which give results close to reality with the use of least parameters and model complexity. Watershed modeling, or hydrologic simulation (sometimes termed rainfall-runoff modeling) began in the 1950s and 1960s with the advent of the digital computer (Donigian and Imhoff, 2006). Since then, a multitude of hydrologic models with various levels of assumption have been developed to simulate various rainfall-runoff processes, some of which are yet to be fully understood (Aghakouchak and Habib, 2010). Hydrological models are developed based on some assumptions for various processes. The assumptions differ from one modeler to another thus resulting into different model structures and configurations and hence giving different results in terms of output and model performance efficiency.

Watershed models simulate natural processes of the flow of water, sediment, chemicals, nutrients, and microbial organisms within watersheds, as well as quantify the impact of human activities on these processes. Simulation of these processes plays a fundamental role in addressing a range of water resources, environmental, and social problems (Singh and Frevert, 2006). A watershed as a hydrologic system undergoes through several hydrological processes at different spatial and temporal scales. According to Beven (2001a) hydrologic modeling is necessary because of limitations of the measurement techniques and the fact that hydrological processes are too complex to understand as they mostly take place underground. Hydrologists are not able to measure everything they would like to know about hydrological systems. They have only a limited range of measurement techniques and a limited range of measurement in space and time. Therefore, a means of extrapolating from those available measurements in both space and time and into the future to assess likely impact of future hydrological change is needed. Models of different types provide a means of quantitative extrapolation or predication that will hopefully be useful in decision-making. Beven (2001a) further provides a modeling framework to be followed in the modeling process which was also applied by Busche (2012) with some few modifications. As shown in Figure 2.8, a modeler normally starts with the *perceptual model* of hydrological processes in a catchment. It is a summary of modeler's perceptions/understanding on how the catchment responds to hydrological processes under different conditions. The perceptual model differs from one modeler to another because it is based on the modeler's background and experience in hydrology. It will depend on the training that a hydrologist has had, the books and articles they have read, the data sets they have analyzed and particularly the field sites they have experiences of in different environments (Beven, 2001a).

Beven (2001a) further contends that the perceptual model end ups with mathematical descriptions of the processes. This leads to a *conceptual model* of the process (es) being considered. It is here where the hypotheses and assumptions being made to simplify the description of the processes are made explicit. The conceptual model may be more or less complex, ranging from the use of simple mass balance equations for components representing storages in the catchment; to couple nonlinear partial differential equations. The conceptual model will then lead to another step whereby the mathematical equations will be translated into programming codes to be used in a computer using programming software of choice. This is called the *procedural model* (Beven, 2001a). It will create the programming codes to be used to compute the hydrological processes based on the mathematical descriptions provided. When all is done the next step will be *model calibration* whereby model parameters are manipulated so that the model gives a desired output under specific catchment conditions. Calibration strives to demonstrate that the model is able to produce a good fit of observed and simulated results based on a set of input parameters specific to the catchment under consideration. This can be performed manually (trial-and –error adjustment of parameters) or by auto-calibration technique. Before this is done modelers normally perform *sensitivity analysis* which evaluates how output parameters are sensitive to input parameters. Sensitivity analyses are valuable tools for identifying important model parameters, testing the model conceptualization, and improving the model structure. They help to apply the model efficiently and to enable a focused planning of future research and field measurement (Sieber and Uhlenbrook, 2005). Once the model parameter values have been specified, a simulation may be made and quantitative predictions about the response obtained. The next stage will be the *validation* of those predictions. According to Refsgaard (1996) model validation is the process of demonstrating that a given site specific model can make sufficiently accurate predictions. This implies the application of the calibrated model without changing of the parameter values that were set during the calibration when simulating the response for another period than the calibration period. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or to provide acceptable errors.

Runoff generation and routing are two key hydrological processes guiding water flow modeling. According to Beven (2001a) every hydrological model requires two essential components, one to determine how much of a rainfall becomes part of the storm hydrograph (runoff production component), the other to take account of the distribution of that runoff in time, to form the shape of the storm hydrograph (the runoff routing component). This study followed the modelling procedure shown in Figure 2.8. However, no new model was developed but rather an existing physically based and semi-distributed hydrological model, SWAT (Arnold et al., 1998) was applied in addressing the research problem (see section 2.7).

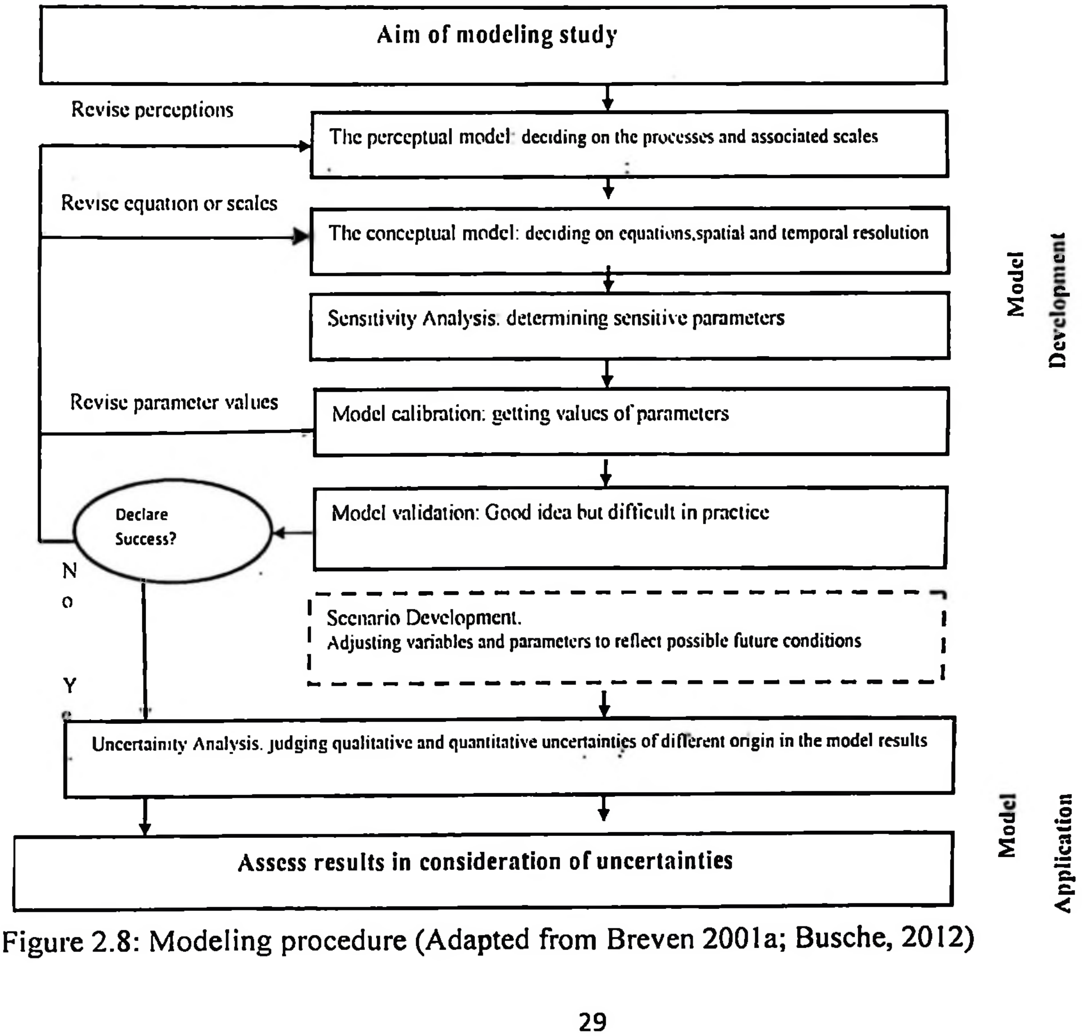


Figure 2.8: Modeling procedure (Adapted from Breven 2001a; Busche, 2012)

2.6.1 Types of hydrological models

As a result of advances in hydrology and mathematical modeling, many hydrological models of different constructs exist today. Several authors have attempted to classify and categorize such models based on some criteria (e.g. Refsgaard, 1996; Singh and Woolhiser, 2002; Wheater, 2008). However, whatever classification system one takes, the fundamental differences among models remain. Refsgaard (1996) classifies hydrological models into *empirical (black box) models, lumped models, distributed models, conceptual (grey box) models and physically based (white box) models.* Empirical models do not consider the physical laws of the underlying watershed processes. They only reflect the relation between the input and outputs. 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. A conceptual model is one that is constructed on the basis of the physical processes that we read into our observations of the catchment. In a conceptual model; physically sound structures and equations are used together with semi-empirical ones. However, the physical significance is not usually so clear that the parameters can be assessed from direct measurements. Thus, it is necessary to estimate the parameters from calibrations, applying concurrent input and output time series (Refsgaard, 1996). Physically-based models describe the natural system in a watershed using mathematical representation of flows of mass and energy. Usually physically –based hydrological models are also fully distributed. Gayathri et al. (2015) classify hydrological models into empirical, conceptual and physically based models.

2.6.2 Scale issues in hydrological models

The hydrological events take place at various temporal and spatial scales within a catchment. This is fundamental to the choice of a hydrological model to develop or to use for producing results which are close to reality. According to Blöschl and Sivapan (1995) most of prediction errors emanating from hydrological models are related to the scale problem. Vinogradov et al. (2010) also share the same opinion whereby they argue that the scaling problem is considered to be fundamental as this is the main source of uncertainties introduced by modeling. The term "scale" refers to a characteristic time (or length) of a process, observation or model. Specifically, processes are often observed and modeled at short time scales, but estimates are needed for very long time-scales. Similarly, models and theories developed in small space-scale laboratory experiments are expected to work at the large scale of catchments. Conversely, sometimes large-scale models and data are used for small-scale predictions. This always involves some sort of extrapolation, or equivalently, transfer of information across scales. This transfer of information is called *scaling* and the problems associated with it are scale issues (Blöschl and Sivapalan, 1995). Recognizant of the scale issue, hydrological models employ either upscaling or downscaling approach of representing catchment hydrological information. In a hydrological perspective, *upscaling* refers to transferring information from a given scale to a larger scale, whereas *downscaling* refers to transferring information to a smaller scale (Gupta *et al.*, 1986). These are also referred to as bottom-up approach and top-down approach respectively (Xiangyu and Yang, 2011).

2.6.3 Model parameters sensitivity analysis

Sensitivity analysis (SA) can be defined as the process of determining the effect of changing the value of an input variable on model output. It is useful not only for model development, but also for model validation and reduction of uncertainty (Hamby. 1994). Without knowledge of the sensitivity of parameters the modeling work can result in time being wastefully spent on non-sensitive ones. Focusing on sensitive parameters can lead to a better understanding and to better estimated values and thus reduced uncertainty (Lenhart et al.. 2002). According to Hamby (1994) modelers employ sensitivity analysis in order to know: (i) which parameters need additional research for enriching the knowledgebase, thus reducing output uncertainty; (ii) which parameters are insignificant and can be excluded in the final model; (iii)which inputs contribute most to the output variability; (iv) which parameters are most highly correlated with the model output; and (v) once the model is operational, what consequences are expected by changing a given input parameter.

Two types of SA are known, local sensitivity and global sensitivity (Saltelli et al., 1999; Massman and Holzman, 2012; Peeters et al., 2014). Local sensitivity analysis (LSA) also known as a One-At-a-Time Sensitivity Analysis estimates the sensitivity at one point in parameter space. It varies one parameter at a time while holding other parameters constant and is suitable for linear model behavior (Saltelli et al., 1999; van Griensven et al., 2006). The advantage of this type of analysis is that it requires less computational time while its shortcoming is that it does not account for interaction between parameters (Tang et al., 2007). The nominal range and differential analysis methods are two highly used LSA methods (Frey and Patil, 2002; Helton and Davis, 2003). In practice, the non-linearity of the hydrological models shows that combining the main parameter effect and its interactions with other parameters is needed to capture the model response behavior. For these reasons, the LSA is inapplicable in non-linear problems (Sun et al., 2012). On the other hand, Global Sensitivity Analysis (GSA) estimates parameter sensitivity by varying all the parameters at the same time. It considers both linear and non-linear interactions between model parameters and thus suggested to be more appropriate to complex and physically-based distributed hydrological models than LSA though it requires more computational time (Tang et al., 2007; Cannavo, 2012: Livneh et al., 2013).

2.6.4 Model calibration

Model calibration involves manipulation of a specific model to reproduce the response of the catchment under study within the range of accuracy specified in the performance criteria (Refsgaard, 1996). It is performed by carefully selecting values for model input parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions (Anord et al., 2012). It is basically an effort to better parameterize a model to a given set of local conditions so as to reduce the prediction uncertainty. According to Refsgaard (1996), errors in hydrological modeling results emanate from four sources of uncertainty namely (i) random or systematic errors in the input data, i.e. precipitation, temperature and evapotranspiration etc. used to represent the input conditions in time and space over the catchment; (ii) random or systematic errors in the recorded data, i.e. the river water levels, groundwater heads, discharge data or other data used for comparison with the simulated output; (iii) errors due to non-optimal parameter values, and (iv) errors due to an incomplete or biased model structure. The objective of model calibration should be to reduce error (iii) making it as insignificant as possible compared to data error sources (i) and (ii) (Refsgaard, 1996). Calibration can be done manually or automatically though each has a set of *pros* and *cons* (Refsgaard, 1996; Senarath et al., 2000; Bahremand and Smedt, 2008; Anord et al., 2012). Automatic calibration is less labor intensive compared to manual calibration, but values of the calibrated parameters may not realistically reflect catchment characteristics (van Liew et al., 2005). To overcome this shortcoming, a combination of both methods is generally recommended (Green and van Griensven, 2008).

2.6.5 Model validation

Validation is the process of evaluation of models to confirm that they are acceptable representations of a real system (Beven, 2001b). Refsgaard et al. (1995) defines model validation as the process of demonstrating that a given site specific model is capable of making accurate predictions for periods outside a calibration period. They further contend that a model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or errors. The term validation is not new in hydrologic and environmental modeling. It is commonly used to indicate a procedure aimed at analyzing the capability of the calibrated model to make simulations which are close to the reality (Biondi et al., 2012). Krause et al. (2005) provide three main reasons for validation of hydrological models which entail the following: (i) to provide a quantitative indicator of model skill at reproducing catchment behavior; (ii) to provide a means for evaluating improvements to the model or method of modeling, and (iii) to provide a mechanism for comparing the results obtained in different modeling studies. They further argue that the process of assessing the performance of a hydrologic model requires the hydrologist to make subjective and/or objective estimates of the 'good fit' of the simulated results of the model to observations made within the watershed.

2.6.6 Evaluation of hydrological model performance

In literature, model performance and model efficiency are used interchangeably but they both address the common issue of the accuracy of the model in simulation as compared to the observed data. Model efficiency evaluation is done at both calibration and validation stages of modeling. Traditionally, both the graphical and numerical methods are used to analyze the performance of hydrological models (Refsgaard et al., 1995; Biondi et al., 2012; Ritter and Carpena, 2013). The numerical methods (also known as objective functions) are typically objective and quantitative; and are based on the summation of the error term (difference between observed data and simulated results). To avoid the canceling of errors of opposite sign, the summation of the absolute or squared errors is often used for many efficiency criteria (Krause et al., 2005). In hydrological modeling there are several objective functions used to evaluate model performance (Dawson et al., 2007; Ritter and Carpena, 2013), but the Nash and Sutcliffe

Efficiency coefficient –NSE is widely used (Gupta and Kling, 2011; McCuen et al., 2006; Harmel and Smith, 2007). It is argued that NSE is better suited to evaluate model goodness-of-fit than the coefficient of determination, R^2, because R^2 is insensitive to additive and proportional differences between model simulations and observations (Harmel and Smith, 2007). The NSE is defined as:

$$E = 1 - \frac{\sum_{i=1}^{n}(x_o - x_s)^2}{\sum_{i=1}^{n}(x_o - \mu_o)^2} \qquad (16)$$

where x_o denotes observed values and x_s represents simulated values at time/place *I*, μ_o is the mean of the observed values. The coefficient of efficiency takes values $-\infty \leq$ NSE ≤ 1. A NSE = 1 indicates a perfect fit, while a NSE≤ 0 suggests that the mean of the observed values is a better predictor than the evaluated model itself (Ritter and Carpena, 2013). Despite the fact that the NSE is a widely used model performance evaluation metric in hydrological modeling, it has a shortcoming of underestimating peak flows and overestimating low flows thus leading to errors (Legates and McCabe, 1999). This is because the differences between observed and predicted values are computed as squared values. Like the coefficient of determination (R^2) metric, NSE is not very sensitive to systematic model overprediction or underprediction notably during low stream flow periods (Krause et al., 2005). To address the NSE weakness, NSE was decomposed into correlation, variability and bias components. Hence an improved objective function known as Kling-Gupta Efficiency(KGE) was coined (Gupta et al., 2009). KGE is expressed as:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \qquad (17)$$

$$\alpha = \frac{\sigma_s}{\sigma_o} \qquad (18)$$

$$\beta = \frac{\mu_s}{\mu_o} \qquad (19)$$

where r is the correlation coefficient between simulated and observed values, α is the variability ratio, β is the bias ratio. σ is the standard deviation while μ is the mean. Subscripts s and o stand for simulated and observed respectively.

Another method to evaluate the performance of hydrological models is through percentage bias (PBIAS) calculation. PBIAS measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated as :

$$PBIAS = 100 * \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})_i}{\sum_{i=1}^{n} Q_{obs,i}} \tag{20}$$

where Q is a variable e.g. stream flow.

2.6.7 Scenario analysis

IPCC (2008) defines a 'scenario' as a coherent, internally consistent and plausible description of a probable future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. Scenarios provide a dynamic view of the future by exploring various trajectories of change that lead to a broadening range of plausible alternative futures (Mahmoud et al., 2009). Scenario analysis provides one tool for considering the implications of a plan or management decision across a range of future possibilities (Steinitz et al., 2003), and therefore also a valuable analytical device for spatial planning (Couclelis, 2005). Scenario studies commonly target issues which are sensitive to stakeholders and they provide the means by which decision-makers can anticipate coming change and prepare for it in a responsive and timely manner (Mahmoud et al., 2009). Moreover, Raskin (2005) argues that scenarios draw from the human imagination as well as science to provide an account of the flow of events leading to vision of the future. He further elaborates that scenarios are plausible stories about how the future might unfold from existing patterns, new factors, and alternative human choices. The ultimate goal of hydrological modeling is to improve watershed and ecosystem management so as to optimize the provision and utilization of hydrologic ecosystem services. Hence, scenario development and analysis is a key ingredient of any hydrological modeling scheme without which the modeling endeavor becomes meaningless.

2.7 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) is a hydrological model that can be applied at the river basin, i.e. on the watershed scale which is relevant for integrated water resources management. The model was developed by the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Texas for the purpose of simulation of impact of land management practices on the fluxes of water, sediment and agrochemicals in large watersheds with varying soils, land-use and agricultural conditions over extended time periods (Neitsch et al., 2011). It is a semi-distributed, time continuous model operating on a daily time step (Arnold et al., 1998). The model is widely used to simulate processes affecting water quantity, sediment and nutrient loads in a catchment (Abbaspour et al., 2007). It allows simulation of a high level of spatial detail by dividing the watershed into a large number of sub-watersheds which are then partitioned into hydrological response units (HRUs). Each HRU corresponds to a particular combination of soil, slope and land-use.

2.7.1 Theory of SWAT model

A complete theoretical documentation of SWAT model is given by Neitsch et al. (2011). They contend that the SWAT model is based on the hydrological cycle whereby the land phase is governed by the soil water balance equation (equation 11). No matter what type of problem is studied with SWAT, water balance is the driving force behind everything that happens in the watershed (Neitsch et al., 2011). Water enters the SWAT model's watershed system boundary predominantly in the form of precipitation. Precipitation inputs for hydrologic calculations can either be measured data or simulated with the weather generator available in the model. Precipitation is partitioned into different water pathways depending on system characteristics. The water balance of each HRU in the watershed contains four storage volumes namely snow, the soil profile (0-2 m), the shallow aquifer (2-20 m); and the deep aquifer (>20 m). The soil profile can contain several layers. The soil-water processes include infiltration, percolation, evaporation, plant uptake, and lateral flow.

2.7.2 Runoff Generation

SWAT estimates surface runoff using the Soil Conservation Service (SCS) curve number procedure (USDA-SCS. 1972) and the Green & Ampt infiltration method. This study applied the curve number method which is well described in USDA-NRCS (2004). Runoff is estimated as:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad (21)$$

Where Q_{surf} 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) estimated as $0.2\,S$ and S is the retention parameter (mm) which is calculated as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (22)$$

Where CN is SCS Curve Number of the day which is a function of soil permeability, land-use and antecedent soil moisture condition. Runoff will take place only when $R_{day} > Ia$. The water that infiltrates into the ground can be stored in the soil as soil moisture and later be removed through evepotranspiration or might move laterally in the soil profile to contribute to stream flow or could seep below the soil profile and recharge the aquifers.

2.7.3 Peak runoff rate

The peak runoff rate is the maximum flow rate that occurs with a given rainfall event. It is an indicator of the erosive power of a storm and is used to predict sediment loss. SWAT calculates peak runoff with a modified rational method. The rational method is based on the assumption that if a rainfall of intensity i begins at time $t = 0$ and continues indefinitely, the rate of runoff will increase until the time of concentration when the entire sub basin area is contributing to flow at the outlet (Neitsch et al., 2011). The rational method is defined by:

$$q_{peak} = \frac{C.i.A}{3.6} \qquad (23)$$

where q_{peak} is the peak runoff rate (m^3 s-^{1}), C is the runoff coefficient , i is the rainfall intensity (mm/hr), A is the sub basin area (km^2) and 3.6 is a unit conversion factor. The modified rational formula is expressed as:

$$q_{peak} = \frac{\propto tc. Q_{surf}. A}{3.6 t_{conc}} \tag{24}$$

where q_{peak} is the peak runoff rate, α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff, A is the subbasin area, t_{conc} is the time of concentration for the subbasin and 3.6 is a unit conversion factor.

2.7.4 Time of concentration

The time of concentration is the amount of time from the beginning of a rainfall event until the entire sub basin area is contributing to flow at the outlet. In other words, the time of concentration is the time for a drop of water to flow from the remotest point in the sub basin to the sub basin outlet (Neitsch et al, 2011). It is calculated by summing the overland flow time and the channel flow time as:

$$t_{conc} = t_{ov} + t_{ch} \tag{25}$$

where t_{conc} is the time of concentration for a sub basin (hr), t_{ov} is the time of concentration for overland flow (in hours) and t_{ch} is the time of concentration for the channel flow (in hours). The time of concentration for overland flow can be computed as

$$t_{ov} = \frac{{L_{slp}}^{0.6} . n^{0.6}}{18. slp^{0.3}} \tag{26}$$

where L_{slp} is the sub basin slop length (m), slp is the average slope in the sub basin (m m^{-1}), and n is the Manning's coefficient for the sub basin.

2.7.5 Evapotranspiration

SWAT requires evapotranspiration estimates in order to compute watershed water balance. Both Potential Evapotranspiration (PET) and Actual evapotranspiration (ET) are considered. SWAT first computes the PET based on the input weather data and the computation method, then ET is calculated. It first evaporates any rainfall intercepted by the plant canopy. Then, calculates the maximum amount of transpiration and the maximum amount of sublimation /soil evaporation. Sublimation will occur if there is snow. Evaporation from the soil surface will take place only if there is no snow. There are three methods used by SWAT to estimate PET. These include various methods: Penman-Monteith (Monteith, 1965), Priestley and Taylor (1972), and Hargreaves et al. (1985). The methods vary in amount of required input data. The minimum data requirements for Penman-Monteith is daily mean temperature, solar radiation, relative humidity and wind speed. The Priestley-Taylor method on the other hand, requires at the minimum daily mean temperature and solar radiation. The Hargreaves method has the least data requirement whereby only the average daily air temperature is required to compute PET. It is expressed as:

$$\mathrm{ET_0} = \mathrm{c_H} . 0.408 R_0 . (T + 17.8)\sqrt{T_{max} - T_{min}} \tag{27}$$

where R_0 is extraterrestrial radiation, T is the daily mean temperature, c_H is the Hargreaves coefficient. The value 0.408 is the inverse of the latent heat flux of vaporization at 20^0C, changing the units from MJ m^{-2} d^{-1} into mm d^{-1} of evaporation equivalent (Allen et al., 1998). This study applied Hargreaves method to compute PET in SWAT.

2.7.6 Water Routing

Water flow in SWAT is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method (McCarthy, 1938). Both methods are variations of the kinematic wave model (Chow et al., 1988). For a given reach segment, variable storage routing is based on

$$V_{in} - V_{out} = \Delta V_{stored} \tag{28}$$

where V_{in} is the volume(m^3) of inflow at time step. V_{out} is the volume (m^3) of outflow at time step and ΔV_{stored} is the change in volume (m^3) of storage at time step.

On the other hand, the Muskingum routing method models the storage volume in a channel as a combination of wedge and prism storages. When advancing into a reach segment, inflow exceeds outflow and a wedge of storage is produced. As the flood wave recedes, outflow exceeds inflow in the reach segment and a negative wedge is produced. In addition to the wedge storage, the reach segment contains a prism of storage formed by a volume of constant cross-section along the reach length. The reach storage volume can be calculated as

$$V_{stored} = K.q_{out} + K.X.(q_{in} - q_{out}) \tag{29}$$

where V_{stored} is the storage volume (m^3), q_{in} is the inflow rate ($m^3\ s^{-1}$), q_{out} is the discharge rate ($m^3\ s^{-1}$), K is the storage time constant for the reach (s), and X is the weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach. The weighting factor, X, has a lower limit of 0.0 and an upper limit of 0.5. This factor is a function of the wedge storage. For reservoir-types storage, there is no wedge thus X= 0.0. For a full wedge, X = 0.5. For rivers, X will fall between 0.0 and 0.3 with a mean value near 0.2 (Neitsch et al., 2011).

2.7.7 Lateral flow

Kinematic wave approximations are used in hydrology to describe the subsurface flow and saturated excess overland flow in the hillslopes with a soil layer overlaying a relatively impermeable bedrock (Beven, 1981; Rezzoug et al., 2005). SWAT incorporates a kinematic storage model for subsurface flow according to Sloan et al. (1983). It simulates subsurface flow in a two-dimensional cross-section along a flow path down a steep hillslope (Neitsch et al., 2011).

2.7.8 Sediment erosion

In simulating sediment yield SWAT uses the Modified Universal Soil Loss Equation (MUSLE: Williams and Berndt, 1977). MUSLE is a version of USLE (equation 12) that directly considers runoff to estimate sediment yield. It is widely used and well suited to model soil erosion at watershed scale. MUSLE operates in the same manner as USLE except for the energy component. USLE depends solely on rainfall as the source of erosive energy (Kinnell, 2005), while MUSLE uses storm-based runoff volumes and runoff peak flows to simulate erosion and sediment yield (Williams, 1975). The use runoff rather than rainfall erosivity as the driving force enables MUSLE to estimate sediment yields for individual storm event (Kinnell, 2005).

In SWAT, the MUSLE is solved for each HRU and final sediment yields are routed down the main channels using a stream power equation (Neisch et al., 2011). This routing method assumes the maximum amount of sediment that can be transported in a given reach is a function of the peak channel velocity (Arnold et al., 1995). MUSLE is written as:

$$sed = 11.8.\left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \tag{30}$$

where *sed* is the sediment yield on a given day (tons/ha), Q_{surf} *is* the surface runoff (mm ha^{-1}), *qpeak is* peak runoff rate ($m^3 s^{-1}$), $area_{hru}$ is the 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 coarse fragment factor.

2.7.9 Sediment routing in stream channels

Sediment transport in the channel network is a function of two processes: deposition and degradation, operating simultaneously in the reach. SWAT computes deposition and degradation using the same channel dimensions for the entire simulation (Neitsch *et al.*, 2011). The deposition process is based on fall velocity and the degradation process is a modification by Williams (1980) to the stream power concept by Bagnold (1977). Fall velocity is estimated as a function of particle diameter squared using Stoke's Law. Excess stream power produces bed degradation that is adjusted by USLE soil erodibility and the cover factor of the channel and flood plain (Phomcha et al., 2011).

2.8 SWAT input data, parameter sensitivity, calibration, validation and uncertainty analysis

SWAT requires a great deal of input data which may vary according to the modeling objective and location of the studied watershed. For example, studies conducted in temperate regions require snow data in addition to the rainfall data. Some inputs are measured data (e.g. climate data) and some estimated through PTFs (e.g. saturated hydrological conductivity of soil layers), while others are parameters for various hydrological processes at different spatial discretization (e.g. soil evaporation compensation factor). The basic SWAT inputs include the digital elevation model, land-use map, soil data (soil map, relevant soil parameters such as texture, bulk density, available water capacity, soil erodibility factor and saturated hydraulic conductivity) and daily climate data which include rainfall, maximum and minimum temperature, relative humidity, wind speed and solar radiation. Further details on SWAT inputs can be found in SWAT2012 -Input-Output documentation (Arnold et al., 2011).

Unlike the previous SWAT versions, the current SWAT2012 version does not have inbuilt automatic calibration and sensitivity analysis algorithm. SWAT has many parameters to be calibrated depending on the hydrological processes of interest, thus manual calibration is not feasible (Abbaspour, 2015). However, a combination of manual and automatic calibration is highly recommended (Arnold et al., 2012; Green and van Griensven, 2008). To date there are several algorithms with capability to optimize SWAT parameters in automatic calibration. These include but are not limited to Particle Swarm Optimization (PSO) algorithm (Eberhart and Kennedy, 1995), Parameter Estimator (PEST, Doherty, 2004) and Sequential Uncertainty Fitting (SUFI-2) developed by Abbaspour et al. (2007). They also developed a calibration and uncertainty analysis computer program for SWAT known as SWAT calibration uncertainty program (SWAT- CUP). It links five calibration algorithms with SWAT, these are: SUFI-2, PSO, Parameter-Solution (Parasol), Generalized Likelihood Uncertainty Estimator (GLUE) and Markov Chain Monte Carlo (MCMC). The user should choose which algorithm to use depending on the modelling objective. SWAT-CUP is a platform that provides a link between the input/output of the calibration algorithm and SWAT. File exchange is through text file formats (Abbaspour, 2015). By default, SWAT compiles and stores input and output files in text file format in one folder called "TxtInOut". During calibration procedures, this folder is linked to the calibration algorithm/program (Figure 2.9). SWAT-CUP incorporates eleven objective functions for evaluating model performance and can perform both one-at-a-time and global sensitivity analysis.

The principle underlying SWAT CUP is that there is an intimate relationship between calibration and uncertainty (Abbaspour, 2015). This means the parameter ranges used during calibration constitute some level of uncertainty which must be reported in the calibration results. The parameter uncertainty leads to uncertainty in the output which is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% and the 97.5% levels of the cumulative distribution obtained through Latin hypercube sampling (Abbaspour et al., 2007). As all uncertainties in the conceptual model and inputs are reflected in the measurements (e.g., discharge), bracketing most of the measured data in the prediction 95PPU ensures that all uncertainties are depicted by the parameter uncertainties (Yang et al., 2008). The strength of calibration is judged based on P-factor and R-factor values besides the objective function. The P-factor represents the percentage of measured data bracketed by 95% prediction uncertainty band. A P-factor of 0.7 and above for streamflow calibration is recommended. The R-factor is the ratio of width of 95PPU band to standard deviation of measured data. Usually, R-factor <1.5 is desirable. Theoretically, the value for the P-factor ranges between 0 and 100%, while that of R-factor ranges between 0 and infinity. A P-factor of 1 and R-factor of 0 is a simulation that exactly corresponds to measured data (Abbaspour et al., 2015).

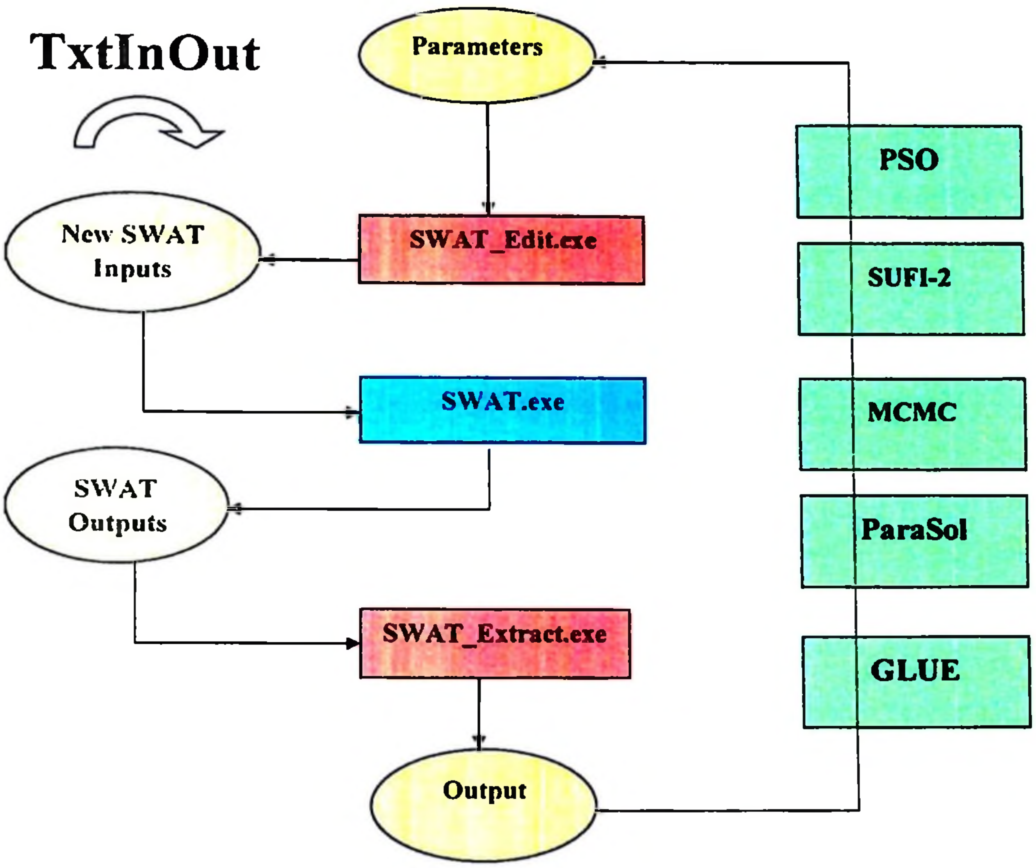


Figure 2.9: A schematic of the linkage between SWAT and five optimization algorithms (adapted from Abbaspour, 2015).

Among the five algorithms in SWAT-CUP, SUFI-2 is preferred to others owing to its advantage of achieving satisfactory results with few model runs and its accuracy in prediction (Wu et al., 2013; Bilondi et al., 2013; Khoi and Thom, 2015; Abbaspour et al., 2015). Thus, it is the most adapted algorithm for the calibration of streamflow (Malago` et al., 2015). As this study applies SUFI-2 to undertake sensitivity analysis, calibration and uncertainty procedures, more details on it are provided here. SUFI-2 maps the aggregated uncertainties to the parameters and aims to obtain the smallest parameter uncertainty ranges (Abbaspour et al., 2007). Parameter uncertainty is described by a multivariate uniform distribution in a parameter hypercube, while the output uncertainty is quantified by the 95% prediction uncertainty band (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution function of the output variables (Abbaspour et al., 2007; Schuol et al., 2008). Latin hypercube sampling is employed to draw independent parameter sets (Abbaspour et al., 2007). According to Schuol et al. (2008), SUFI-2 starts with large but physically meaningful parameter ranges that bracket most of the measured data within the 95PPU and decreases the parameter uncertainties iteratively. New and narrower parameter uncertainty ranges are calculated following every iteration, where the more sensitive parameters find a larger uncertainty reduction than the less sensitive parameters. Yang et al. (2008) summarize procedure for SUFI-2 algorithm in SWAT-CUP as follows:

Step 1: In the first step, the objective function g (b) and the initial uncertainty ranges [bj, abs_mean, bj, abs_ max] for the parameters are defined. This study applied KGE and NSE objective functions

where bj is the jth parameter; j = 1, . . ., m; and m is the number of parameters to be estimated.

Step 2: The Latin Hypercube sampling is carried out in the hypercube [bmin, bmax] (initially set to [bj, abs_mean, bj, abs_ max]), the corresponding objective functions are assessed, and the sensitivity matrix J and the parameter covariance matrix C are calculated according to:

$$J_{ij} = \frac{\Delta g_i}{\Delta b_j} \quad i = 1 \ldots C_2^n, j = 1, \ldots, m \tag{31}$$

$$C = S_g^2 (J^T J)^{-1} \tag{32}$$

S_g^2 is the variance of the objective function values resulting from the model runs.

Step 3: A 95% predictive interval of a parameter hj is computed as follows:

$$\theta_{j,upper} = \theta_j^* + t_{v,0.025}\sqrt{C_{jj}}\,\theta_{j,lower} = \theta_j^* - t_{v,0.025}\sqrt{C_{jj}}. \tag{33}$$

where θ_j^* is the parameter θ_j for the best estimates and v is the degree of freedom (m-n).

Step 4: The 95PPU is calculated as well as the two indices, i.e the p-factor and r-factor. The r-factor is calculated as shown below:

$$r - factor = \frac{\frac{1}{n}\sum_{t_1=1}^{n}\left(Y_{t_{i,97.5\%}}^{M} - Y_{t_{i,2.5\%}}^{M}\right)}{\sigma_{obs}} \qquad (34)$$

where $Y_{t_{i,97.5\%}}^{M}$ and $Y_{t_{i,2.5\%}}^{M}$ represent the upper and lower boundary of the 95PPU and σ_{obs} stands for the standard deviation of the measured data.

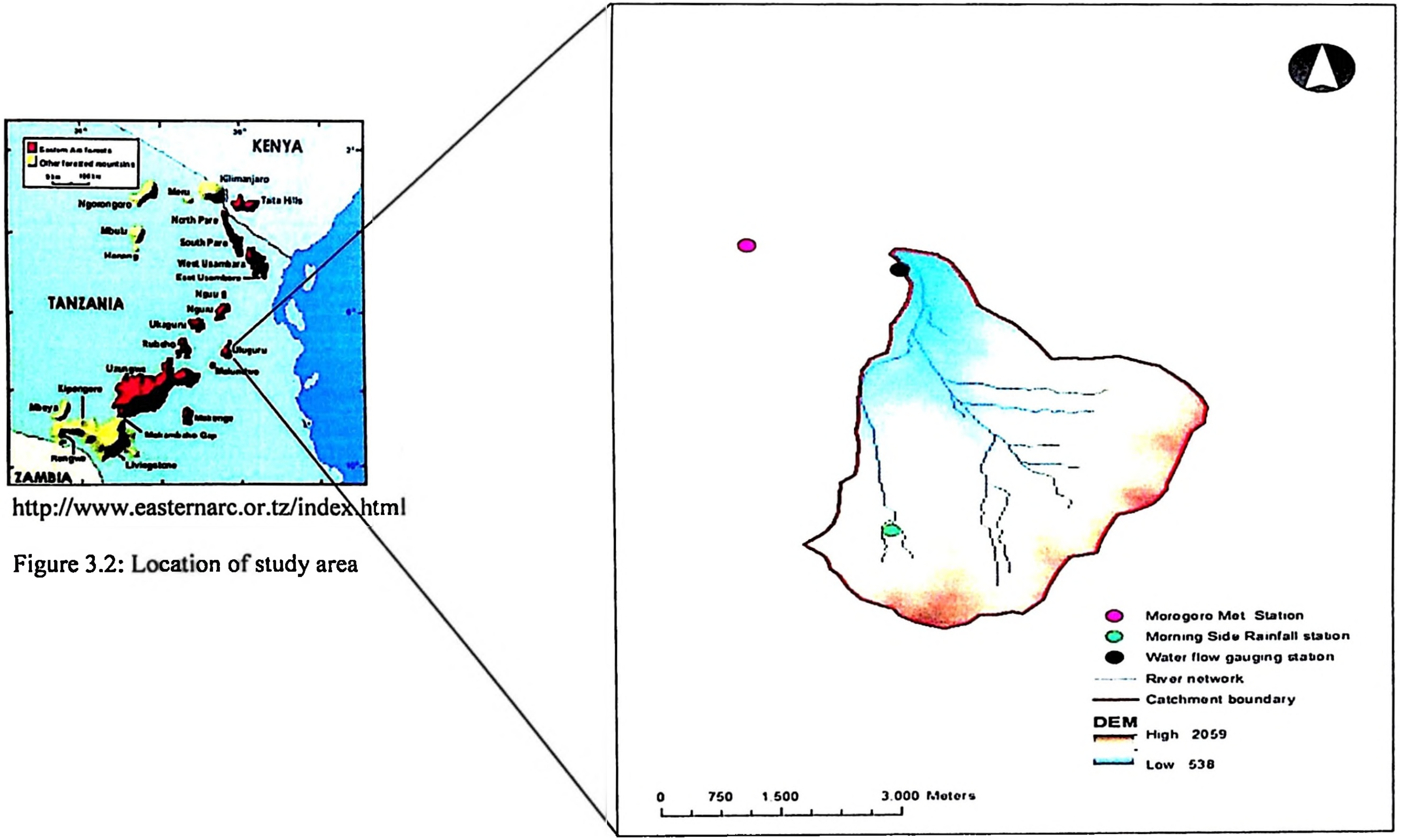
Simulation of sediment yield in SWAT also suffers from uncertainty. Sediment modeling is a challenging and error prone process driven by a suite of factors (Ndomba et al., 2008; Vigiak et al., 2015; Me et al., 2015). Most of water quality monitoring data (sediments and nutrients) used to calibrate water quality models, are collected at regular time intervals such as biweekly or monthly (Me et al., 2015). Thus, there is likelihood that sediment concentrations/loadings during storm flows are not well captured, resulting into wrong representation of actual hydrological conditions in the catchment (Bieroza et al., 2014). Therefore, calibration and validation of the sediment models may experience high uncertainty levels leading to overestimation or underestimation of model performance. For example, Yesuf et al. (2015) applied SWAT in sediment modeling and reported low model performance in both calibration and validation data sets, especially the P and R factor values of SUFI-2. They attributed low model performance to errors in measuring sediment concentrations and conceptual model errors (Abbaspour, 2015). Another reason which renders sediment calibration a daunting task is its dependence on the calibrated runoff parameters which are firstly calibrated (Me et al., 2015). Hence, errors emanating from calibration of runoff parameters are transferred into sediment calibration, making the process more complicated. Furthermore, there are two sediment processes normally accounted for in modeling, the landscape process which involves soil erosion and transport through overland flow and channel process involving transport of the sediments in the stream channel networks under the influence of stream power (transport capacity). Striking a balance between these two processes is prerequisite to sediment calibration and validation (Vigiak et al., 2015)

3.1.2 Land-use

Agriculture and forest are the dominant land-use types in the Morogoro catchment covering areas of about 47.7% and 44.6%, respectively. Human settlement occupies 5.8% of the catchment. The remaining 1.9% is occupied by miombo woodlands, wooded grasslands and patches of grassland. Maize, beans, cocoyams and banana are main crops grown, but maize is the most common. Vegetables such as carrots, cabbages and onions are also grown in the area mainly through irrigation during short rains and the dry season.

3.1.3 Soils

According to Kimaro et al. (1999) cited in Kimaro et al. (2008), the dominant soils in Uluguru Mountains are *Endoskeletic* and *Leptic Cambisols* found on mountain ridges while on the foothills the dominant soils are *Chromic Lixisols* and *Profondic Acrisols*. However, the data extracted from SoilGrids (Hengl et al., 2016) suggest that *Haplic Acrisols* are the main soil group found in the Morogoro catchment. Differences are mainly due to changes in the FAO-WRB classification over time (FAO. 2015). Acrisols occur in old land surfaces characterized by hilly or undulating topography in tropical and sub-tropical climate. These acid and base-poor soils are quite typical for the Eastern Arc Mountains (e.g. the Usambaras: Kirsten et al., 2016).



http://www.easternarc.or.tz/index.html

Figure 3.2: Location of study area

3.2 Methods

3.2.1 Examination factors affecting smallholder farmers' adoption of soil and water conservation measures

To guide the investigation of factors affecting farmers' decisions making towards implementing SWC practices, a household survey was conducted in the study area from April through June 2014. Determination of sample size was preceded by purposeful sampling whereby only hamlets within Morogoro municipality which were involved in the soil conservation related projects were selected, notably Ruvuma, Kisosa, Nyandira, Towelo, Mbete and Choma. A total of 75 farm households were involved in the study. This is about 10% of total households (Kadigi et al., 2011) in the entire catchment. Stratified random sampling method was used whereby the study sample was stratified into three slope zones, namely gentle slope (0 - 27%), moderate (28 - 59%) and steep slope (60 - 100%) zone respectively. A base map with slope classes (Appendix 2) for the study area was generated in ArcGIS using a DEM. The map was further used to locate farmers to be interviewed in the respective slope zones. These slope zones represent locations where farmers do farming activities. The data collected involved basic household information such as age of head of household, gender of head of household, household size and household income. Moreover, data on implementation of SWC methods and constraints for implementation were collected. The questionnaire used to collect such data can be found in Appendix 1.

Data analysis employed both descriptive and inferential statistics whereby SPSS 12 was used. The descriptive part involved cross tabulation, bar charts and frequency tables. Inferential statistical analysis employed the binary choice model, i.e. binary logistic regression. The model applies the maximum likelihood approach to compute model parameters. In the context of this study, the logistic regression model can be expressed as:

$$\mathrm{Ln}\,\frac{\mathrm{P}}{1-\mathrm{P}} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \varepsilon \tag{35}$$

where:

X1 = Slope characteristics of the area

X2 = Age of the head of household

X3 = Gender of the head of household

X4 = Number of adults in the household

X5 = Access to extension services (soil and water conservation education)
X6 = Annual household income
X7= Proximity to the farm
X8= Perception on the effect of soil erosion
β_0 = Constant
ε = Error term

The dependent variable takes the value of 1 for adopting and 0 for not adopting. In this equation, the dependent variable is the natural log of the probability of adopting SWC measures divided by the probability of not adopting. The binary logistic regression model was estimated for two practiced SWC measures namely contour ridges and bench terracing. They were separately entered in SPSS as dependent variables. Therefore, the eight independent variables were fed into two different models.

Consideration of these independent variables resulted from researcher's experience in the study area and literature review (e.g. Wilson, 1996; Wilson and Hart, 2000; Napier and Cockerill, 2015). Therefore, these eight variables included in the model were considered to be relevant. Slope characteristics of the area determine whether a farmer should apply SWC method or not. Farmers in steep slope areas are more likely to apply soil and water conservation as a way to abate soil erosion than those in gentle slope zones. Moreover, the slope characteristics of the farm area will determine which SWC method to use. Age of head of the household was assumed to influence adoption due to fact that young individuals are more energetic than old ones, hence they implement SWC scheme more easily. For example, construction of fanya juu trench or digging up the soil to establish a bench terrace requires a strong labor force with reasonable stamina. The number of adults in the household was assumed to be one of key factors because the adults provide labor in farming activities. A member of household was considered to be adult if his/her age was 15 years old or above. This is because boys or girls of the age of 15 participate fully in household farming activities and their contribution to household labor is considered to as significant as that of senior household members. Households with many adults are assumed to have higher likelihood of adopting soil and water conservation than those with few adults. Access to extension services was also considered to be a key factor with the assumption that farmers who have been trained on how to construct various SWC structures are more likely to adopt than those who have not received any training. Annual household income was hypothesized to influence adoption in the sense that households with a relatively high income can afford to supplement household labor with a hired labor. Moreover, since most of the respondents for this study depend on agriculture for their daily livelihoods, much of annual household income comes from agricultural earnings. Households whose incomes increases as a result of adoption of SWC method are more likely to invest more in it. Proximity to the farm was hypothesized to affect the adoption process. Farm households living nearby the farming area are more likely to adopt SWC than those living far from the farm. Due to rough terrain of the area, some farmers are required to walk through valleys and hike up to reach the farm locations which are arguably far from home. Therefore, by the time a farmer arrives at the farm he/she is already exhausted and cannot work effectively. This may in return discourage a farmer to implement SWC measure.

Table 3.1: Variables and their coding in SPSS

Variable	Type	Coding
Practice of SWC method	Binary	0 = do not practice, 1= practice
Slope characteristics	Categorical	1= Gentle slope zone. 2 = Moderate slope zone 3=steep slope zone
Age	Continuous	None
Gender	Binary	0 = female, 1= male
Number of adults in the household	Continuous	None
Perception on the effect of soil erosion	Binary	0= not sure of the impacts, 1= loss of soil fertility and water pollution
Access to SWC education	Binary	0= Not had access. 1 = Had access
Annual household income (TZS), 1EUR= 2400TZS	Binary	0= Income below 2,000,000 1= Income above 2.000.000
Proximity to the farm	Binary	0= far from home, 1= not far from home[1]

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[1] This was based on farmer's perception on how far is the farm from the household, considering the effort needed

3.2.2 Parameterization of Morogoro catchment for SWAT

This study applied ArcSWAT2012, the most up-to-date ArcSWAT version. The model was set up to suit the Morogoro catchment and was used to simulate the baseline hydrological and sediment processes. The hydrological model was first built then followed by a sediment model. The climate input data was obtained from Tanzania Meteorological Agency (TMA). The rainfall data for the simulation period was obtained from two rainfall stations, one within the watershed (Morning side rainfall station) and the other slightly outside the watershed at Morogoro meteorological station (MOROMET). The data from both stations was nearly 100% complete. The missing data for particular day in Morning side station was filled by an arithmetic mean observed for the day in the surrogate station in vicinity[2]. For Morogoro rainfall station, the missing data was filled using data from global weather data for SWAT (https://globalweather.tamu.edu/). The temperature data (daily minimum and maximum) from MOROMET was used for the study. But this meteorological station is located at foothills at 532 m a.s.l. Thus, for daily air temperature at mountain ridges (elevation 1000 -1500 m a.s.l) where no climate station exists, a hypothetical temperature station was created using the lapse rate calculations based on daily observation at MOROMET whereby; the temperature lapse rate of decrease of 0.56 °C per 100 m (Hemp, 2005) was used. As this study intended to use Hargreaves method to compute potential evapotranspiration (equation 27), data for other climatic variables such as relative humidity, wind speed and solar radiation was not collected. Daily air temperature is the only input data required by Hargreaves method. Like rainfall data, the temperature data was also nearly 100% complete and the same method was used to fill missing data of a given day.

Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) Digital Elevation Model (DEM) with a resolution of 30 m x 30 m was used to perform automatic watershed delineation. This DEM was sourced from https://glovis.usgs.gov/. Under this process, the watershed was divided into 21 sub watersheds, also known as subbasins which were further subdivided into smaller units called hydrological response units (HRUs). Each HRU has a unique combination of land-use, soil and slope characteristics. SWAT computes all simulations at HRU

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[2] This rainfall station is monitored by Wami Ruvu Basin Water Office

scale and prints output at HRU, sub-basin and basin scales. Both land-use and soil distribution thresholds for defining HRUs were set at 0% to avoid lumping of land-uses and soils. A total of 267 HRUs were created for the study catchment. Soil data was obtained from SoilGrids250m (Hengl et al., 2016). This is a system of soil mapping based on global soil profile and environmental covariate data at a spatial resolution of 250 m x 250 m with up to seven soil layers. Relevant soil properties for the study area were extracted from the raster file using R program. These included particle size distributions of sand, silt, clay and rock fragments in percentages (texture); and organic carbon content (%). To properly regionalize soil parameters into SWAT for the study catchment, the soil data was overlaid with land-use data and thus reclassified based on land-use type. To obtain appropriate values for various soil parameters (e.g. organic carbon for agriculture land-use, forest land-use) field measured data was used and complimented by data from Kimaro (2003). Such soil field data comprised of 72 samples obtained from forest, wooded grassland and agriculture land-use types in the study area. For each land-use type, three replication sites were selected and the soil sample was taken at each site at three different depths, i.e. 0-5 cm, 5-15 cm and 15-30 cm (see Appendix 4 for some results). Parameters which could not be measured such as soil available water capacity (SOL_AWC), saturated hydraulic conductivity (SOL_K) and soil erodibility factor (USLE_K) were determined through PTFs developed by Saxton and Rawls (2006). The Land-use map of 2005 obtained from Hieronimo (2007) was used for model setup and was considered a baseline during scenario analysis.

Maize is the main crop in Morogoro catchment. Two types of maize are grown, short rain maize and long rain maize. The former is grown in mountain ridges while the latter is grown in foot hills (Kimaro et al., 2008). Management operations included 1st October, planting (plant begin, beginning of the grown season) and 28th February, harvest and kill operation for short rain maize. Operations for long maize were 1st January, planting and 5th June, harvest and kill operation. The SCS Runoff Curve Number method for estimating surface runoff from precipitation was applied while the Hargreaves method for estimating potential evapotranspiration was chosen. For channel water routing, the variable-storage method was used. The model was run for the period 2004 - 2014 with a 3-year warm up period. Thus, the model produced output for 8 years at daily time step. The warm up period is important for allowing the model to learn the catchment processes and stabilize before initiating the simulations. Absence or very short warm up period may lead to model errors.

Sensitivity analysis, calibration, validation and uncertainty analysis

SUFI-2 algorithm in SWAT-CUP was used to perform sensitivity analysis, calibration, validation and uncertainty analysis. Stream flow parameters to be included in calibration were drawn from SWAT literature. Special attention was paid to parameters that have direct influence on water balance. However, they were subjected to One-At-a-time sensitivity analysis before inclusion in calibration. A total of 13 parameters were selected which included SCS runoff curve number (CN), base flow alpha factor (ALPHA_BF), ground water delay (GW_DELAY), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), revap coefficient (GW_REVAP), deep aquifer percolation fraction (RCHRG_DP), available water capacity of the soil layer (SOL_AWC), Manning's "n" value for overland flow(OV_N), saturated hydrological conductivity of the soil layer (SOL_K), soil evaporation compensation factor (ESCO), Manning's "n" value for the main channel (CH_N2), effective hydraulic conductivity in the main channel alluvium (CH_K2) and surface runoff lag time (SURLAG).

Both manual and automatic calibration approaches were employed during the calibration process as recommended by Arnold et al. (2012). CN was manually calibrated by setting reasonable CN values for each land-use type in the management file. Thus, the CN was not included in automatic calibration by SWAT-CUP (Table 3.2). The parameter ranges for each parameter were manually adjusted based on researcher's knowledge of the watershed and literature. Once the parameter ranges were assigned and the calibration method for each parameter was chosen, the automatic calibration was performed following the calibration procedure recommended by Abbaspour et al. (2015). Measured daily and monthly river discharge data was used to calibrate the model. Calibration was done for 2007 - 2010 period as this was the time when the stream flow gauging station was repaired and monitoring was good due to availability of funds. The period 2011 - 2014 was chosen for validation though the data quality was not good especially the last 2 years. During this period, there was no more funding to support the monitoring program and hence the collected data was of low quality. The daily water level data used to compute stream flow were not properly recorded. The SUFI-2 program performs dual functions, parameter optimization and uncertainty analysis (Schuol and Abbaspour. 2006). Thus, for each calibration solution generated, uncertainty was accounted for. The P factor and R factor indices served this purpose. The criteria used to judge the strength of calibration and validation were the goodness-of-fit between measured and simulated stream flow, the P-factor and the R-factor. For goodness-of-fit analysis. KGE and NSE objective functions were used.

Table 3.2: SWAT water flow calibrated parameters

Parameter	Description	Range	Fitted value
ALPHA_BF.gw	Base flow alphafactor (days)	0 - 1	0.97
GW_DEAY.gw	Ground water delay (days)	0 - 31	2.31
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	100 - 2000	834.35
GW_REVAP.gw	Revap coefficent	0.02 - 0.2	0.19
RCHRG_DP.gw	Deep aquifer percolation fraction	0 - 0.1	0.06
SOL_AWC.sol*	Available water capacity of the soil layer	-0.2 - 0.2	0.15
SOL_K.sol*	Saturated hydrological conductivity of the soil layer	-0.1 - 0.1	0.06
ESCO.Hru	Soil evaporation compensation factor	0 -1	0.88
OV_N.hru	Manning's "n" value for overland flow	0 - 1	0.15
CH_K2.rte	Manning's "n" value for the main channel	0 - 500	399.25
CH_N2.rte	Effective hydraulic conductivity in the main channel alluvium	0 - 0.3	0.22
SURLAG.bsn	Surface runoff lag time (days)	0 - 1	0.69

* Percent of the parameter for a layer of each soil

Building the sediment model

Owing to lack of reliable and adequate measured data for sediment model calibration and validation, the sediment model applied to Morogoro watershed was simplified by focusing only on the landscape component of sediment simulation. This was implemented by turning off the channel processes (deposition and degradation). Sediment deposition in the channel was suppressed by setting the linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing (SPCON) and exponent parameter for calculating sediment reentrained in channel sediment routing(SPEXP) parameters to maximum values so that the stream power increases and thus no sediment is deposited in the channel. Channel erosion was eliminated by setting the channel erodibility factor and channel cover factor to zero. A support practice factor (USLE_P) of 0.95 was used during simulation of baseline sediment process. A value of 1 indicates non-existence of SWC measures. The value of 0.95 was used after consideration of the fact that some farmers practice SWC in the catchment though very negligible. thus a value of 0.05 was subtracted from the default value of 1. Other parameters were left as per SWAT default. By suppressing channel processes implied that the sediments coming out of the outlet represented the sediment loading generated from the landscape (HRUs).

3.2.3 Simulating the impact of selected SWC measures on water flow and sediment yield

The constructed water flow and sediment models for the studied catchment were applied to simulate the impact of implementing SWC practices. The agricultural land-use was involved in simulation of SWC scenarios which included contouring. fanya juu terraces and bench terraces. Other land-use types remained unchanged. Each scenario was simulated throughout the simulation period. Implementation of the suggested SWC measures affect hydrological and soil erosion processes. Practicing contour farming results in reduction of surface runoff by impounding water in small depressions and reduction of sheet and rill erosion by reducing erosive power of surface runoff. Terracing if properly implemented and well maintained reduces surface runoff volume by impounding water into small depressions, reduces peak flow rate by reducing slope lengths (Arabi et al., 2008). Fanya juu terraces gradually convert to bench terraces over time.

Table 3.3: SWC scenarios implemented in the agricultural area using SWAT

Code	SWC scenario	Slope range (%)	Mean slope (%)	Area (km^2)	% Area
Base	Business as usual	All	All	9	100
S1	Contour farming	0-20	12	1	10
S2	Fanya juu terraces	20-40	30	3	34
S3	Bench terraces	>40	58	5	56
S4	Fanya juu +Bench terraces	>20	30	8	90
S5	Combination of S1, S2 and S3	All	All	9	100

Contour farming, coded as S1 in this study was implemented in all HRUs whose slope range was 0 - 20% with a mean slope of 12% covering an area of 1 km^2; equivalent to 10% of the total agricultural area (Table 3.3). It was implemented in SWAT by adjusting the CN and USLE_P parameters. CN was reduced by 5 from the calibrated value of 70 and USLE_P was changed from the value of 0.95 to 0.6 based on Appendix 3. The CN adjustment was based on the values for CN for different practices given in Neitsch et al. (2011). Fanya juu terracing (S2) was assigned to HRUs within the slope range 20 - 40%, with a mean slope of 30% covering an area of 3 km^2 which accounts for 34% of the total agricultural area. It was simulated in SWAT by adjusting the CN and USLE_P and SLSUBBN (average slope length) simultaneously. CN was reduced by 7 from the calibrated value of 70 and USLE_P was reduced from the baseline value of 0.95 to 0.2 using the USLE_P values for contoured and terraced farmlands provided by Haan et al. (1994) as shown in Appendix 3. The slope length for Fanya juu terraces was obtained through reduction of SWAT default average slope length (SLSUBBSN) by 20% whereby the slope was reduced from the default value of 9.1 m to 7.3 m. The same procedure was done for bench terracing (S3) which was applied to HRUs with a slope >40%, but the CN was reduced by 9 and USLE_P reduced to 0.25. The reduction of CN for bench terracing was 2 units higher than fanya juu terracing because, the former is more effective than the latter; thus, this was done to demonstrate the difference between the two. Fanya juu terraces are limited to areas with slope up to 48.7% (Hurni. 1986) while Bench terraces can be applied to areas with slope up to 55% (Widomski. 2011).

Chapter 4: Results and Discussion

This chapter contains the main findings of the thesis. It comprises of three main sections which are systematically arranged in accordance with the study objectives and research questions.

4.1 Factors affecting smallholder farmers' adoption of SWC measures

This section unveils the biophysical and socio-economic factors influencing smallholder farmers' decisions to adopt SWC measures in the study area whereby, 75 farm households were involved. The section is divided into two parts, the first part presents the descriptive results with their discussions while the second part reports and discusses the inferential results, mainly from binary logistic regression analysis.

4.1.1 Description of the study sample

Age distribution of the respondents indicates that many of them, 33 % (*n* = 25) were in the age group 47 - 55 followed by those >55, 28% (*n* = 21) (Figure 4.1.1,). Other age groups had relatively less number of respondents. Male headed households are dominant accounting for 92% of the total surveyed households (Table 4.1.1). The number of adults in the household ranged between 2 and 6 while in most of households (40%, *n* = 30), the number of adults were found to be 4 (Figure 4.1.2)

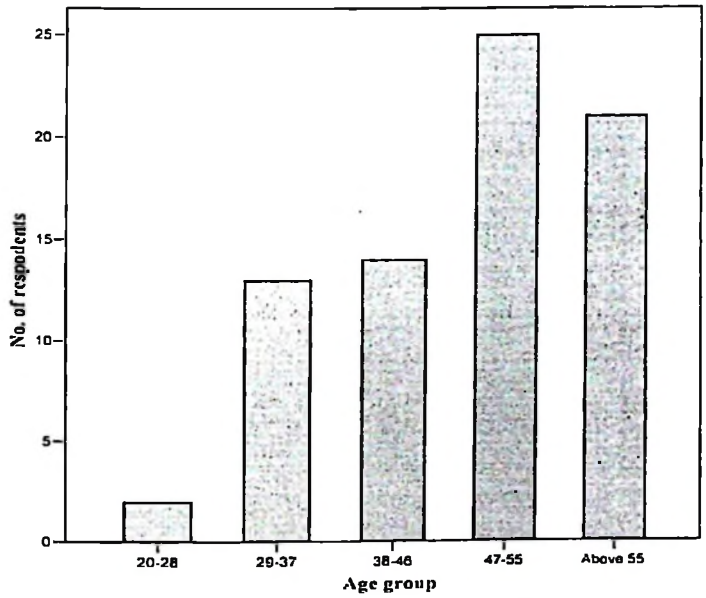


Figure 4.1.1: Age distribution of the study sample.

Only 21 farmers (28%) farmers from the study sample were found to have had the opportunity to attend training sessions (extension services) on how to implement various SWC practices, the rest did not have access to training (Table 4.1.1). But it is assumed that the knowledge and skills gained by the 21 will be diffused to other farmers in the village (Rodgers ,1983; Feder and Umali 1993). 62.7% (*n* = 47) of respondents reported that their farms are not far from home while the rest, 37.3% (*n* = 28) indicated that their farming sites are relatively farm from home (Table 4.1.1).

Table 4.1.1: Summary of responses on some of the investigated variables

Variable	**Responses**	*n*	%
Gender	Males headed households	69	92
	Female headed households	6	8
Access to extension services	Did not have access	54	72
	Had access	21	28
Perception on the impact of soil erosion	Not sure about the impacts	9	12
	Loss of soil fertility and water pollution	66	88
Annual household income	Below TZS. 2.000.000*	59	78.7
	Income above TZS. 2,000,000	16	21.3
Proximity to the farm	Far from home	28	37.3
	Not far from home	47	62.7

*1TZS = 0.000397020 EUR

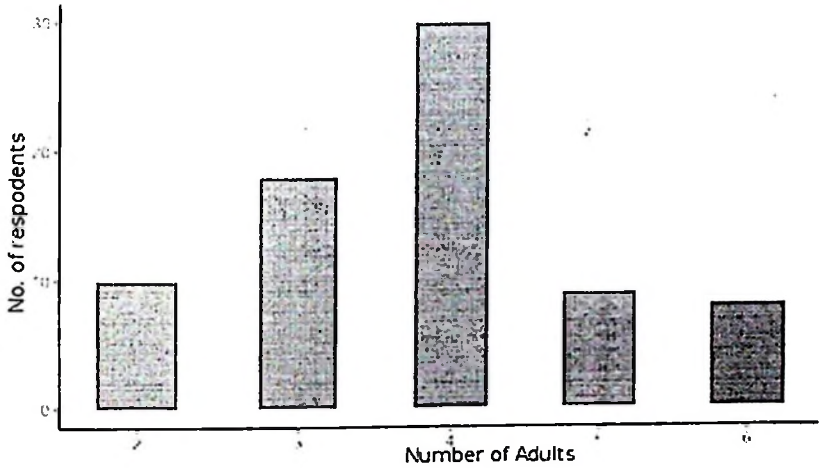


Figure 4.1.2: Number of adults in the household

Table 4.1.2 shows the cross tabulation of SWC adoption and slope characteristics. Out of 75 respondents involved in the study only 21 (28%) were found to practice SWC methods, the rest 54 (72%) did not practice. They are engaged in non-SWC methods characterized by flat cultivation. No any initiative is done to contain the soil erosion problem. It can also be seen that contour ridges and bench terraces have better number of adopters than fanya juu. This could be attributed to the fact that contour farming and bench terracing practices were introduced in the area many years ago, hence farmers are more familiar with such practices than fanya juu terracing which still appear to be new in the area. While contour ridges were found to be practiced in all three slope zones, bench terracing was observed to be common in steep slope zone. Fanya juu was found to be restricted to moderate slope zone. Figure 4.1.3 summarizes the response of farmers as to why they don't practice SWC measures in their daily farming activities (These are 54 farmers who practice none of the SWC methods as indicated in Table 4.1.2). While 38.9% (n = 21) cite the long time taken to construct the SWC structures, other 38.9% (n =21) consider high labor cost as the main barrier. 18.5% (n = 10) argue that some space in the farm will be lost thus growing few crops. This is because crops are grown on contour ridges only for contour ridge method, on the bench level for bench terrace method and on the embankment for fanya juu. Overall, terracing reduces the cropped area, but due to reduced erosion and increased infiltration the planted crops usually provide a relatively high yield. Because water availability to the plants is increased and much of the nutrients are retained in the soil. Understanding of the effect of soil erosion was found to be sufficiently high, 88% of the responses affirmed that farm households know the adverse impact of soil erosion (Table 4.1.1). But surprisingly, the adoption of SWC measures is very low. As seen in chapter 2, the adoption of SWC methods is a complex process. Farmers' knowledge of benefits associated with the application of SWC such as improvement of soil fertility, does not necessarily lead to adoption.

Table 4.1.2: Cross tabulation of SWC adoption and slope characteristics (numbers represent the number of respondents)

	Slope characteristics			
SWC methods	**Gentle slope**	**Moderate slope**	**Steep slope**	**Total**
Contour ridges	2	6	2	10
Bench terraces	0	0	9	9
Fanya juu	0	2	0	2
No SWC methods	19	15	20	54
Total	21	23	31	75

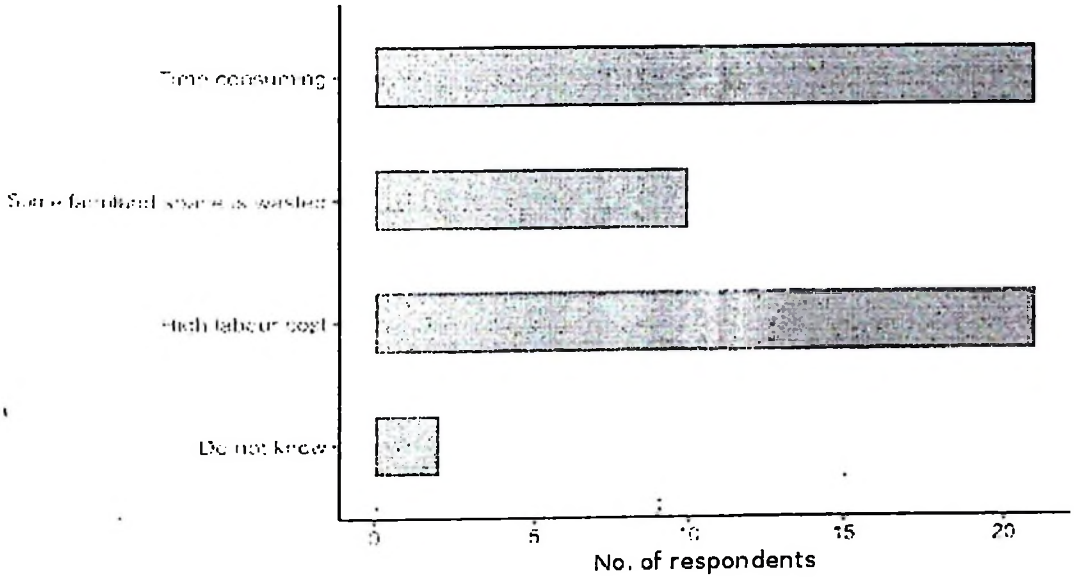


Figure 4.1.3: Farmers' reasons for not practicing SWC methods.

4.1.2 Binary logistic regression of the studied variables

Table 4.1.3 summarizes the results from the application of the binary logistic regression model for two SWC methods in the Morogoro catchment. Fanya juu was not included in the regression model due to its very small number of cases. Traditionally, logistic regression model has five model parameters which are used to assess the relationship between dependent variable and independent variable. These are independent variable coefficient (β), standard error (S.E), Wald value, significance level (p-value) and odds ratio [(Exp (β)]. The choice of a parameter to be used to interpret model results differs across disciplines (Landau and Everett, 2004). But it also depends on the researcher preference. In this study, the level of significance and odds ratio were used to interpret the model results.

Table 4.1.3: Parameter estimates of logistic models of factors affecting farmers' adoption of SWC measures in the study catchment.

	Contour ridges		Bench terraces	
Explanatory variables	**p-value**	**E(β)**	**p-value**	**E(β)**
Slope characteristics (1)**	0.99	0.00	0.998	0.000
Slope characteristics (2)	0.99	0.00	0.998	0.000
Age	0.02*	0.788	0.002*	0.788
Gender	0.999	3.1E+08	0.803	0.750
Number of adults in household	0.068	0.538	0.068	0.538
Access to extension services	0.016*	5.2	0.001*	11.455
Perception on the effect of soil erosion	0.999	3.2+08	0.999	2.9E+08
Annual HH income	0.058	4.000	0.037*	4.750
Distance from home to the farm	0.116	2.842	0.015*	0.164
Sample size (N)	75	75	75	75

Level of significance, p = 0.05   * = Statistically significant, p<0.05

** = For categorical variables, the last category is set as a reference for computation of model parameters. The numbers in brackets indicates the categories of the independent variable as coded in SPSS (see Table 3.1)

Slope characteristics and number of adults in household are the only variables which, though very important, had no significant correlation with the adoption of SWC measures. The fact that slope characteristics of the farm and number of adults in the household showed no meaningful relationship with adoption suggest that there are other inherent covariates which could not be captured in this study. Several literatures (e.g. Tiwari et al., 2008; Meseret, 2014; Ngwira et al., 2014) report that biophysical farm characteristics are one of the determinants of farmer's decision to adopt soil and water conservation methods. However, the findings of this study report the contrary. Out of 31 respondents whose farms are located in steep slope zone, it is only 11 who practice SWC methods. A comparable study by Tiwari et al. (2008) in Nepal also found no significant influence of slope characteristics on SWC adoption. Another fact reported in literature is the number of adults in a household which are considered to positively influence adoption because they are assumed to provide labor for implementation of SWC practices. This study also reports results which are contrary to this generally accepted hypothesis. This finding agrees with that of Kalineza et al. (1999) and Tiwari et al. (2008) who also found no significant relationship between number of adults in household and adoption.

Age of the farmer had a significant negative influence on adoption of both contour ridges and bench terraces (p= 0.02 and 0.002, respectively). The odds ratio is 0.788 meaning that a unit increase in age reduces the odds of adoption by 0.212. Age has a negative coefficient in the regression model, this explains why it has an odds ratio <1. It reduces the *logits (log-odds)* of adoption. As the farmer's age increases, the ability to adopt farming methods which require extensive use of energy such as bench terraces reduces. This suggests that any future interventions should include a sizeable number of young farmers. Gender of the head of household and perception on the effect of soil erosion had no considerable influence on adoption. Access to extension services significantly and positively influence adoption of contour ridges and bench terraces, p= 0.016 and p= 0.001 respectively while the odds ratio was 5.2 and 11.455, respectively. Extension services are the main source of information on farming technologies or methods through which farmers learn how to implement the technology. Therefore, if farmers have access to extension services, they become familiar with the technology and can finally implement in their farms. Farmers with access to soil and water conservation education are more likely to adopt SWC methods than those who have no access. This result resembles with findings in other studies (e.g. Jaminson and Moock 1984; Senkondo et al., 1998; Mignouna et al., 2011) who also found a significant relationship between farmers' access to extension services and adoption. This finding also supports the Innovation Diffusion model by Rodgers (1983) which suggests that information about technology is the key factor in determining adoption.

Annual household income had a noteworthy influence on bench terraces adoption (p = 0.037, odds ratio = 4.750) while the influence on contour ridges was insignificant. This could be attributed to the fact that bench terrace construction is labor intensive and takes longer time than contour ridges. Households with a relatively high income can afford to hire labor for bench terrace installation in the farm. This is supported by findings of Sulo et al. (2012) who investigated socio-economic factors affecting the adoption of agricultural technologies among women in Kenya. They found that income level had significant relationship with adoption. Proximity to the farm had no significant influence on contour ridges but it had a significant but negative influence on bench terraces (p = 0.015, odds ratio = 0.164). A unit increase in distance from home to the farm reduces the odds of adopting bench terraces by 0.836. This implies that, the longer a farmer has to walk to reach the farm, the less will be chances for bench terrace implementation. Since preparation of this SWC method is strenuous, if a farmer spends much time and energy walking to the farm location it unlikely that he/she will adopt the method. Therefore, proximity to the farm location could determine whether a farmer adopts SWC method or not. Similar observation was made by Hailu et al. (2014) who studied the adoption of agricultural technologies in Ethiopia. They found that distance to the farm plot significantly influenced farmers' decision to adopt the farming technology.

4.2. Parameterization of the Morogoro catchment for SWAT

4.2.1 Building the water flow model

This section reports results and discussion on calibration, validation and uncertainty analysis of for building the hydrological model for Morogoro catchment using SWAT. Table 4.2.1 presents daily and monthly calibration results. Daily calibration results indicate that the model could simulate stream flow close to reality as demonstrated by the KGE and NSE model performance statistics as well as the hydrograph (Figure 4.2.1). The model achieved a KGE value of 0.71 and NSE of 0.50 which are satisfactory (Gupta et al., 2009; Moriasi et al., 2007; Arnold et al., 2012). The calibrated P-factor and R-factor of SUFI-2 for daily calibration was

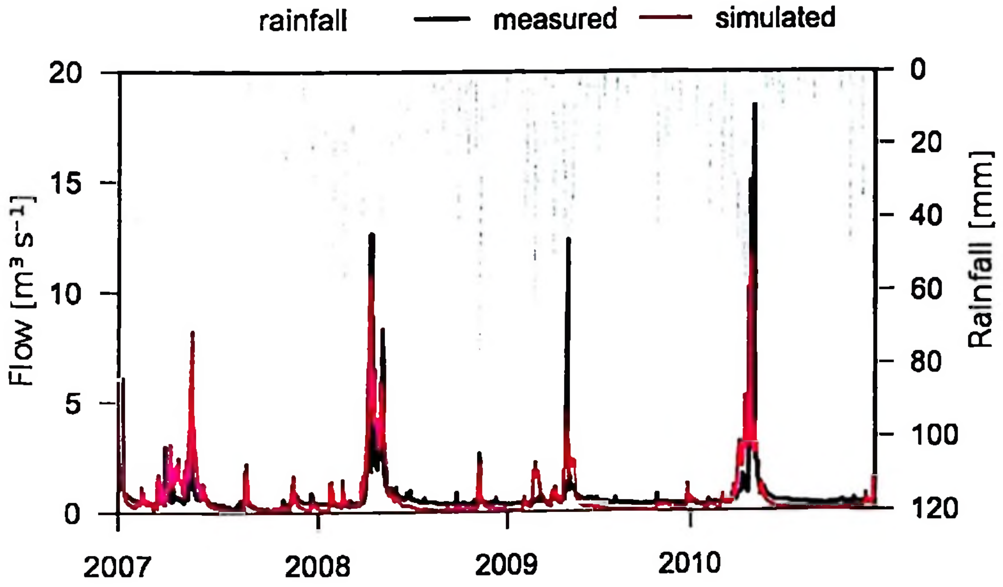
0.83 and 0.91 respectively. This implies that based on the parameter ranges chosen for calibration, the model could bracket 83% of the measured data by 95PPU. As the ideal case is to have 100% of the measured data bracketed, this result indicates that the model was capable of accounting for most of uncertainty sources during calibration.

Table 4.2.1: Calibration and validation results for daily and monthly water discharge

	Calibration		Validation	
	Daily	Monthly	Daily	Monthly
KGE	0.71	0.87	0.35	0.64
NSE	0.5	0.82	0.26	0.5
P-factor	0.83	0.88	0.44	0.42
R-factor	0.91	1.14	0.46	0.66

All uncertainties in the conceptual model and inputs are normally reflected in measurements (Yang et al., 2008). Thus, bracketing most of measured data enables the model to capture all the uncertainties. The R-factor of 0.91 suggests that the ratio of width of the 95PPU band to standard deviation of measured data is within the acceptable threshold of <1.5. The R factor accounts for measurement errors, conceptual model uncertainty and parameter non-uniqueness problem (Schuol and Abbaspour, 2006). The model had a PBIAS value of -4.1% which is within the ± 25% range recommended by Moriasi et al. (2007) for satisfactory calibration. The slight overestimation bias of -4.1% can be attributed to higher simulated peak flows (e.g. in the year 2007) and uncertainty of measured data. Furthermore, the daily hydrograph indicates that the model underestimated baseflow. This may be attributed to uncertainty in measured data, parameter uncertainty and uncertainty of the input data, particularly soil input data such as SOL_AWC and SOL_K which influence soil water movement between the unsaturated and the saturated zones. Although such parameters were calibrated using the relative change method, the original values for each soil layer were obtained using PTFs for temperate soils whose hydraulic properties are different from tropical ones (Hodnett and Tomasella, 2002; Tomasella et al., 2000). Parameter uncertainty could be attributed to the chosen parameter ranges which were fed into SUFI-2 for parameter optimization. The parameter ranges, number of simulations and number of iterations have effect on calibration results. This study ran 1000 simulations per iteration as recommended by Abbaspour et al. (2015). After 1000 simulations the calibrated results were found reasonable based on objective function, P-factor and R-factor criteria. Thus, no more iterations were done because no significant improvement in the objective function was expected. Furthermore, in each iteration parameter sensitivity changes and the P-factor tends to decrease from one iteration to another (Abbaspour, 2015). As this study sought to optimize both the objective functions and uncertainty indices, the results obtained after one iteration with 1000 simulations were found to be the best. But it is important to recognize that the obtained calibration results with their associated uncertainties emanated from the parameter ranges chosen. If the parameter ranges are changed, different calibration results would be expected.

Monthly calibration improved the model performance whereby KGE and NSE was 0.87 and 0.82 respectively. This is also confirmed by the monthly hydrograph (Figure 4.2.2) in which the simulated monthly discharge mimics well the measured monthly discharge. Improved performance at monthly time step calibration is attributed to the fact that errors of daily calibration are neutralized at monthly time scale (Sudheer et al., 2007).



.Figure 4.2.1: Daily simulated and observed hydrographs of the Morogoro catchment for the calibration period (2007 – 2010)

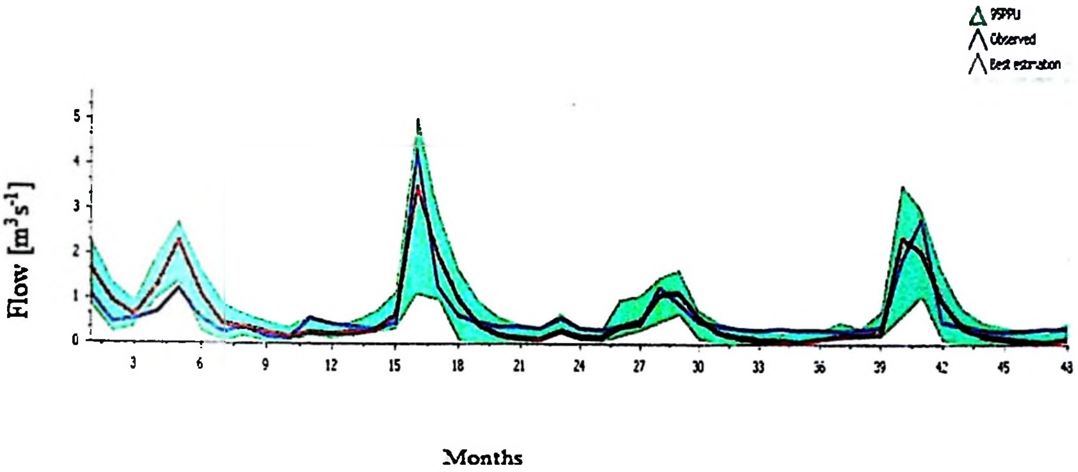


Figure 4.2.2: Monthly hydrograph of the Morogoro catchment for the calibration period (2007 - 2010)

Model validation results indicate that the model performance dropped significantly, especially the daily simulation. The KGE, NSE, P-factor and R-factor dropped to 0.35, 0.26, 0.44 and 0.46 respectively. Only 44% of the measured data in the validation period could be bracketed in the 95PPU band. The KGE and NSE values are within the acceptable range but indicate a weak goodness -of-fit between simulated and measured data (Figure 4.2.3). Many factors may be attributed to such results, but inadequate quality of discharge data greatly contributed to weak model performance. Water level recording is done manually by a local gauge reader who may sometime be absent. Moreover, this method does not capture all water level data resulting from each rainfall event. Thus, computation of stream flow will always contain some errors.

The monthly validation results (Figure 4.2.4) also indicate a drop in objective function and uncertainty statistics, but the model performance is still satisfactory, KGE = 0.64, NSE = 0.50. On the other hand, the P-factor = 0.42 and R-factor = 0.66. The model bracketed only 42% of the measured by 95PPU. The validated model also had an overestimation PBIAS of -17.3% which is within the acceptable range. Generally, these validation results are not an extreme case in hydrological modeling practice, it is a common phenomenon. While in calibration the parameter values are modified until the predictions best fit with the observed data, validation parameters are dependent on calibrated parameter ranges; as a result, the validation performance metrics were a bit weaker than calibration performance values (Yesuf et al., 2015). Nevertheless, the model could represent the hydrological processes in the studied Morogoro catchment to a satisfactory level.

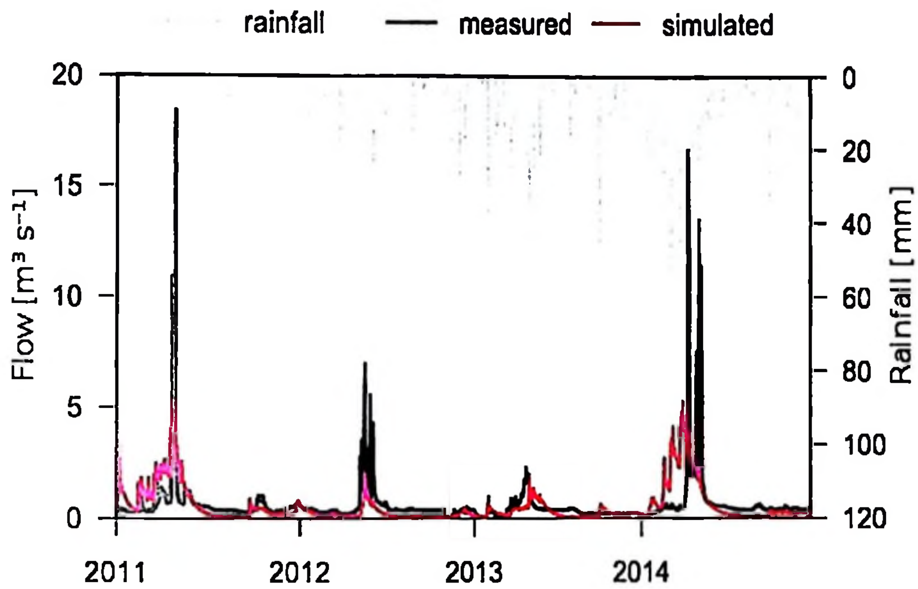


Figure 4.2.3: Daily hydrograph of the Morogoro catchment for the validation period (2011-2014)

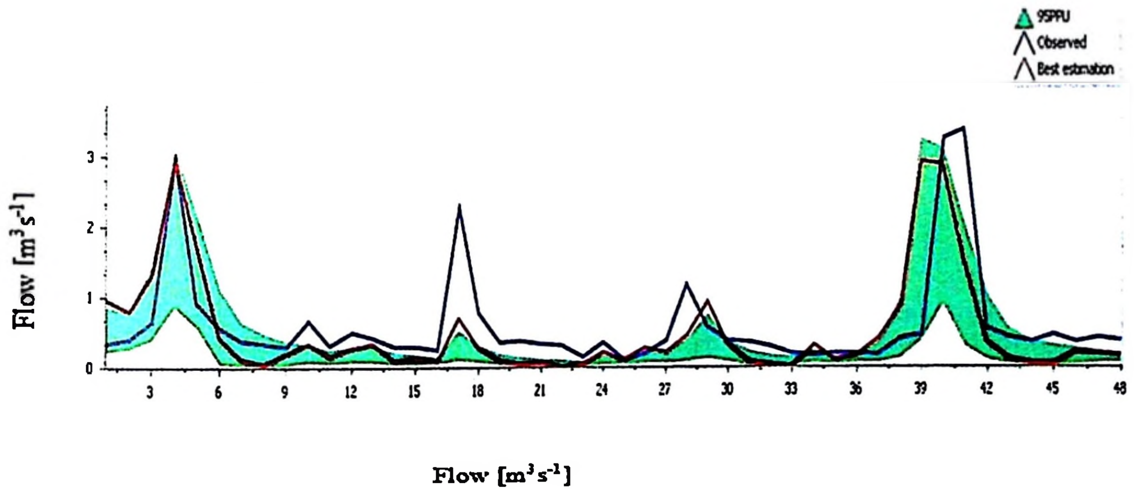


Figure 4.2.4: Monthly hydrograph of Morogoro catchment for the validation period (2011-2014)

Generally, the quality of measured flow data used in this study was relatively good for model calibration period but was poor in the validation period. Measured water flow data greatly influence the performance of calibrated model and its associated uncertainties (Abbaspour, 2015). The calibration procedure aims to generate optimal parameter ranges and values that forces the model to mimic the observed data. Therefore, if the observed data have uncertainties, will also be reflected in the optimal parameter values. According to Schoul and Abbaspour (2006), there are three types of uncertainty in hydrological modelling, these are input uncertainty (e.g. rainfall, soil), parameter uncertainty and conceptual model uncertainty. While this study noted input and parameter uncertainties, the conceptual model uncertainty was not identified because the model adequately represented the processes of interest. Generally, in SUFI-2 the combined effect of all uncertainties is reflected in the final estimates of parameter uncertainties (Schoul and Abbaspour, 2006). Therefore, besides input uncertainty, parameter uncertainty is another key factor affecting model performance. While sensitivity analysis results may neglect some important parameters based on statistical analyses, the calibration of the so called "sensitive parameters" is associated with uncertainty. Unfortunately, some of hydrological modelling studies ignore parameter uncertainty analysis while reporting the modelling results (Benkea et al., 2008). This study has acknowledged the effect of parameter uncertainty on model predictions. The choice of parameter ranges to be used in the automatic calibration will affect the final parameter value which will subsequently affect the model output.

4.2.2 Building the sediment model

Construction of the sediment model faced a challenge, there was no reliable and adequate observed data to perform calibration of sediment parameters. Water quality monitoring in Tanzania is rarely done owing to high cost involved and inadequacy of water quality monitoring equipment. To address this challenge and considering the modelling objective, the sediment model was simplified by assuming that landscape sediment yield was a dominant process in Morogoro as described in section 3.2.2. Thus, the built sediment model assumes that the amount of sediment transported does not exceed the transport capacity of the main channel and the amount of sediment transported is not below the channel's transport capacity. However, such assumptions may cause the built model to overestimate sediment yield at watershed scale. Because under natural conditions, sediment deposition and channel degradation are common channel sediment processes. The SWAT model by default accounts for these processes through the simplified Bagnold stream power equation. But adjusting the stream power parameters without the observed sediment data for calibrating and validating the model is likely to compound the simulation uncertainty. Therefore, in data scarce areas like the studied catchment, the built model can assist to simulate baseline sediment yield which can be applied to model the impact of land management scenarios. But absolute values should not be used during impact analysis owing to lack of observed data to calibrate the model. Instead, the relative change (%) approach should be used to analyze the impacts.

Sediment yield in SWAT is estimated using the peak runoff rate calculated through modified rational method. As shown in the modified rational formula (equation 24), peak runoff rate is a function of rainfall proportion, surface run off volume, sub basin area and time of concentration. Hence, the model must be able to simulate sediment yield according to magnitude of rainfall/ runoff storms. Based on monthly basin values (Figure 4.2.5) the model reasonably predicted sediment yield during big rainfall storms occurring between February and May. Generally, the model demonstrated a correlation between surface runoff and sediment yield as expected.

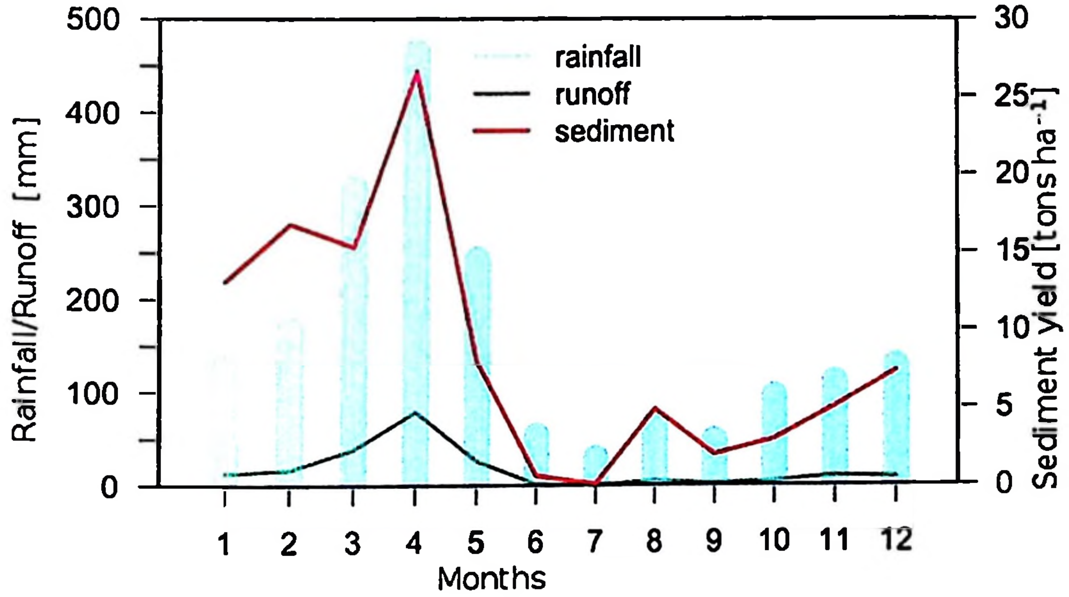
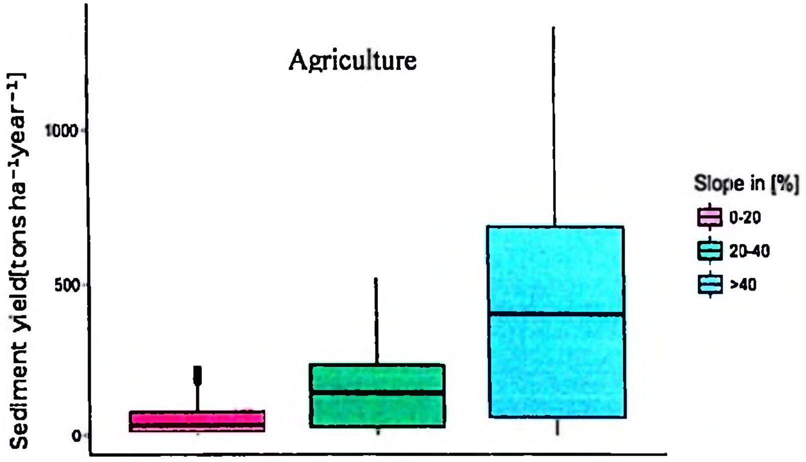
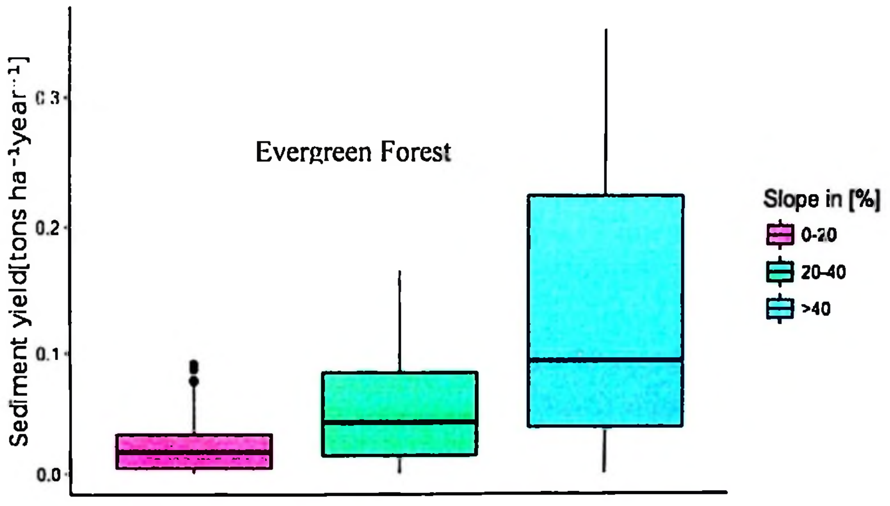


Figure 4.2.5: Catchment mean monthly rainfall, mean monthly surface runoff and mean monthly sediment yield (8 years monthly average for 2007-2014 period)

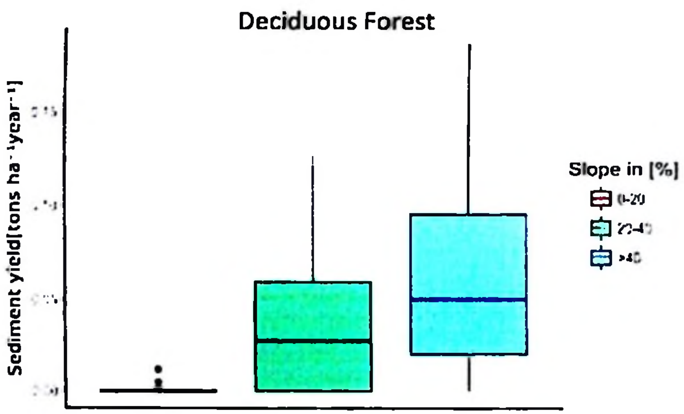
The model could quantitatively and spatially represent the erosion hotspot areas contributing greatly to sediment export as expected (Figure 4.2.7). HRU analysis indicate that the agriculture land-use is the most contributing area accounting for over 95 % of all landscape sediment load (Figure 4.2.6). In particular, most of the sediments come from HRUs with slope 20 - 40% and >40% covering 34% and 56 % of agriculture area, respectively. Nearly, all sub-basins contribute to sediment export. As the catchment topography is predominantly steep, the topographic factor, SL_{USLE} in the MUSLE (equation 30) is high, leading to high sediment yield. Therefore, the SWC scenarios simulated in SWAT aimed at the curbing this problem. The results at both HRU and catchment scale are reported with a view of representing the spatial scale variations of impacts for each scenario.


Agriculture
Sediment yield[tons ha⁻¹year⁻¹]
1000
500
0
Slope in [%]
0-20
20-40
>40

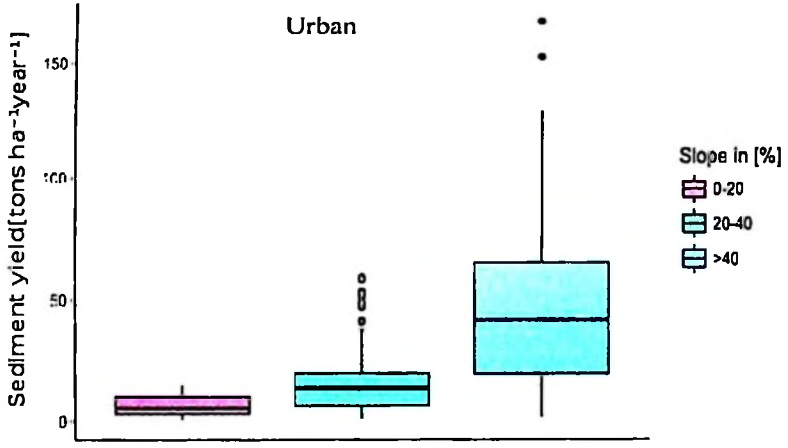
(a)


Evergreen Forest
Sediment yield[tons ha⁻¹year⁻¹]
0.3
0.2
0.1
0.0
Slope in [%]
0-20
20-40
>40

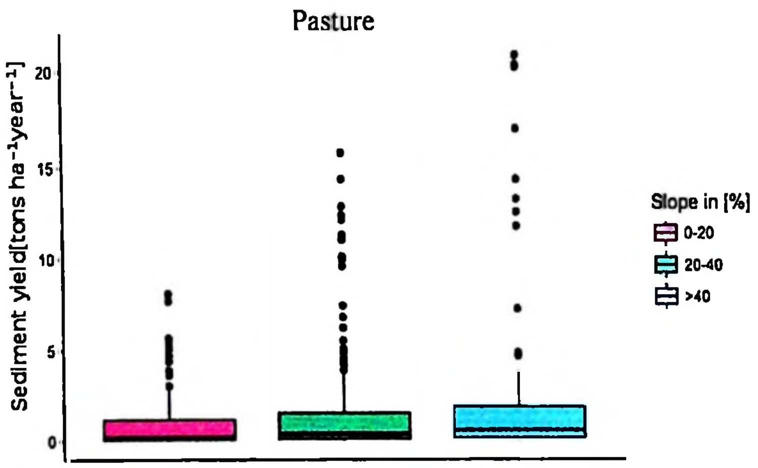
(b)


Deciduous Forest
Sediment yield[tons ha⁻¹year⁻¹]
Slope in [%]
0-20
20-40
>40

(c)

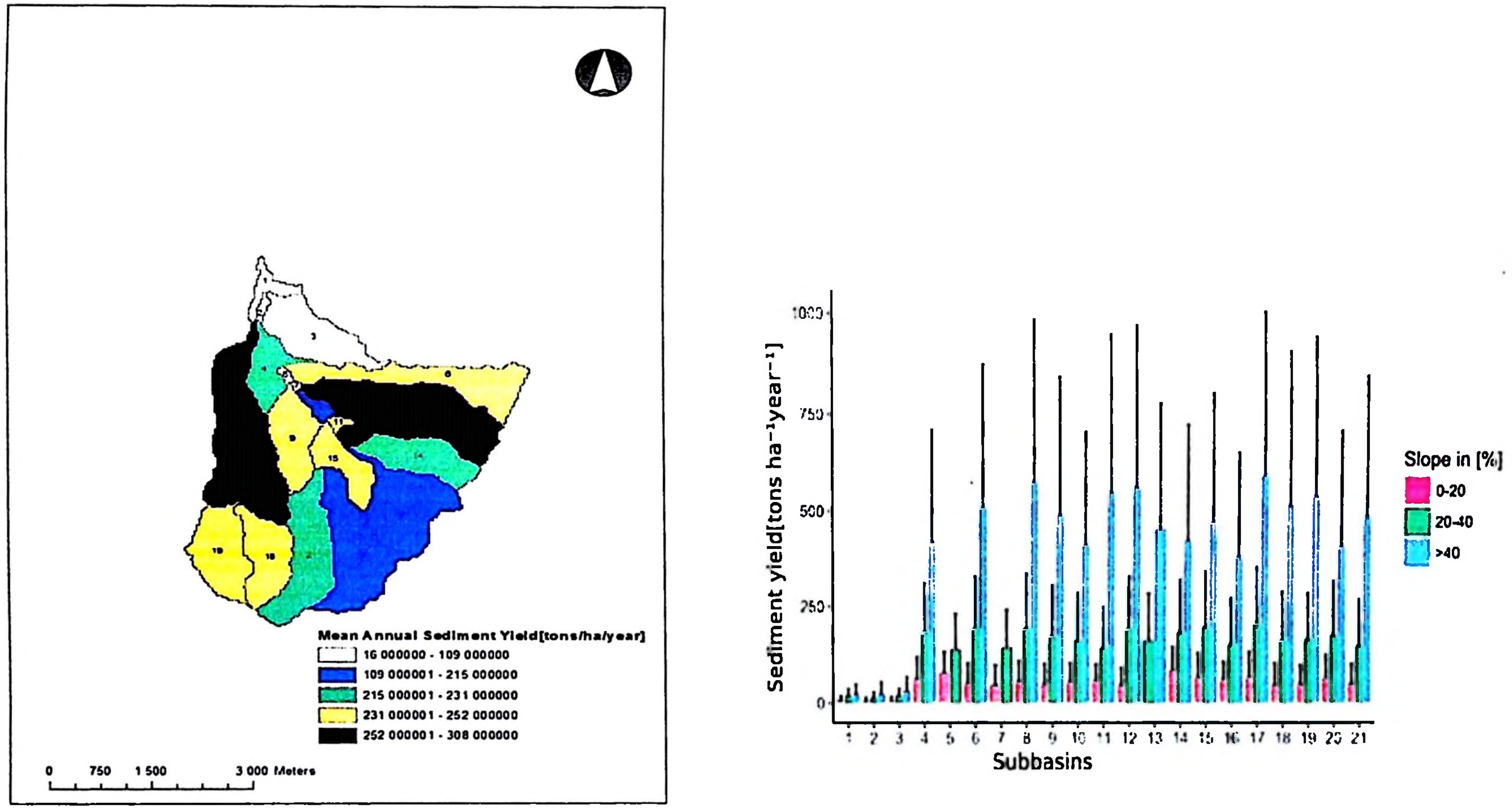

Urban
Sediment yield[tons ha⁻¹year⁻¹]
150
100
50
0
Slope in [%]
0-20
20-40
>40

(d)



(e)

Figure 4.2.6: Sediment yield by land-use type: (a) agriculture (b) evergreen forest (c) deciduous forest (d) urban sand (e) pasture in the Morogoro catchment.



(a)

(b)

Figure 4.2.7: The prevailing sediment processes in Morogoro catchment (a) Erosion hotspot areas and (b) mean annual sediment yield in various slope ranges

4.3 The impact of SWC measures on water flow and sediment yield

4.3.1 Simulating the impact of SWC scenarios on water flow

Simulation results demonstrate that implementation of SWC measures would potentially affect water balance components (Table 4.3.1). While the scenarios S2, S3 and S4 would significantly reduce surface runoff, increase groundwater flow and lateral flow; S1 would have less impact. This is attributed to a relatively small area that was put under that scenario during simulation (Table 3.3). Fanya juu terracing (S2) would reduce surface runoff by 9% and would increase both lateral flow and groundwater flow by 1 % and 5 % respectively (Figure 4.3.1). On the other hand. Bench terracing (S3) would reduce surface runoff by 19% and increase both lateral flow and groundwater flow by 5% and 8% respectively. A combination of fanya juu and bench terraces (S4) would improve the effectiveness whereby surface runoff would be reduced by 27% proportional with increase of lateral flow and groundwater by 6% and 13% respectively. This is attributed to the fact that the area under SWC would be increased to 90% of the total agricultural area following this combination (Figure 4.3.2). Similar studies show the same trend of impact of terraces and contour ridges/bunds on water balance. For example, Schmidt and Zemadim (2013) found that implementing terraces in areas with slopes >5% and contour bunds in areas with slopes <5% would reduce surface runoff by 50% and increase groundwater by 15%. Furthermore, Mwangi (2011) found that implementation of bench terraces would reduce surface runoff by 22%, increase later flow and groundwater by 3% and 10% respectively. Krois and Schulte (2013) reported that terraces and contour bunds would reduce overland flow by 19% and 12% respectively. It is important to understand that there are differences in findings between this study and other similar studies especially on the magnitude of percentage change of water balance components per scenario simulated. Such differences are attributed to the fact that the studies were conducted in different regions of the world whereby catchment characteristics in terms of water flow, climate, topography, land-use and soils are different.

Table 4.3.1: Water balance components under various SWC scenarios (mm)

	Baseline	S1	S2	S3	S4	S5
Precipitation			1840			
Surface runoff	202	199	185	164	147	144
Lateral flow	403	404	409	423	429	429
Groundwater flow (Baseflow)	191	194	201	206	216	219
Total Water Yield	821	820	820	819	818	817
Evapotranspiration	911	910	910	910	910	910
Potential Evapotranspiration			1500			

S1 = Contour farming, S2 = Fanya juu terracing, S3 = Bench terracing, S4 = Fanya juu + Bench terracing, S5 = Contour farming+ Fanya juu terracing + Bench terracing.

The reduction of surface runoff and increase of lateral and ground flows are attributed to increased infiltration rate caused by terracing. Terraces impound water into small depression thus allowing water to infiltrate into the soil in a more effective way. They also reduce peak flow rate owing to reduction in slope length (Arabi et al., 2008). The increased infiltration leads to the increase in groundwater recharge which in turn increases groundwater contribution to stream flow. The significant reduction of surface runoff also demonstrates the role of terraces in flood control as much of the flood water will be impounded and allowed.to infiltrate into the soil.

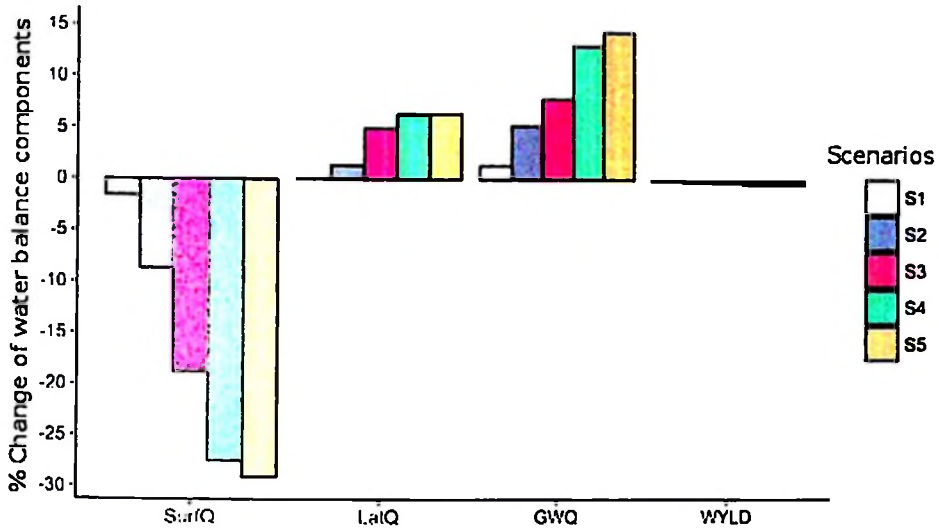


Figure 4.3.1: Relative impact of implementing SWC scenarios on water balance (SurfQ = surface runoff, LatQ = lateral flow, GWQ = groundwater flow, WYLD = water yield, S1 = Contour farming, S2 = Fanya juu terracing, S3 = Bench terracing, S4 = Fanya juu + Bench terracing, S5 = Contour farming+ Fanya juu terracing + Bench terracing)

Although fanya juu (S2) and bench terraces (S3) both have significant effect on water balance components through increased infiltration, they differ in effectiveness (Figure 4.3.1). Generally, the effectiveness of terraces is enhanced by the maintenance operations. If terraces are not regularly maintained, they become less effective (Arnáez et al., 2015). According to Hurni (1986) fanya juu terraces are effective in retarding surface runoff in areas with slope up to 49% beyond which the terraces will collapse during peak runoff events. This is because the embankment of fanya juu terraces develops from the soils being thrown and piled up during construction of a trench. Such piled soils should be stabilized by planting some grass plant species and require regular maintenance. Thus, the strength of embankment of fanya juu terraces will depend on maintenance operations and the quality of soil and plant materials used. Bench terraces may develop from either fanya juu terraces (but sometimes it may not be the case depending on maintenance, or may take long time depending on the runoff /sediment process) or by digging out the hill slope. The embankment of a constructed bench terrace is made of the wall created in the soil during the digging processes. It can be stabilized by stones, bricks or with strips of grass (cf. Arnáez et al., 2015). This suggests that the bench terrace embankment is stronger than that of fanya juu terraces. But the former has also some limitations, they are only effective in areas with slopes up to 55% (Widomski, 2011). It was because of such reasons that fanya juu terraces were simulated in HRUs with slope of 20-40% and bench terraces in HRUs with slope >40% thus covering disproportionally different percentages of the agricultural area.

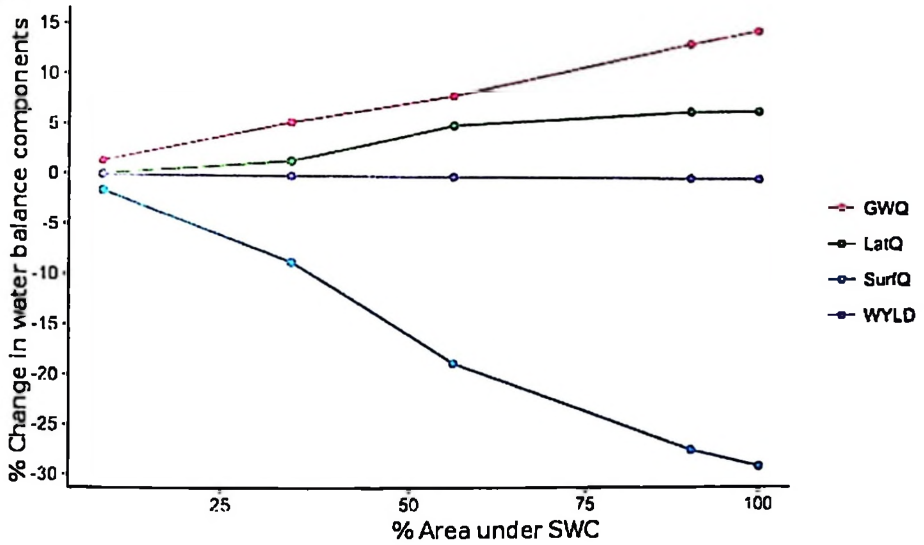


Figure 4.3.2: Effect of area under SWC on percentage change of water balance components (SurfQ = surface runoff, LatQ = lateral flow, GWQ = groundwater flow, WYLD = water yield)

Scenario 5 which assumes that 100% of the agricultural area (Figure 4.3.2) is put under SWC measures through implementation of S1, S2 and S3 seems to have the highest level of impact on water balance. If implemented S5 would reduce surface runoff annually by 29%, increase groundwater flow by 14% and increase lateral flow by 6%. This is attributed to the cumulative impact of the three scenarios. The distribution of the three SWC methods across the slope gradients of the catchment, reinforces the capacity of the catchment to retard the surface runoff through increased infiltration. The in-coming rainfall water will be allowed to run off after the soil becomes fully saturated. The surface run-off generated from upstream sites will further be reduced as it moves down to the channel. This is because the SWC structures are located strategically to match with the topographical setting of the catchment and thus achieving the highest surface run-off reduction which in return also leads to highest increase in groundwater storage. In many parts of the world, groundwater is the most reliable source of freshwater (UNESCO, 2012). Therefore, increasing groundwater is of great benefit to Morogoro catchment which has over last 40 years experienced a decline in streamflow (Yanda and Munish, 2007; Ludovic, 2012).

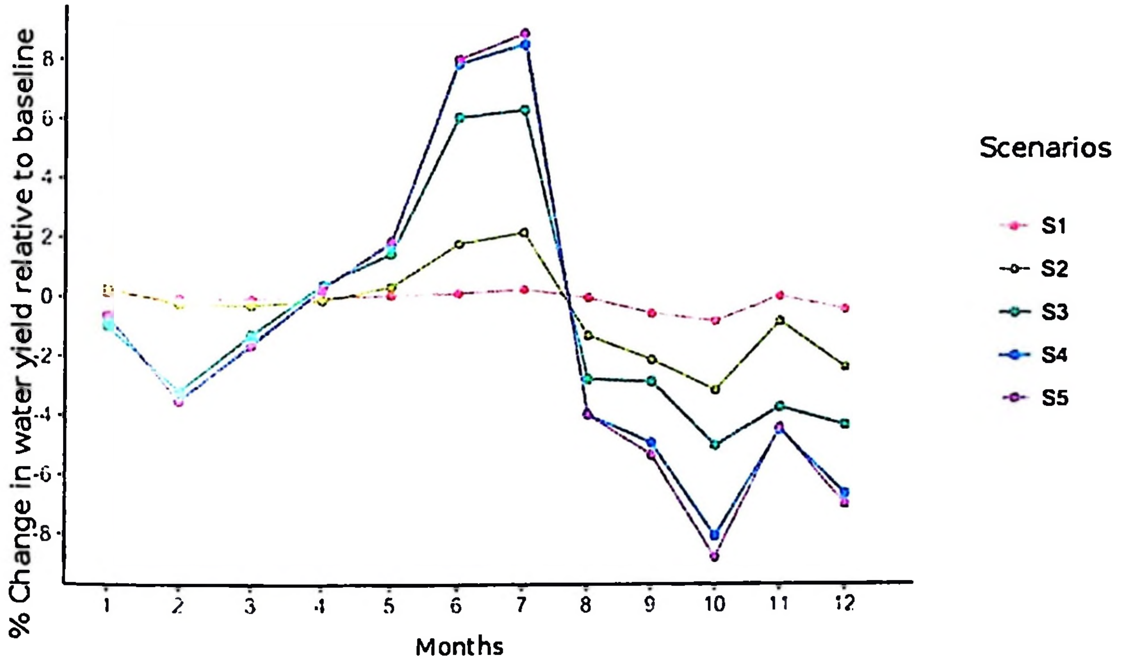


Figure 4.3.3: Seasonal variations in percentage change of water yield under SWC scenarios (8 years monthly averages, from 2007 - 2014). S1 = Contour farming, S2 = Fanya juu terracing, S3 = Bench terracing, S4 = Fanya juu + Bench terracing, S5 = Contour farming+ Fanya juu terracing + Bench terracing.

Despite all the benefits that would be gained through implementation of SWC scenarios, there would be no overall gain in water yield. Based on annual catchment values, water yield decreases in each scenario (Figure 4.3.1). Similar results were found in other studies (e.g. Mwangi, 2011; Schmidt and Zemadim, 2013; Krois and Schulte, 2013; Guzman et al., 2017). In Figure 4.3.2, water yield decreases proportionally with increase in percentage area under SWC.

The decrease in water yield despite increased infiltration and increased groundwater is attributed to water uptake by plants and subsequent losses through evapotranspiration. The infiltrating water is instantly absorbed by plants (Krois and Schulte, 2013). Figures 4.3.1 and 4.3.3 demonstrate temporal scale impact on water yield. While annual catchment values indicate a decrease in water yield in the range of 0.0% - 0.4% for all scenarios, monthly values reveal a different pattern of water yield among the SWC scenarios (Figure 4.3.3 and Table 4.3.2). The monthly values suggest that there are seasonal variations in percentage change of water yield characterized by rise and fall cycles. The peak increase in water yield is observed in the months of June and July. As this is the dry season, increase in water yield is attributed to the increased groundwater storage. Furthermore, evapotranspiration losses are reduced as there is no rainfall interception (evaporation of intercepted water), thus soil evaporation is the dominant process accounting about 80% of evapotranspiration losses (Krois and Schulte, 2013). During the rainy season (January – April and October – December), water yield reduces significantly. This is attributed to high interception (evaporation losses) and transpiration losses from plants which are predominantly forest and maize. Forest land cover occupies about 45% of the catchment area, while maize (agriculture land-use/land cover) covers 47% of the catchment. Pasture land cover (1.7%) also contributes to interception losses. Therefore, implementation of selected SWC scenarios would not increase water yield during the rainy season but rather reduces it. Although SWC methods increase water infiltration and percolation into the soil owing to reduced surface runoff, the overall catchment water yield would be adversely affected by evapotranspiration losses. However, increase in crop yield would be realized due to increased water and nutrients availability in the soil. Looking at the benefits and effect of S4 and S5 scenarios, it suffices to say that there are no significant differences between the two. While the benefits brought by S4 require SWC investment in 90% of agricultural area, S5 requires 100% of the area.

Table 4.3.2: Monthly percentage change (%) in water yield per simulated SWC scenario

Month	S1	S2	S3	S4	S5
1	0.1	0.3	-1.0	-0.7	-0.6
2	-0.1	-0.3	-3.2	-3.5	-3.5
3	-0.1	-0.3	-1.3	-1.6	-1.6
4	-0.0	-0.1	0.4	0.30	0.3
5	0.1	0.4	1.5	1.8	1.9
6	0.1	1.8	6.1	7.9	8.0
7	0.3	2.2	6.4	8.6	9.0
8	0.0	-1.3	-2.7	-4.0	-4.0
9	-0.5	-2.1	-2.8	-5.0	-5.3
10	-0.8	-3.1	-5.0	-8.0	-8.8
11	0.1	-0.8	-3.7	-4.5	-4.4
12	-0.4	-2.3	-4.3	-6.6	-7.0

S1 = Contour farming, S2 = Fanya juu terracing, S3 = Bench terracing, S4 = Fanya juu + Bench terracing, S5 = Contour farming+ Fanya juu terracing + Bench terracing.

4.3.2 Simulating the impact of SWC scenarios on sediment yield

In this section, sediment yield reduction benefits of contour farming, fanya juu terracing and bench terracing are described. While the reduction of surface runoff translates into increased infiltration thus affecting water flow components, it also leads to reduction of sediment yield in the sediment model. The findings indicate that sediment reduction followed the order: contour farming < fanya juu terracing < bench terracing. The size of the agricultural area covered by a given SWC scenario and its effectiveness in retarding surface runoff and trapping sediments, determined the magnitude of the impact brought by the SWC measure being simulated.

Simulation results show that the model successfully demonstrated what would be the effect of each SWC scenario relative to the baseline. Table 4.3.3 gives the simulation results at HRU scale, particularly sediment yield among HRUs in different slope ranges under each simulated scenario. The results indicate a wide range of standard deviation from the annual mean values implying the presence of variations in model predictions. The variations are more pronounced in HRUs with slope >40%. This is attributed to the spatial heterogeneity of topographical and geomorphological features (Kimaro et al., 2008) in the catchment especially the slope percentage, slope shape, slope length and steepness. These are among of the factors determining the magnitude of sediment yield simulated by sediment models. Soil properties also account for the observed variations. Although in the soil data base the catchment is characterized by one soil type, Haplic Acrisols with a sandy clay textural class, it has varied proportions of sand. This explains why it was subdivided into sand-rich and sand-poor Haplic Acrisols (section 3.2.2.). Sand-poor soils have a relatively higher proportion of fine particles which according to Wischmeier and Smith (1978) have a higher erodibility factor than sand-rich soils. Thus, Sand-poor Haplic Acrisols are eroded more easily than Sand-rich Haplic Acrisols.

Table 4.3.3: Mean annual sediment yield of HRUs in different slope ranges under various SWC scenarios for the simulation period (tons ha^{-1})

Scenario	Slope	Mean	SD	SE
Baseline	0-20	52	51	0.1
	20-40	155	128	0.3
	>40	443	363	1.7
S1	0-20	26	26	0.1
	20-40	155	128	0.3
	>40	443	363	1.7
S2	0-20	52	51	0.1
	20-40	18	16	0.0
	>40	443	363	1.7
S3	0-20	52	51	0.1
	20-40	155	128	0.3
	>40	58	51	0.2
S4	0-20	24	20	0.1
	20-40	37	44	0.1
	>40	58	51	0.2
S5	0-20	26	26	0.1
	20-40	18	16	0.0
	>40	58	51	0.2

SD = Standard Deviation, SE = Standard Error

Figure 4.3.4 shows the HRU scale (and catchment scale in parenthesis) results in which contour farming (S1) would reduce sediment amount by 50% (0.9%) while fanya juu terraces (S2) would reduce sediment yield by 88% (15%). Bench terraces (S3) would reduce sediment production by 87% (69%). A combination of fanya juu and bench terraces (S4) would potentially reduce sediment output by 84% (84%); while a combination of contour farming, fanya juu terraces and bench terraces (S5) covering the entire agricultural area, would reduce sediment export by 84% (85%). Other studies also indicate that implementation of such SWC measures would reduce sediment yield. Although contour farming appears to have less impact in this study owing to the topography of the studied catchment which restricts contour farming scenario only to areas with slopes ≤ 20 %, other studies have demonstrated that it can effectively reduce sediment yield at watershed scale (e.g. Gassman et al., 2006; Arabi et al., 2008; Brunner et al., 2008; Quinton and Catt, 2004). Mwangi (2011) found that contour farming would reduce sediment loading by 49%. Contour bunds reduce surface runoff and hence reduction of erosive power of water. Thus, less soil is eroded and some of the eroded particles are trapped in the contour bunds.

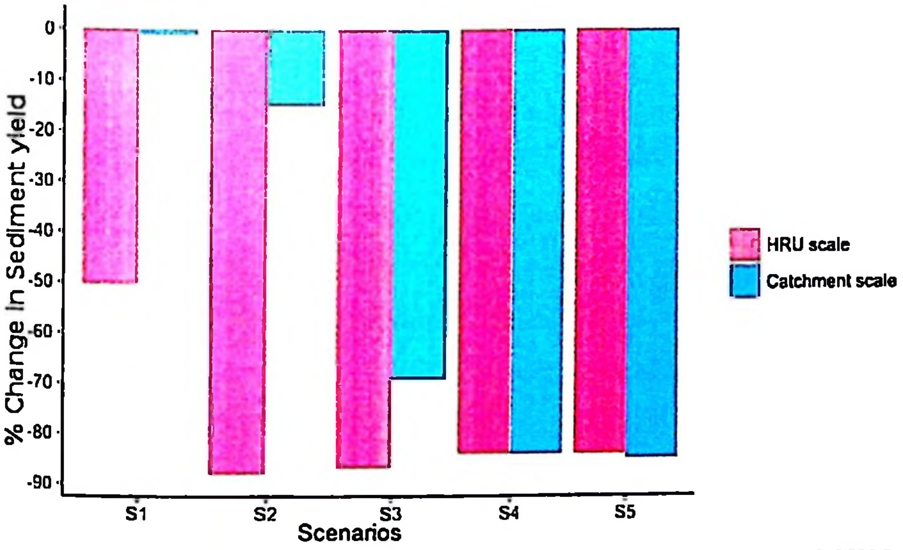


Figure 4.3.4: Relative change (%) in sediment yield per simulated SWC scenario (S1 = Contour farming, S2 = Fanya juu terracing, S3 = Bench terracing, S4 = Fanya juu + Bench terracing, S5 = Contour farming + Fanya juu terracing + Bench terracing)

Both fanya juu and bench terraces would significantly retard surface runoff which in turn reduces sediment yield (Figure 4.3.4). Generally, terraces are very effective in reducing sediment yield at catchment scale though the extent of reduction differ from one watershed to another due to differences in topography, climate, soils, type of terraces and maintenance operations. Many other studies have demonstrated the role of terraces in soil erosion control and reducing sediment yield (e.g. Chekol, et al., 2007; Arnáez et al., 2015; Mwangi, 2011; Arabi et al., 2008; Khelifa et al., 2017). A global review of terraces by Wei et al. (2016) found that the most prominent role of terracing is erosion control among other ecosystem services offered by terraced landscapes.

The effectiveness of bench terraces in sediment yield reduction is higher than that of fanya juu terraces. This is attributed to the difference in capacity to withstand peak runoff rates of various magnitude owing to the strength of terrace embankment. Furthermore, bench terraces were simulated in areas with slope >40% which covers a larger area than that of fanya juu (Figure 4.3.5). A combination of fanya juu and bench terraces (S4) covers a big portion of the agricultural area hence increases sediment yield reduction. This combination covers 90% of the total agriculture area. Since agriculture is the main sediment contributor at the river outlet, covering 90 % of the area would reduce sediment yield to a higher degree. The highest sediment reduction would be achieved by combining contour farming, fanya juu terracing and bench terracing (S5). This would cover 100% of the agricultural area (Figure 4.3.5). However, implementing this scenario does not make much difference with that of S4. As noted in previous section on water balance, the benefits of S4 are nearly the same as those of S5. To implement S5 and obtain the associated benefits, 100% of the agriculture area will have to be put under SWC interventions while for S4 only 90% of the area will be converted into SWC.

Results further indicate that S1and S2 reduce considerably large amount of sediments at HRU scale, but seem to have less impact at catchment scale. This is attributed to the size of the area covered by the scenario (Figure 4.3.5). Sediment yield is reduced at specific sites where the scenario is being implemented only. Areas not covered by the particular scenario remain unchanged. Thus, at catchment scale, an average sediment yield value for all HRUs is computed. Since the agriculture land-use is the main source of sediments in the catchment, the impact of reducing sediment yield within the agriculture land-use will be reflected at catchment level. From Figure 4.3.5, it is evident that the relative percentage change in sediment yield at catchment scale increases with the percentage increase in agricultural area under SWC. S4 and S5 show that the sediment reduction at HRU scale equals to the reduction at catchment scale. This is attributed to the fact that both scenarios cover almost the entire agriculture area. Therefore, all the HRUs within agriculture land-use are impacted by the SWC intervention and thus lowering the catchment wide sediment yield average.

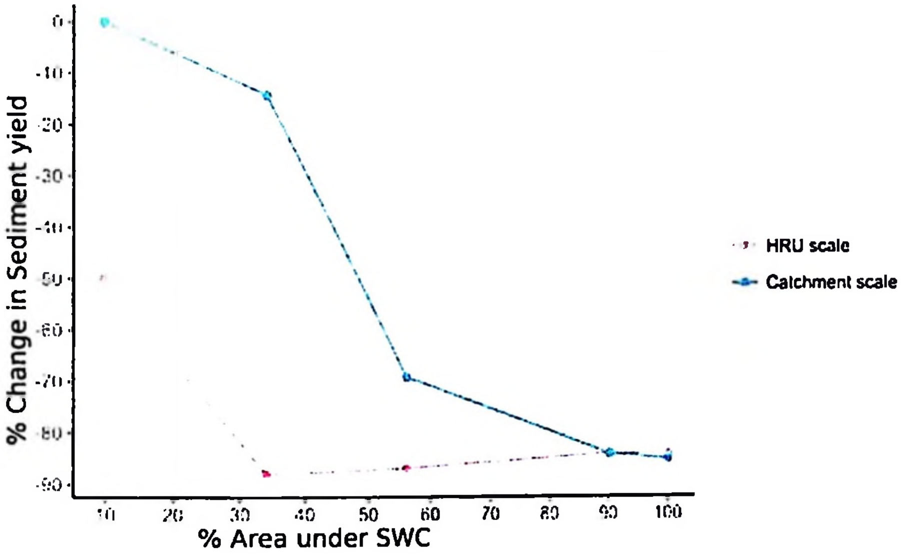


Figure 4.3.5: Effect of percentage of agricultural area converted into SWC on relative change in sediment yield.

Chapter 5: Conclusion, Outlook and Recommendations

5.1 Conclusion

Unsustainable land management practices which do not consider soil and water conservation are the main drivers of land degradation. Soil erosion by water is the most common form of land degradation in which the land loses its capacity to perform key functions such as a conduit of water and nutrients fluxes through hydrological and biogeochemical processes. Land degradation also leads to watershed deterioration in terms of its ability to provide water (quality and quantity). It is in that context, that this thesis was formulated with the overall objective of simulating and assessing the impact of SWC measures on water flow and sediment yield. It contributes to watershed management in Morogoro catchment and in Tanzania at large.

The findings on SWC adoption suggest that the sustainability of the studied catchment is in jeopardy. Very small and insignificant portion of farm households practice SWC methods, which are deemed to protect the catchment. Despite some initiatives to introduce SWC measures in the past, adoption rate has been decreasing following termination of the projects. This suggests that there is a need for a long-term plan that continuously involve farmers and empowers them to implement SWC methods. Soil erosion does not only affect rivers and water bodies through siltation, but also affects the livelihoods of farmers. Soil erosion washes away plant nutrients leading to poor agricultural production. This will exacerbate poverty and food insecurity among farm households many of whom depend on agriculture for their livelihoods. Consequently, there will be more degradation of the catchment ecosystem as farmers try to look for alternative livelihoods. Smallholder farmers are an integral part of integrated watershed management (cf. Mwangi et al., 2015a). failure to involve them and persistently monitor their activities in the watershed leads to watershed degradation as what is happening in the studied catchment. They conduct unsustainable farming activities upstream of the river which affect downstream users.

The goal of watershed management is to ensure the sustainable supply of water in adequate quality and quantity. Implementation of SWC scenarios as shown in the modelling results would help to control soil erosion, hence protecting the soils and plant nutrients which are important for smallholder farmers who live and conduct farming activities in the upstream part of the catchment. This would increase food production and thus increasing the food security and income of farm households. If well sustained and closely monitored such benefits brought by

SWC can be an incentive for farmers to continue implementing the soil and water conservation methods and the adoption rate may increase. For example, Lopa et al. (2012) reported improved agricultural production as an incentive for farmers to adopt bench terraces and Fanya juu terraces in Kibungo juu, Uluguru Mountains. Furthermore, the reduction of sediment yield reduces siltation of the river and reservoirs, hence reducing water treatment costs by water supply authority (e.g. MORUWASA for Morogoro municipality). SWC methods also reduce surface runoff, an important hydrological process. By reducing surface runoff to a high degree, the SWC measures (especially terraces) play a key role in flood control as they facilitate the infiltration of the flood water into the soil. In so doing, they save lives and properties. Moreover, reduction in surface runoff translates into increased infiltration and percolation into shallow aquifers which contribute to groundwater recharge. Increased groundwater storage increases water discharge during the dry season, this in turn contributes to the sustainability of Morogoro river, making water to flow throughout the year hence continuing to provide water supply and other ecosystem services.

5.2 Outlook

The methodology applied in this thesis has demonstrated the role of interdisciplinary approach in addressing a research problem related to water resources management. Like other common pool resources, water resources management requires participatory approach which involves a wide range of stakeholders (cf. Mwangi et al., 2015a+b). Riparian communities comprising of smallholder farmers are primary stakeholders in water resources management, hence any intervention geared towards improving the resource management must involve them. The social science approach in analysing adoption of soil and water conservation by small holder farmers augmented the hydrological modelling work which applies natural science, notably geoscience principles (hydrological and sediment processes). In practice, some hydrological modelling studies that simulate the effect of land management practices on catchment processes do not incorporate the analysis of adoption level of such management practices by farmers (e.g. Arabi et al., 2008; Krois and Schulte, 2013; Schmidt and Zemadim, 2013). Understanding the extent of SWC adoption by farmers in the study catchment enables the modeler to describe the baseline conditions adequately and the likely land management scenarios to be simulated by the model. Thus, before embarking on the modelling work with SWAT, this study examined the existing SWC methods, the extent of their adoption by farmers and factors influencing the adoption. This was important step because the modelling work built on the existing SWC measures which are already known to the farmers. Parameterization of the study catchment for SWAT was done to build water flow and sediment models for simulating the baseline conditions which was later followed by simulation of SWC impacts by adjusting some relevant parameters.

The approach employed in this study is transferable to other sites with problems comparable to the Morogoro catchment in Tanzania. In particular, the built hydrological model can be transferred to other catchments within Uluguru Mountains many of which are ungauged. Thus, the same parameters and their optimal values used to build the water flow model for Morogoro catchment can be transferred to other nearby catchments which are ungauged but have similar topographic, climatic, soil and land-use characteristics to that of the studied catchment. Furthermore, some of gauged catchments do not have well monitored and properly recorded water flow data needed to construct hydrological models. Therefore, the water flow model built in this thesis provides enabling environment for further hydrological modelling studies in Morogoro catchment and Uluguru Mountains at large. In absence of water quality monitoring data, the constructed sediment model can be a suitable decision supporting tool for watershed managers and policy makers for catchment protection and water quality improvement. The study on factors affecting adoption of SWC measures by smallholder farmers provides some insights into watershed management, particularly on how to implement the simulated SWC scenarios.

5.3 Recommendations

Based on research findings described in chapter 4 and their conclusions, some recommendations can be devised. The recommendations address researchers, practitioners (watershed managers) and policy makers. As discussed in this thesis, the water flow and sediment models had some limitations due to uncertainty of observed water flow data, soil data and lack of observed sediment data. The developed models can be improved by estimating the soil input parameters using PTFs for tropical soils. Where possible the PTFs for Tanzanian soils should be used (if at all they exist). It is worth also to note that, the plant database (land cover) used in this thesis was based on SWAT default values for plant growth parameters which were meant for temperate plants. But the catchment studied is located in the tropical region whose soils and plants might behave differently. Thus, adjusting the plant growth parameters to reflect tropical plants might improve the model performance as plants play a key role in the hydrological cycle, notably through the evapotranspiration process. The sediment model can be improved by establishing a water quality monitoring scheme involving sediment load/ concentration data collection for at least two years on weekly basis including a compulsory water sample collection after every rainfall event. Funds for the monitoring scheme can be sourced from various grant makers. This will generate some observed data which will be used to calibrate and validate the sediment model. Furthermore, some improvements are needed in water discharge monitoring. In particular, the installation of data loggers at the gauging station will reduce errors in computing daily water discharge, hence improving the water flow model for Morogoro catchment. The SWC scenarios simulated in this thesis were based on baseline land-use and climatic conditions. Since land-use change and climate variability (or change) are the main drivers of change in stream flow (Mwangi et al., 2016), the SWC scenarios may be modified to incorporate land-use change and climate change scenarios. Land-use change scenarios such as deforestation and afforestation of agricultural land have implications on both water quantity (supply) and quality. On the other hand, climate change scenarios demonstrating changes in rainfall patterns in the catchment would provide some insights on the suitable SWC scenarios to be considered for climate change adaption. Therefore, it is important to understand how the water resources would be affected by such scenario settings. Because adverse impacts from any of the scenarios would jeopardize people's livelihoods.

Implementation of the simulated SWC scenarios requires technical and financial support as the smallholder farmers cannot afford the costs involved. Owing to catchment topography which is characterized by steep slopes, fanya juu and bench terraces should be implemented. Presently, there are no reliable mechanisms to finance SWC activities in Tanzania. Payment for ecosystems services scheme appears to be one of the options to finance catchment protection activities (Asquith et al., 2008; Ferraro, 2009; Drechsler et al., 2010; Lopa et al., 2012; Mwangi et al., 2015b). In such a scheme, smallholder farmers upstream of the watershed are paid for implementing SWC measures in their farms. The challenge is, who will be the buyer of the services? The Wami-Ruvu Basin Water Board which has a legal mandate to oversee all the activities in the Ruvu basin of which Morogoro catchment is part, is the primary potential buyer of the services. The Board regulates water use and management activities in the basin. It offers water use permits to various categories of users who pay water abstraction fees. MORUWASA which supplies water to Morogoro municipality, is another potential buyer of water services from the upstream farmers. The implementation of SWC measures is particularly important for MORUWASA because will reduce water treatment costs owing to reduced sediment load in the water. The Wami-Ruvu Basin Water Board like other Basin Water Boards in Tanzania has budgetary constraints. Thus, they are unable to fund SWC activities adequately. Most of the watershed management activities in the Water Basins of Tanzania are dependent on donor funding, hence making them unsustainable. Because once the donor funding ends, the watershed management activities stop too. Looking at the importance of water resources to the national economy and to the people's well-being, the Tanzanian government should establish a national water fund which will finance watershed management activities in the country through the Water Basin Boards. The establishment of such a fund will not be novel. In other sectors similar funds exist, e.g. the national forest fund and the national wildlife protection fund. However, the current Tanzanian water policy which was formulated in 2002, has no provision for the national water fund establishment with a purpose of financing watershed management activities. Moreover, the Water Resources Management Act, 2009 does not mention such a fund. Thus, there is a need for policy and legal reforms to incorporate formulation of the fund which is not only important for funding water resources management activities. but also water related research activities.

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Appendix 1: Farmers' Questionnaire

Village/Hamlet:.................................	**Watershed name: ....**
Name of Enumerator..................................	**Date:.......................................**

A: RESPONDENT CHARACTERISTCIS (Head of Household)

A1 Age :..............................	A2 Gender 1= Male, 2= Female
A3 Education 1= No formal education 2= Primary education 2= Post primary vocational education 3= Secondary 4=Post secondary vocational 5= Tertiary education	A4 Main activity of the head of household Farming ....1 Fishing..................2 Firewood ....3 Charcoal...............4 Timber.................5 Employee..............6 Own business.........7 Not active ....8 Other (specify) 9

B: HOUSEHOLD SIZE AND INCOME

B1 How many adults in the household? . People able to work in the farm (from the age of 15)................

B2 How many children in the household?................

B3 What is household annual income? ....

C: LAND ONWERSHIP AND AGRICULTURAL PRODUCTION

C1 Do you own a piece of land for agriculture?
1= Yes 2= No

C4 Do you apply irrigation in your agricultural land

Yes.....1
No......2

C2 (a) How big is your farm?
1 =less than a acre 2= 1 acre 3= 2 acres 3= 3 acres 4 = 4 acres and above
(b) Where is your farmland located.......................
(c) Is your farmland far from home?
1= YES
2 = NO

C3 If you don't have land for agriculture on which land do practice agriculture
1= rented land with cash payment 2= rented land in exchange of labour provision 3= rented land with payment in kind 4= rented land with nothing to give back. 5 = Other (specify)..................

D: Housing

D1 What building materials were used for the walls of the household's main dwelling?

Burn brick/cement 1
Mud/mud brick............2
Poles and mud 3
Poles, braches, grass.......4

D2: Household items

ITEM	
Bicycle	
Radio	
Motor cycle	
Mobile phone	
Watch	

E : PERCEPTION ON THE EFFECT OF SOIL EROSION

In General , what do you think could be the effects of soil erosion to your farm and the river downstream?

Don't know...............1

Pollution of rivers.......2

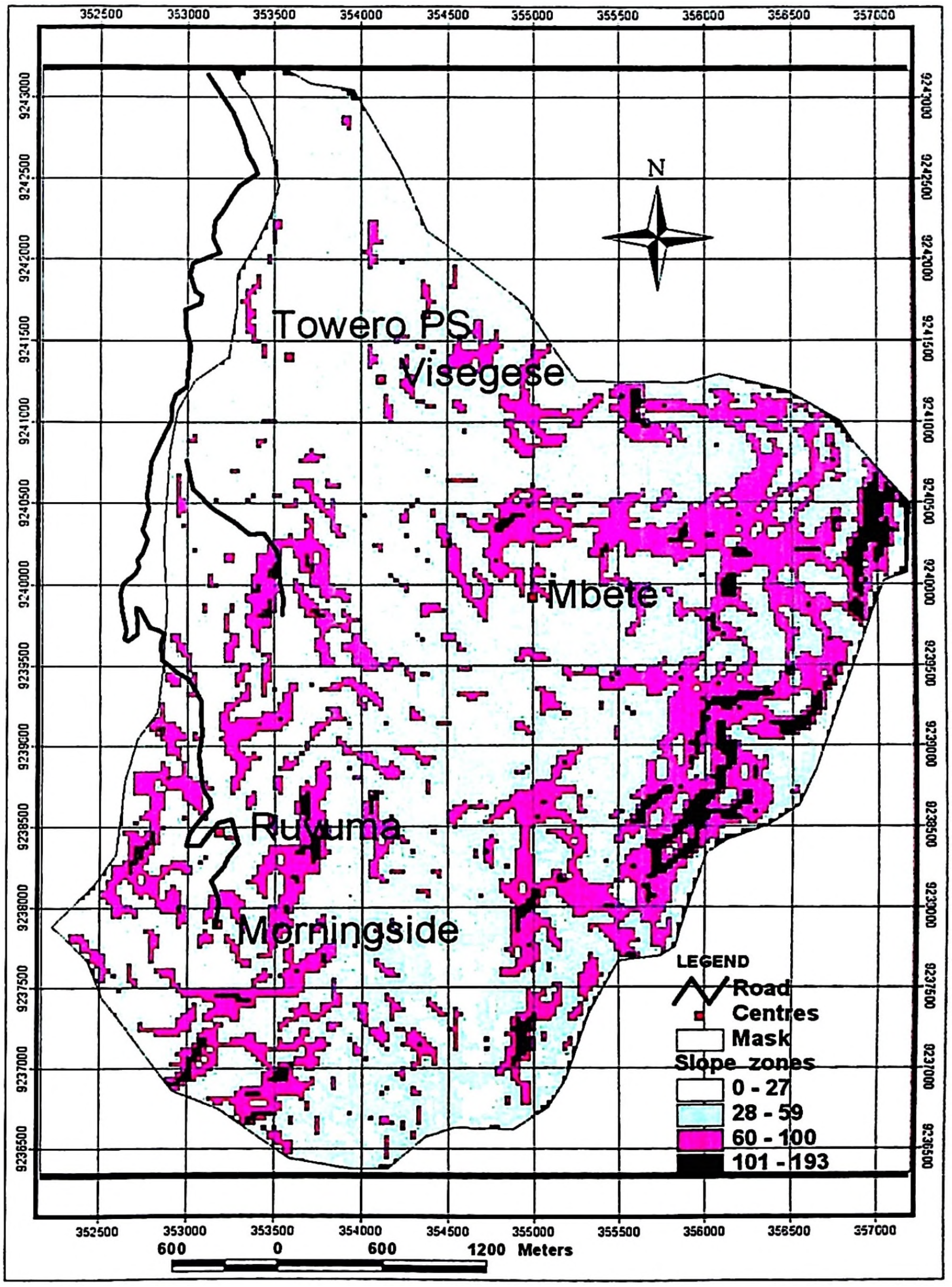
Loss of Nutrients in farmlands.......3 **F: SOIL AND WATER CONSERVATION (SWC) EXPERIENCE**		
F01: Do you practice SWC in your agricultural activities	1= No (if No then go to question F04) 2= Yes If you practice go to **F02**	
F02 Which SWC methods do you practice?	Fanya juu	
	Contour farming	
	Bench terracing	
	Buffer strips	
F03 Where did you learn the SWC method you practice? *(Tick all that apply)*	From parents/relatives	
	From other farmers	
	Government Extension officers	
	NGO Extension officers	
	Researchers from SUA and other places	
F04: Why don't you practice SWC in your farm? *(Till all that apply)*		
	It is time consuming requires much labor	
	It is just expensive, can't afford	
	Because I want to stick to our traditions	
	If I apply SWC in my farm much land is wasted and will plant crops on a small area	

	I have e no skills	
F5. Do you currently receive support for SWC	Yes.............1, No................2	
Describe(below)		

From whom	Provides support 1=Yes 2=No	In what form			How often (mention the most dominant frequency)
		1.Extension services	2.In-kind (implements: seeds, tools)	3.Cash	
NGOs					
Government					
Government Agency					
Church					
Private companies					
Financial institutions					

THANK YOU FOR YOUR COOPERATION

Appendix 2: Base map used during farmers' interviews



Appendix 3: USLE_P values for contoured and terraced areas

Condition	Slope range (%)	P factor
Strait Row	0-25	1.00
Contour	0-2	0.90
Contour	2-5	0.80
Contour	5-8	0.70
Contour	8-12	0.60
Contour	12-16	0.50
Contour	16-20	0.50
Contour	20-25	0.60
Terraced	0-2	0.12
Terraced	2-8	0.10
Terraced	8-12	0.12
Terraced	12-16	0.14
Terraced	16-20	0.16
Terraced	20-25	0.18

Source: Haan et al. (1994)

Appendix 4: Soil properties results from field campaign conducted in February 2015

(a) Mean soil particle size distribution (mass%) in various land-use types

Land-use	Sand (%)	Silt (%)	Clay (%)
Forest	49.6	16.7	33.7
Wooded grassland	54.8	14.4	30.8
Vegetables	46.7	18.4	34.9
Mixed cropping	58.6	16.5	24.8
Maize	57.3	14.9	27.8
Flat cultivation	51.2	25.5	23.4
Contour ridges	68.1	12.3	19.6
Bench terraces	45.0	19.4	35.5

(b) Mean bulk density, porosity, organic matter content (OMC) and infiltration rate across land-use types. CV = coefficient of variatio

Land-use	**Bulk density (g cm^{-3})**	CV	Porosity (%)	CV	OMC (%)	CV	**Infiltration rate (cm h^{-1})**	CV
Forest	1.0	17.4	63.7	9.9	5.0	50.0	260	13.3
Wooded grassland	1.2	9.5	56.3	7.4	3.1	19.3	160	21.6
Vegetables	1.4	8.2	47.7	9.0	2.2	47.0	110	56.8
Mixed cropping	1.4	8.8	46.9	10.0	2.9	37.0	150	20.0
Maize	1.5	11.6	45.0	14.1	2.5	25.0	70	24.7
Flat cultivation	1.2	16.1	53.1	14.2	3.7	20.2	220	15.7
Contour ridges	1.3	6.6	49.0	6.8	1.8	6.9	100	34.6
Bench terraces	1.2	6.6	55.1	5.4	3.1	23.0	80	43.3

(b) Mean bulk density, porosity, organic matter content (OMC) and infiltration rate across land-use types. CV = coefficient of variation in

Land-use	**Bulk density** (g cm^{-3})	CV	Porosity (%)	CV	OMC (%)	CV	**Infiltration** rate (cm h^{-1})	CV
Forest	1.0	17.4	63.7	9.9	5.0	50.0	260	13.3
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Vegetables	1.4	8.2	47.7	9.0	2.2	47.0	110	56.8
Mixed cropping	1.4	8.8	46.9	10.0	2.9	37.0	150	20.0
Maize	1.5	11.6	45.0	14.1	2.5	25.0	70	24.7
Flat cultivation	1.2	16.1	53.1	14.2	3.7	20.2	220	15.7
Contour ridges	1.3	6.6	49.0	6.8	1.8	6.9	100	34.6
Bench terraces	1.2	6.6	55.1	5.4	3.1	23.0	80	43.3

Declaration on the Opening of the Doctorate Procedures

1. I hereby assure that I have produced the present work without inadmissible help from third parties and without aids other than those stated; ideas taken directly or indirectly from external sources are identified as such.

2. When selecting and evaluating the materials and also when producing the manuscript, I have received support from the following persons: Prof. Dr. Karl-Heinz Feger, Dr. Stefan Julich and Prof. Dr. Didas N. Kimaro.

3. No further persons were involved in the intellectual production of the present work. In particular, I have not received help from a commercial doctoral adviser. No third parties have received monetary benefits from me, either directly or indirectly, for work relating to the content of the presented dissertation.

4. The work has not previously been presented in the same or a similar format to another examination body in Germany or abroad, nor has it - unless it is a cumulative dissertation - been published.

5. If this concerns a cumulative dissertation in accordance with Section 10 Para. 2, I assure compliance with the conditions laid down therein.

6. I confirm that I acknowledge the doctoral regulations of the Faculty of Environmental Sciences of the Technische Universität Dresden.

Morogoro, 10.09.2017

Dominico Benedicto Kilemo